CUMULATIVE FATIGUE DAMAGE MODELS

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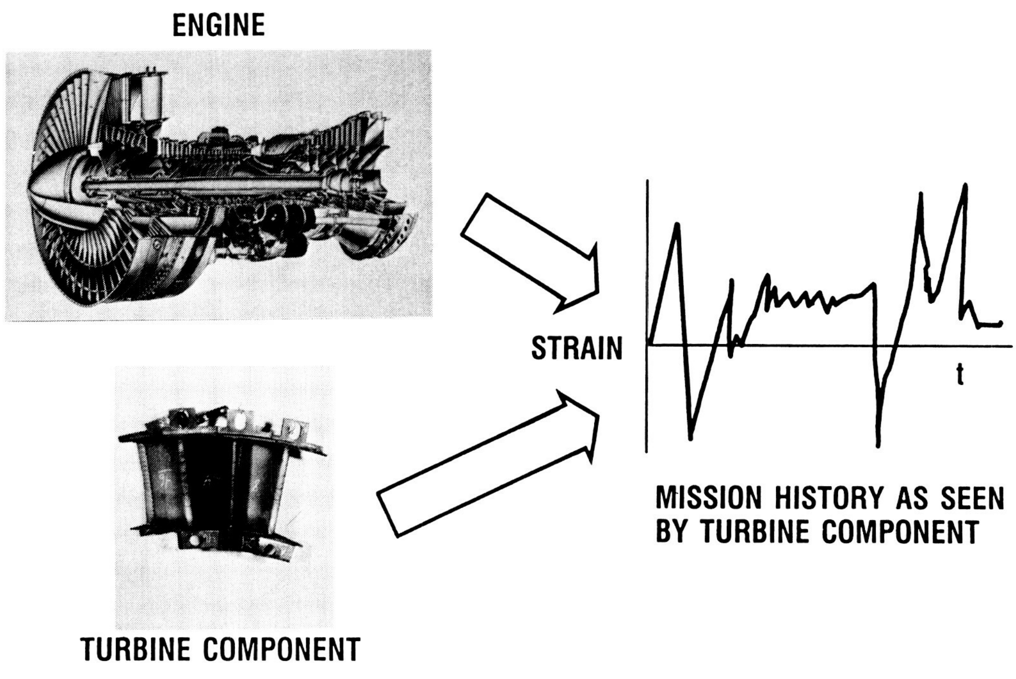
ABSTRACT

The problem of calculating expected component life under fatigue loading conditions is complicated by the fact that component loading histories contain, in many cases, cyclic loads of widely varying amplitudes. In such a case one requires a cumulative damage model, in addition to a fatigue damage criterion, or life relationship, in order to compute the expected fatigue life. The traditional cumulative damage model used in design is the linear damage rule. This model, while being simple to use, can yield grossly unconservative results under certain loading conditions. Research at the NASA Lewis Research Center has led to the development of a nonlinear cumulative damage model, named the double damage curve approach (DDCA), that has greatly improved predictive capability. This model, which considers the life (or loading) level dependence of damage evolution, has been applied successfully to two polycrystalline materials, 316 stainless steel and Haynes 188. The cumulative fatigue behavior of the PWA 1480 single-crystal material is currently being measured to determine the applicability of the DDCA for this material.

OVERVIEW

MISSION HISTORY PRODUCES COMPLEX COMPONENT LOADING HISTORIES

Mission profiles derived from aircraft gas turbine engine usage resolve into complex thermal and mechanical loading histories on many hot-section components. Components whose useful life is limited by such loadings experience creep and fatigue in varying and interacting degrees, both within a cycle and over the service life. A typical component is a hot-section turbine blade. The figure shows the strain history resulting from thermal and mechanical loading induced by the mission history. The strain history is that experienced at the life-limiting, or critical, location of the turbine blade.



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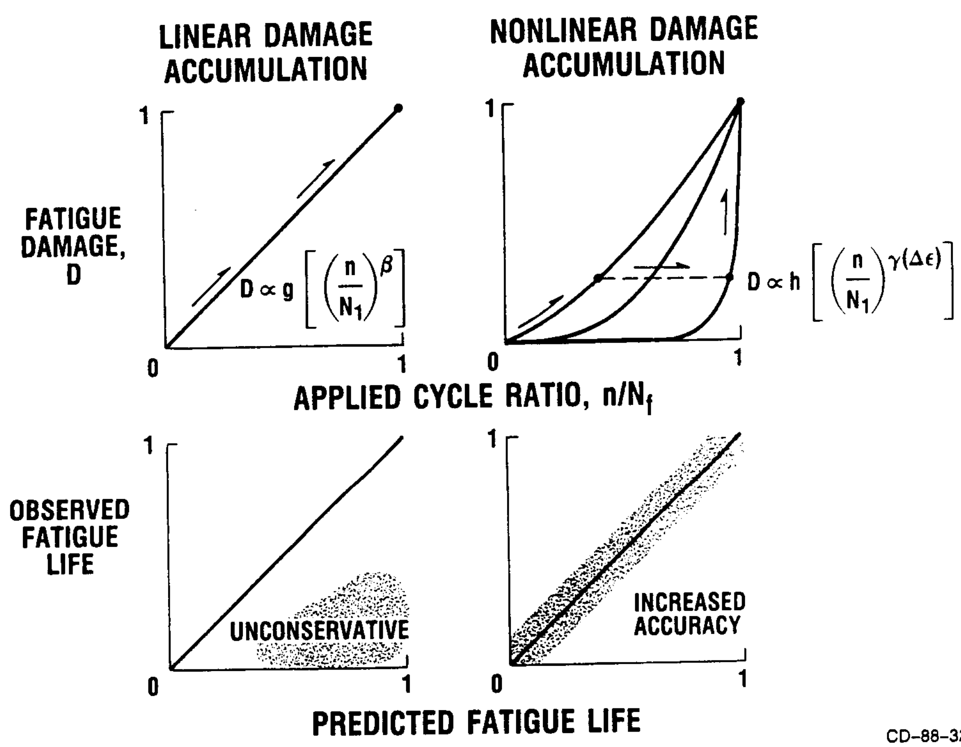
A MORE ACCURATE CUMULATIVE FATIGUE DAMAGE RULE

When considering the life of components subjected to complex fatigue loading histories in the interest of predicting the useful component life as limited by fatigue, it is common practice to employ a fatigue crack initiation life relationship in conjunction with a cumulative damage model. Traditionally the cumulative damage model used is the linear damage rule. Although using this rule greatly simplifies life prediction calculations, it can lead to unconservative results under certain loading conditions. Research at NASA Lewis has led to the development of a nonlinear cumulative damage model that greatly increases the accuracy of such calculations. Named the double damage curve approach (DDCA), this new model considers the life (or loading) level dependence of fatigue damage evolution. In certain cases the predictions resulting from using the DDCA are nearly an order of magnitude more accurate than those made under the linear damage rule. Example applications are given below.



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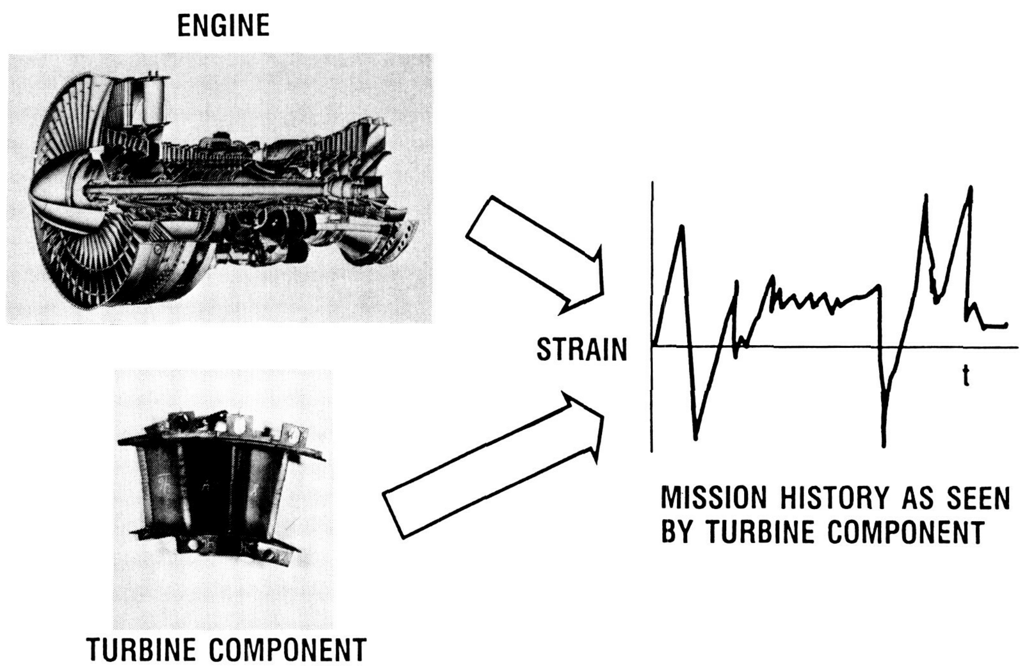
POSTER PRESENTATION

MISSION HISTORY PRODUCES COMPLEX COMPONENT LOADING HISTORIES

Mission profiles derived from aircraft gas turbine engine usage resolve into complex thermal and mechanical loading histories on many hot-section components. Components whose useful life is limited by such loadings experience creep and fatigue in varying and interacting degrees, both within a cycle and over the service life. A typical component is a hot-section turbine blade. The figure shows the strain history resulting from thermal and mechanical loading induced by the mission history. The strain history is that experienced at the life-limiting, or critical, location of the turbine blade.



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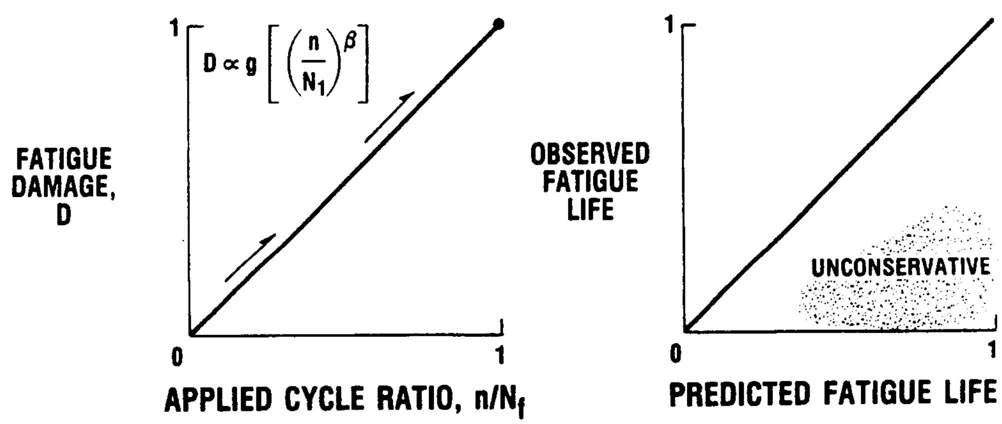
LINEAR DAMAGE RULE

When considering the life of components subjected to complex fatigue loading histories in the interest of predicting the useful component life as limited by fatigue, it is common practice to employ a fatigue crack initiation life relationship in conjunction with a cumulative damage model. Traditionally the cumulative damage model used is the linear damage rule (Miner, 1945). This rule considers the evolution of fatigue damage to be independent of the life (or loading) level. This implies that all life levels share the same fatigue damage evolution curve, regardless of the shape of this curve. Although this assumption greatly simplifies life prediction calculations, in certain cases it can lead to unconservative results. An example of this is high-amplitude straining (low-cycle fatiguing) followed by low-amplitude straining (high-cycle fatiguing). The life predicted by the linear damage rule for this case can be in error from that observed in experiment by as much as nearly an order of magnitude, depending on the relative life levels involved (Manson and Halford, 1981).



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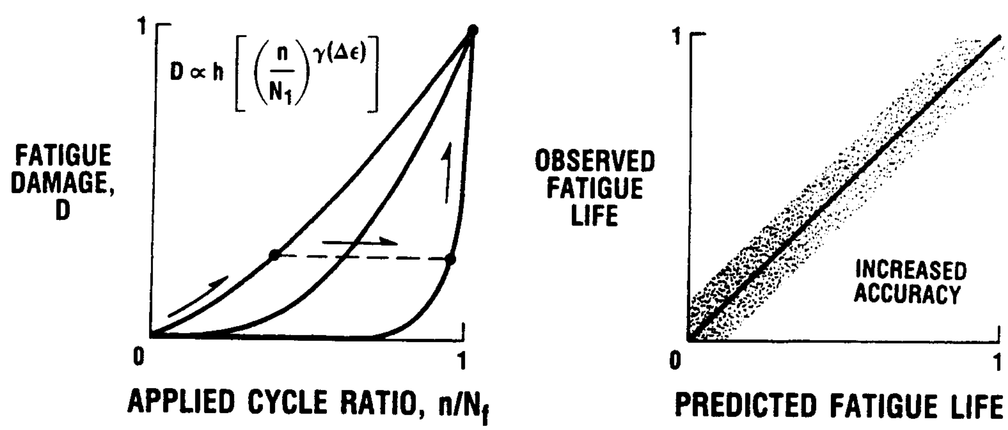
A MORE ACCURATE CUMULATIVE FATIGUE DAMAGE RULE

Research at NASA Lewis has led to the development of a nonlinear cumulative damage model that greatly increases the accuracy of cumulative fatigue life calculations. Named the double damage curve approach (DDCA), this new model considers the life (or loading) level dependence of fatigue damage evolution (Manson and Halford, 1986). In this way each life level possesses an individual damage evolution curve, the shape of which may vary to the extent that the relationship to the other life curves is maintained. In certain cases such as in the previous example, wherein a block of low-cycle fatigue is followed by high-cycle fatigue to failure, the predictions resulting from the use of the DDCA are nearly an order of magnitude more accurate than those made under the linear damage rule. These predictions thus more realistically model the fatigue damage interaction behavior of polycrystalline materials.



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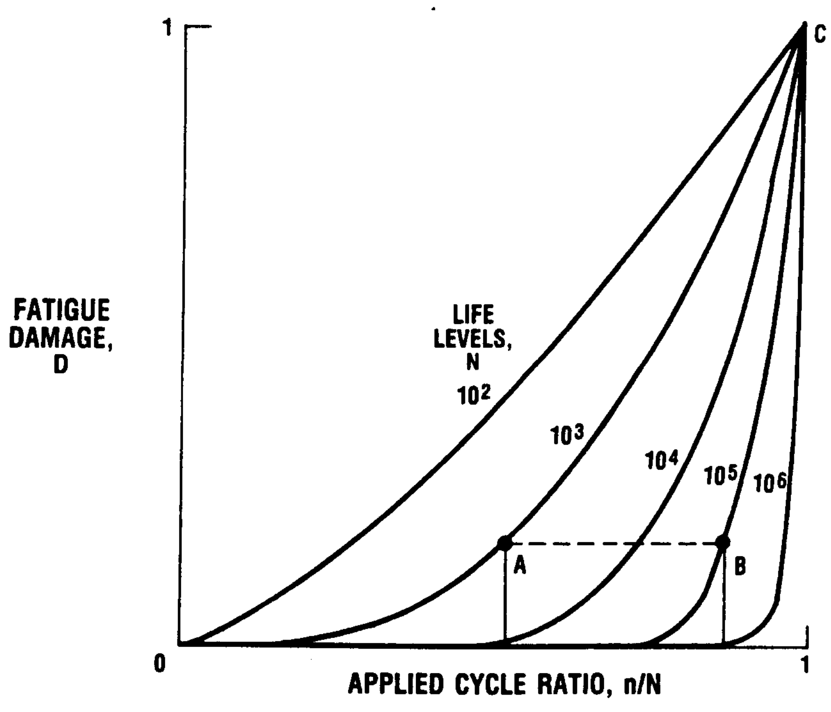
DEVELOPMENT OF DAMAGE CURVE APPROACH

The approach taken at Lewis has been to phenomenologically model the damage accumulation process. It is generally recognized that the major manifestation of fatigue damage is the creation, nucleation, and growth of cracks. Although the usual approach is to treat a single, dominant crack, the early stages of development of such a crack are characterized by many complicated processes, including dislocation agglomeration, subcell formation, multiple microcrack formation, and the growth of these cracks to the point of linkup to form the dominant crack. Clearly the mechanisms by which fatigue damage occur are complex, and thus an empirical formulation of the "effective crack growth" equation was developed that accounts for the effects of these processes without specifically identifying them (Manson and Halford, 1981). Taking the effective crack growth as the measure of fatigue damage and applying it to the multiple loading level case resulted in the damage curve approach (DCA). A schematic representation of the damage evolution described by this approach is shown in the figure. Note that, in contrast to the linear damage rule, the dependence of damage evolution on life (or loading) level is accounted for in the damage curve approach.



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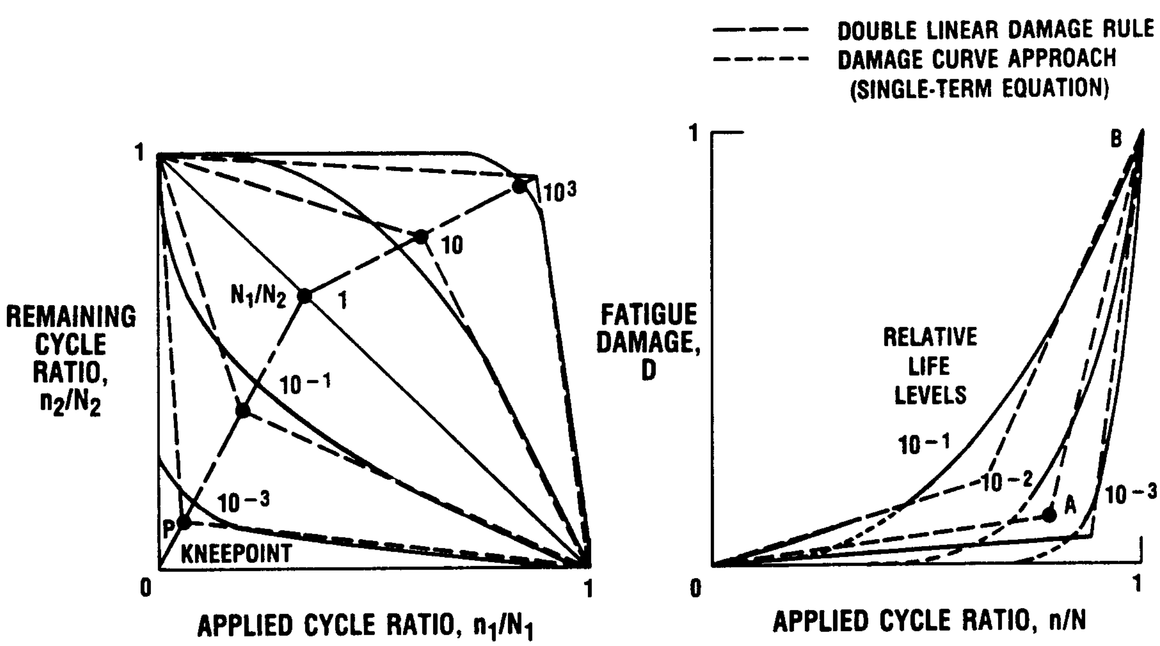
DEFICIENCIES OF DCA AND DLDR

The damage curve approach provided a much more realistic picture of fatigue damage accumulation under variable amplitude loading. However, experience with the approach in conjunction with prior work on another cumulative damage method, the double linear damage rule (DLDR), suggested that the single-term DCA was perhaps overly conservative in certain cases (Manson and Halford, 1985). This was especially evident in the two-level loading case, wherein low-cycle fatiguing for a certain number of cycles is followed by high-cycle fatiguing to failure. In this case the DCA predicts a substantial reduction in remaining high-cycle-fatigue capability for small amounts of low-cycle fatigue. In contrast, the double linear damage rule, a method that models the accumulation of fatigue damage by considering the process as the sum of two linear damage accumulation regimes, predicts a more physically realistic behavior in this case. This leads to the consideration of a double-term damage curve equation that would accurately model damage accumulation behavior while retaining the attractive aspects of the DCA.



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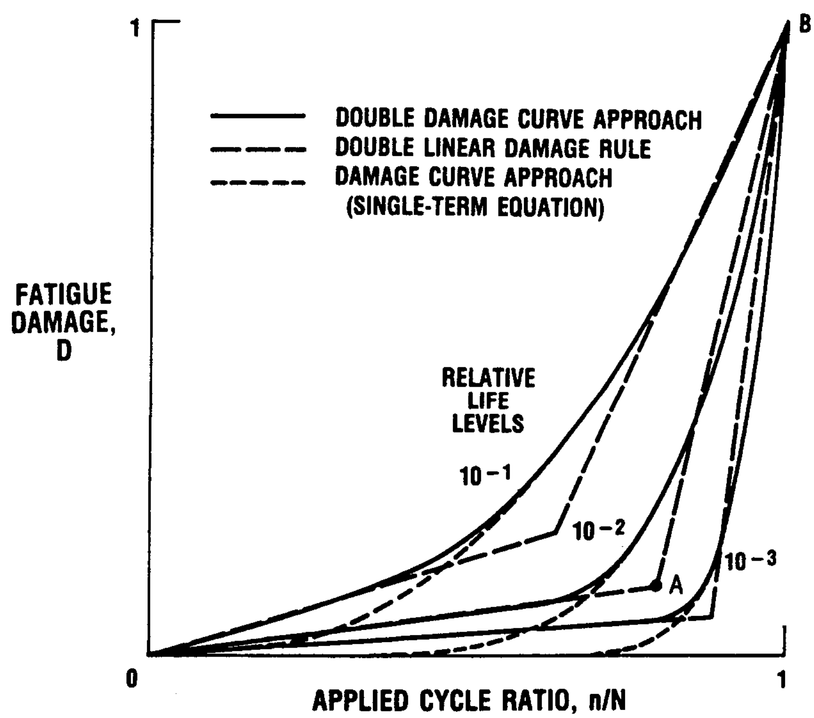
DEVELOPMENT OF DOUBLE DAMAGE CURVE APPROACH

To ameliorate this difficulty with the DCA, we developed another term, guided by the experience provided by the double linear damage rule (DLDR). The resulting expression was termed the double damage curve approach (DDCA) (Manson and Halford, 1985). As the figure shows, at low values of the cycle fraction, the DDCA followed closely the damage accumulation behavior predicted by the DLDR, but at mid to high values of the cycle fraction it followed the DCA. The resulting cumulative damage equation retains the attractive features of the DCA, viz, no specialized materials tests are required and the equation is cast in terms of the life level, so that any appropriate fatigue life expression may be used to relate the fatigue life to macroscopic variables such as strain or stress. Note that in the DDCA (and the DCA as well) the degree of damage interaction depends on the ratio of the life levels involved; the further apart the respective low- and high-cycle-fatigue life levels are, the more pronounced is the interaction.



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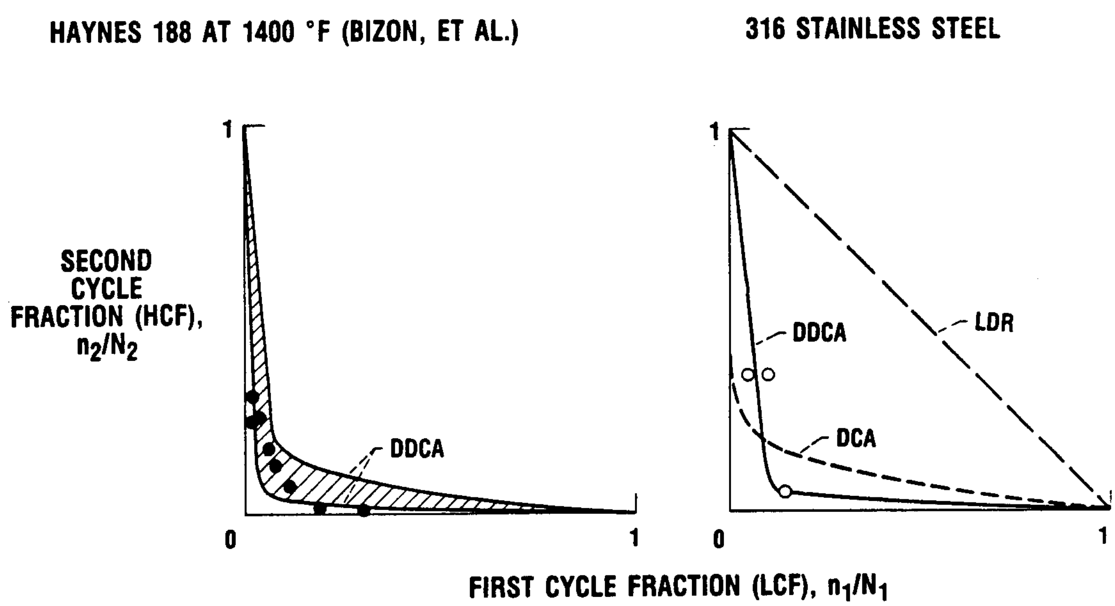
APPLICATION OF DDCA TO POLYCRYSTALLINE ALLOYS

The DDCA has been applied to two polycrystalline materials: 316 stainless steel and Haynes 188, as shown in the figures (Manson and Halford, 1985). For the 316 stainless steel the low-cycle-fatigue portion of the tests was conducted under thermomechanical conditions and the high-cycle-fatigue portion under isothermal conditions to loosely approximate the loading experienced by a component in a rocket engine undergoing initial firing and subsequent operation. The nature of the thermomechanical cycle used for the low-cycle fatigue was such that a negligibly small amount of creep was introduced, so that the failure mode was by transcrystalline cracking (fatigue failure). The cumulative damage analysis of these experiments could therefore be made only on considerations of fatigue damage. The tests conducted on the Haynes 188 material were performed under isothermal conditions, with the strain rates such that creep was precluded. In general, the predictive accuracy of the DDCA in these two cases was quite good and represented a substantial improvement over the linear damage rule.



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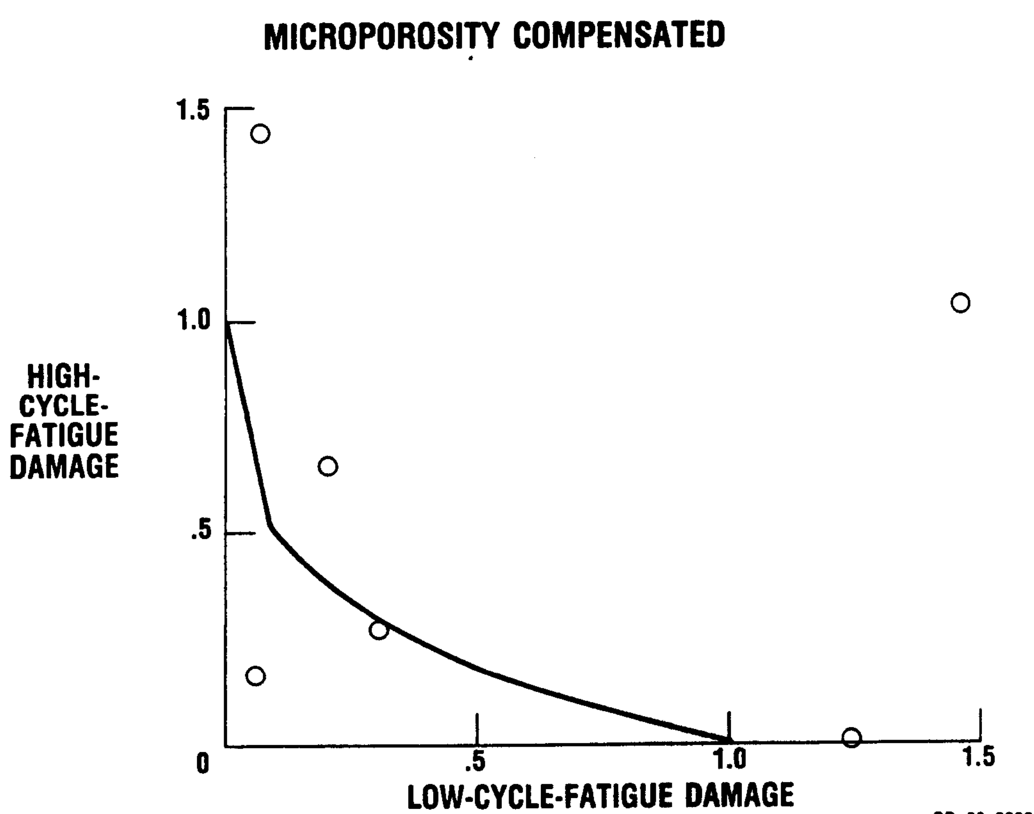
APPLICATION OF DDCA TO SINGLE-CRYSTAL ALLOY PWA 1480

Recent cumulative damage work being carried out at Lewis concerns the cumulative fatigue damage behavior of two materials of interest in space shuttle main engine (SSME) turbopump applications: MAR-M 246 + Hf, the current bill of materiel for SSME turbine blading, and a single-crystal superalloy, PWA 1480, a candidate replacement material for turbopump blading. The work will identify the cumulative damage behavior of these materials, so that the relative applicability of the polycrystalline-based DDCA may be determined. Experimental results to date have only been obtained for the single-crystal material, with limited cumulative fatigue data having been generated. This material contains significant levels of microporosity as a result of current processing techniques; microporosity is generally responsible for producing failure in fatigue. The effects of microporosity have been incorporated into the baseline fatigue life relationship for this material (McGaw, 1987), so that the reference life levels can be more accurately determined for the cumulative fatigue analysis. The microporosity-compensated interaction data generated to date are shown in the figure, with the DDCA prediction. Additional experiments are being conducted to more clearly determine the cumulative fatigue behavior of this material.



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