NASA Technical Memorandum 100907

Isothermal and "Bithermal" Thermomechanical Fatigue Behavior of a NiCoCrAlY-Coated Single Crystal Superalloy

(NASA-TM-100907) ISOTHERMAL AND BITHERMAL THERMOMECHANICAL FATIGUE BEHAVIOR OF A NiCoCrAlY-COATED SINGLE CRYSTAL SUPERALLOY (NASA) 14 p CSCL 11F N88-24766

Unclas G3/26 0148161

J. Gayda, T.P. Gabb, and R.V. Miner
Lewis Research Center
Cleveland, Ohio

Prepared for the
Sixth International Conference on Superalloys
sponsored by the American Institute of Mining, Metallurgical and Petroleum Engineers
Seven Springs, Pennsylvania, September 18–22, 1988

NASA

ISOTHERMAL AND "BITHERMAL" THERMOMECHANICAL FATIGUE BEHAVIOR OF A NiCoCrAlY-COATED SINGLE CRYSTAL SUPERALLOY

J. Gayda, T.P. Gabb, and R.V. Miner
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

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 simplified 'bithermal' thermomechanical fatigue (TMF) tests between these temperatures. These tests were examined as a bridge between isothermal LCF and general TMF. In the bithermal test, an inelastic strain is applied at one temperature, T_{max}, and reversed at T_{min}. The 'out-of-phase' (OP) test type imposing tension at T_{min} and compression at T_{max} received most study, since it was more damaging than the 'in-phase' type. 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, and drastically so for the 650-1050°C cycle. Surface cracks initiated and propagated rapidly in the 650-1050°C OP 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 to 1050°C). Time at T_{max}, however, had only a small detrimental effect.

ORIGINAL PAGE IS
OF POOR QUALITY

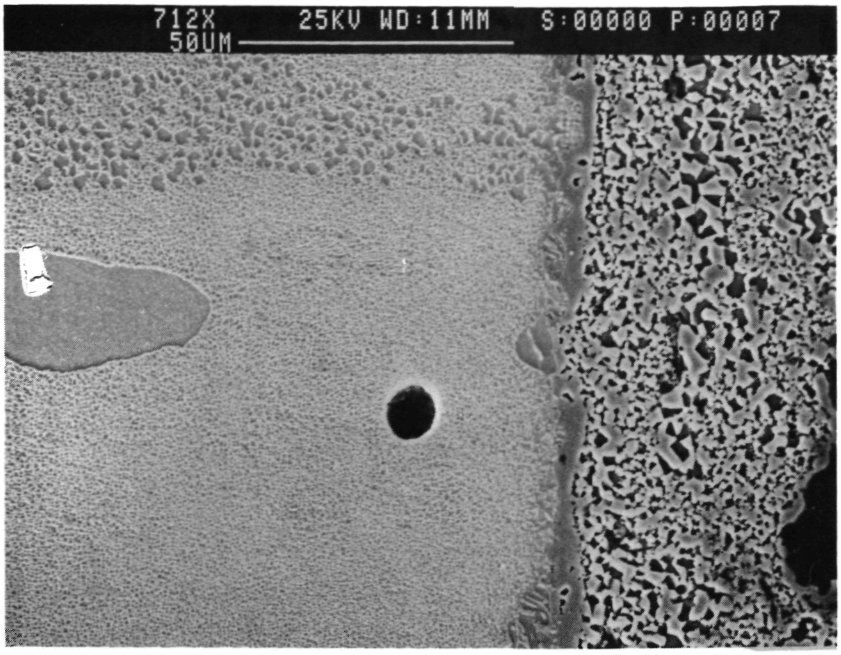

Figure 1. Microstructures of single crystal superalloy, PWA 1480, and NiCoCrAlY overlay coating, PWA 276 (left).

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 termperature 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

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.

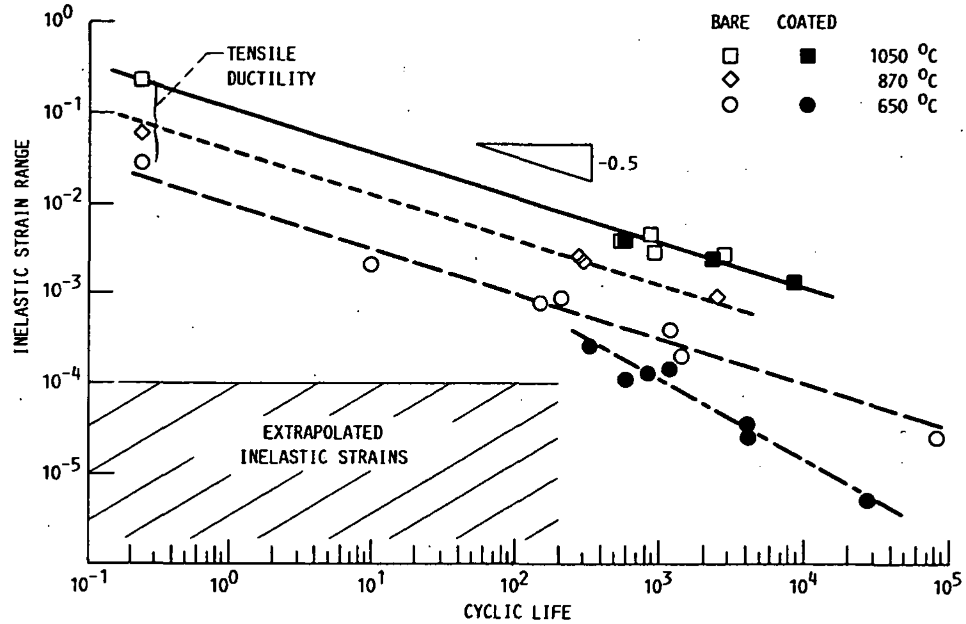

Figure 3. Isothermal inelastic strain - cyclic life behavior for bare and PWA 276 coated, PWA 1480.

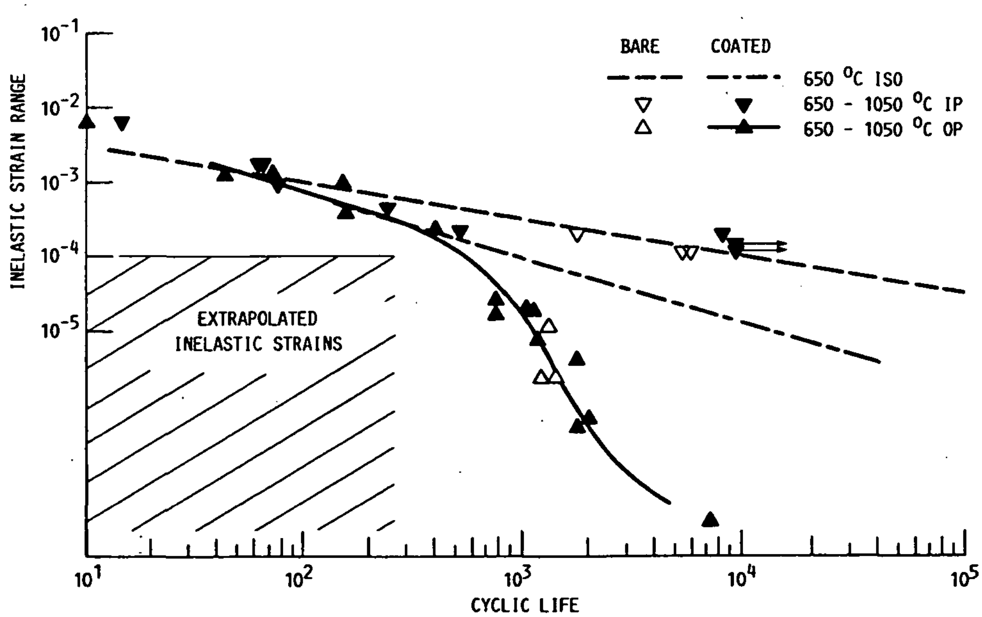

Figure 4. In- and out-of-phase bithermal inelastic strain - cyclic life behavior of bare and PWA 276 coated, PWA 1480.

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

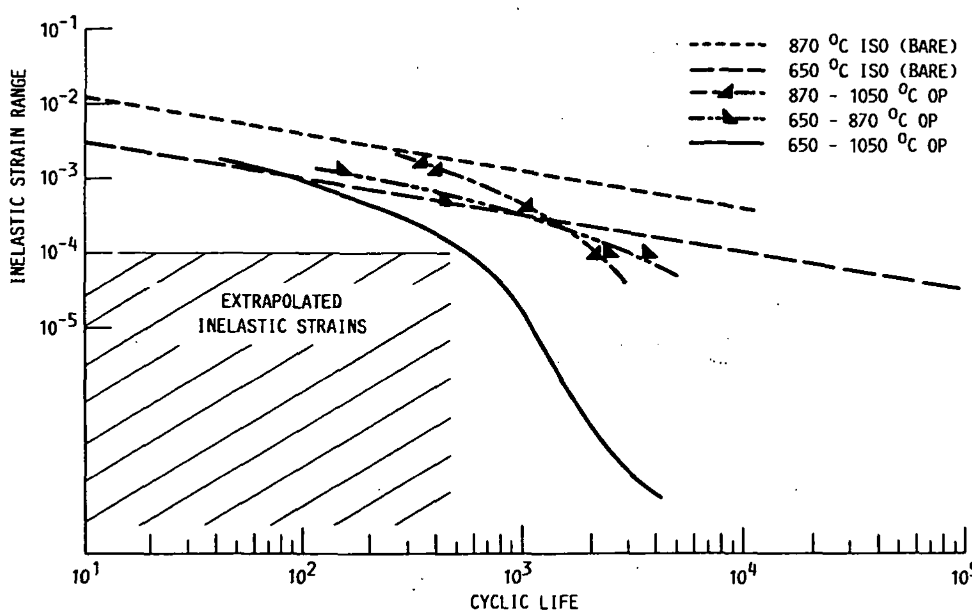

Figure 6. Effect of T_{max} and T_{min} on out-of-phase bithermal fatigue life of PWA 276 coated PWA 1480.

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 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 is 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 is the result of the high temperature exposure to air followed by tensile loading at low temperature and is 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 closer matching that of the <001> single crystal direction, and greater ductility and strength are of course desireable. 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.

Appendix

The following data compilation was used to construct the plots in this report. The stress and strain data reflects the appropriate value at half life for isothermal and bithermal tests.

TABLE I. - ISOTHERMAL FATIGUE DATA AT HALF LIFE

[Note: No entry implies strain measurement below 0.01 percent or for the case of vacuum tests no strain measurement made.]

S/N	Coating	Environment	Temperature, °C	$\Delta\varepsilon_{in}$, percent	$\Delta\varepsilon_T$, percent	σ_{max}, MPa	σ_{min}, MPa	N_f
60	N	A	1050	0.41	1.14	313	-292	581
77				.47	1.17	294	-280	891
38				.30	.97	267	-270	952
24				.27	.84	206	-200	2 895
143A	Y			.41	1.16	298	-279	600
253B	Y			.25	.76	222	-216	2 379
133B	Y			.13	.55	170	-163	8 637
346-2	N		870	.25	2.05	815	-827	286
340-2			870	.23	1.72	626	-721	302
328-1			870	.09	1.19	446	-529	2 562
113-1			650	.22	2.00	1010	-935	10
4H				.08	1.64	991	-930	153
21B				.09	1.79	988	-924	215
91G				.04	1.66	880	-863	1 228
333A				.02	1.46	829	-787	1 455
408-1				----	1.08	595	-595	83 012
58B	Y			.03	1.67	887	-861	338
141B				.01	1.57	814	-790	598
234B				.01	1.53	793	-796	858
420A				.02	1.27	697	-698	1 209
104A				----	1.21	636	-618	4 128
215A				----	.99	558	-558	4 214
135A				----	.92	466	-466	27 731
212B				----	.59	620	0	50 000+
99B		V		----	----	552	-552	6 052

TABLE II. - IN-PHASE BITHERMAL FATIGUE DATA AT HALF LIFE

S/N	Coating	Environment	$\Delta\varepsilon_{in}$, percent	T_{max}, °C	σ_{Tmax}, MPa	$\Delta\varepsilon_{Tmax}$, percent	T_{min} °C	σ_{Tmin} MPa	$\Delta\varepsilon_{Tmin}$ percent	N_f
402A	N	A	0.02	1050	124	0.19	650	-745	-0.73	1812
416	N		.01		140	.17		-632	-.50	5500
348A	N		.01		110	.19		-614	-.61	5940
238A	Y		.62		457	1.08		-928	-1.18	15
214B			.18		306	.56		-969	-.95	63
411B			.18		330	.53		-896	-.83	65
119A			.10		318	.46		-891	-.78	78
190A			.04		223	.33		-914	-.84	250
198B			.02		198	.29		-853	-.82	530
253A			.02		158	.24		-707	-.61	8338
428B			.01		126	.18		-745	-.71	9600+
447B			.01		100	.14		-652	-.60	9700+

NASA National Aeronautics and Space Administration

Report Documentation Page

1. Report No.
NASA TM-100907

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Isothermal and "Bithermal" Thermomechanical Fatigue Behavior of a NiCoCrAlY-Coated Single Crystal Superalloy

5. Report Date

6. Performing Organization Code

7. Author(s)
J. Gayda, T.P. Gabb, and R.V. Miner

8. Performing Organization Report No.
E-4077

10. Work Unit No.
505-63-11

9. Performing Organization Name and Address
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546-0001

13. Type of Report and Period Covered
Technical Memorandum

14. Sponsoring Agency Code

15. Supplementary Notes
Prepared for the Sixth International Conference on Superalloys sponsored by the American Institute of Mining, Metallurgical and Petroleum Engineers, Seven Springs, Pennsylvania, September 18-22, 1988.

16. 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 simplified 'bithermal' thermomechanical fatigue (TMF) tests between these temperatures. These tests were examined as a bridge between isothermal LCF and general TMF. In the bithermal test, an inelastic strain is applied at one temperature, T_{max}, and reversed at T_{min}. The 'out-of-phase' (OP) test type imposing tension at T_{min} and compression at T_{max} received most study, since it was more damaging than the 'in-phase' type. 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, and drastically so for the 650 to 1050 °C cycle. Surface cracks initiated and propagated rapidly in the 650 to 1050 °C OP cycle. Damage mechanisms in the low-$\Delta\varepsilon_{in}$ regime for OP bithermal tests were different, however, for bare and coated crystals. A 650 to 1050 °C OP vacuum test of a bare crystal was discontinued after 10 000 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 to 1050 °C). Time at T_{max}, however, had only a small detrimental effect.

17. Key Words (Suggested by Author(s))
Fatigue
Superalloys
Single crystals

18. Distribution Statement
Unclassified - Unlimited
Subject Category 26

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No of pages	22. Price*
Unclassified	Unclassified	12	A02

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161