

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF RESEARCH ADMINISTRATION

RESEARCH PROJECT INITIATION

Date: February 4, 1974

Project Title: The Effect of Microstructural Features on the Response of Aluminum Alloys to Cyclic Deformation
Project No: E-19-622

Principal Investigator: Dr. E. A. Starke, Jr.

Sponsor: AFOSR, Arlington, Virginia

Agreement Period: From 1/1/74 Until 12/31/74

Type Agreement: Grant No. AFOSR 74-2615

Amount: \$36,000 AFOSR Funds (E-19-622)
10,325 GIT Contrib. (E-19-322)
\$46,325 Total

Reports Required: Final Scientific Report; Interim (Annual) Report if project extended beyond one year.

Sponsor Contact Person (s):

Technical Matters

Alan H. Rosenstein
Program Manager
AFOSR (NE)
1400 Wilson Boulevard
Arlington, Virginia 22209

Contractual Matters

(Thru ORA)
Joan O. Marshall
Buyer
AFOSR (PMD)
1400 Wilson Boulevard
Arlington, Virginia 22209

NOTE: Follow-on project to E-19-616.

Assigned to: Chemical Engineering

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GEORGIA INSTITUTE OF TECHNOLOGY
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Date: April 13, 1978

Project Title: The Effect of Microstructural Features on the Response of Aluminum Alloys to Cyclic Deformation.

Project No: E-¹⁹~~16~~-622 *OK OCA quoted*

Project Director: Dr. E. A. Starke

Grant AFOSR 74-2615

Sponsor: Air Force Office of Scientific Research

Effective Termination Date: 12/31/77

Clearance of Accounting Charges: 12/31/77

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- ☐ Final Invoice and Closing Documents
- ☒ Final Fiscal Report
- ☐ Final Report of Inventions
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- ☐ Classified Material Certificate
- ☐ Other _____

Assigned to: Chem. Aerospace Engineering (School/Laboratory)

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THE EFFECTS OF MICROSTRUCTURAL FEATURES
ON THE RESPONSE OF ALUMINUM ALLOYS
TO CYCLIC DEFORMATION

by

Edgar A. Starke, Jr.

December, 1974

This research was supported by the
Air Force Office of Scientific Research
(AFSC) under Grant No. AFOSR-74-2615

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Summary of Research

This program has been designed to isolate and determine the various parameters which control the mechanical behavior during monotonic and cyclic loading of alloys containing various microstructural features developed during the decomposition of 7XXX type aluminum alloys. In addition, the stress-corrosion resistance and corrosion-fatigue resistance is also being characterized. It is hoped that an understanding of the fundamentals of the deformation processes will be obtained from this study. These results will be applied to improve the properties of existing alloy systems through control of the microstructure and to suggest ways of developing fatigue resistant age hardenable aluminum alloys.

The alloys being investigated are based on 7050, the new alloy developed by ALCOA for the Navy and Air Force. This alloy combines strength with improved fracture toughness, and stress-corrosion resistance. In addition to 7050, three other alloys are being investigated. These differ from 7050 by the elimination of, and/or variation of, the copper and zirconium additions. They have the same zinc and magnesium concentrations as 7050 and serve to isolate those effects which are associated with copper and other alloying additions.

Much of the first year's effort has been spent in the characterization of the four alloys after various thermal and mechanical treatments. This characterization, which includes texture, grain morphology, size, type, volume fraction, and spacing of pre-precipitates and precipitates,

is being accomplished by using x-ray, transmission electron, scanning electron, and optical metallographic techniques as described in our proposals. We have included grain boundary characterization since we have observed that small changes in copper concentration have significant effects on the size, shape and distribution of the grain boundary precipitate, and consequently on the resulting cyclic behavior of the alloy.

We have made significant progress on determining the effect of microstructure on the monotonic and low cycle fatigue properties of a high purity, large grain, ternary aluminum-zinc-magnesium (Al-Zn-Mg) alloy and a high strength 7050 aluminum alloy. The number of steps in the precipitation sequence; super-saturated solid solution \rightarrow Guinier Preston (G.P.) zones $\rightarrow \eta' \rightarrow \eta$ (MgZn_2) is unaltered by the presence of copper in the 7050 alloy. Copper and aluminum are thought to enter directly into the zone formation. The presence of copper and aluminum in the zones are justified on the basis of the electron:atom stability of the Friauf-Laves MgZn_2 structure. The presence of copper in the alloys increases the G.P. solvus temperature, presumably by a reduction in the barrier to nucleation.

The microstructure that produced the highest static strength while maintaining good ductility occurred when the ternary alloy was aged at 150°C to produce a maximum number of semicoherent η' precipitates which had a Guinier radius of approximately 65\AA . Aging at 120°C increased the frequency of nucleation and a greater tendency toward brittle fracture as shown by the brittle nature when the ternary alloy was aged at 120°C . The highest static yield strength was obtained when

7050 was double aged to produce a high density of small, semicoherent (40 Å) η' precipitates.

The monotonic fracture behavior of the ternary alloy progressively changed with aging from ductile microvoid coalescence to brittle, low energy intergranular separation. This contrasted to the ductile, transgranular fracture nature of 7050 alloy under similar aging conditions. The brittle nature of the ternary alloy was related to the large grain size. The nonhomogeneous deformation associated with the large grain ternary alloy produced large slip steps at the grain boundaries which induced large stress concentrations across the grain boundaries.

Fatigue behavior was found to be sensitive to aging in both alloys investigated. The best combination of fatigue life, strength and ductility for the ternary alloy resulted when aged to produce a microstructure containing predominately η' having a Guinier radius of approximately 70 Å and a small amount of incoherent η (MgZn_2).

Superior fatigue life, strength and ductility were found when the 7050 alloy was aged to produce the maximum number of partially coherent η' precipitates having a Guinier radius of approximately 35 Å. Aging the 7050 alloy to produce particles of about 50 Å gave a microstructure that had poor fatigue properties at low plastic strain amplitudes,

$$\frac{\Delta \epsilon_p}{2} < 1.0 \text{ per cent.}$$

The empirical Coffin-Manson relation was found to adequately describe the fatigue behavior when the deformation process did not depend upon the plastic strain amplitude.

Scientific Papers

1. S. B. Chakraborty and E. A. Starke, Jr. "Deformation Twinning of Cu_3Au ," Acta Met. (in press). (Sponsored by AFOSR)
2. K. H. Chien and E. A. Starke, Jr. "The Effect of Ordering on the Low Cycle Fatigue of Cu_3Au Single Crystals," submitted to Acta Met. (sponsored by AFOSR)
3. B. Chakravarti, E. A. Starke, Jr., C. J. Sparks, Jr. and R. O. Williams, "Short Range Order and the Development of Long-Range Order in Ni_4Mo ," Phys. and Chem. of Solids 35, 1317-1326 (1974). (Sponsored by AEC)
4. Fu-Wen Ling, E. A. Starke, Jr. and B. G. LeFevre, "Deformation Behavior of Beta-Ti-V Alloys," Met. Trans., 5, 179-188 (1974). (Sponsored by ONR)
5. K. C. Chen, Fu-Wen Ling and E. A. Starke, Jr., "Structure and Mechanical Properties of Stress-Ordered Ni_4Mo ," Mater. Sci. and Engr. 13, 255-262 (1974) (Sponsored by AEC).

Professional Personnel

Dr. Edgar A. Starke, Jr. Professor of Metallurgy, School of Chemical Engineering and Dr. M. Marek, Research Scientist, School of Chemical Engineering.

Dissertations

1. Deformation Modes of Copper-25 Atomic Percent Gold Alloy, January, 1974, Saghana Baran Chakraborty, Doctor of Philosophy, received March, 1974. (Sponsored by AFOSR)
2. The Effect of Ordering on Low Cycle Fatigue in Cu_3Au , September, 1974, Kuang-Ho Chien, Doctor of Philosophy, received December, 1974. (Sponsored by AFOSR)
3. The Effect of Microstructure on the Monotonic and Cyclic Properties of Two Age Hardenable Aluminum Alloys, December, 1974, Thomas H. B. Sanders, Doctor of Philosophy, December, 1974 (Sponsored By AFOSR)

Coupling

A. Interactions with Other Groups

Dr. Starke visited Professor Morrie Fine, at Northwestern University, presented a seminar on low-cycle fatigue and held discussions with Professor Fine and his group on the fatigue of high strength aluminum alloys.

Dr. Starke attended the AFOSR/ARL Materials Workshop at Fairborn, Ohio, presented a talk and held numerous discussions with the other attendees.

Professor Volkmar Gerold of the Max Planck Institut fur Metallforschung, Stuttgart, Germany, visited Dr. Starke for six days to discuss fatigue and microstructural studies of high strength aluminum alloys.

Dr. Starke attended the Sagamore Conference on Advances in Deformation Processing and held discussions with J. Waddman of the Frankford Arsenal on thermomechanical processing of high strength aluminum alloys.

Dr. Starke visited the Alcoa Research Laboratories for discussions with Alcoa personnel on the development and properties of high strength aluminum alloys. Alcoa personnel also visited Dr. Starke at Georgia Tech for discussions and information exchange. Alcoa is furnishing, free of charge, the alloys used in this investigation, approximate value \$5,000.

Dr. Starke organized a symposium on Modulated Structures and Properties in Non-Ferrous Systems and served as Chairman at the Spring Meeting of AIME, Pittsburgh, Pa., May, 1974.

Dr. Starke had discussions at Georgia Tech with Dr. Alan Rosenstein, AFOSR, Terry Ronald, Skip Grant and Pete Blau of AFML and Frank Cocks

of Duke University on current research in high strength aluminum alloys.

A graduate student on a Georgia Tech Fellowship has been working on this program since its inception at no cost to AFOSR. Approximate monetary contribution to grant is \$4,800/year.

B. Papers Presented

E. A. Starke, Jr. and M. Marek, "The Effects of Microstructure on Stress Corrosion Cracking of Aluminum Alloys" Invited talk presented at the symposium Aluminum Alloys" Mechanical Properties and Microstructural Effects, Detroit, October, 1974.

C. J. Sparks, Jr., B. Chakravarti, E. A. Starke, Jr. and R. O. Williams. "Local Atomic Arrangements in Ni_4Mo ", paper presented at the International Discussion Meeting on Studies of Lattice Distortions and Local Atomic Arrangements by X-Ray, Neutron and Electron Diffraction", held in Jülich, Germany, April 29-May 3, 1974.

B. G. LeFevre, H. G. Parris, and E. A. Starke, Jr. "The Mechanical Behavior of Quenched and Aged Beta Isomorphous Ti-V Alloys" presented at the Materials Science Symposium of ASM and AIME Cobo Hall, Detroit, Michigan, 21-24 October 1974.

Patentable Inventions

No patentable inventions have resulted from the sponsored research.

Respectfully submitted:

Professor Edgar A. Starke, Jr.
Principal Investigator

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
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19. KEY WORDS (Continue on reverse side if necessary and identify by block number) aluminum alloys, fatigue, microstructure		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The effect of microstructure on the monotonic and low cycle fatigue properties of a high purity ternary Al-Zn-Mg alloy and a high strength 7050 aluminum alloy has been studied. The microstructure that produces the best combination of monotonic and cyclic properties is described. The decomposition sequence and the effect of copper additions are also discussed.		

THE EFFECTS OF MICROSTRUCTURAL FEATURES
ON THE RESPONSE OF ALUMINUM ALLOYS
TO CYCLIC DEFORMATION

by

Edgar A. Starke, Jr.

March 12, 1976

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Abstract

This research is concerned with correlating microstructural features of high strength aluminum alloys with mechanical behavior in an effort to distinguish those features which cause the low fatigue strength/static strength ratio inherent in these materials. Both monotonic and cyclic measurements in inert and hostile environments are being made. We have found that the low cycle fatigue behavior is very sensitive to the size, spacing, and type of precipitates and can be changed by heat treatment. This is only accomplished, however, when the changes in microstructure produce changes in deformation mode. In addition, crack propagation rates, long thought independent of microstructure in high strength aluminum alloys, have been found to vary when the deformation mode is altered if the volume fraction of insoluble impurities is kept low. The low cycle fatigue behavior and crack propagation in a hostile environment is more sensitive to the stage of aging, i.e., type of precipitate present, than to any other variable. This is attributed to the potential differences between the matrix and the various precipitates, e.g., G.P. zones, η' or the equilibrium precipitate η .

Summary of Research

This program has been designed to isolate and determine the various parameters which control the mechanical behavior during monotonic and cyclic loading of alloys containing various microstructural features developed during the decomposition of 7XXX type aluminum alloys. In addition, the stress-corrosion resistance and corrosion-fatigue resistance is also being characterized. It is hoped that an understanding of the fundamentals of the deformation processes will be obtained from this study. These results will be applied to improve the properties of existing alloy systems through control of the microstructure and to suggest ways of developing fatigue resistant age hardenable aluminum alloys.

The alloys being investigated are based on 7050, the new alloy developed by ALCOA for the Navy and Air Force. This alloy combines strength with improved fracture toughness, and stress-corrosion resistance. In addition to 7050, three other alloys are being investigated. These differ from 7050 by the elimination of, and/or variation of, the copper and zirconium additions. They have the same zinc and magnesium concentrations as 7050 and serve to isolate those effects which are associated with copper and other alloying additions.

During the first year of this Grant, the effect of microstructure on the monotonic and low cycle fatigue properties of a high purity, large grain, ternary aluminum-zinc-magnesium (Al-Zn-Mg) alloy and a high strength 7050 aluminum alloy was investigated. The best combination of fatigue life, strength, and ductility for the ternary alloy resulted when aged to produce a microstructure containing predominately η' having a Guinier radius of approximately 70 Å and a small amount of incoherent η (MgZn_2). Superior fatigue life, strength, and ductility

were found when the 7050 alloy was aged to produce the maximum number of partially coherent η' precipitates having a Guinier radius approximately 35 Å. Aging the 7050 alloy to produce particles of about 50 Å gave a microstructure that had lower fatigue properties at the low plastic strain amplitudes, $\frac{\Delta\epsilon_p}{2} < 1.0$ percent. The empirical Coffin-Manson relation was found to adequately describe the fatigue behavior when the deformation process did not depend upon the plastic strain amplitude. This work was presented at the May, 1975, meeting of AIME and has been accepted for publication in Metallurgical Transactions. A preprint of the manuscript is attached.

Fatigue crack propagation studies have been made on the 7050 alloy for three different heat treatments (1) 24 hr @ 120°C (2) 24 hr @ 150°C and (3) 24 hr @ 120°C + 24 hr @ 150°C. Treatment (1) produced a high density of small particles which could be sheared at all plastic strain amplitudes and gave the best fatigue life, strength and ductility over the investigated LCF range. Treatment (2) produced large, closely spaced precipitates that were looped in the low plastic strain regime ($\Delta\epsilon_p/2 < 1.0$) leading to premature failure. At high plastic strain amplitudes the precipitates were by-passed by a cross slip mechanism. Treatment (3) produced a microstructure in which there was a high precipitate density which could be sheared at all plastic strain amplitudes. Coffin-Manson plots of the LCF results were linear only when a single deformation mechanism was operative over the entire strain range studied: when the deformation mode changed, there was a corresponding break in the LCF curve. The LCF, TEM, SEM and mechanical property results were used to predict FCP behavior using a model developed by Antolovich, Saxena, and Chanani and the prediction was in good agreement with experiment. This work was presented at the November, 1975, AIME and a manuscript for publication is under preparation.

Tensile and low cycle fatigue tests have been conducted on an Al-Zn-Mg-Zr alloy which differs from the ternary alloy previously studied primarily in its grain size. The zirconium addition produces a very fine partially recrystallized microstructure analogous to that found in the commercial 7050 alloy. The smaller grain size, when compared to a similarly processed ternary alloy, leads to considerable increases in ductility and low cycle fatigue life for the aging treatments studied (solutionized @ 480°C , 4 hrs @ 120°C ; 2 hrs 120°C + 12 hrs 150°C ; 12 hrs @ 120° + 12 hrs @ 150°C ; 24 hrs @ 120°C + 24 hrs @ 150°C , 24 hrs @ 150°C). However, the slope of the Coffin-Manson plot, $/c/$, is larger than that observed previously for the largest grained Al-Zn-Mg alloy, indicating that for large values of N_f , a reduction in grain size may be less beneficial in increasing fatigue life. The break in the Coffin-Manson plot previously observed for 7050, aged to produce incoherent η precipitates, was also found for the Al-Zn-Mg-Zr alloy aged to produce a similar microstructure. This behavior, noted in aluminum alloys since the original works of Coffin, is related to changes in deformation mode with strain amplitude, as mentioned previously.

Low cycle corrosion fatigue experiments have been conducted on the Al-Zn-Mg-Zr alloy in order to examine the Coffin-Manson relationship in a hostile environment; to correlate the corrosion fatigue behavior with microstructure; and to compare the work hardening characteristics of the alloy in argon (with an oxide layer) to that in a 2.7 pH solution (which removes the oxide layer). No break was observed in the Coffin-Manson plots and the slope was found to be independent of aging treatment, i.e., microstructure. However, the plots were displaced with aging treatment with life increasing as the microstructure approached that of the equilibrium condition. This phase of the program is still in progress; however, the increase in life may be attributed to the potential differences between the matrix and the various precipitates, e.g., G.P. zones, η' , or the equilibrium precipitate η .

Scientific Papers

1. S. B. Chakraborty and E. A. Starke, Jr., "Deformation Twinning of Cu_3Au ," Acta Met., 23, 63-71 (1975) (Sponsored by AFOSR).
2. K. H. Chien and E. A. Starke, Jr., "The Effect of Order on the Low Cycle Fatigue Response of Cu_3Au Single Crystals," Acta Met., 23, 1173-1184 (1975). (Sponsored by AFOSR).
3. E. Y. Chen and E. A. Starke, Jr., "Effects of Ion-Plating on the Low Cycle Fatigue Behavior of Copper Single Crystals," Mater. Sci. & Engr. (in press). (Sponsored by AFOSR).
4. M. Marek and E. A. Starke, Jr., "Potential Distributions Relating to Grain Boundaries on Corroding Aluminum Alloys," British Corrosion Journal, (in press) (Sponsored by AFOSR).
5. T.H.B. Sanders and E. A. Starke, Jr., "The Effects of Microstructural Features on the Response of Aluminum Alloys to Cyclic Deformation," Met. Trans. (in press). (Sponsored by AFOSR).
6. H. G. Paris, B. G. LeFevre, and E. A. Starke, Jr. "Deformation Behavior in Quenched and Aged Beta Titanium Alloys," Met. Trans. 7A, 273-278, (1976). (Sponsored by ONR).
7. E. Henry Chia, S. Spooner, and E. A. Starke, Jr., "Directionality of Microstructure and Texture of Continuously Cast and Rolled Aluminum Rod and Wire Products," Aluminium (in press).
8. E. Henry Chia and E. A. Starke, Jr., "Application of Subgrain Control to Aluminum Wire Products," Met. Trans. (in press).

Professional Personnel

Dr. Edgar A. Starke, Jr., Professor of Metallurgy and Dr. M. Marek, Research Scientist, (School of Chemical Engineering and Metallurgy).

Graduate Students

Mr. R. E. Sanders, Jr., M.S. Student
 Mr. E. J. Coyne, M.S. Student
 Mr. K. C. Chen, Ph.D. Student
 Mr. Fu-Shiong Lin, Ph.D. Student

Dissertations

1. Deformation Modes of Copper-25 Atomic Percent Gold Alloy, January, 1974; Saghana Baran Chakraborty, Doctor of Philosophy, received March, 1974. (Sponsored by AFOSR)
2. The Effect of Ordering on Low Cycle Fatigue in Cu_3Au , September, 1974, Kuang-Ho Chien, Doctor of Philosophy, received December, 1974. (Sponsored by AFOSR)
3. The Effect of Microstructure on the Monotonic and Cyclic Properties of Two Age Hardenable Aluminum Alloys, December, 1974, Thomas H. B. Sanders, Doctor of Philosophy, December, 1974 (Sponsored By AFOSR).

COUPLING

A. Interactions with Other Groups

Professor E. Hornbogen of the Institut fur Werkstoffe, Ruhr Universitat, Bochum, Germany, visited Professor Starke on February 16 and 17, 1975, for discussions of mutual interest on deformation mechanisms and fatigue.

Professor Starke organized a Fatigue and Fracture Workshop at Georgia Tech, April 8 and 9, 1975, which was attended by AFOSR, AFML personnel and Principal Investigators sponsored by AFML and AFOSR. The following attended and discussed their results:

Professor Stephen D. Antolovich
Department of Materials Science
University of Cincinnati
Cincinnati, Ohio 45221

Professor Morris E. Fine
Department of Material Science
Northwestern University
Evanston, Illinois 60201

Dr. Peter J. Blau
AFML/LLS
Wright Patterson Air Force Base
Ohio 45433

Dr. James Lankford
Mechanical Sciences Department
Southwest Research Institute
San Antonio, Texas 78284

Dr. Robert J. Bucci
Aluminum Company of America
Alcoa Technical Center
Alcoa Center, Pa. 15069

Professor Campbell Laird
Department of Metallurgy and
Materials Science
University of Pennsylvania
Philadelphia, Pa. 19174

Dr. David Mauney
Aluminum Company of America
Alcoa Technical Center
Alcoa Center, Pa. 15069

Professor Edgar A. Starke, Jr.
Georgia Institute of Technology
Atlanta, Georgia 30332

Dr. Alan H. Rosenstein
AFOSR/NE
1400 Wilson Blvd.
Arlington, Virginia 22209

Dr. William G. Truckner
Alcoa Technical Center
Alcoa, Pennsylvania 15069

Dr. Starke visited the Alcoa Technical Center twice during 1975 and had discussions with J. T. Staley, T. H. Sanders, and Harold Hunsinger on AFML sponsored work at Alcoa and AFOSR sponsored work at Georgia Tech. It was agreed that information would be exchanged and research at the two laboratories would be coupled. Alcoa is furnishing special alloys for Dr. Starke's program at no cost to AFOSR or Georgia Tech.

Dr. Starke attended the Gordon Conference on Fracture and Fatigue held at Franklin Pierce College, Rindge, N.H., June 15-20, 1975.

Dr. Starke received a NATO grant and attended the NATO Advanced Study Institute on Stress Corrosion Cracking in Copenhagen, Denmark, July 14-25, 1975. During the Institute, Dr. Starke held discussions with Drs. R. N. Parkins,

J. P. Fidelle, J. Scully, Markus Speidel, Peter Swann, R. P. Wei, and E. N. Pugh, on SCC of Aluminum Alloys.

Dr. J. C. Scully of the University of Leeds, England, visited Georgia Tech, September 1-5, 1975, and held discussions with Drs. M. Marek, and E. A. Starke, on the SCC phase of their research grant with AFOSR.

Dr. Starke attended the Sagamore Army Materials Research Conference on Fracture and Fatigue, September 9-12, 1975. During the conference, Dr. Starke held numerous discussions with Mr. Marvin Van Wanderham of Pratt Whitney Aircraft, on Materials problems in aircraft engines.

Dr. Starke attended the Working Group meeting at the University of Cincinnati, November 10, 1975, that was organized by Drs. A. H. Rosenstein of AFOSR and James A. Hall of AFML. Dr. Starke discussed his research program on the fracture and fatigue of Ti alloys

B. Papers Presented

1. E. A. Starke, Jr., "Low Cycle Fatigue Behavior of High Strength Aluminum Alloys," Sandia Laboratory, Albuquerque, N.M., February 21, 1975.
2. T. H. Sanders, and E. A. Starke, Jr., "The Effects of Microstructural Features on the Response of Aluminum Alloys to Cyclic Deformation," AIME Meeting, Toronto, Canada, May 18-27, 1975.
3. Stephen Antolovich, T. H. Sanders, and E. A. Starke, Jr., "Low Cycle Fatigue and Crack Propagation of 7050," AIME Meeting, Cincinnati, Ohio, November 11-13, 1975.
4. E. A. Starke, Jr., "Effect of Microstructure on the Deformation Behavior of Al-Zn Alloys," St. Joe Minerals Corp., Monaca, Pa.
5. E. A. Starke, Jr., "Control of Mechanical Behavior By Controlling the Microstructure," General Electric Research Laboratory, Schenectady, N. Y., November 18, 1975.
6. E. A. Starke, Jr. and E. Henry Chia, "Application of Subgrain Control to Aluminum Wire Products," AIME Meeting, Las Vegas, Nev., Feb. 23-26, 1976.
7. E. A. Starke, Jr., "The Production of Fine Subgrains by the Control of Processing Parameters," Colorado School of Mines, Golden, Col., Feb. 26, 1976

Patentable Inventions

No patentable inventions have resulted from the sponsored research.

Respectfully submitted:

Edgar A. Starke, Jr.
Principal Investigator

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E-14-622
Annual Report

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by

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February 23, 1977

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Abstract

This research is concerned with correlating microstructural features of high strength aluminum alloys with mechanical behavior in an effort to distinguish those features which cause the low fatigue strength/static strength ratio inherent in these materials. Both monotonic and cyclic measurements in inert and hostile environments are being made. We have found that the low cycle fatigue behavior is very sensitive to the size, spacing, and type of precipitates and can be changed by heat treatment. This is only accomplished, however, when the changes in microstructure produce changes in deformation mode. In addition, crack propagation rates, long thought independent of microstructure in high strength aluminum alloys, have been found to vary when the deformation mode is altered if the volume fraction of insoluble impurities is kept low. The low cycle fatigue behavior and crack propagation in a hostile environment is more sensitive to the stage of aging, i.e., type of precipitate present, than to any other variable. This is attributed to the potential differences between the matrix and the various precipitates, e.g., G.P. zones, η' or the equilibrium precipitate η .

Summary of Research

This program has been designed to isolate and determine the various parameters which control the mechanical behavior during monotonic and cyclic loading of alloys containing various microstructural features developed during the decomposition of 7XXX type aluminum alloys. In addition, the stress-corrosion resistance and corrosion-fatigue resistance is also being characterized. It is hoped that an understanding of the fundamentals of the deformation processes will be obtained from this study. These results will be applied to improve the properties of existing alloy systems through control of the microstructure and to suggest ways of developing fatigue resistant age-hardenable aluminum alloys.

The alloys being investigated are based on 7050, the new alloy developed by ALCOA for the Navy and Air Force. This alloy combines strength with improved fracture toughness, and stress-corrosion resistance. In addition to 7050, four other alloys are being investigated. These differ from 7050 by the elimination of, and/or variation of, the copper and zirconium additions. They have the same zinc and magnesium concentrations as 7050 and serve to isolate those effects which are associated with copper and other alloying additions.

Low Cycle Fatigue Studies

During the past year, the microstructure and low cycle fatigue behavior of an Al-Zn-Mg-Zr alloy were investigated and compared to the properties of a similar Al-Zn-Mg alloy determined previously⁽¹⁾. The zirconium addition inhibited recrystallization during the solutionization heat treatment and resulted in an elongated, partially recrystallized microstructure. The grain size of the Al-Zn-Mg-Zr was reduced considerably compared to Al-Zn-Mg due to

the presence of the zirconium as stable Al_3Zr in the microstructure. These precipitates were shown to have no effect on the aging kinetics in the Al-Zn-Mg-(Zr) system. The large increase in ductility and elimination of brittle fracture observed for the Al-Zn-Mg-Zr alloy were attributed to the promotion of more homogeneous deformation by the refined grain structure. Brittle, intergranular fracture in aged Al-Zn-Mg tensile samples was caused by the presence of inhomogeneous deformation bands.

Improvements in LCF resistance were obtained in Al-Zn-Mg-Zr by an improved homogeneity of deformation which delayed crack initiation and failure. An overaged microstructure of large η particles obtained by aging for 24 hours at $150^\circ C$ exhibited the best low cycle fatigue resistance observed in this study. The improved low cycle fatigue life of this aging treatment was attributed to the increased homogeneity of slip resulting from the occurrence of dislocation looping as the primary deformation mechanism. Comparison of the Al-Zn-Mg-Zr low cycle fatigue data was made with existing data for a 7050 alloy, but complex microstructural differences between the two alloys prevented definitive conclusions. The break in the Coffin-Manson plot of low cycle fatigue data of samples aged for 24 hours at $150^\circ C$ is due to a change in the capacity of the microstructure to absorb energy prior to crack initiation at high and low plastic strain amplitudes.

The cyclic stress strain response of the Al-Zn-Mg (Zr) alloy described above was also measured in a corrosive solution of distilled water and H_2SO_4 (pH=2.7). The objective of this research was to evaluate the effect of the oxide layer on the fatigue behavior in order to obtain information on the surface and bulk contributions to crack initiation and cyclic hardening. The

oxide layer can have two major effects on the deformation characteristics:

(a) adherent oxide films can act as barriers, preventing the egression of dislocations at the surface, and (b) the high shear modulus of the oxide (the elastic constants of aluminum oxide are three to four times larger than those of aluminum) produces an elastic repulsive force on dislocations in the substrate which effects the hardening characteristics of the surface region.

Based on the previous AFOSR research of Livesay and Starke⁽²⁾ the aluminum oxide, when present, should exert a very large repulsive force on the dislocations in the aluminum alloy substrate. This increases the probability for surface layer hardening as proposed by Kramer⁽³⁾, and Kramer and Kumar⁽⁴⁾. The probability of surface layer hardening should be reduced when the oxide is absent, e.g., in the corrosive environment. The cyclic stress-strain response, as described by the stress amplitude versus cycles, for samples aged 4 hrs @ 120°C and 24 hrs @ 150°C and tested in both dry argon and the $H_2O-H_2SO_4$ solution, showed no significant difference in the cyclic hardening behavior for the two environments, suggesting that the surface layer effect is not significant for these test conditions. These results are consistent with those of Finney and Laird,⁽⁵⁾ and Chen and Starke,⁽⁶⁾ who showed that cyclic hardening in single crystals was a bulk hardening effect, insensitive to the surface condition, and not controlled by the surface layer.

The effect of aging on the low cycle fatigue behavior was independent of environment. The poorest fatigue resistance was shown by samples aged 4 hrs @ 120°C, a treatment that produced small Guinier-Preston zones which are sheared by dislocations resulting in a banded deformation structure^(1,7). The best fatigue resistance for the range of strain amplitudes tested was shown by samples aged 24 hrs @ 150°C, a treatment which produced semi- and incoherent

MgZn₂ particles which are looped by dislocations producing a more homogeneous deformation than those of the other aging treatments of this study. A reduction in life by one half occurred when testing in the corrosive environment. An examination of the ratio, cycles to crack initiation/cycles to failure, revealed that the liquid environment was equally detrimental to crack initiation and crack propagation. The ratio varied, depending on the magnitude of the plastic strain amplitude, from 0.67 to 0.88, and was insensitive to environment. Optical examination of the surface at various stages of testing revealed that the cracks initiated, in order of frequency, (a) at slip bands in the unrecrystallized grains, (b) at pits and inclusions, and (c) along grain boundaries of recrystallized grains which were approximately normal to the stress direction. The removal of the oxide film by the corrosive environment increases the probability of dislocation egression from the surface and accelerates extrusion-intrusion formation and crack initiation. In addition, crack initiation may be enhanced by preferential dissolution at deformation bands, inclusions and grain boundaries.

In order to establish the effect of environment on crack propagation, some samples were cycled in the H₂O-H₂SO₄ solution until the crack had propagated approximately one quarter way through the cross section. The liquid was then removed and the sample cycled to failure in dry argon. The fracture surfaces were examined in the scanning electron microscope and the type and spacing of the fatigue striation were found to be environment sensitive. When crack propagation occurred in the argon environment, closely spaced, ductile striations were formed. However, brittle striations having "cliff edges" and "river markings" running normal to the striation were formed during crack

propagation in the $H_2O-H_2SO_4$ solution. Similar striations have been observed by Stubbington⁽⁸⁾ on aluminum samples fatigued to failure in a NaCl solution. The mechanism for changing the fracture mode may be due to anodic dissolution at the crack tip⁽⁹⁾ and to the formation and adsorption of hydrogen gas by cathodic reaction^(10,11) in this region.

Fatigue Crack Propagation

The effect of microstructure on the fatigue crack growth behavior of Al-Zn-Mg-Zr alloy was also investigated. The fatigue crack behavior was compared to the low cycle fatigue behavior of the same alloy discussed above. The major effect of the microstructure on the fatigue crack propagation rates was found at the low stress intensity ranges. At these stress intensity levels the overaged condition was found to have lower crack growth rates. This improved fatigue resistance was attributed to the increased homogeneity of deformation resulting from the occurrence of dislocation looping as the primary deformation mode. At the intermediate stress intensity levels tested, the microstructure appeared to have little or no effect.

A correlation was attempted between the observed data and the crack growth rates predicted by some proposed fatigue crack growth laws. The proposed laws that contain a variable power dependence for the stress intensity factor predicted the crack growth rate with extreme accuracy. Laws which had a fixed power dependence for the stress intensity factor did not accurately predict the observed crack growth rate.

Values of the parameters in the fatigue crack propagation equations were found to correlate with the cyclic low cycle fatigue parameters. No correlation was found between monotonic tensile parameters and the fatigue crack law parameters.

Stress Corrosion Cracking

The primary objective of this phase of our research program is to evaluate, systematically, the effect of copper on the stress corrosion characteristics of 7xxx alloys. Another objective is to correlate the metallurgical parameters like matrix and grain boundary precipitates, dislocation structure, degree of recrystallization, etc., with the SC behavior of the alloys of varying copper contents. The four alloys have the same zinc, magnesium and zirconium contents, and 0, 1.0, 1.55, and 2.1 weight percent copper. Care has been taken during processing and heat treatment operations so that we have essentially the same microstructure in all the four alloys. Stress corrosion cracking behavior is being studied by the linear elastic fracture mechanics analyses approach and complete v - k curves are being determined under controlled test conditions.

Stress corrosion crack growth rates of the copper containing alloys are much slower than the copper free alloy. During a period of four months, the SC cracks in the 0.0%, 1.0%, 1.5% and 2.1% Cu alloys have grown by about 7, 2.5, 0.8 and 0.6 cms respectively. The v - k_1 plot for the 0.0% Cu alloy shows both the plateau and the stress dependent regions, whereas the other alloys are still in their plateau regions. The data for the copper containing alloys show wide scatter and the crack growth rates have been calculated by taking averages over longer periods of time than for the 0.0% Cu alloy. The copper containing alloys show frequent incidents of crack-branching.

Scientific Papers Resulting From Current AFOSR Contract Research

1. S. B. Chakraborty and E. A. Starke, Jr., "Deformation Twinning of Cu_3Au ," Acta Met., **23**, 63-71 (1975).

2. K. H. Chien and E. A. Starke, Jr., "The Effect of Order on the Low Cycle Fatigue Response of Cu₃Au Single Crystals," Acta Met., 23, 1173-1184 (1975).
3. E. Y. Chen and E. A. Starke, Jr., "Effects of Ion-Plating on the Low Cycle Fatigue Behavior of Copper Single Crystals," Mater. Sci. & Engr., 24, No. 2, 209-221 (1976).
4. M. Marek and E. A. Starke, Jr., "Potential Distributions Relating to Grain Boundaries on Corroding Aluminum Alloys," British Corrosion Journal, 11, 31-34 (1976).
5. T.H.B. Sanders and E. A. Starke, Jr., "The Effects of Microstructural Features on the Response of Aluminum Alloys to Cyclic Deformation," Met. Trans. 7A, 1407-1418, (1976).
6. R. E. Sanders, Jr., and E. A. Starke, Jr., "The Effect of Grain Refinement on the Low Cycle Fatigue Behavior of an Aluminum-Zinc-Magnesium (Zirconium) Alloy" Mater. Sci. & Engr., 28, No. 1, 53-68 (1977).
7. Fu-Shiong Lin and E. A. Starke, Jr., "Low Cycle Corrosion Fatigue on an Al-Zn-Mg (Zr) Alloy," Proc. Fourth Intl. Conf. on Fracture (1977).
8. E. A. Starke, Jr. "The Fatigue Resistance of Aircraft Materials, The Current Frontier," (paper submitted to Journal of Aircraft.)

Professional Personnel

Dr. Edgar A. Starke, Jr., Professor of Metallurgy and
Dr. M. Marek, Associate Professor of Metallurgy

Graduate Students

Saghana Chakraborty
T. H. B. Sanders, Jr.
K. H. Chien
E. J. Coyne

R. E. Sanders, Jr.
E. Y. Chen
Fu-Shion Lin
B. Sarkar

Dissertations

1. Deformation Modes of Copper-25 Atomic Percent Gold Alloy, January, 1974, Saghana Baran Chakraborty, Doctor of Philosophy, received March, 1974. (Sponsored by AFOSR)
2. The Effect of Ordering on Low Cycle Fatigue in Cu₃Au, September, 1974, Kuang-Ho Chien, Doctor of Philosophy, received December, 1974. (Sponsored by AFOSR)
3. The Effect of Microstructure on the Monotonic and Cyclic Properties of Two Age Hardenable Aluminum Alloys, December, 1974, Thomas H. B. Sanders, Doctor of Philosophy, December, 1974 (Sponsored by AFOSR).

4. Effects of Ion-Plating on Low Cycle Fatigue Behavior of Copper Single Crystals, July, 1975, Edmund Yung Chen, Doctor of Philosophy, received, August, 1975.
5. The Effect of Zirconium on the Low Cycle Fatigue Behavior of an Aluminum-Zinc-Magnesium Alloy," June, 1976, Robert Edward Sanders, Jr., Master of Science in Metallurgy, received, June, 1976.

Coupling

A. Interactions with Other Groups

1. Professor Morrie Fine of Northwestern University, Walter Griffith of AFML and Professor Starke organized a Symposium on the Fatigue of Aluminum Alloys to be held during the Annual AIME Meeting in Atlanta, Georgia, March 9, 1977.
2. Participated in the AFOSR-AFML Aluminum Working Group Meeting, March 30-31, 1976, San Antonio, Texas.
3. Dr. Starke visited the Alcoa Technical Center twice during 1976 and had discussions with J. T. Staley, T. H. Sanders, and Harold Hunsinger on AFML sponsored work at Alcoa and AFOSR sponsored work at Georgia Tech. It was agreed that information would be exchanged and research at the two laboratories would be coupled. Alcoa is furnishing special alloys for Dr. Starke's program at no cost to AFOSR or Georgia Tech.
4. Participated in Lockheed Aircraft Company's Corrosion Working Group Meeting, Atlanta, Georgia, September, 1976, and discussed corrosion problems in Aluminum Alloys.

B. Papers Presented on Research Supported by Current Contract

1. E. A. Starke, Jr., "The Effect of Microstructure on Stress Corrosion Cracking of Aluminum Alloys, Matcon '74, Detroit, Mich., October 21-24, 1974.
2. E. A. Starke, Jr., "Low Cycle Fatigue Behavior of High Strength Aluminum Alloys," Sandia Laboratory, Albuquerque, N.M., February 21, 1975.
3. T. H. Sanders, Jr., and E. A. Starke, Jr., "The Effect of Microstructural Features on the Response of Aluminum Alloys to Cyclic Deformation," AIME Meeting, Toronto, Canada, May 18-27, 1975.
4. Stephen Antolovich, T. H. Sanders, and E. A. Starke, Jr., "Low Cycle Fatigue and Crack Propagation of 7050," AIME Meeting, Cincinnati, Ohio, November 11-13, 1975.
5. E. A. Starke, Jr., "Effect of Microstructure on the Deformation Behavior of Al-Zn Alloys," St. Joe Minerals Corp., Monaca, Pa.

6. E. A. Starke, Jr., "Control of Mechanical Behavior By Controlling the Microstructure," General Electric Research Laboratory, Schenectady, N. Y., November 18, 1975.
7. E. A. Starke, Jr., "Fatigue Research in Al-Zn-Mg-Type Alloys," Southwest Research Institute, San Antonio, Texas, March 30, 1976.
8. E. A. Starke, Jr., "Stress Corrosion Cracking of Al-Zn-Mg-Type Alloys," Lockheed-Georgia Company Seminar, September 12, 1976.

Patentable Inventions

No patentable inventions have resulted from the sponsored research.

Respectfully submitted:

Edgar A. Starke, Jr.
Principal Investigator

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