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The Analysis of Fatigue Crack Growth Mechanism and Oxidation and Fatigue Life at Elevated Temperatures

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May 1988

NASA

National Aeronautics and
Space Administration

THE ANALYSIS OF FATIGUE CRACK GROWTH MECHANISM
AND
OXIDATION AND FATIGUE LIFE AT ELEVATED TEMPERATURES

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Summary

Two quantitative models based on experimentally observed fatigue damage processes have been made: (1) a model of low cycle fatigue life based on fatigue crack growth under general-yielding cyclic-loading, and (2) a model of accelerated fatigue crack growth at elevated temperatures based on grain boundary oxidation. These two quantitative models agree very well with the experimental observations.

FINAL REPORT

The Analysis of Fatigue Crack Growth Mechanism and
Oxidation and Fatigue Life at Elevated Temperatures

Grant Number: NAG 3-348

Funding Period: October 30, 1982 to November 31, 1987

Principal Investigators: Hao-wen Liu and Yoshiki Oshida

Monitoring Scientist: Jack Telesman

Objective:

Fatigue life consists of fatigue crack nucleation and propagation
periods. In order to predict fatigue life accurately, the methodology
for the quantitative assessments of these two fatigue damage processes
has to be developed.

The objectives of this research program are to analyze low cycle
fatigue life in terms of fatigue crack propagation, to study grain
boundary oxidation and its effects on fatigue crack nucleation and
propagation, and to study the crystal orientation effects on crack tip
slip systems and the shear-decohesion fatigue crack growth mechanism.
With a thorough understanding of the crack nucleation and propagation
processes based on the physical damage mechanisms, more accurate
fatigue life prediction will be possible.

Significant Accomplishments:

Fatigue life consists of crack nucleation and propagation periods.
For high cycle fatigue, stage I shear fatigue crack nucleation and
growth consists of the major portion of the total fatigue life. On the
other hand, low cycle fatigue life consists of primarily tensile crack
growth.   At elevated temperatures, oxidation might accelerate both

processes of crack nucleattion and propagation. We have made substantial progress in the analysis of low cycle fatigue life, in the study of grain boundary oxidation and its effects on crack nucleation and propagation, and in the analysis of shear fatigue crack growth.

At the room temperature, the crack initiation period is only a small portion of the total low cycle fatigue life. Hence, low cycle fatigue life can be analyzed entirely in terms of fatigue crack propagation.

Fatigue crack growth under a general-yielding cyclic-loading was found to be related ΔJ and ΔJ was found to be related to the deformation work density. The analysis leads to a simple power law relationship between low cyclic fatigue life and the cyclic deforamtion work density. The low cycle fatigue life data of a number of materials agree very well with the non-linear fracture mechanics analysis.

The deformation work density, in turn, is related to the applied stress range and the imposed cyclic strain range. It is shown that the Manson-Coffin low cycle fatigue law can be derived by a rational analysis based on fatigue crack growth under a general-yielding cyclic-loading. (References: 4, 7, 8, 11).

Dr. Liu was invited to present their recent results on the low cycle fatigue life analysis at the Second International Conference on Low Cycle Fatigue in Munich, FRG, in September 1987.

Two primary damage mechanisms of high temperature low cycle fatigue are creep and oxidation. Both of these two mechanisms are thermally activated as illustrated in the figure.

The question is not which of these two mechanisms is the dominant one. The more pertinent question is rather which of these two mechanisms is dominant in the high temperature region and which one is dominant in the low temperature region. Quantitative studies on both creep and oxidation damage mechanisms are necessary in order to answer

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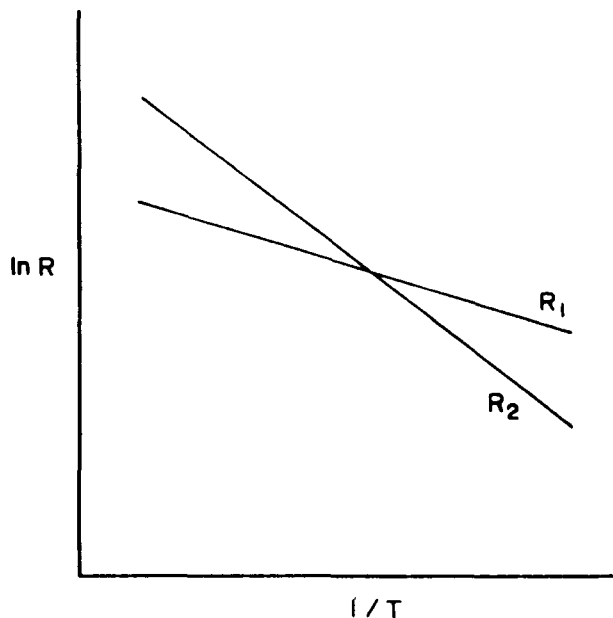
The schematic plot of two rate processes.

A quantitative study on grain boundary oxidation and its effects on fatigue life was conducted. (References: 3, 5, 6, 10, 12)

Grain boundary is a path of rapid diffusion. Grain boundary oxidation is controlled by the diffusion of oxygen along the grain boundary. The rapid oxygen diffusion causes a deep grain boundary oxidation penetration, and the fast oxidation penetration causes the accelerated intergranular fatigue fractures at high temperatures.

Two different grain boundary oxide morphologies were found: the pancake type and the cone type. The larger and deeper pancake type is more damaging.

Grain boundary oxidation penetration, a_m, in a nickel base superalloy (TAZ-8A) was measured as a function of the oxidation temperature, T, and the exposure time, t.

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$$a_m = \alpha \, t^n \, \exp\left(-\frac{Q}{RT} \right) \qquad \text{(1a)}$$

$$= 1.34 \, t^{0.25} \, \exp\left(-\frac{4.25}{RT} \right) \qquad \text{(1b)}$$

Q = apparent activation energy

The coefficient of correlation is 0.96 for 144 data points.

This quantitative relationship for the grain boundary oxidation kinetics can be used to study the accelerated fatigue crack nucleation and fatigue crack growth rate at elevated temperatures.

Grain boundary oxide penetration varies widely. This wide variation of oxide penetration rate may cause the variations in the rates of crack nucleation and growth and the scatter of the fatigue life data.

The statistical scatter of the grain boundary oxide penetration depth follows the Weibull's distribution law. The empirical distribution law can be used to extrapolate the data obtained in a laboratory using small samples to a much larger structural component in service.

When an oxide reaches a critical size, it will fracture. A grain boundary oxide crack becomes a fatigue crack nucleus or a pre-crack. The pre-crack will shorten the crack nucleation period and the total fatigue life. This reduction in nucleation life will be substantial, if the cyclic frequency is very low, the temperature is very high, and the oxidation exposure time is very long.

It has been found that the ratio between the fatigue life of a precracked specimen and the fatigue life of a smooth specimen is a function of the pre-crack size.

$$N_{fi}/N_{fo} = f(\text{pre-crack size}) \qquad \text{(2)}$$

N_{fi} = fatigue life of a pre-cracked specimen

N_{fo} = fatigue life of a smooth specimen

For a given pre-crack size, the ratio was found to be constant. The functional relationship between the ratio and the pre-crack size can be found empirically.

The wide variations in oxidation penetration and oxide crack size may cause a wide variation in N_{fi} and in the total fatigue life. A large structural component has a high probability of having a large oxide crack and a short fatigue life. The empirical relation of Equation (2) together with the grain boundary oxide penetration kinetics and the Weibull distribution would be able to predict the effect of the oxide crack on the nucleation life of a large structural component.

The basic concept of grain boundary oxidation kinetics was used to analyze fatigue crack growth rate at the elevated temperatures. A high temperture fatigue crack growth model based on intermittent micro-ruptures of grain boundary oxides was proposed. The model is consistent with the observed intergranular fracture and the observed inverse relationship between crack growth rate and the cyclic frequency in the low frequency region. (References: 1, 5, 6, 9, 10). In the high frequency region, fatigue failure is mixed intergranular and transgranular or transgranular entirely.

The fatigue crack growth in large grain polycrystals and single crystals has been investigated. The shear decohesion mechanism of fatigue crack growth has been proposed and observed by a number of researchers. Shear decohesion is caused by dislocation slip at a crack tip. Shear decohesion is caused by the force acting on the dislocations at a crack tip and the force on a dislocation is related to the resolved shear stresses on the slip plane. Therefore, it is reasonable to expect that the ductile fatigue crack growth mechanism of shear decohesion is related to the resolved shear stresses on the slip

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planes in the crack tip region. It was found that the crack plane in a crystal can be determined by the slip planes with the highest resolved shear stress intensity coefficient. This observation indicates strongly that fatigue crack growth in large grains and single crystals can be analyzed in terms on the crack tip resolved shear stress intensity coefficient. (References: 2, 7, 13)

In conclusion, considerable progress has been made on the quantitative studies based on the physical damage mechanisms. Such studies will lead to a quantitative damage assesment and an improved life prediction methodology.

Students Supported:

Name	Dates	Degree
Gerhard Maurer:	11/1/82 – 5/1,83	M.S.
Qi Chen:	5/1/83 – present	M.S.

In addition, the grant has supported 50% of Dr. Yoshiki Oshida's time for a period of two years and Mr. Zheng Minzhong for his computer time and manuscript preparation and publication costs.

Publications:

Thus far twelve papers and NASA reports have been published and one is in preparation. The reprints of the papers have been sent to the monitoring scientist of the grant as they were published.

1. OSHIDA, Y., and LIU, H.W. *Oxidation and Low Cycle Fatigue Life Prediction*, Proceedings of Hot Section Technology Conference, NASA Lewis Research Center, Cleveland Ohio, Oct. 1984.

2. MAURER, G., and LIU, H.W. *Morphological Study of Near Threshold Fatigue Crack Growth in a Coarse Grain Aluminum Alloy*, Proceedings of the Second International Conference on Fatigue and Fatigue Threshold, Birmingham, England, September 1984.

3. LIU, H.W., and OSHIDA, Y. *Literature Survey on Oxidation and Fatigue Lives at Elevated Temperatures*, NASA Contract Report 174639, March 1984.

4. ZHENG, MINZHONG, and LIU, H.W. *Crack Tip Field and Fatigue Crack Growth in General Yielding and Low Cycle Fatigue*, NASA Contract Report 174686, Sept. 1984.

5. OSHIDA, Y., and LIU, H.W. *Grain Boundary Oxide Crack, Oxidation Accelerated Fatigue Crack Growth and Fatigue Life,* Proceedings of the 40th Meeting of the Mechanical Failures Prevention Group, Symposium on the Use of New Technology to Imporve Mechanical Readiness, Reliability and Maintainability, National Bureau of Standards, Gaithersburg, MD, Cambridge University Press, April 1985. pp. 287-295

6. LIU, H.W., and OSHIDA, Y. *Grain Boundary Oxidation and Oxidation Accelerated Fatigue Crack Nucleation and Propagation*, Proceedings of the Minnowbrook Conference on Life Prediction for High Temperature Gas Turbine Materials, Blue Mountain Lake, NY, Aug. 1985.

7. LIU, H.W., *Shear Fatigue Crack Growth: A Literature Survey*. the International J. of Fatigue and Fracture of Engineering Materials and Structures, Vol. 8, No. 4, pp. 295-313, 1985.

8. Zheng, Minzhong and LIU, H.W., *Fatigue Crack Growth under General-Yielding Cyclic-Loading*, J. of Engineering Materials and Technology, ASME Transactions, Vol. 108, pp. 201-205, July 1986

9. LIU, H.W. and OSHIDA, Y., *Grain Boundary Oxidation and Fatigue Crack Growth at Elevated Temperatures"*, Theoretical and Applied Fracture Mechanics, Vol. 6, No 2. pp. 85-94, Oct. 1986

10. Liu, H. W. and Oshida, Yoshiki, *Grain Boundary Oxidation and Its Effects on High Temperature Fatigue Life,* Turbine Engine Hot Section Technology, NASA Conference, Cleveland, Ohio, Oct., 1986

11. Liu, H. W.; Zheng, Minzhong; and Chen, Qi, *Low Cycle Fatigue Life -- An Analysis Based on Fatigue Crack Growth Behavior under General-Yielding Cyclic-Loading,* Accepted as an invited paper to be published in the Proceedings of the Second International Conference on Low Cycle Fatigue and Elastic-Plastic Behavior of Materials, Munich, West Germany, September, 1987

12. Y. Oshida and H. W. Liu "Grain Boundary Oxidation and an Analysis of the Effects of Pre-oxidation on Subsequent Fatigue Life", ASTM Symposium on 'Low Cycle Fatigue -- Direction for the Future' Lake George, NY, 1985.

13. Qi Chen and H. W. Liu, "Resolved Shear Stress Intensity Coefficient and Fatigue Crack Growth in Large Crystals" in preparation.

Report Documentation Page

1. Report No. NASA CR-182129	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle	5. Report Date
The Analysis of Fatigue Crack Growth Mechanism and Oxidation and Fatigue Life at Elevated Temperatures	May 1988
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
H.W. Liu	None
	10. Work Unit No. 505-63-1B

9. Performing Organization Name and Address	11. Contract or Grant No.
Syracuse University Department of Mechanical and Aerospace Engineering Syracuse, New York 13244	NAG3-348
	13. Type of Report and Period Covered

12. Sponsoring Agency Name and Address	Contractor Report Final
National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191	14. Sponsoring Agency Code

15. Supplementary Notes

Project Manager, Jack Telesman, Structures Division, NASA Lewis Research Center.

16. Abstract

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Fatigue; Crack growth mechanisms; Oxidation; Crack nucleation; Crystal orientation; Crack tip slip systems; Life prediction	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	10	A02