ISOTHERMAL AND "BITHERMAL" THERMOMECHANICAL FATIGUE

BEHAVIOR OF A NiCoCrAlY-COATED SINGLE CRYSTAL SUPERALLOY

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Abstract

Specimens of single crystal PWA 1480 with <001> orientation, bare or with NiCoCrAlY coating PWA 276, were tested in low cycle fatigue (LCF) at 650, 870, and 1050°C, and in "bithermal" thermomechanical fatigue (TMF) tests between these temperatures. The bithermal test was examined as a bridge between isothermal LCF and general TMF. In it an inelastic strain is applied at one temperature, T_{max}, and reversed at T_{min}. The "out-of-phase" (OP) type bithermal test, which imposes tension at T_{min} and compression at T_{max}, was studied most, since it was most damaging. Specifically investigated were the effects of: inelastic strain range ($\Delta\varepsilon_{in}$), the coating, ΔT, T_{max}, time at T_{max}, T_{min}, and the environment.

On a $\Delta\varepsilon_{in}$ basis, isothermal LCF life of bare crystals exhibited classic dependence on ductility, decreasing with temperature from 1050 to 650°C. Coated crystals exhibited the same life at 1050°C, but at 650°C, cracks initiating in the coating reduced life in the low-$\Delta\varepsilon_{in}$, long-life regime. Life for various bithermal TMF tests in the high-$\Delta\varepsilon_{in}$ regime was also controlled by ductility, and approached the life exhibited for isothermal LCF at the T_{min} of the cycle. However, in the low-$\Delta\varepsilon_{in}$ regime, the OP bithermal test (which imposes tension at T_{min}) reduced lives of both bare and coated crystals, drastically so for the 650-1050°C cycle.

Damage mechanisms in the low-$\Delta\varepsilon_{in}$ regime for OP bithermal tests were different, however, for bare and coated crystals. A 650-1050°C OP vacuum test of a bare crystal was discontinued after 10000 cycles (five times the life observed in air tests) without evidence of cracking. Yet, coated crystals tested in vacuum formed cracks through the coating nearly as fast as those tested in air. The total OP bithermal lives of the coated crystals were, however, longer in vacuum than in air tests, due to slower crack entry and propagation through the crystal itself. Additional tests illustrated the effects of other OP bithermal cycle variables on the life of coated crystals in air. As expected, life decreased with increasing ΔT, increasing T_{max}, and decreasing T_{min}, since, respectively, they increase the thermal mismatch strain between crystal and coating, increase oxidation, and decrease the ductility of the crystal (in the range 650-1050°C). Time at T_{max}, however, had only a small detrimental effect.

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Introduction

Gas turbine engine components are subject to complex strain-temperature-time cycles during operation. Damage from such cyclic loading is termed thermomechanical fatigue (TMF). Advanced single crystal superalloy turbine blades are covered by coatings which are basically more Al-rich for protection from the environment. Relative to the <001> orientation of superalloys, these coatings have greater coefficients of thermal expansion; higher elastic moduli; lower flow stress, particularly at high temperature; and better ductility at high temperature. Both coatings and single crystal superalloys have rather low ductility at temperatures below about 700°C (1). Coating cracks are promoted in areas cycled into tension at low temperatures and may propagate into the superalloy below (2,3). The greater coefficient of thermal expansion for the coating adds to this problem, since it places the coating in tension simply upon cooling from high temperatures (3).

The system chosen for study, Ni-base single crystal superalloy PWA 1480 and NiCoCrAlY low-pressure-plasma-sprayed (LPPS) overlay coating PWA 276, was developed by Pratt and Whitney Aircraft. PWA 1480 crystals from the same lot studied herein have been characterized in isothermal monotonic (4,5), fatigue (5,6), and creep-fatigue tests (7), and preliminary TMF tests (8). The bulk coating alloy PWA 276, produced as thick plates by the same LPPS process, has also been studied in high temperature monotonic (9,10) and fatigue tests (11). TMF behavior in more complicated cycles than those employed herein have been performed on crystals from other heats of PWA 1480 and having different coatings (12,13).

The objective of this investigation was a greater understanding of the fatigue behavior of coated and bare crystals in isothermal low cycle fatigue (LCF) at 650, 870, and 1050°C and "bithermal" TMF cycles. The temperature 650°C represents about the upper limit of low temperature behavior in both materials and is characterized by relatively constant high strength and low ductility. Whereas, 1050°C is about the upper limit of allowable temperature in turbine engine blades and is in the regime where the coating is extremely weak and ductile. The bithermal test was proposed as a bridge between isothermal LCF and TMF (14). It is relatively simple experimentally and analytically since the mechanical and thermal strains are not superimposed. Since deformation, at least in the superalloy, occurs only at the two temperature limits some unification with isothermal LCF behavior at the two temperatures may be possible. The qualification above is presented because stresses generated during heating and cooling due only to thermal mismatch are likely to produce some inelastic deformation in the coating.

Materials and Procedures

Materials

PWA 1480 contains nominally 10Cr, 5Al, 1.5Ti, 12Ta, 4W, 5Co, in weight percent and balance Ni. It has about 65 v/o of the γ' phase, but no carbides or borides. Crystals were cast commercially as bars about 21 mm in diameter and 140 mm long. Those having <001> within 7° of the axis were selected and solution treated 4 hr at 1290°C before machining. The fatigue specimens had a 4.8 mm diameter and 15 mm long reduced section. The PWA 276 coating was applied to some specimens after machining. Both coated and uncoated specimens were given the coating cycle heat treatment of 1080°C for 4 hr and aged at 870°C for 32 hr. Fig. 1 shows the heat treated alloy and coating. Interdendritic porosity averaged about 0.3 v/o of the alloy and about 7 μm in diameter. Interdendritic areas also contained undissolved γ' eutectic nodules a few μm to tens of μm in diameter and occupying 1-2 v/o of the alloy. Elsewhere, the γ' was cuboidal averaging about 0.6 μm on edge.

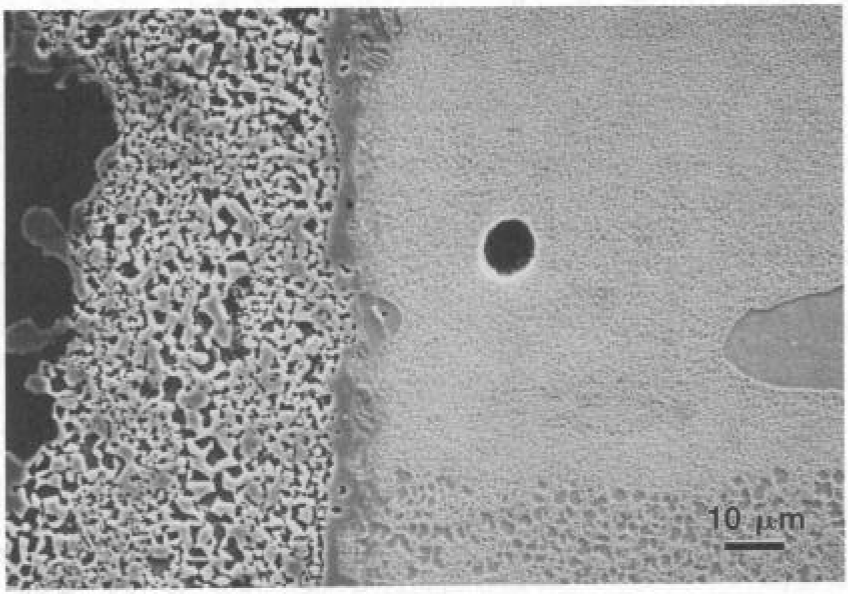

Figure 1. Microstructures of single crystal superalloy, PWA 1480, and NiCoCrAlY overlay coating, PWA 276 (left).

The PWA 276 LPPS coating composition was 20.3Co, 17.3Cr, 13.6Al, 0.5Y, in weight percent and balance Ni. It contains about 50 v/o fcc solid solution and 50 v/o NiAl-based intermetallic compound. The coating thickness was about 0.13 mm with a grain size of about 1.5 μm, and contained 1-2 v/o of pores averaging about 20 μm in diameter.

Test Procedures

All fatigue testing was done on servohydraulic, closed-loop machines, one of which was equipped with a diffusion pumped vacuum chamber. Radio frequency induction heating with closed-loop control was employed. For tests of coated specimens in air, an infrared pyrometer was used. However, for tests of bare specimens in air, and all tests in vacuum, emissivity was found to vary significantly with time, so a thermocouple wrapped against the specimen was employed. At the start of the test, the thermocouple output was calibrated against an optical pyrometer which measured the temperature of a small area of the specimen surface coated with a high temperature 'paint' of known emittance. Strain was measured using an axial extensometer with a 12.5 mm gage length. Strain/time and load/time data were recorded continually, while load/strain hysteresis loops were recorded periodically.

Isothermal LCF tests were conducted at 650, 870, and 1050°C under total mechanical strain control at a frequency of 0.1 Hz with a sinusoidal control waveform and an R ratio of -1 (minimum/maximum strain). TMF behavior was studied in simplified bithermal cycles between the above temperatures. Specimens were strained at one temperature, unloaded, changed to the other temperature, and then strained in the opposite direction to produce a completely reversed strain cycle. Fig. 2 shows the stress-strain hysteresis loop for what is termed an "out-of-phase" (OP) cycle in which the tensile and compressive strains are imposed at the lower and higher temperatures, respectively. This is reversed in the "in-phase" (IP) cycle. A 16 bit computer, equipped with dual digital/analog converters, was used to generate the control waveforms for load and temperature. For most tests the total cycle time was about 120s, of which 100 to 110s elapsed while changing and stabilizing temperature. The mechanical strain rate in the bithermal tests was within a factor of two of that used in the isothermal tests.

For large-strain bithermal tests, equal tensile and compressive inelastic strains, $\Delta\varepsilon_{in}$, were produced at the two temperatures by controlling between two fixed values of the total strain (the sum of the mechanical, $\Delta\varepsilon_{mech}$, plus thermal, $\Delta\varepsilon_{th}$, strain as shown in Fig. 2). Under this condition the material rapidly equilibrated the tensile and compressive $\Delta\varepsilon_{in}$. A constant $\Delta\varepsilon_{mech}$ test results if the temperature endpoints, and thus $\Delta\varepsilon_{th}$, are held constant. However, for small-strain, essentially elastic tests it becomes questionable whether such self-equilibration ever occurs. Thus, tests with expected $\Delta\varepsilon_{in} \leqq 10^{-4}$ were run in load control with endpoints extrapolated from those of the higher strain range tests run in strain control. A sensitivity study indicated no significant effect on life for various tension/compression load ratios considered in the range of reasonable extrapolation. Out-of-phase tests in vacuum were also conducted with tensile/compressive load limits identical to tests run in air. The vacuum was about 10^{-6} Torr. The effects of various maximum temperatures, T_{max}, and times at T_{max} on OP bithermal life were investigated in a series of essentially elastic tests having a tensile stress of 620 MPa applied at 650°C, but no load at T_{max}.

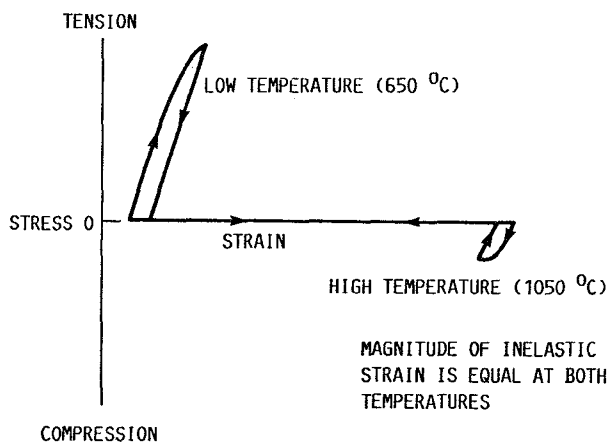

Figure 2. Stress-strain hysterisis loop for an out-of-phase (OP) bithermal test.

Results and Discussion

Specimens of single crystal superalloy PWA 1480 with <001> orientation, either bare or coated with a NiCoCrAlY alloy, PWA 276, were tested in LCF at 650, 870, and 1050°C and in 'bithermal' TMF tests between these temperatures. Fig. 3 presents previous (9) and new isothermal LCF results. It shows that isothermal LCF life of the bare crystals exhibited nearly classic dependence on inelastic strain range and monotonic tensile ductility at all temperatures investigated. Coated crystals had lives equivalent to bare specimens at the highest test temperature, 1050°C. Both failed at internal micropores (8). However, at 650°C, where the coating has little ductility (9), cracks initiating in the coating reduced life in the low-$\Delta\varepsilon_{in}$, long-life regime (8). In this and other figures comparing tests on an $\Delta\varepsilon_{in}$ basis, values of $\Delta\varepsilon_{in} \leq 10^{-4}$ are based on extrapolation of the relationship between the $\Delta\varepsilon_{in}$ and the maximum absolute value of σ at 650°C from tests with measurable $\Delta\varepsilon_{in}$. This is treated in detail elsewhere (8). For this reason, close comparisons between test types on the $\Delta\varepsilon_{in}$ basis must be avoided in the low-$\Delta\varepsilon_{in}$ regime, however the effects to be discussed are large and would also be observed on the basis of σ at 650°C.

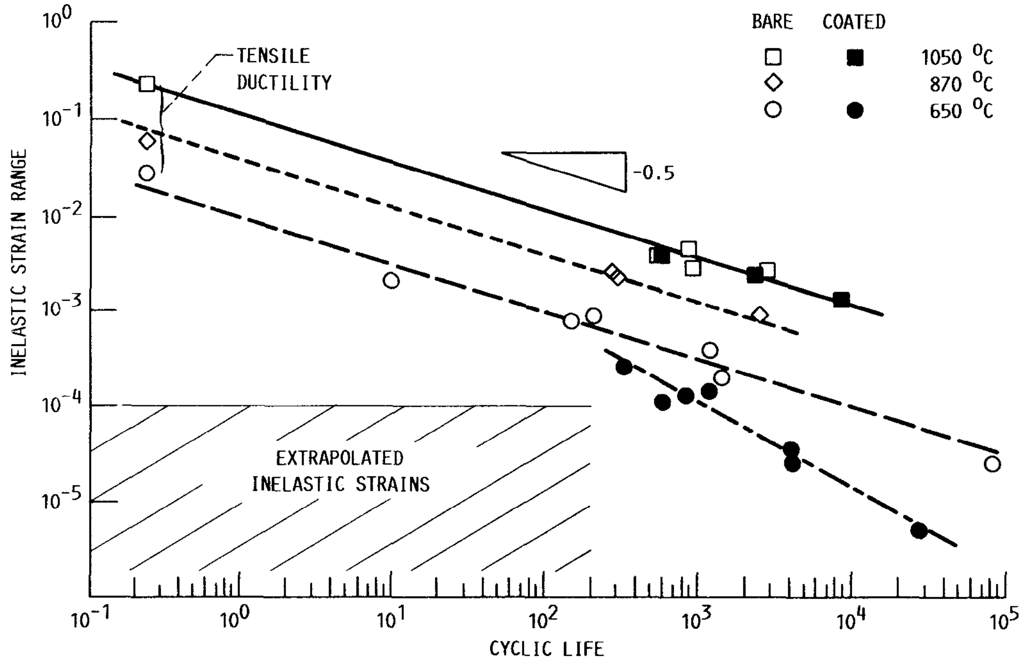

Figure 3. Isothermal inelastic strain - cyclic life behavior for bare and PWA 276 coated, PWA 1480.

The $\Delta\varepsilon_{in}$-based comparison in Fig. 4 shows the link between 650°C LCF and 650-1050°C TMF behavior in the high-$\Delta\varepsilon_{in}$ regime. On the $\Delta\varepsilon_{in}$ basis, both IP and OP bithermal life approached that for isothermal LCF at 650°C, where the single crystal has the least ductility. Fig. 4 also shows that in the low-$\Delta\varepsilon_{in}$ regime, OP bithermal lives of both bare and coated crystals decreased drastically compared with 650°C life. In both bare and coated crystals, surface cracks initiated very early, and roughly 90% of the short lives observed represented crack propagation through the single crystal (8). This was not true of the IP bithermal test, which imposed compression rather than tension at the low temperature. In the low-$\Delta\varepsilon_{in}$ regime, failure in the IP bithermal tests initiated at internal micropores just as for 1050°C isothermal tests.

Comparative tests were performed in vacuum in order to separate the effects of environment and coating on fatigue life. It may be seen in Fig. 5 that the 650°C isothermal LCF lives of coated specimens in air and vacuum are about the same, both being considerably less in the low-$\Delta\varepsilon_{in}$ regime than that for bare specimens. This small enviromental effect indicates that the decrease in isothermal LCF life at this temperature for coated crystals is largely a mechanical effect. Because the coating is weaker, large inelastic strains are produced in the coating at strains which are almost totally elastic in the single crystal. Cracks initiate rapidly in the coating and propagate into the single crystal.

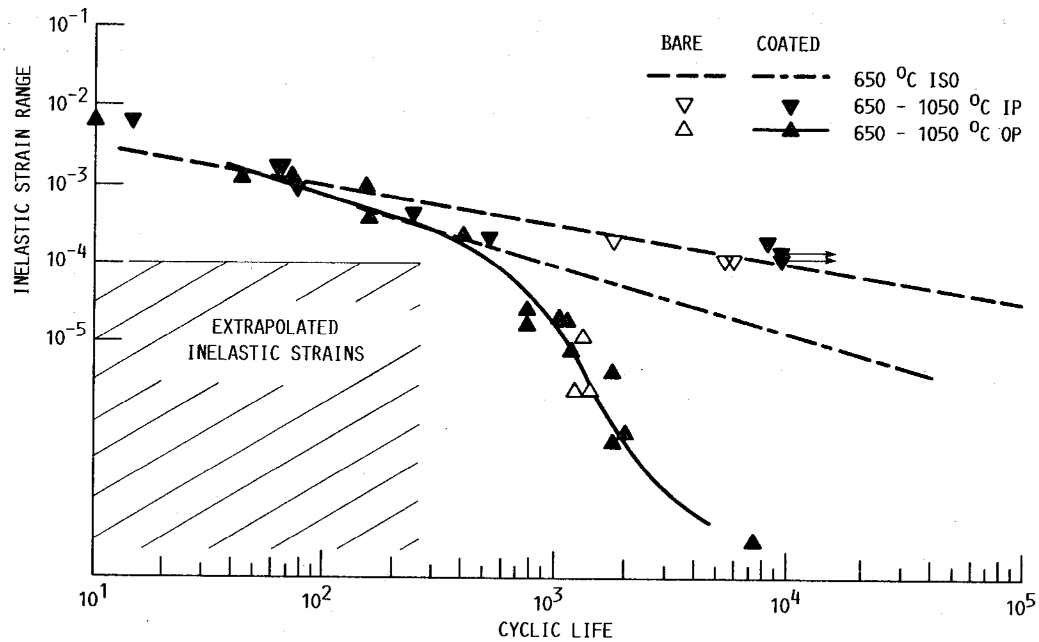

Figure 4. In- and out-of-phase bithermal inelastic strain - cyclic life behavior of bare and PWA 276 coated, PWA 1480.

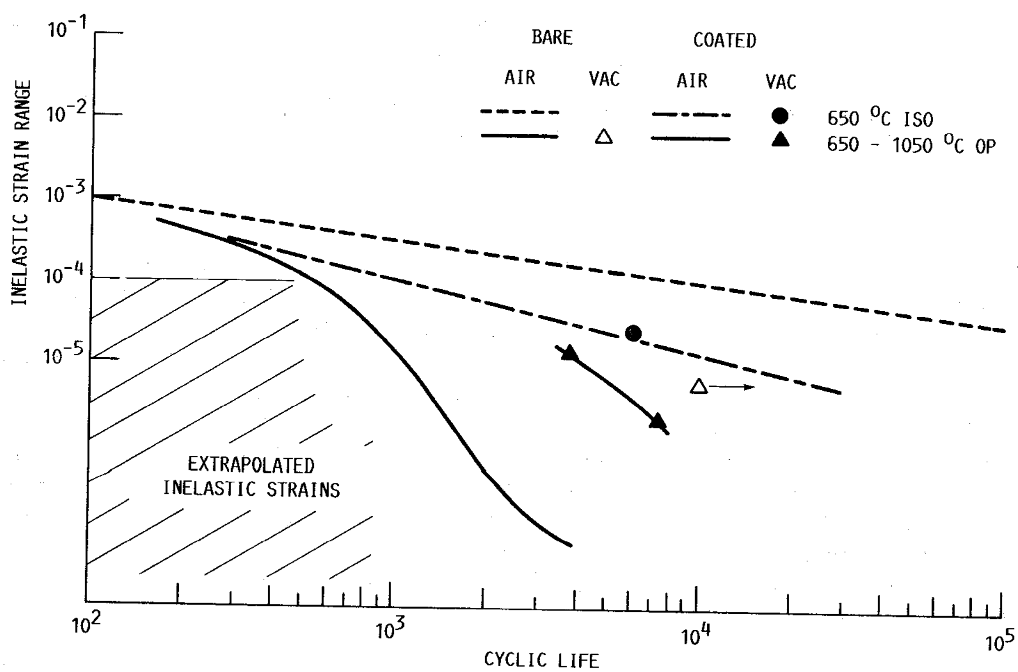

Figure 5. Comparison of cyclic life in air and vacuum for various tests.

In contrast, for the 650-1050°C OP bithermal test there was a large, detrimental effect of the air environment on bare crystals. Surface cracks initiated rapidly during the tests in air, however no cracks had yet initiated in the discontinued test in vacuum. The lives of coated crystals also showed degradation due to the air environment, however interrupted tests in vacuum showed rapid cracking through the coating, almost as soon as in air tests. Thus, the rapid crack initiation in coated crystals in both vacuum and air appears largely the result of the thermal mismatch strains in the coating. The longer total life of coated crystals in vacuum is primarily due to slower crack entry and propagation through the single crystal itself.

The effects of other T_{max}, T_{min}, and ΔT in OP bithermal tests of coated crystals with nominally reversed $\Delta\varepsilon_{in}$ are shown in Fig. 6. Again, comparison with the isothermal tests results shows that in the high-$\Delta\varepsilon_{in}$ regime, behavior was controlled by the cycle temperature with limiting ductility, which is T_{min} in this temperature range. Bithermal behavior approached isothermal LCF behavior at T_{min} in the high-$\Delta\varepsilon_{in}$ regime. In the low-$\Delta\varepsilon_{in}$ regime, the slope of the $\Delta\varepsilon_{in}$-life line became quite steep for the 870-1050°C OP bithermal tests, as for the 650-1050°C OP tests. A less rapid change in the slope of the 650-870°C OP bithermal tests was also observed. Life reductions in the low strain regime resulted from early coating failure in the OP bithermal cycle which is accelerated by the thermal expansion mismatch between the coating and single crystal. This adds to the tensile, mechanical strain in the coating[3] applied at T_{min}. Of course, increasing ΔT of the OP cycle directly increases the thermal mismatch strain and more rapidly cracks the coating. The test results in Fig. 6 reflected this in the shorter lives for the 650-1050°C OP tests in comparison with either the 650-870°C or 870-1050°C OP tests. The detrimental effect of increasing T_{max}, which increases the rate of environmental damage, is illustrated by comparison of the 870-1050°C OP and 650-870°C OP test results. Though ΔT is somewhat smaller for the 870-1050°C OP cycle than the 650-870°C OP cycle , the rate of change in the

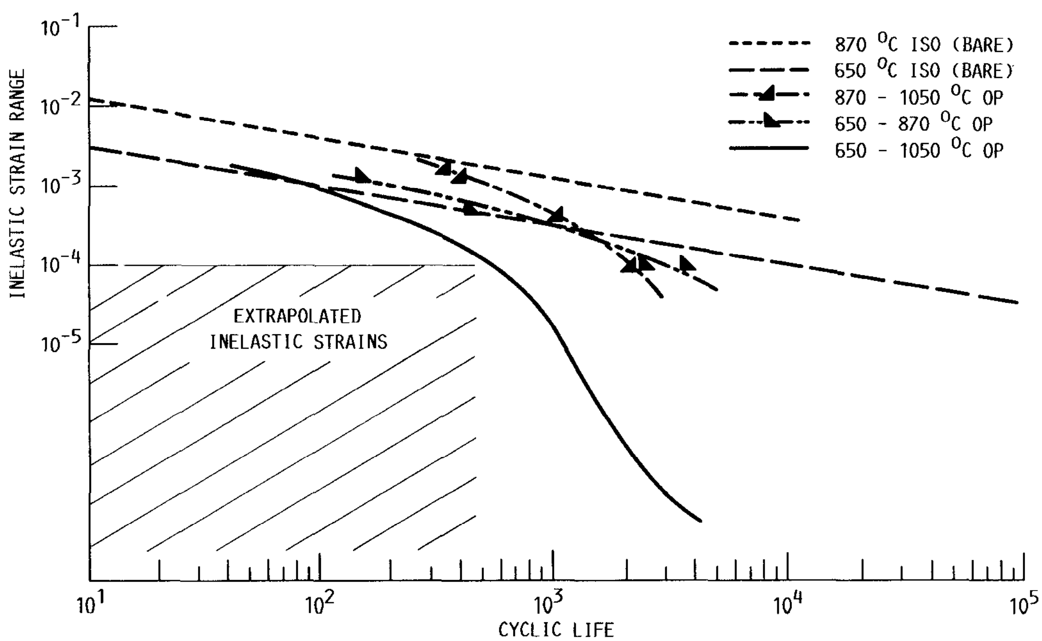

Figure 6. Effect of T_{max} and T_{min} on out-of-phase bithermal fatigue life of PWA 276 coated PWA 1480.

slope of the 870-1050°C OP cycle $\Delta\varepsilon_{in}$-life curve appears considerably more rapid.

The role of high temperature deformation on life for the 650-1050°C OP bithermal cycle was also investigated. Nominally elastic 650-1050°C OP bithermal tests without load at 1050°C were conducted and compared with the tests having compressive loads at 1050°C. In this low strain, long life regime there was little, if any, effect of high temperature deformation.

The time/temperature dependence of damage in the OP bithermal cycle was examined in more detail in tests where T_{max} or time at T_{max} was varied. These were nominally elastic tests with no compressive loading as discussed above. Fig. 7 shows the effect of T_{max} in tests having T_{min} of 650°C, and the normal cycle period of 120 seconds. As shown previously, the lives of bare and coated crystals in tests with T_{max} of 1050°C are the same due to rapid surface crack initiation in either case. The lives of both bare and coated crystals also increased as T_{max} was reduced. For bare specimens, the surface damage, which we indicated previously to be largely environmental, decreases rapidly with decreasing T_{max}. However surface damage of coated crystals, is less sensitive to T_{max} as coating cracks can arise from purely mechanical loads applied at 650°C. These coating cracks can foreshorten crack initiation in the single crystal in the absence of environmental effects, as was the case in isothermal tests at 650°C.

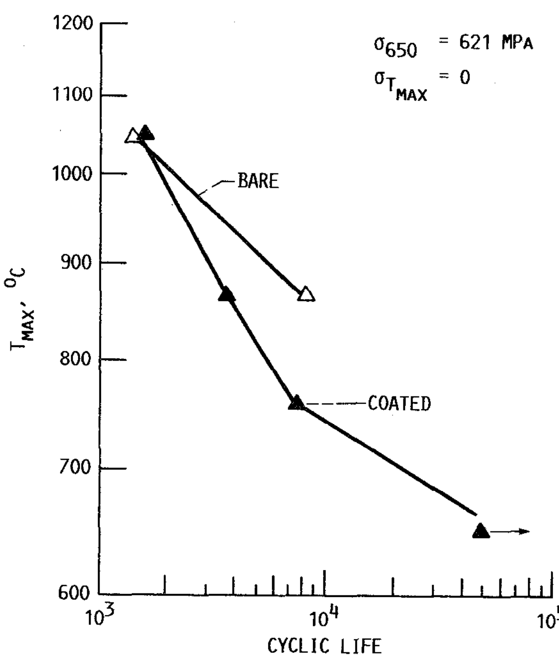

Figure 7. Effect of T_{max} on 650°C-T_{max} bithermal fatigue life.

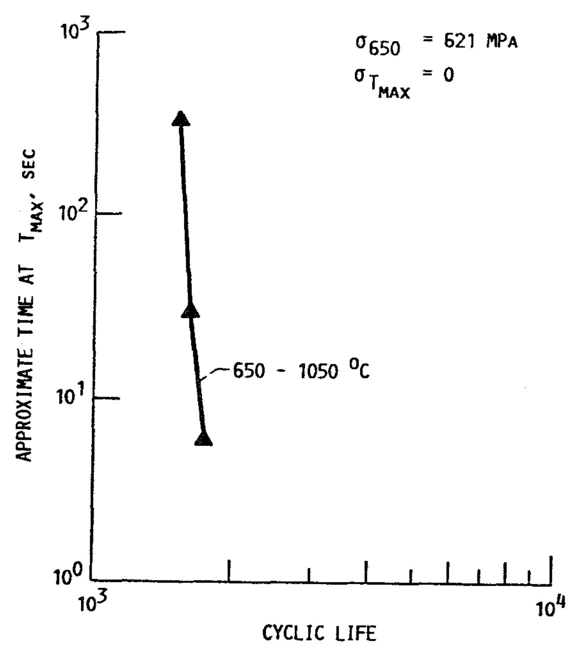

Figure 8. Effect of time at T_{max} on bithermal fatigue life.

Increasing dwell time at T_{max} in 650-1050°C OP bithermal fatigue tests did decrease the life of coated specimens, as shown in Fig. 8. However, the magnitude of the effect was surprisingly small. Since cracks through the coating form rapidly in these tests, and the majority of life is spent in crack entry and propagation through the superalloy, a discussion of environmental effects with respect to the superalloy is necessary. It should be noted that due to the heating and cooling rates achievable, even in tests with the shortest dwell times, the exposure time above 650°C was still on the order of one minute. It therefore appears that most of the environmental damage at the crack tip occurs quite rapidly, well within the time of the fastest test, and does not increase rapidly with extended dwell time at 1050°C. A crack growth mechanism is proposed in which an environmentally damaged zone, whether actual oxides and a γ' depleted zone, or only dissolved oxygen, forms ahead of the crack tip at elevated temperatures and is completely fractured by tensile loads applied at low temperature. As virgin superalloy is exposed, the process would be repeated and the depth of environmental attack would not accumulate with cycling. Such a mechanism would also explain the steep slope of the OP bithermal life line in the low $\Delta\varepsilon_{in}$ regime, Fig. 4. The critical strain required to fracture the embrittled zone appears to be below that applied at 650°C, thus resulting in life almost independent of $\Delta\varepsilon_{in}$. The apparent turn out in life for the lowest $\Delta\varepsilon_{in}$ test, which was also observed on a stress basis, suggests that such a critical fracture strain may exist.

Conclusions

Bithermal TMF behavior was examined in the hope of providing a bridge in understanding between isothermal LCF and general TMF behavior. For the bare and NiCoCrAlY coated PWA 1480 single crystals studied, the bithermal test has shown that connection. Life in the high-$\Delta\varepsilon_{in}$ regime for isothermal LCF, IP-, and OP-type bithermal TMF was controlled by ε_{in}, and the superalloy ductility at the appropriate temperature. For TMF, this is the cycle temperature where the superalloy has least ductility, T_{min} in this case. Further, lives of coated and bare crystals were about the same, since crack initiation and propagation in the superalloy determined life.

The similarity, for example, between high-$\Delta\varepsilon_{in}$ 650°C LCF and 650-1050°C bithermal TMF is some indication that deformation at temperatures as high as 1050°C does not introduce additional damage mechanisms. We should caution, however, that one might not expect this similarity in a material in which other damage mechanisms might operate at the high temperature, say, in a polycrystalline alloy which might experience grain boundary cavitation, or in an alloy with a less stable precipitate. The similarity between IP bithermal TMF behavior and the LCF behavior at T_{min} of bare crystals continued into the low-$\Delta\varepsilon_{in}$, long-life regime. Crack initiation in the superalloy continued to control life in the IP bithermal test, and lives were similar between bare and coated specimens.

However, relative to the isothermal LCF behavior of bare specimens, cracks initiating in the coating reduced the life of coated specimens in 650°C LCF tests, and drastically so in 650-1050°C OP bithermal tests. The strictly mechanical effect of the coating was demonstrated in vacuum tests, and was, as would be expected, greater in the bithermal test due to the additional thermal mismatch strain in the coating. Additionally, for OP bithermal tests in air there was severe environmental damage. Even in bare crystals, surface cracks initiated and propagated very rapidly leading to very short lives in the low-$\Delta\varepsilon_{in}$ regime. The environmental damage was the result of the high temperature exposure to air followed by tensile loading at low temperature and was therefore limited to the OP TMF cycle.

To develop coated single crystals with improved TMF life in OP type cycles, coatings with coefficients of thermal expansion more closely matching that of the <001> single crystal direction, and greater ductility and strength are of course desirable. Yet, this work shows the importance of improved environmental resistance in single crystal superalloys themselves. Any coating defect exposing the superalloy to the environment could lead to very early failure, as exhibited in bare specimens. It also shows that in efforts to develop single crystal superalloys which can operate in gas turbine engines without coatings, OP TMF behavior may still be critical. Thus, OP TMF behavior should be assessed early on, rather than relying on simple isothermal or cyclic oxidation tests.

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