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Thermal Fatigue Durability for Advanced Propulsion Materials

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THERMAL FATIGUE DURABILITY FOR ADVANCED PROPULSION MATERIALS

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SUMMARY

A review is presented of thermal and thermomechanical fatigue (TMF) crack initiation life prediction and cyclic constitutive modeling efforts sponsored recently by the NASA Lewis Research Center in support of advanced aeronautical propulsion research. A brief description is provided of the more significant material durability models that have been created to describe TMF fatigue resistance of both isotropic and anisotropic superalloys, with and without oxidation resistant coatings. The two most significant crack initiation models are the cyclic damage accumulation model and the total strain version of strain range partitioning. Unified viscoplastic cyclic constitutive models are also described. A troika of industry, university and government research organizations contributed to the generation of these analytic models. Based upon current capabilities and established requirements, an attempt is made to project which TMF research activities most likely will impact future generation propulsion systems.

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INTRODUCTION

Background

Life cycle costs ranging from initial design costs to field replacement costs of limited durability component parts are the driving elements for improved analytic life prediction capability. Since life cycle costs are the highest for hot section gas turbine engine components, efforts have concentrated on durability problems in this area. Accurate calculation of expected service lifetimes is crucial to the final judgment to proceed with a particular design. Inaccurate life calculations result in overly expensive designs-either from an under utilization of potential or a lack of adequate life. Specific areas of primary concern are thermal and thermomechanical fatigue (TMF) crack initiation of both isotropic and anisotropic superalloys used in hot section turbine engine components.

ISOTROPIC MATERIAL MODELING

Cyclic Crack Initiation

The usable cyclic lifetime of turbine engine hot section components is spent in what is known as "cyclic crack initiation," i.e., cracks smaller than about 0.8 mm. Such a definition of cyclic crack initiation is used in the Cyclic Damage Accumulation (CDA) Model.

Cyclic damage accumulation (CDA) model. - The interaction of creep with fatigue at high temperatures has been studied in detail at Pratt & Whitney Aircraft by Moreno (ref. 1), Moreno, et al. (ref. 2), and Nelson, et al. (ref. 3) under contract to NASA. These efforts investigated engineering approaches to high temperature fatigue crack initiation life prediction using the cast nickel-base alloy, B1900+Hf(PWA 1455). Over 350 specimen tests of this superalloy were performed over the course of the program. A review of existing fatigue models was conducted, and desirable features of each were identified. A new method of high temperature fatigue life prediction called cyclic damage accumulation (CDA) subsequently was developed which incorporated many of these desirable features.

Complex loading conditions such as thermomechanical fatigue (TMF), multiaxial loading, cumulative damage, and imposed mean stresses, and the effects of complicating factors such as oxidizing environments and oxidation-protective coatings were factored into the program. Three different surface treatments were utilized: bare (no coating), overlay NiCoCrAlY coated, and diffusion aluminide coated. Several refinements have been incorporated into the CDA life prediction model based on the results of these tests. Nonlinear damage accumulation calculations are now possible for both cycle-dependent and time-dependent, cases. Modular terms which capture the effects of multiaxiality, coatings, and intergranular cracking have been developed, but have as yet to be published. The ability of the model to correlate TMF data is shown in figure 1 for coated B 1900+Hf. Complete details of test conditions employed are given by Nelson (ref. 3). Most of the TMF tests were performed at temperatures between 538 and 871 °C at one CPM with total mechanical strain ranges between 0.4 and 0.5 percent. Validation of the CDA model has been accomplished using test results from about 100 specimens of forged Inconel 718.

Total strain version of strainrange partitioning. - The strainrange partitioning (SRP) method for characterizing and predicting creep-fatigue behavior of alloys has long been associated with using inelastic strains to relate to cyclic life. Recent advances by Halford and Saltsman (ref. 4) and Saltsman and Halford (ref. 5) now permit the approach to be expressed in terms of total strain range versus cyclic life. The latter advance (ref. 5) permits an alloy to be characterized with reduced time and cost. These developments make the SRP method more attractive for application to life prediction of aeronautical gas turbine hot section components. Here, materials and loading conditions result in strain levels that, while they are severe and produce low-cycle fatigue cracking, involve only small amounts of inelastic deformation within nominally elastic strain fields. The limited inelasticity produced locally may exert a significant influence on life. The type of inelastic strains present (time-dependent creep and time-independent plasticity) and the direction of the strains (tension or compression) can be quite important in governing the resultant cyclic crack initiation life. The total strain based SRP approach (TS-SRP) has been developed to deal explicitly with the above conditions. A brief description is given below to show how the procedures are employed.

The total strain range, $\Delta\varepsilon_t$, is the sum of two terms, the elastic, $\Delta\varepsilon_e$, and the inelastic, $\Delta\varepsilon_i$, strain ranges. Each strain range is related to cyclic life by a power law relation as shown in equation (1) and figure 2.

$$\Delta\varepsilon_t = \Delta\varepsilon_e + \Delta\varepsilon_i = B\,(N_f)^b + C'\,(N_f)^c \qquad (1)$$

N_f is the cyclic crack initiation life for a zero mean stress condition. To apply equation (1) at high temperatures requires the experimental/analytical evaluation of the coefficients, B and C', and the exponents, b and c. It is assumed, initially, that b and c are constants for all conditions at a given temperature, i.e., they are time- and waveshape-independent, and B and C' are time- and cycle waveshape-dependent.

To determine C', as many of the four basic SRP inelastic strain range versus life relations, PP, CC, PC, and CP (P = Plasticity, C = Creep, first letter implies tension, second, compression), as are required for the cycle of interest must be known. How the inelastic strains are partitioned within the cycle must also be known, i.e., how much of each type of PP, CC, PC, or CP strain range is present in the hysteresis loop. Experimental procedures for establishing the four inelastic SRP life relations, techniques for approximating them, and experimental partitioning procedures are given by Hirschberg and Halford (ref. 6), Halford, et al. (ref. 7), and Manson, et al. (ref. 8), respectively. In principle, the partitioning and thus the determination of C' could be accomplished analytically using advanced cyclic constitutive equations such as those reported by Lindholm (ref. 9) and Ramaswamy, et al. (ref. 10). Advanced cyclic constitutive models are capable of computing the exact details of a stress-strain hysteresis loop, knowing only the imposed temperature, total mechanical strains, and how they vary with time for a representative cycle. Details of the inelastic straining rates are also computable, and hence creep strains (time-dependent) and plastic strains (time-independent) can be separated, i.e., partitioned. If a constitutive model is not available, an empirical approach can be used to determine C' and B. The governing equations are given by Saltsman and Halford (ref. 5).

To apply the TS-SRP approach, the specific mission cycles of interest are identified and the cyclic stress-strain-temperature history is determined at the critical location in the structural component. Then, the appropriate elastic and inelastic strain range versus life relations are calculated and added together to obtain the desired total strain range versus cyclic life curve shown in figure 2 (i.e., eq. (1)). Entering the curve with the known total strain range, the cyclic life is determined directly without having to calculate the magnitude of the inelastic strain range. Example life prediction calculations by the TS-SRP approach have been reported by Moreno, et al. (ref. 11). Figure 3 shows the degree of success of the method when applied to a series of five different types of complex verification experiments performed at 871 and 983 °C on the nickel-base superalloy, B1900+Hf The TS-SRP approach has recently been adapted to predict TMF lives, Saltsman and Halford (ref. 12). The key feature of the TMF approach is the introduction of what is known as a bithermal fatigue test. This type test is described in reference 12, and is used to approximate in phase and out-of-phase thermomechanical cycles in a much simpler, easier to interpret manner.

The SRP approach can be applied using any arbitrary definition of cyclic crack initiation. Most published SRP data have been reported for complete specimen separation, i.e., a crack initiation size of between 2 and 6 mm.

ANISOTROPIC MATERIAL MODELING

Constitutive Modeling

Because of the exceptionally strong link between the cyclic deformation mechanisms in single crystal alloys and the fatigue crack initiation process, it was deemed advisable to develop both the cyclic constitutive and cyclic crack initiation life prediction models within a single program. Furthermore, since single crystal alloys invariably require a protective coating for successful high-temperature applications, it was also necessary to develop a cyclic constitutive and life model for the coating systems. The constitutive models will be discussed in the following section.

Single crystal constitutive model. - A unified constitutive model has been formulated for PWA 1480 single crystal material and is currently in the final stages of development. The model uses the unified approach for computing all inelastic strain rather than the conventional approach of treating creep and plasticity separately. The model assumes that all inelastic behavior results from shear strains on each of the 12 octahedral and 6 cube slip systems and that the global inelastic strains are simply the sum of these slip systems strains. Slip system inelastic shear strain rates are governed by a set of viscoplastic equations which involve the slip system stresses and two evolutionary state variables. The general form of the equation governing inelastic shear strain on any given slip system has been given by Swanson, et al. (ref. 13). The model has been formulated to include several effects that have been reported to influence deformation. These include contributions from slip system stresses other than the Schmid shear stress, latent hardening due to simultaneous straining on all slip systems, and cross-slip from the octahedral to the cube slip systems.

A large body of isothermal constitutive data has been obtained at temperatures ranging from 427 to 1149 °C using uniaxial specimens oriented in the ⟨001⟩, ⟨011⟩, ⟨111⟩, ⟨123⟩ crystal orientations. The constitutive model constants have been determined from these isothermal tests. Figure 4 shows the calculated constitutive model behavior for two orientations at 871 °C for strain rates of 0.001 to 0.5 percent/sec. The model is currently being evaluated against the stress-strain response of TMF tests which were conducted for life modeling. The single crystal constitutive model as well as the coating constitutive model reported below are compatible with a commercially available finite element computer code.

Coating constitutive model. - TMF cracks in turbine airfoils of PWA 1480 material generally originate from a coating crack. Thus, for airfoil life prediction, it is important to model the coating mechanical behavior as well as that of the PWA 1480 substrate. Viscoplastic constitutive models are being developed for two fundamentally different coating types which are commonly used in gas turbines to provide oxidation protection: (1) a plasma sprayed NiCoCrAlY overlay coating, and (2) a pack-cementation-applied NiAl diffusion coating. The isotropic formulation of Walker (ref. 14) was chosen as the overlay coating constitutive model, based on its ability to reproduce isothermal and TMF hysteresis loop data reported in reference 13. The predicted overlay coating response of an out-of-phase TMF cycle is compared to data in figure 5. For these purposes, solid cylindrical specimens of coating material were cut from a billet prepared by hot isostatically pressing material powder. The diffusion coating constitutive model is currently under development, and will be more difficult to determine owing to the fact that it will be impossible to make solid specimens of stand-alone coating material.

Cyclic Crack Initiation

Directionally cast, anisotropic, nickel-base superalloys (particularly single crystals) exhibit greater creep-fatigue resistance than their conventionally cast polycrystalline counterparts. To take full advantage of these improved material properties, however, requires the development of accurate cyclic constitutive and life prediction models for these highly directional alloys. Direct modification of polycrystalline behavior models is inadequate, and a new approach that recognizes the micromechanisms of crystal response is necessary.

Coating and single crystal life prediction model. - Generally, all coated PWA 1480 orientations (i.e., ⟨001⟩, ⟨011⟩, ⟨111⟩, and ⟨123⟩) which were tested in TMF produced cracks in the metal at sites where coating cracking had occurred first. Isothermal tests of coated ⟨001⟩ PWA 1480 also typically initiated cracks first in the coating layer. However, many coated non-⟨001⟩ isothermal fatigue tests initiated cracks underneath the specimen outer surface in either the base material (PWA 1480) or the coating/PWA 1480 interfacial region. Initiation occurred predominately at porosity sites.

The following life prediction approach was developed to account for the observed specimen cracking modes. The smaller of the two lives is used.

$$\left.\begin{aligned} N_f &= N_c + N_{sc} + N_{sp} \\ \text{or} \qquad N_f &= N_{si} + N_{sp} \end{aligned}\right\} \qquad (2)$$

where: N_c = cycles to initiate a crack through the coating; N_{sc} = cycles for coating initiated crack to penetrate a small distance into the substrate; N_{si} = cycles to initiate a substrate crack due to macroscopic slip, oxidation effects, or defects; N_{sp} = cycles to propagate substrate crack to failure; N_f = total cycles to fail specimen or component.

The following modified tensile hysteretic energy model was developed for the overlay coating,

$$N_c = G(W_t)^g\,(\nu)^m \qquad (3)$$

where: W_t = tensile hysteretic energy; ν = modified frequency; and G, g, and m are constants. The modified frequency term (see Swanson, et al. (ref. 13)), is an extension of the Ostergren (ref. 15) time-dependent damage frequency term. As used herein, it includes both temperature- and time-dependent damage functions to model thermally activated processes. Model constants were determined from isothermal tests conducted at 427, 760, 927, and 1038 °C. Hysteresis loops were predicted using the overlay coating constitutive model incorporated into a one-dimensional model. This model determines the stress-strain of the substrate and coating by imposing an equal displacement history for both substrate and coating. Differences in coefficients of thermal expansion between substrate and coating are included in the model. The model unifies isothermal and TMF predicted lives within a factor of about 2.5, as seen in figure 6. Generally, the worst predicted test lives were limited to 1149 °C maximum temperature TMF tests. Prediction of these test results should improve when 1149 °C isothermal tests are included in the data set used to determine model constants. Additional model modification will be necessary to include the effect of biaxial coating loads introduced by the thermal growth mismatch between the coating and the substrate during uniaxial TMF tests and engine transients.

Crack initiation model development is currently in process for calculating N_{sc}, N_{sp}, and N_{si} for aluminide coating and PWA 1480. At present, based on isothermal fatigue correlations, the most promising candidate models for these materials are also derived from an approach based on hysteretic energy.

FUTURE DIRECTIONS

Interactive Effects of Primary Variables

Thermal and thermomechanical fatigue (TMF) research up to this date has concentrated on the effects of single variables, despite the fact that structural components experience simultaneous combinations of influences. For example, TMF testing under multiaxial loading or under nonrepetitive cumulative damage loading is a virtually unexplored research area that needs to be better understood. A strong need exists for analytic modeling of nonsteady thermal loadings that produce multiaxial stress-strain states.

Long Life Durability

As high-temperature engine components are built to endure longer lifetimes, considerable improvements must be made to life prediction models that will permit accurate long-time extrapolations from shorter time databases. While not as great a problem in aeropropulsion systems, space propulsion devices are now being envisioned for 20 to 30 year useful design lifetimes. Techniques for extrapolation of complex TMF failure modes into this regime are clearly needed. The important issue involves development of models that can never be truly calibrated with real-time laboratory data. An obvious starting point is to borrow technology from the electric power industry that has been designing high temperature structures for many decades. However, their factors of safety are naturally much greater than can be tolerated in the extremely weight-conscious aerospace industry.

Probabilistic Interpretation of TMF

Aerospace propulsion researchers are beginning to recognize the potentially beneficial impact of probabilistic analyses. Such analyses can be used to better define loading envelopes, perform structural analyses, assess durability, and more realistically establish life cycle costs of expensive, long-lead time hardware. Since TMF is one of the major failure modes in advanced aerospace propulsion hardware, greater attention should be focused on developing probabilistic modeling tools for this mode.

Advanced Material Concepts

As greater engine performances are sought, engine metal temperatures rise above the practical use temperatures of existing monolithic alloys. This has sparked an intense interest in the development of alternate materials that are more thermally resistant, and are stronger, stiffer, and lighter. Continuous fiber-reinforced metal matrix, intermetallic matrix, and ceramic matrix composites offer the promise of these better properties. They may also prove to be more durable from the standpoint of unidirectional high-temperature strength and creep resistance. Whether they can also maintain sufficiently high TMF resistance remains to be seen. High coefficient of thermal expansion mismatches between currently available fibers and metallic or intermetallic matrix materials imparts an additional large component of cyclic strain to the matrix material during thermal cycling. Ceramic fiber reinforced ceramic matrix composites do not suffer from this problem. Under certain thermal and mechanical load phasings, the mismatch thermal strain adds directly to any mechanical or thermal gradient induced strains. This situation creates grave concern for TMF durability of these new material systems. Consequently, the demand will increase over the next few years for TMF durability models for continuous fiber reinforced composites.

Simplified Thermal Fatigue Models

As more sophisticated TMF models evolve, they have a tendency to become computational intensive. While this condition may be acceptable for highly sophisticated, expensive hardware, it is unworkable for use in the design of more mundane, yet important components. A serious need exists to simplify the complex models. By so doing, the extent of inaccuracies created during simplification can be assessed, and knowledgable restrictions can be place on the use of the simplified approaches. Such capability would not be possible had not the more sophisticated approaches been created first.

CONCLUDING REMARKS

Significant improvements to TMF life prediction technology have resulted from the modeling efforts of the NASA Lewis aerospace propulsion durability programs. Industry is now in a much better position to deal with durability enhancement in the aeronautical propulsion industry through analytical approaches. Continued enhancement of capabilities can be ensured by pursuing programs such as those suggested for future research activities. The major accomplishments to-date are:

1. Two new crack initiation life prediction methods have been developed for application to complex TMF loading of nominally isotropic superalloys at high temperatures.

2. Cyclic constitutive models for oxidation protective coatings and for highly anisotropic single crystal turbine blade alloys have been developed and verified.

3. A preliminary cyclic crack initiation life prediction model for coated single crystal superalloys has been proposed and remains under evaluation. The model utilizes tensile hysteretic energy and frequency as primary variables.

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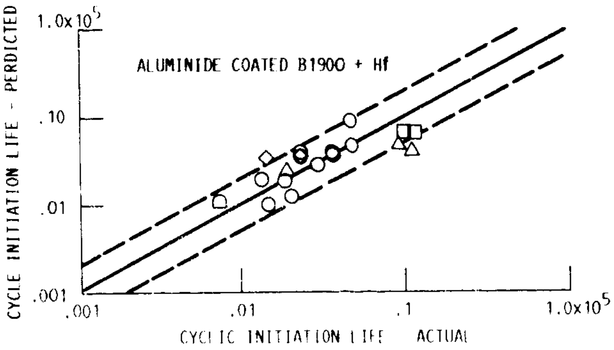

FIGURE 1. - TMF LIFE CORRELATION AND PREDICTION USING CDA MODEL.

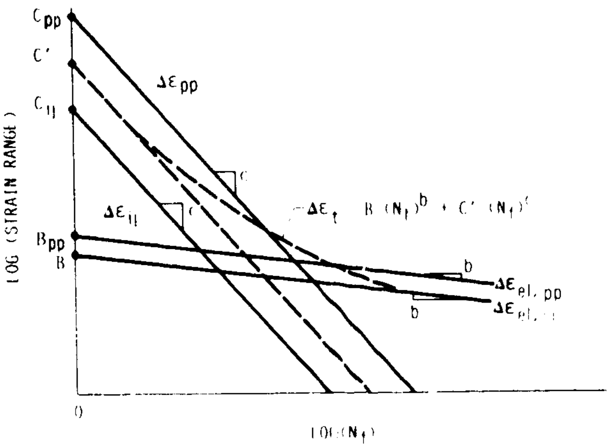

FIGURE 2. SCHEMATIC OF TOTAL STRAIN VERSION OF STRAIN RANGE PARTITIONING (TS SRP).

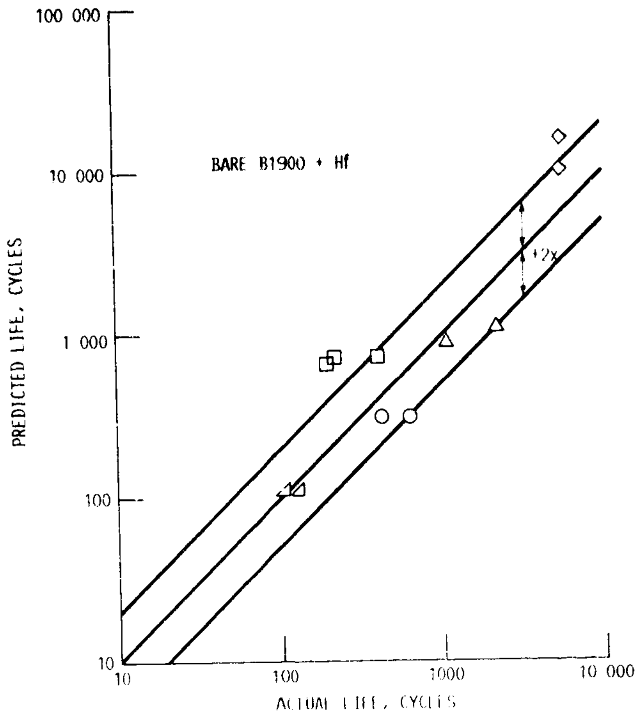

FIGURE 3. VERIFICATION OF TS - SRP MODEL SYMBOLS REPRESENT VARIOUS ISOTHERMAL TESTS AT 871 AND 983 °C (11).

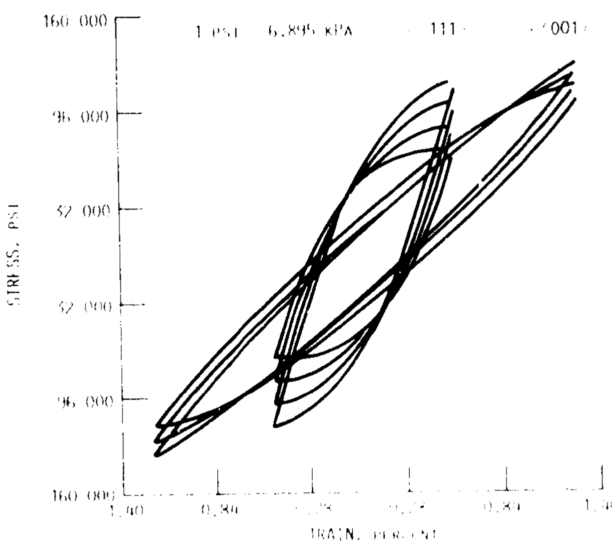

FIGURE 4. STRESS STRAIN PREDICTION OF SINGLE CRYSTAL PWA 1480 ALLOY AT 871 °C USING STRAIN RATES OF 0.001, 0.0025, 0.01, 0.1, AND 0.5% PER SECOND.

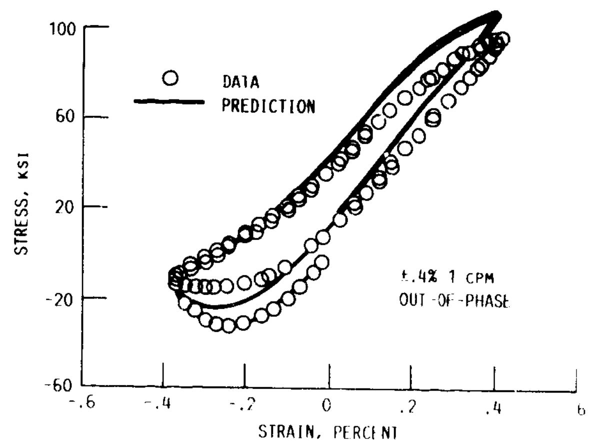

FIGURE 5. - TMF STRESS-STRAIN PREDICTION OF OVERLAY COATING 427 - 871 °C.

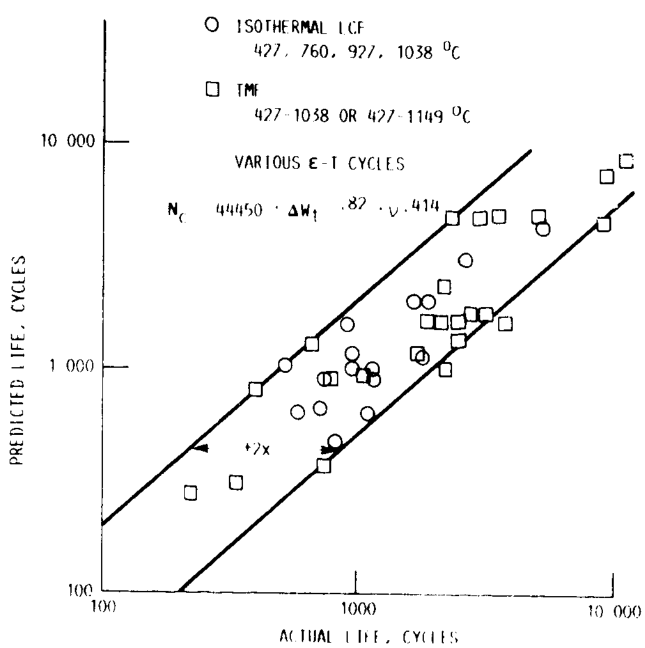

FIGURE 6. - ISOTHERMAL AND TMF LIFE PREDICTION OF OVERLAY COATING MATERIAL.

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