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FINAL SCIENTIFIC REPORT

Air Force Contract F49620-79-C-0004

October 1, 1979 - September 30, 1980

Research Program on

The Fatigue of Titanium Alloys

A. J. McEvily

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A two year period of research on the fatigue characteristics of titanium alloys has been completed. Many of the aims of the program have been achieved. However, due to the late receipt of a large number of the test specimens, not all of the testing and study of the low cycle fatigue behavior investigations could be completed on schedule. Despite the extra costs involved, we expect to complete the test portion of the program by the end of 1980. Research on fatigue crack growth and the effects of overloads as well as a study of creep crack growth in a titanium alloy has been completed.

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Research Program on

The Fatigue of Titanium Alloys

Submitted to

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ABSTRACT

A two year period of research on the fatigue characteristics of titanium alloys has been completed. Many of the aims of the program have been achieved. However, due to the late receipt of a large number of the test specimens, not all of the testing and study of the low cycle fatigue behavior investigations could be completed on schedule. Despite the extra costs involved, we expect to complete the test portion of the program by the end of 1980. Research on fatigue crack growth and the effects of overloads as well as a study of creep crack growth in a titanium alloy has been completed.

INTRODUCTION

The principal interest of the research program for the period October 1, 1979, to September 30, 1980, had been to carry out research on the fatigue behavior of titanium alloys at elevated temperatures. The research program was directed at:

The study of creep-fatigue interactions in two high temperature titanium alloys, Ti 5524S and Ti 685. Specimens for this program were supplied by the Ladish Corp. as arranged by the AFML. Unfortunately, production problems at Ladish resulted in the late delivery of these specimens, but at any rate all but six specimens have by now been received and the test program is nearing completion. Since research personnel had been assigned to the program we were fortunate that the AFML through Dr. F. H. Froes and Dr. D. Eylon were able to supply specimens of the alloy Ti 6242S and we were able to utilize our resources to carry out a study of the mechanism involved in crack retardation after an overload and the effects of environment on crack growth at room and elevated temperatures. A third area of research was the study of the mechanics of creep crack growth. Further information concerning these projects is provided below.

SCIENTIFIC ACTIVITIES

1. The high temperature low cycle fatigue resistance of three titanium alloys had been investigated (Ti 6242S, Ti 5524S and Ti 685). Different types of microstructures have been developed for each of these alloys by various combinations of mechanical processing and heat treatment above and below the β-transus. Two microstructures of the Ti 6242S alloy were examined while 16 microstructures were tested for each of the Ti 5524S and Ti 685 alloys (see Table 1).

TABLE 1 - LIST OF CONDITIONS

CONDITION	PRELIMINARY BREAK DOWN TEMP °C	FINAL FORGE TEMP °C	SOLUTION TREATMENT TEMP °C	REASON FOR SELECTION
		Ti 5524S (Ti-5Al-5Sn-2Zr-4Mo-0.25Si)		
1	β-30	β-30	β-15(OQ)	Producer recommended condition for disk material.
2	β-30	β-30	β+20(OQ)	Effect of β S.T.
3	β-30	β+30	β-50,24hr(OQ)	Broken up microstructure (Ref. 1).
4	β-30	β+30	β-15(OQ)	Effect of final β forging.
5	β-30	β-30	β-60(OQ)	Effect of S.T. temperature (compare with #1).
6	β+30	β-30	β+20(OQ)	Comparison with Ti-685 #2.
7	β-30	β-30	β-15(AC)	Cooling rate effect (compare with #1).
8	β-30	β+30	β-15(AC)	Cooling rate effect (β forged),(compare with #4).
		Ti 685 (Ti-6Al-5Zr-0.5Mo-0.25Si)		
1	β+30	β+30	β+20(OQ)	All β forging.
2	β+30	β-30	β+20(OQ)	Producer recommended condition for disk material.
3	β-30	β-30	β+20(OQ)	Isothermal forging examination.
4	β-30	β-30	β-15(OQ)	Comparison with Ti-5524 #1.
5	β+30	β+30	β-15(OQ)	Effect of S.T. temperature (compare with #1).
6	β-30	β+30	β+20(OQ)	Final β forging effect (compare with #2).
7	β+30 (72% red)	β-30 (25% red)	β+20(OQ)	Forging reduction effect (compare with #2).
8	β+30	β-30	β+20(OQ)	Stabilization temp (600°C) effect (compare with #2).

Ref. 1: D. Eylon, J.A. Hall, C.M. Pierce and D.L. Ruckle: Metallurgical Transactions A, Volume 7A (1976), pp 1817-1826.

Stabilization treatment for all Ti 5524 conditions: 600 C/2hr/AC

Stabilization treatment for all Ti-685 conditions: 550 C/24hr/AC (except #8-685: 600°C/2hr/AC

Solution treatment time for Ti-5524 and Ti-685: 1 hr.

Forging reduction for each step approx. 50% (except #7-685: 72% and 25%).

In order to study the effect of the environment on the high temperature low cycle fatigue behavior a number of tests were performed in vacuum utilizing the Ti 6242 alloy. The results of this portion of the low cycle fatigue study have been discussed in the paper:

> "The Influence of Microstructure on the Elevated Temperature Fatigue Resistance of a Titanium Alloy," C. Hoffmann, D. Eylon, and A. J. McEvily, Int. Symposium on Low Cycle Fatigue, Firminy, France, Sept. 1980.

A main point of this paper was that $\alpha+\beta$ processed microstructures have superior HTLCF resistance as compared to β processed microstructures of the same alloy. The fatigue resistance of β processed microstructures is lower because of a decreased resistance to fatigue crack initiation. It has been found that in tests performed in air fatigue crack initiation occurs at the specimen surface, predominately along $\alpha-\beta$ interfaces. This is believed to be a result of preferred oxidation occurring at these locations. Equiaxed primary alpha particles present in $\alpha-\beta$ processed microstructures reduce the overall number and length of $\alpha+\beta$ interfaces thereby increasing resistance to fatigue crack initiation. Subsurface crack initiation was found to occur during HTLCF testing in vacuum; the role of surface cracking in vacuum was minimal. These observations demonstrate a strong environmental-fatigue interaction for these materials and test conditions.

The bulk of the test program on the Ti 5524S and Ti 685 alloys has been completed. A total of 256 tests were required of which 250 have been performed. Difficulties in machining the remaining 6 specimens have delayed them from being shipped to us. One of the goals of this program was to define the microstructures most resistant to fatigue. In order to do this 16 microstructures of each alloy were prepared as mentioned previously. Of these 8 were produced by conventional forging techniques and 8 by isothermal forging of the material. The 8 different conditions for each alloy were achieved by varying forging and heat treatment temperatures above and below the β transus.

As for the Ti 6242S alloy it has been found that α+β processing generally provides better HTLCF resistance than β processed microstructures. Isothermal forging provided only a small increase in HTLCF life compared to the same microstructure as conventionally forged. Other comparisons of HTLCF lifetimes for each of the microstructural variations are also being made.

Microstructural characterization of all of these microstructures is presently being carried out using optical as well as transmission electron microscopy.

Scanning electron microscope studies of fracture surface are also underway to provide insight into how the different microstructures behave in HTLCF. Distinct differences have been observed in the fracture surface features of microstructures which show the largest differences in fatigue lifetimes.

Some specimens have also been sectioned in order to study crack initiation behavior and to provide further information about crack path microstructural feature relationships.

2. A study of crack retardation in the alloy Ti 6242S due to overloads and the attendant crack closure behavior has been carried out. Crack opening loads were measured using an elastic compliance method and strain gauge techniques. At both room and elevated temperature (1000°F) in vacuum the number of delay cycles N_D, due to a single spike overload, decreased with increasing ΔK (range of ΔK was from 15 ksi$\sqrt{in}$ to 35 ksi$\sqrt{in}$) with this

being most pronounced below $\Delta K = 25\ ksi\sqrt{in}$. For all ΔK values the extent of crack retardation was greater at the elevated temperature. Below $\Delta K = 20\ ksi\sqrt{in}$, the number of delay cycles at elevated temperature was six times that at room temperature, but at higher ΔK levels the ratio of N_D at 1000°F to room temperature decreased to two or less. Although fatigue crack growth rates in vacuum at 1000°F are independent of test frequency over the range of 1 to 30 Hz, N_D was found to be freq·ency dependent at the elevated temperature. For a $\Delta K = 25\ ksi\sqrt{in}$, a decrease in test frequency from 20 Hz to 1 Hz resulted in a 50 percent decrease in N_D.

Crack closure measurements were obtained (at room temperature) before and after application of an overload and exhibited two types of behavior.

1. Below $\Delta K = 20\ ksi\sqrt{in}$, K_{op}, following the overload, immediately increased above the baseline value, reached a maximum and then with continued cycling decreased towards the baseline K_{op} value. Retardation usually occurred immediately.
2. Above $\Delta K = 20\ ksi\sqrt{in}$, K_{op}, following the overload, immediately decreased below the baseline value. With continued cycling and crack extension K_{op} increased above the baseline value, reached a maximum and then decreased towards the baseline K_{op} value. Delayed retardation was frequently observed.

Results demonstrate that crack retardation is strongly influenced by near surface effects, since removal of the specimen surface indicated that the crack was open internally but very tightly closed within the overload plastic zone. Observations also imply that following an overload crack opening at the surface is a two stage process consisting of (1) crack opening up to the point of overload application, followed by (2) crack opening of the tightly closed surface crack within the overload plastic zone.

The importance of residual compressive stresses on retardation behavior is borne out by considering the effects of rest periods and test frequency on the number of delay cycles. A frequency effect can result particularly at elevated temperature if relaxation of overload induced stresses occurs during subsequent fatigue cycling. Results indicate that as the test frequency at 1000°F is decreased the number of delay cycles also decreases and approaches a lower limiting value. Thus, the relaxation of residual compressive stresses during rest periods or during cycling can have pronounced effects on N_D.

Finally, using a normalization parameter $\frac{N_D}{a^*/(da/dN)}$ where da/dN is the crack growth rate for a given baseline stress intensity level and a* is the overload affected crack length, the relative amount of retardation was found to be independent of baseline ΔK level.

3. Subsurface fatigue crack initiation of β-annealed Ti-6Al-4V high cycle fatigue specimens has been investigated with the aid of a precision sectioning technique. It was found that

   a. None of the examined subsurface initiation sites were associated with any kind of defect.

   b. Subsurface initiation was not always associated with lower fatigue lives as compared to specimens with surface initiation.

   c. In all cases the initiation facet was across one or more colonies of similarly aligned α platelets.

d. The initiation facets were inclined at 45 and 55 degrees to the tensile axis and were probably caused by intense shear across the colonies.

e. The coarsened bar specimen showed two colony orientations on the fracture facets, with 59 degree angle between their α/β interfaces, and within the same prior β zone. This angular relationship satisfies the Burger's relation and indicates that a common $(0001)_\alpha$ plane in both colonies allowed this two colony initiation facet.

4. Fatigue crack growth behavior of annealed Ti 6242S in the near threshold region was investigated with the following results:

Test Condition	ΔK_{th}, ksi$\sqrt{in}$ R=0.05	R=0.05
Air 25°C	7.8	4.4
Vac 25°C	13.9	9.1
Vac 540°C	10.2	-

a. For comparative purposes ΔK_{th} for $\alpha+\beta$ heat treated material was also determined at 25°C in air environment, and ΔK_{th} was found to be 6.1 ksi$\sqrt{in}$. Thus, the heat treated material had superior crack growth resistance, a circumstance attributable to a larger colony size and the presence of large prior β grains. These resulted in a more faceted, rougher fracture surface and a more tortuous, bifurcated crack path. This was also supporting evidence from the crack closure measurements, since the ratio of K_{op}/K_{max} for the β heat treated and $\alpha+\beta$ heat treated material was .75 and .65 respectively.

b. K_{op} measurements or heat treated material in vacuum (25°C) were higher than the values measured in air. Attempts to unify air and vacuum data based solely on ΔK_{eff} approach were not completely successful, indicating that environmental effects were also important.

c. Preliminary results indicate greater retardation in vacuum than in air at room temperature, a circumstance which appears to result from the greater amount of plastic deformation in vacuum than in air for a given stress intensity level. As expected, a greater retardation for specimens of 4 mm thickness as compared to usual thickness of 6.4 mm has been observed.

5. The process of creep crack growth has also been investigated in both titanium and aluminum alloys. For 6061-T6 aluminum alloy a parametric approach has been used to connect the three variables - crack growth rate, $\dot{a}$, the local point deflection rate, $\dot{\Delta}$, and the applied load, P, in the form

$$\dot{a} \; \alpha \left[\dot{\Delta}/\left(\frac{P}{P_o}\right)^{\alpha}\right]^{1/\theta} \tag{1}$$

where α, θ and P_o are constants.

In a related study using Ti 6242S it was found that the material was much more creep-brittle than the aluminum alloy, and the dependency on load level was not observed. Therefore the above expression could be reduced to

$$\dot{a} \; \alpha \; (\dot{\Delta})^{1/\theta}$$

The creep-ductile or creep-brittle nature of the alloy is reflected in the constant α.

CONCLUDING REMARKS

In addition to the four publications stemming from this program and reported last year, an additional seven papers have been prepared in the past year. The listing of these publications is on the next page. Additional publications resulting from recently completed experimental work are expected.

PUBLICATIONS

OCT. 1978 - SEPT. 1979

1. J. Ruppen and A. J. McEvily, "The Effect of Elevated Temperature and Environment on the Fatigue Crack Growth Characteristics of Ti-6Al-2Sn-4Zr-2Mo-0.1Si," to be published in Fatigue of Engineering Materials and Structures, 1979. Presented at Fatigue Conference, Sheffield, England, July, 1979.

2. J. Ruppen and A. J. McEvily, "The Influence of Microstructure and Environment on the Fatigue Crack Growth Fracture Topography of Ti-6Al-2Sn-4Zr-2Mo-0.1Si," to be published in an ASTM STP. Presented at Symposium on Fractography in Materials Science, Williamsburg, Virginia, November, 1979.

3. V. M. Radhakrishnan and A. J. McEvily, "Creep Crack Growth in 6061 Al Alloy," Z. Metallkunde, 71, 1980, 133.

4. M. Gouda, K. M. Prewo and A. J. McEvily, "On the Mechanism of Fatigue in Boron-Aluminum Composites," to be published by ASTM.

OCT. 1979 - SEPT. 1980

5. J. A. Ruppen, C. L. Hoffmann, V. M. Radhakrishnan and A. J. McEvily, "The Effect of Environment and Temperature on the Fatigue Behavior of Titanium Alloys," Sagamore Conference, July, 1980.

6. J. A. Ruppen and A. J. McEvily, "Crack Retardation and Closure Effects in a Titanium Alloy," 4th International Conference on Titanium, Japan, 1980.

7. J. A. Ruppen, D. Eylon and A. J. McEvily, "Subsurface Fatigue Crack Initiation of β-Annealed Ti-6Al-4V," Met. Trans., 11A, June 1980, 1072.

8. C. Hoffmann, D. Eylon and A. J. McEvily, "The Influence of Microstructure on the Elevated Temperature Fatigue Resistance of a Titanium Alloy," International Symposium on Low Cycle Fatigue, Firminy, France, Sept., 1980.

9. V. M. Radhakrishnan and A. J. McEvily, "Effect of Temperature on Creep Crack Growth," to be published in J. Eng. Mats. and Tech.

10. V. M. Radhakrishnan and A. J. McEvily, "Time Dependent Crack Growth on Titanium Alloy," to be published in Scripta Met.

11. V. M. Radhakrishnan and A. J. McEvily, "A Critical Analysis of Crack Growth in Creep," J. of Eng. Mats. and Tech., 102, 1980, 200.

INSTITUTE OF MATERIALS SCIENCE

The Institute of Materials Science (IMS) was established at The University of Connecticut in 1966 in order to promote academic research programs in materials science. To provide requisite research laboratories and equipment, the State of Connecticut appropriated $5,000,000, which was augmented by over $2,000,000 in federal grants. To operate the Institute, the State Legislature appropriates over $500,000 annually for faculty and staff salaries, supplies and commodities, and supporting facilities such as an electronics shop, instrument shop, a reading room, etc. This core funding has enabled IMS to attract over $2,500,000 annually in direct grants from federal agencies and industrial sponsors.

IMS fosters interdisciplinary graduate programs in Alloy Science, Biomaterials, Corrosion Science, Crystal Science, Metallurgy, and Polymer Science. These programs are directed toward training graduate students while advancing the frontiers of knowledge and meeting current and long-range needs of our state and our nation.