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The attached paper "Effects Of Aging On The LCF Behavior Of Three Solid-Solution Strengthened Superalloys," by D. L. Klarstrom and G. Y. Lai will be presented at the Sixth International Symposium on Superalloys, Seven Springs, Pa., September 18-22, 1988. It will also be published in the conference proceedings entitled Superalloys 1988.

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EFFECTS OF AGING ON THE LCF BEHAVIOR OF THREE SOLID-SOLUTION-STRENGTHENED SUPERALLOYS

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Abstract

A study was conducted to examine the effects of thermal aging at 760°C (1400°F)/1000 Hrs. on the low temperature LCF behavior of HASTELLOY® alloy X, HAYNES® alloy No. 230 and HAYNES alloy No. 188. Results of LCF tests on samples in the annealed condition indicated that alloy 188 had the best fatigue resistance over the whole range of test conditions, followed by 230™ alloy and alloy X. In the aged condition, the fatigue of alloys X and 188 were significantly degraded under conditions in which the inelastic strain was greater than 0.10%. A much smaller amount of degradation was noted for 230 alloy. Taking data scatter into account, the aged fatigue resistances of alloy 188 and 230 alloy were essentially equivalent, and superior to alloy X. In all cases, the alloys were found to cyclically harden with plateaus or peak stresses not reached until near the point of crack initiation. The 230 alloy was found to harden to a greater extent than the other two alloys. The cyclic stress response of alloy 188 was unusual in the sense that observed stress amplitudes at the low end of the strain test range were higher than some tests at higher strain range levels. Microstructural observations indicated that the precipitation of carbides and brittle intermetallic compounds were responsible for the fatigue life degradations of alloys X and 188. In contrast, only carbide precipitation was observed in 230 alloy.

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Introduction

Solid-solution strengthened superalloys are widely used in gas turbine engines as combustor cans, transition ducts, and other static components. In such applications, they are repeatedly exposed to cyclic thermal and mechanical stresses during the start-up, steady-state and shut-down portions of engine operation. Not surprising, therefore, is the fact that fatigue cracking is a major mode of failure in such parts. Hence, fatigue behavior must be taken into account by the designer in order to achieve satisfactory operating lives. This should include not only the behavior at maximum steady-state design temperatures, but also the behavior at lower temperatures encountered during the engine transients.

Most often the approach used to generate the required data is to run iso-thermal low cycle fatigue tests using materials in the solution annealed condition. While such data may provide a useful baseline for nominal design purposes, it cannot be considered wholly satisfactory since it does not take into account changes in mechanical properties that can occur during service exposure. Examples of such changes, especially with respect to ductility loss, have been extensively reported in the literature. The effects of these changes can be expected to be significant at low temperatures since the recovery of mechanical properties generally occurs at temperatures on the order of 0.5 Tm or higher. It was, therefore, the purpose of this investigation to examine the low temperature LCF behavior of three solid-solution strengthened superalloys in the annealed and aged conditions.

Experimental Procedures

The nominal compositions of the alloys studied in this investigation are listed in Table I. The materials consisted of 19mm (0.75-inch) thick plate of alloy X with a grain size of ASTM 5.5, 16mm (0.625-inch) thick plate of 230™ alloy with a grain size of ASTM 5.5 and 19mm (0.75-inch) diameter bar of alloy 188 with a grain size of ASTM 4 which were produced from commercial heats by Haynes International, Inc. The materials were tested in the as-received, solution annealed condition, and after aging at 760°C (1400°F) for 1000 hours. Tensile testing was conducted in accordance with ASTM standards to document mechanical properties of the alloys in the two conditions.

TABLE I

Nominal Compositions of Alloys

Alloy	Ni	Co	Cr	Mo	W	Fe	Si	Mn	C	Al	La
HASTELLOY® alloy X	Bal.	1.5	22	9	0.6	18.5	1.0*	1.0*	0.10	-	-
HAYNES® alloy No. 230	Bal.	5.0*	22	2	14	3.0*	0.40	0.50	0.10	0.30	0.02
HAYNES alloy No. 188	22	Bal.	22	-	14	3.0*	0.35	1.25*	0.10	-	0.04

* Maximum

Fully reversed, axial, strain-controlled, low cycle fatigue tests were performed by Metcut Research Associates, Inc., Cincinnati, Ohio. The LCF tests were conducted on smooth bar samples at a temperature of 427°C (800°F) and a frequency of 0.33 HZ (20 cpm). The fracture surfaces of selected samples were examined in an SEM to determine the modes of fracture initiation and propagation. Metallographic analysis was also performed on the selected samples to examine secondary fatigue cracks and general microstructural features.

Results

Tensile Properties

A summary of the 427°C (800°F) tensile properties of the three alloys in the annealed and aged conditions is presented in Table II. It can be seen that alloys X and 188 exhibit strengthening as the result of the aging process as evidenced by increases in yield and ultimate strengths. In contrast, the strength changes of 230 alloy were small and mixed, with the yield strength increasing slightly, and the ultimate strength decreasing slightly. In all cases, aging caused a significant decrease in ductility values. The largest absolute and relative decreases occurred for alloy X, while 230 alloy suffered the least such changes. In terms of absolute magnitude, alloy X exhibited the least residual ductility, followed by 230 alloy and alloy 188.

TABLE II

Summary of 427°C (800°F) Tensile Properties
For Materials In The Annealed and Aged* Conditions

Alloy	Condition	0.2% YS MPa (Ksi)	UTS MPa (Ksi)	% EL in 5D	% RA
X	Annealed	234 (34)	613 (89)	57	54
	Aged	379 (55)	841 (122)	20	24
230	Annealed	282 (41)	751 (109)	57	46
	Aged	296 (43)	730 (106)	40	35
188	Annealed	269 (39)	792 (115)	89	61
	Aged	386 (56)	841 (122)	40	40

* Aged at 760°C (1400°F)/1000 Hrs.

Low Cycle Fatigue Life Behavior

A listing of the 427°C (800°F) low cycle fatigue lives of the three alloys in the annealed and aged conditions is given in Table III. At the 0.55% total strain range level, the inelastic components were less than 0.10%, and tests ran to 10^5 cycles and beyond. In the case of alloy 188, tests were discontinued before failure. A graphical presentation of the data above 0.55% total strain range is provided in Figure 1.

TABLE III

Comparison of Annealed vs. Aged
427°C (800°F) LCF Behavior
R = -1.0, f = 0.33 HZ (20 cpm)

Nominal Total Strain Range, %	Cycles to Failure					
	Annealed			Aged @ 760°C (1400°F)/1000 Hrs.		
	Alloy X	230 Alloy	Alloy 188	Alloy X	230 Alloy	Alloy 188
1.50	2,051	2,398	3,710	1,756	2,260	2,848
1.00	7,750	8,742	12,647	4,889	7,033	6,970
0.80	14,417	16,575	21,089	10,320	15,310	12,470
0.65	28,679	46,523	59,652	21,367	34,571	38,841
0.55	100,486	115,456	>150,000*	97,325	123,200	>155,000*

* Test Discontinued

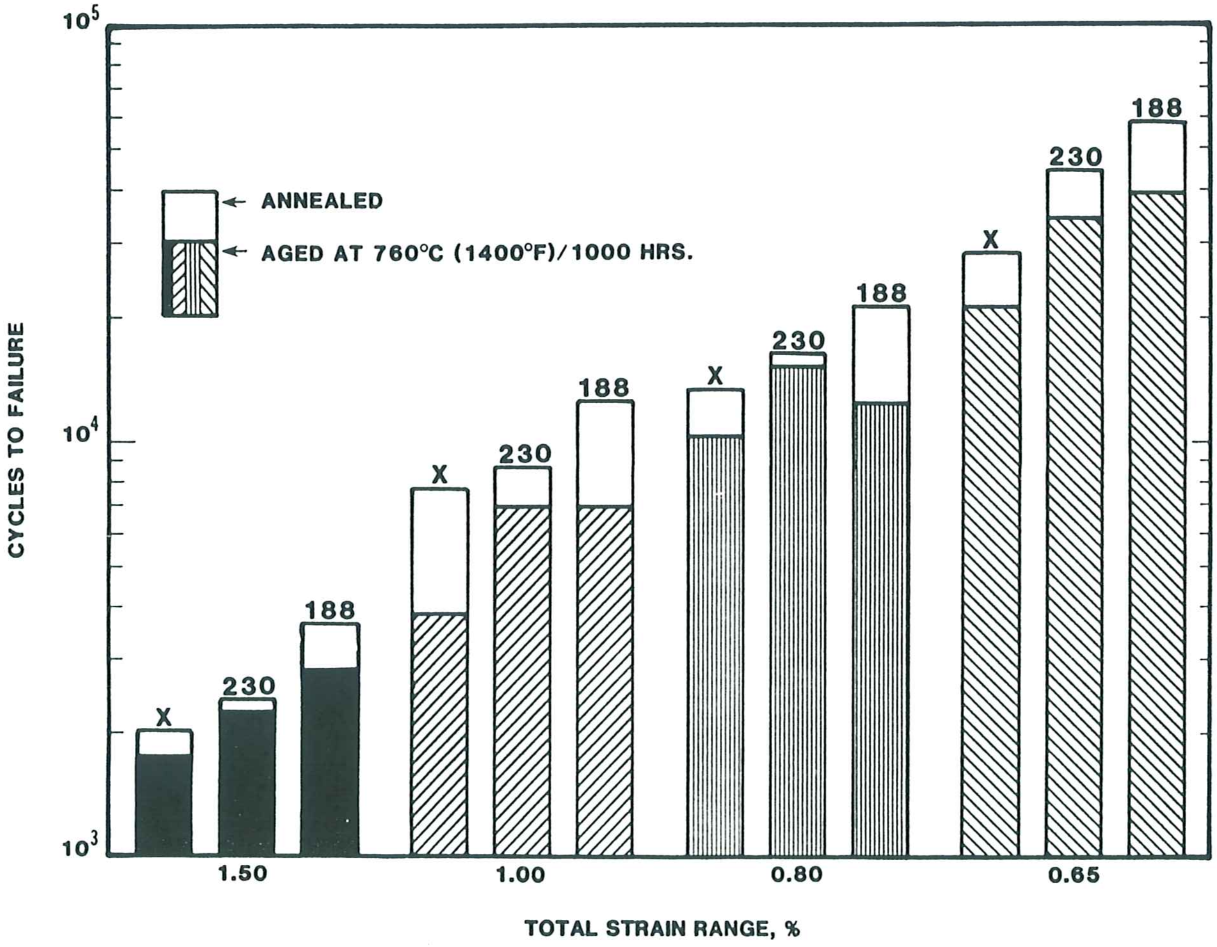


Figure 1. Fatigue life comparison of alloys in the annealed and aged condition.

In the annealed condition, the alloy ranking in terms of highest to lowest lives was in the order of alloy 188, 230 alloy and alloy X. This ranking is in good agreement with what might be anticipated on the basis of the mechanical properties of Table II. In the aged condition, a fatigue life degradation was observed for all of the alloys for total strain range levels above 0.55%. Again, alloy X exhibited the lowest fatigue lives, while near parity was reached for the fatigue lives of alloy 188 and 230 alloy taking data scatter into account. If the fatigue life degradation of each alloy is viewed on a relative basis as illustrated in Table IV, then it can be seen that overall alloy 188 was proportionately degraded the most, and 230 alloy was degraded the least.

TABLE IV

Aged/Annealed Fatigue Life Ratios

Nominal Total Strain Range, %	Ratios of Cycles to Failure Aged/Annealed		
	Alloy X	230 alloy	Alloy 188
1.50	0.86	0.94	0.77
1.00	0.63	0.80	0.55
0.80	0.72	0.92	0.59
0.65	0.75	0.74	0.65
0.55	0.97	1.07	-

Cyclic Stress Behavior

The cyclic stress behavior of the three alloys in the annealed and aged conditions is shown in Figure 2. In all cases, the alloys were found to cyclically harden, and, with few exceptions, well defined plateaus were not achieved prior to crack initiation. The greatest amount of hardening in both the annealed and aged conditions was observed for 230 alloy. Alloy 188 exhibited an unusual response in the sense that the extent of hardening observed at the lowest strain range levels was higher than that at some of the higher strain range levels. In the annealed condition, the degrees of hardening reached by alloys X and 188 were about the same.

There were some notable differences in the cyclic stress behavior of the materials in the annealed and aged conditions. Generally, the initial stress levels of the aged materials were higher as might be anticipated from the tensile data in Table II. The largest upward shifts were observed for alloy X followed by alloy 188 and 230 alloy. The extent of hardening for the aged condition tended to be about the same or slightly higher for 230 alloy and alloy X, but notably higher for alloy 188. In spite of the upward shift of the initial stress, the configurations of the curves for 230 alloy and alloy 188 were similar to the corresponding curves for the annealed condition. Alloy X, on the other hand, displayed markedly different characteristics. The curves for the aged condition exhibited more gradual and steady hardening compared to the annealed condition.

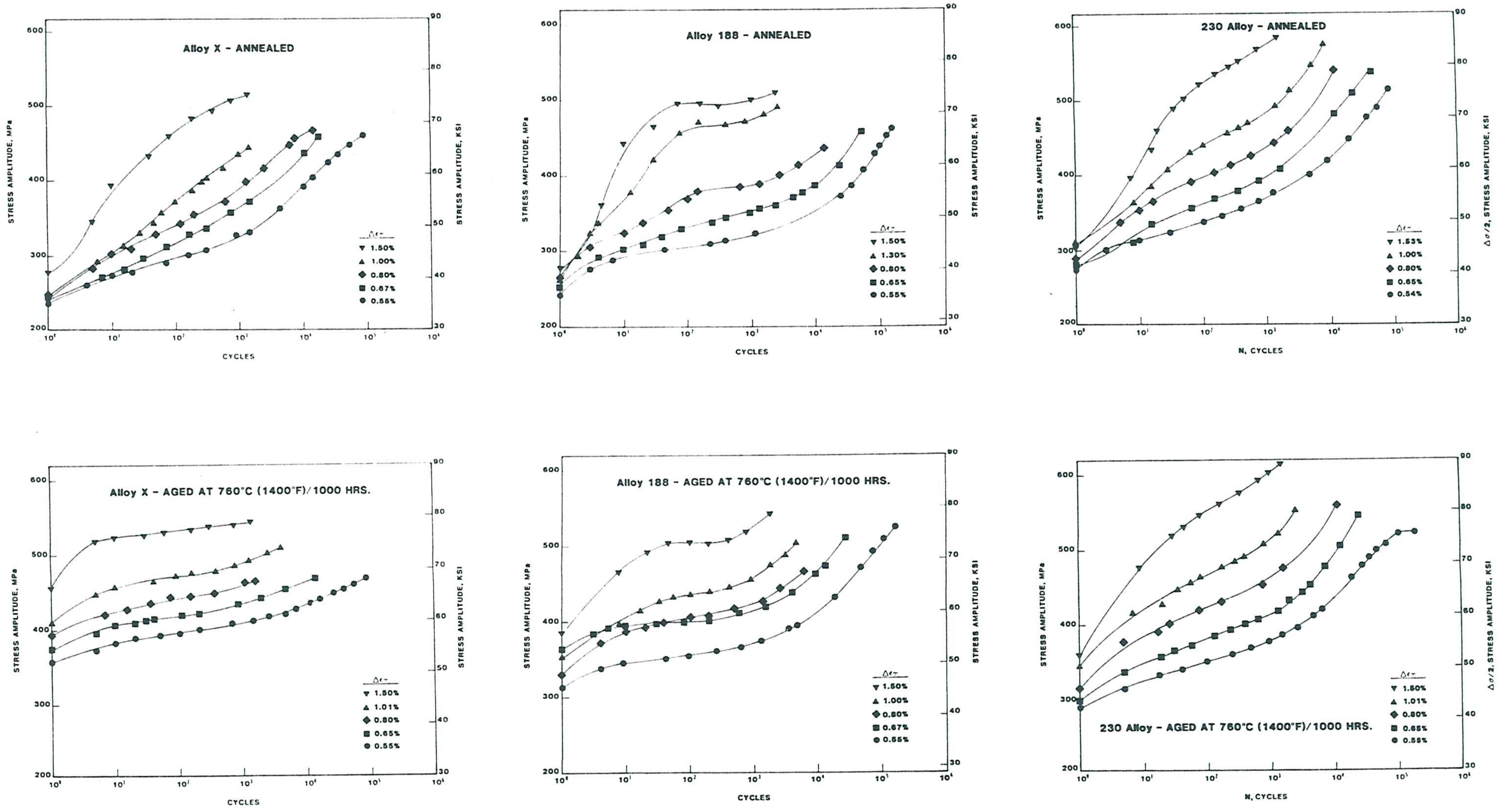
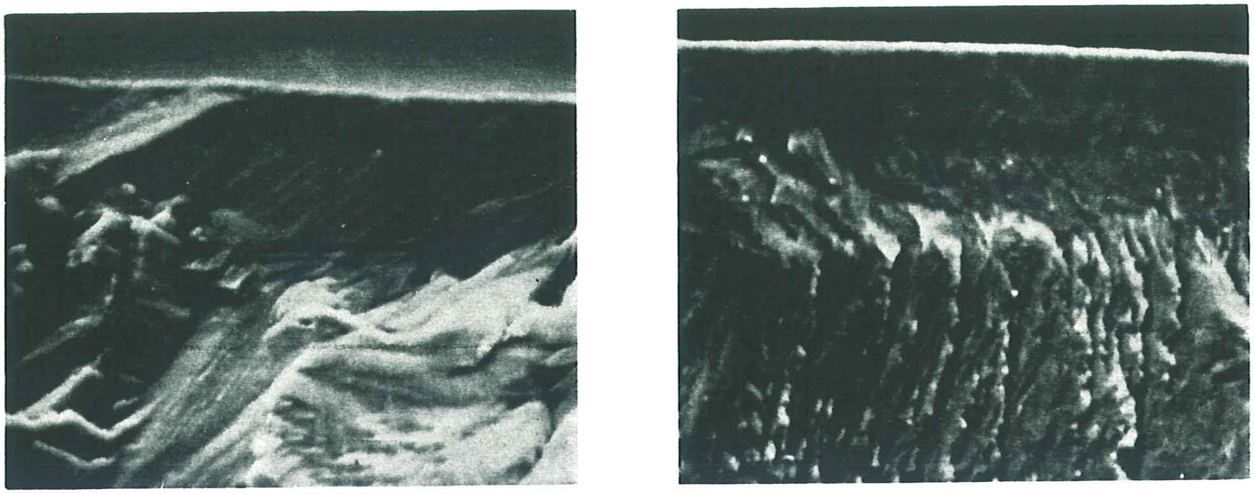
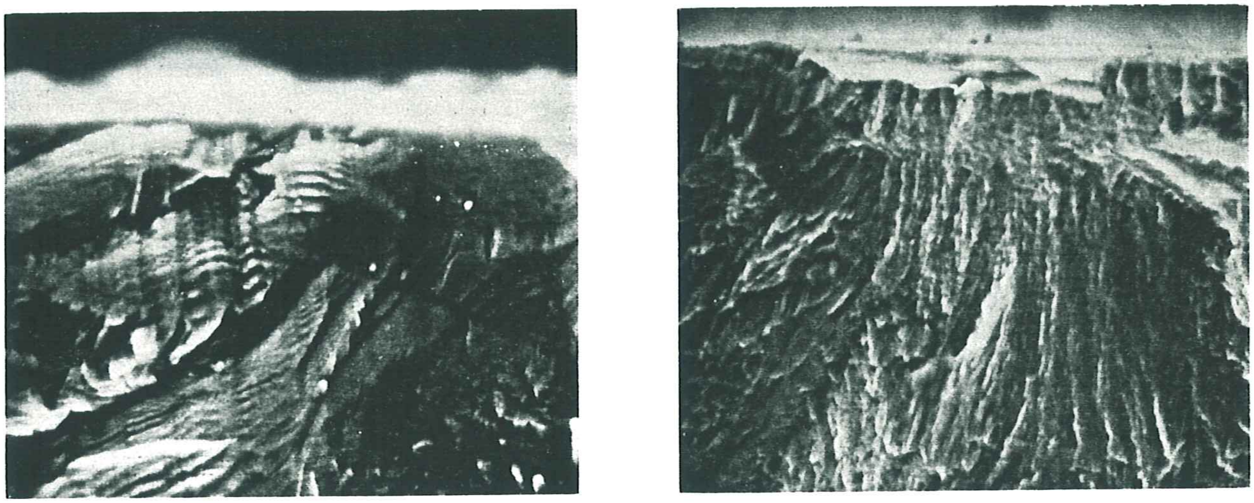


Figure 2. The cyclic stress behavior of the alloys in the annealed and aged conditions.



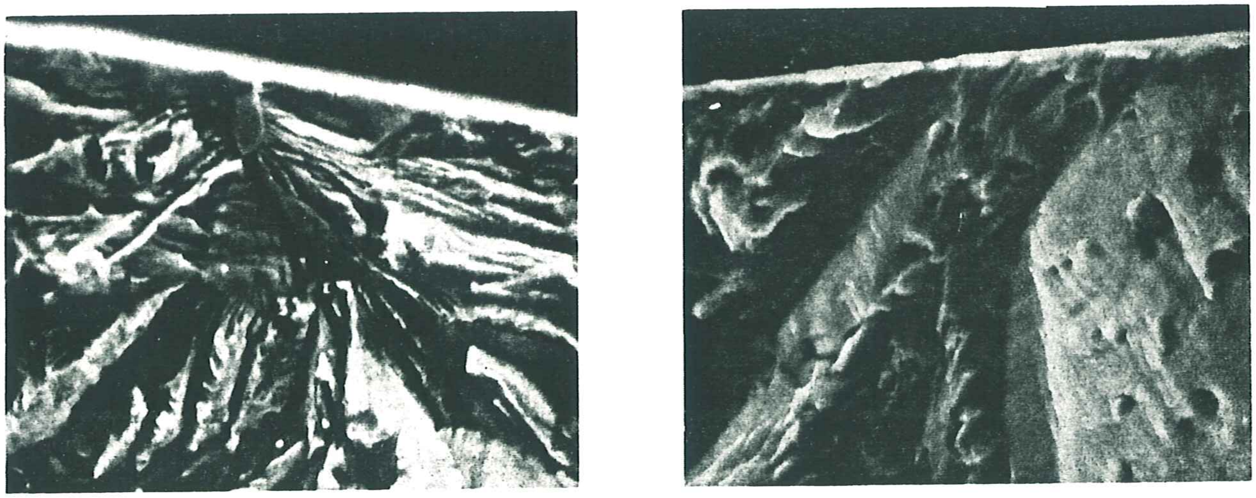
(a) Alloy X - annealed
Neg. No. 56523

(b) Alloy X - aged
Neg. No. 56525



(c) Alloy 188 - annealed
Neg. No. 56519

(d) Alloy 188 - aged
Neg. No. 56521

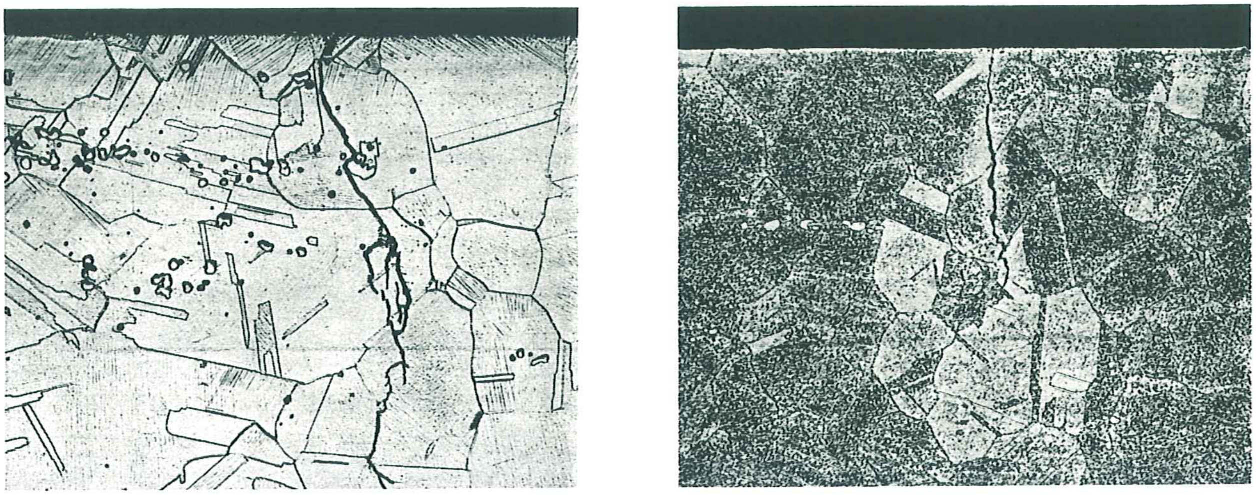


(e) 230 alloy - annealed
Neg. No. 56515

(f) 230 alloy - aged
Neg. No. 56517

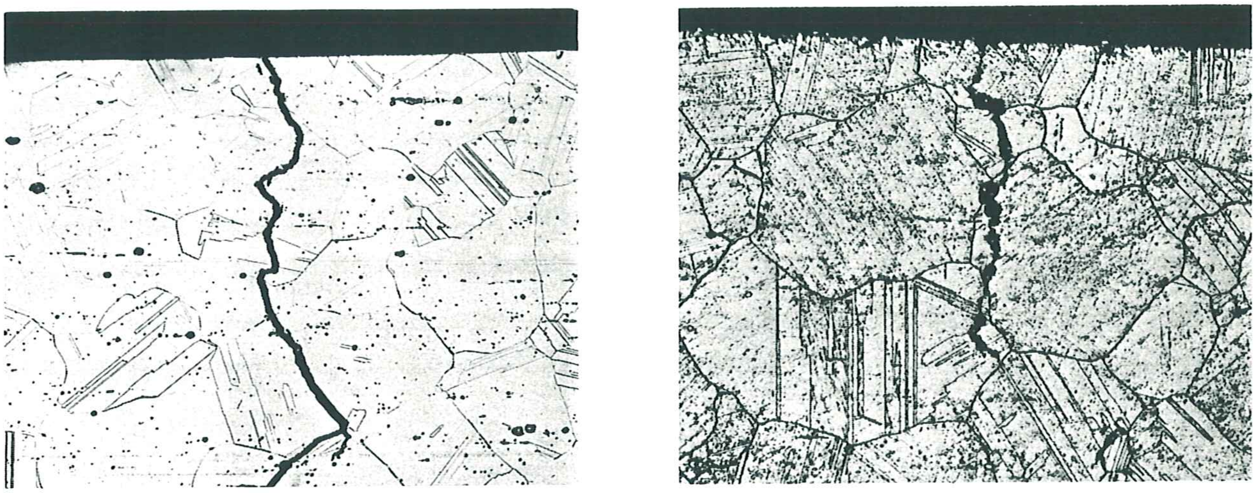
10 μm

Figure 3. SEM photos of fracture surfaces.



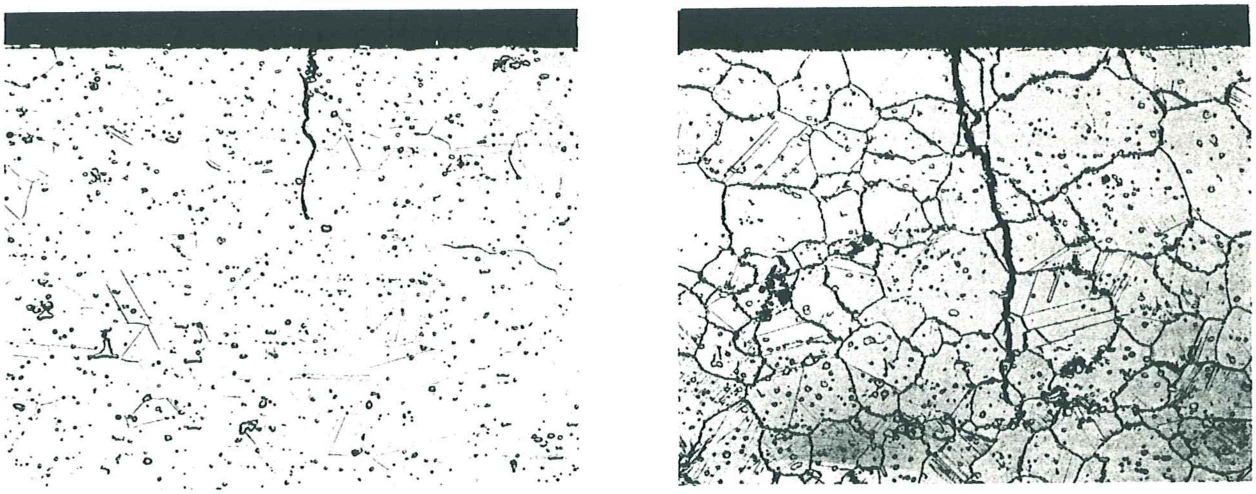
(a) Alloy X - annealed
Neg. No. 56347

(b) Alloy X - aged
Neg. No. 56349



(c) Alloy 188 - annealed
Neg. No. 56342

(d) Alloy 188 - aged
Neg. No. 56345



(e) 230 alloy - annealed
Neg. No. 56339

(f) 230 alloy - aged
Neg. No. 56341

50 μm

Figure 4. Secondary cracks and microstructural features.

Fracture Surface Characteristics

The fracture surfaces of the samples tested at a total strain range of 0.80% were selected for SEM examination. A summary of the fracture features observed at the fracture initiation sites is presented in Figure 3. In the annealed condition, all of the alloys exhibited Stage I type fracture initiation which is characterized by transgranular, cleavage type features. Within very small distances all of the alloys experienced a transition of Stage II crack propagation which is characterized by the familiar transgranular fatigue striations. In the aged condition, alloy 230 again displayed Stage I crack initiation and a rapid transition to Stage II crack propagation. In contrast, both alloys X and 188 in the aged condition exhibited an extensive area of transgranular crack initiation in a mode commonly described as quasi-cleavage. As will be shown later, this behavior is most likely the result of the copious precipitates that formed in these alloys during the aging treatment. Eventually, both alloys underwent a transition to Stage II crack propagation, but, in the case of alloy 188, occasional flat facets were noted in the fracture surface.

Secondary Cracking and Microstructural Features

Figure 4 summarizes the nature of the secondary cracking and the microstructural features for the samples tested at a total strain range of 0.80%. In all cases, the secondary cracks were observed to propogate in a transgranular fashion. Some branching and deviation of the cracks can be noted.

In terms of microstructure, all of the alloys in the annealed condition displayed clean grain boundaries, and there were primary M_6C-type carbides randomly distributed throughout the matrix as is typical for alloys of this class. In the aged condition, alloys X and 188 exhibited extensive grain boundary and matrix precipitation. The extent of the matrix precipitation was much greater in the case of alloy X. Previous studies have shown that the precipitates present in alloy X are $M_{23}C_6$ carbides and sigma-phase (1), and those present in alloy 188 are M_6C and $M_{23}C_6$ carbides and a Co_2 W-type Laves-phase (2). In the case of 230 alloy, extensive grain boundary and very slight matrix precipitation was in evidence for the aged condition. These precipitates have been previously identified as $M_{23}C_6$ carbides (3).

Discussion and Conclusions

The results clearly indicate that the 427°C (800°F) fatigue lives of all of the alloys were degraded by the 760°C (1400°F)/1000 Hrs. aging treatment. On a relative basis, the extent of the degradation was greatest for alloy 188 and least for 230 alloy. The cause of the decline in alloys X and 188 was the precipitation of sigma- and Laves-phases respectively in addition to the precipitation of carbides which are fully anticipated in substitutionally strengthened alloys of this class. The degradation in 230 alloy was lower since only carbide precipitation occurred.

The observed fatigue life degradation was expected based on the lower tensile ductilities recorded for each alloy in the aged condition. It is important to recognize here that this investigation covered the LCF behavior of the materials after 1000 hours of exposure time, and longer times might be expected to result in further declines in ductility. To gain some insight on this prospect, the results of a previous study of alloys X and 188 (4) were compiled along with recently developed data on 230 alloy into Table V. It can be seen from this table that additional aging would significantly reduce the ductility of alloy 188, while alloy X and 230 alloy maintain essentially constant ductility levels beyond the first 1000 hours. Accordingly, it would be expected that alloy 188 would exhibit much lower fatigue lives with additional aging than reported here, but those of alloy X and 230 alloy would be expected to remain about the same.

TABLE V

The Effect of Exposure Time at 760°C (1400°F)
On Room Temperature Tensile Elongation

Alloy	RT Tensile Elongation (%) After Indicated Exposure Time			
	None	1000 Hrs.	4000 Hrs.	8000 Hrs.
230	51	33	38	35
X	47	23	21	20
188	63	35	11	9

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