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

AFOSR Final Scientific Report
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by

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Abstract

This research was concerned with the relationship between microstructure and the monotonic, cyclic-stress-strain response, and crack propagation of age-hardenable 7XXX aluminum alloys. Our main efforts were concentrated on 7050-type alloys. We have shown that the deformation mode and LCF behavior is sensitive to microstructure and varies with strain amplitude. Consequently we have been able to explain anomalies which have previously and currently been observed in the Coffin-Manson relationship for aluminum alloys. Certain microstructures in these age-hardened aluminum alloys are more resistant to cyclic strains, while others are more resistant to cyclic stresses. The importance of the homogeneity of deformation for fatigue resistance has been established and ways to increase the homogeniety by microstructure control has been examined. Crack propagation was found to be sensitive to the type, size and spacing of precipates at low ΔK values and a relationship between parameters derived from the cyclic-stress-strain tests and fatigue crack propagation was established. Some corrosion fatigue and SCC studies have been completed and results from the former have shown that corrosion fatigue life is primarily controlled by the type of precipitates present and related to electrochemical aspects. Linear fracture mechanics, in combination with microstructure deformation mode-chemical potential relationship have been used for separating the mechanical and electrochemical aspects of SCC in high strength aluminum alloys.

Some of our studies have been concerned with understanding some basic fatigue phenomena, i.e., the local softening that occurs during cyclic deformation of ordered materials, and the surface and bulk contributions to cyclic-stress-strain response and crack initiation. Relationships between degree of atomic order, LCF, and crack initiation and propagation have been developed. Bulk and surface effects on the CSSR and crack initiation have also been examined. A general review of the subject of cyclic plastic deformation and microstructure is under preparation and will be presented at the ASM-TMS 1978 Seminar on Fatigue. The methods of analyzing important microstructural features in fatigue will be presented at the ASTM Symposium on Fatigue Mechanisms, and published in the proceedings of that Symposium.

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, limited studies of the stress-corrosion resistance and corrosion-fatigue resistance has been made. The primary goal has been to understand the fundamentals of the deformation processes involved in monotonic and cyclic loading. The results obtained from this study should lead to improvements in the properties of existing alloy systems through control of the microstructure and suggest ways of developing fatigue resistant age-hardenable aluminum alloys.

Single crystals of Cu_3Au and Cu were used in the initial studies to obtain a fundamental understanding of both the effect or order and bulk versus surface contributions on cyclic stress strain response measurements. The aluminum alloys investigated were 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 were investigated. They differed from 7050 by the elimination of, and/or variation of, the copper and zirconium additions. Zinc and magnesium concentrations were the same as 7050 in order that the effects associated with copper and other alloying additions could be isolated.

Low Cycle Fatigue

1. The effect of order: most commercial age-hardenable alloys obtain their strength from a homogeneously dispersed ordered precipitate. Consequently, the effect of atomic order on cyclic behavior is of fundamental importance. The main purpose of this research was to evaluate the effect of ordering on the low cycle fatigue behavior of Cu_3Au single crystals in order to understand the mechanisms involved. The fatigue crack nucleation, fatigue crack propagation, fatigue hardening/softening, and fracture behavior of Cu_3Au single crystals, in the ordered and disordered state, have been investigated. Single crystals were chosen so that ambiguities in the interpretation of results could be minimized. The details of the study have been published in reference (1) and can be summarized as follows:

   a. Fully ordered Cu_3Au single crystals exhibited an initial rapid fatigue hardening followed by fatigue softening. The rate of hardening or softening increases with increasing strain amplitude. Disordered Cu_3Au single crystals exhibited continuous fatigue hardening until fracture. The hardening rate increases with increasing strain amplitude and is low when compared to those in the initial stage of fully ordered crystals. Fatigue hardening is interpreted by the application of unidirectional hardening concepts and softening by disordering.

b. The Manson-Coffin low cycle fatigue law is a good approximation of the low cycle fatigue behavior of Cu_3Au single crystals in both the fully ordered and disordered states.

c. For both fully ordered and disordered crystals, the cyclic stress-strain curves are above the monotonic stress-strain curves. The fully ordered crystals cyclically harden much more than the disordered crystals.

d. For both fully ordered and disordered crystals deformation bands develop during fatigue hardening for all strain amplitudes investigated. Fatigue cracks were observed to nucleate at the intersection of primary slip bands and deformation bands and then propagated along the deformation band boundaries. Ordering has little effect on the fracture mode, both fully ordered and disordered crystals show ductile fractures.

2. Surface and bulk effects: There is considerable evidence that the mechanical properties and deformation behavior of materials can be influenced by altering the state of the surface. There is also considerable debate over the importance of surface-geometry versus surface-stress and surface-hardening versus bulk-hardening when interpretating the cyclic hardening and/or softening behavior observed during low cycle fatigue. The objective of this research was to obtain information on the surface and bulk contributions to crack initiation and cyclic hardening. Studies were made on ion-plated copper single crystals and a polycrystalline Al-Zn-Mg-(Zr) alloy. The copper single crystals were used to evaluate the effect of ion-plated coatings, of various stacking fault energies, on the low cycle fatigue behavior of copper single crystals in order to obtain information on surface and bulk contributions to crack initiation and cyclic hardening. By using copper single crystals of identical orientation, we hoped to eliminate the influence of many factors which might lead to misinterpretation of the final results. The coating materials were chosen so as to have quite different stacking fault energies when compared with copper and yet be compatible with respect to crystal system and atomic size. Ion plating was used since a clean strongly

adherent interface is formed between the coating material and the substrate; and a uniform coating could be obtained on cylindrical samples. The question of whether the ion plating process generates significant damage on the surface was also evaluated. The details of the study have been published in reference (2) and can be summarized as follows:

a. The critical resolved shear-stress of copper single crystals can be changed by a coating material which has a different modulus. The magnitude and direction of that change depends on the modulus difference and whether it is larger or smaller than that of the substrate.

b. The ion-plating process itself does not significantly affect the deformation behavior in unidirectional tensile and low cycle fatigue tests.

c. Initial fatigue hardening was observed followed by a saturated period, fatigue softening and secondary hardening. The fatigue softening is associated with the high strain amplitudes increasing the incidence of duplex slip.

d. The cyclic hardening observed in this study is a result of a bulk hardening effect and is insensitive to the surface condition and not controlled by the surface layer as suggested by Kramer.

e. Crack initiation is sensitive to the topography of the slip bands on the surface and can be changed by using coating materials of different SFE's.

f. Crack nucleation in single crystals at high cyclic strains is virtually equivalent to that which occurs at low strain amplitudes.

The objective of the low cycle corrosion fatigue study on the Al-Zn-Mg-(Zr) alloy 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. The details of the study were published in reference (3) and can be summarized as follows:

The cyclic hardening observed in this study is a result of a bulk hardening effect and is insensitive to the surface condition and not controlled by the surface layer. Both crack initiation and propagation are environment sensitive; initiation being effected by the corrosive environment's influence on intrusion-extrusion formation, and propagation being effected by the corrosive environment producing a change in fracture mode from ductile to brittle.

3. LCF-Microstructure Relationships of a ternary Al-Zn-Mg and a 7050 aluminum alloy: It was the purpose of this study to investigate the fatigue behavior of two 7XXX aluminum alloys by varying the aging temperature, time, and composition, and to systematically determine the microstructure that appears best suited for reversed loading. A high purity 7050 alloy and a ternary Al-Zn-Mg alloy having the same Zn and Mg concentrations as the 7050 material were examined. The results which have been published in reference (4) can be summarized as follows:

a. The copper present in 7050 that is in solid solution at the solutionizing temperature of 480°C directly enters into the precipitation process during low temperature aging. The critical temperature for homogeneous precipitation for Al-6Zn-2Mg is less than 150°C, and the presence of copper increases it to about 150°C.

b. The best combination of static strength and ductility for the ternary alloy obtained in this study occurred when the alloy was aged at 150°C to produce the partially coherent η' precipitates with a Guinier radius of approximately 65Å. The best monotonic properties for the 7050 were obtained when aged to produce the maximum density of η' particles having a Guinier radius of approximately 45Å. This type of microstructure resulted when 7050 was double aged for 4 hours at 120°C followed by 24 hours at 150°C.

c. The fracture mode of the ternary Al-Zn-Mg alloy changes progressively with aging from ductile, microvoid coalescence to low energy, intergranular separation. This contrasted to the ductile transgranular fracture behavior of the 7050 alloy at all aging conditions investigated. The variation in fracture behavior between the two alloys was related to the development of coarse slip bands in the large grained ternary alloy. The coarse slip produced large stress concentrations across the grain boundaries resulting in intergranular fracture.

d. The cycles to failure, at constant strain amplitude, increase with aging time at both 120°C and 150°C for both alloys. The best fatigue performance in the ternary alloy was found when the greatest density of η' occurs. Aging 7050 for 24 hours at 120°C produces a high density of small particles with a Guinier radius of 35Å, giving the best fatigue life, strength, and ductility over the range of low cycle fatigue investigated.

e. The deviation from single slope behavior in a Coffin-Manson plot is attributed to changes in deformation processes as a function of the plastic strain amplitude.

4. The effect of grain refinement on the LCF behavior of Al-Zn-Mg alloys: Our results described in section 3 indicated that microstructures which reduced inhomogeneous deformation were more resistant to fatigue. A well-known means of promoting homogeneous deformation is a reduction in grain size, and in aluminum alloys the grain size can be controlled by additions of $\sim$ 0.1% zirconium. This study was undertaken to establish the effects of grain structure refinement and variation in aging treatment on the tensile and low cycle fatigue behavior of two Al-Zn-Mg-(Zr) alloys. The results of this study, which have been published in reference (5) can be summarized as follows:

a. The increased homogeneity of deformation observed for the fine-grained Al-Zn-Mg-Zr alloy resulted in greatly improved ductility and LCF resistance at high plastic strain amplitudes when compared with the large-grained Al-Zn-Mg alloy. The inferior resistance of the Al-Zn-Mg alloy to plastic strains was attributed to the occurrence of brittle intergranular fracture resulting from the presence of planar dislocation bands.

b. The fatigue ductility coefficients, -c, were smaller for Al-Zn-Mg than for Al-Zn-Mg-Zr due to a larger degree of slip reversibility.

c. A microstructure consisting primarily of simi- and incoherent $MgZn_2$ particles ($R_G \sim 71$ Å), produced by aging for 24 hours at 150°C exhibited the best LCF resistance at high plastic strain amplitudes for the aging treatments studied. This is attributed to an increased incidence of dislocation looping which resulted in more homogeneous deformation when compared with the other aging treatments of this study. In the long fatigue life range (> 10^5 cycles) an underaged microstructure, consisting of shearable GP zones is predicted to have superior fatigue resistance.

d. Current semi-empirical relationships do not predict adequately the LCF parameters, -c and ε'_f for aluminum alloys. An increase in the cyclic work hardening exponent, η' was found to be associated with an increase in -c, in contrast to the predictions of these relationships.

<u>Fatigue Crack Propagation</u>

The effect of microstructures on the fatigue crack growth behavior of the Al-Zn-Mg-(Zr) alloy used for the LCF studies of (4) was investigated. In addition, the observed crack growth rates were compared to the values predicted by various crack growth rate equations. This research will be published in the International Journal of Fracture and can be summarized as follows:

a. No differences were observed in the crack growth rates for the underaged and maximum strength conditions for low ΔK values, however the overaged condition exhibited a slower crack growth rate.

b. The better fatigue resistance of the overaged condition, is believed to be associated with an increased incidence of dislocation looping, compared to the other conditions resulting in more homogeneous deformation.

c. At larger ΔK values the deformation of all three aging conditions become more homogeneous and the crack growth rates appear to converge.

d. The microstructural feature that affects the crack growth rate in this alloy the most is the type of precipitate. Thus, the incoherent η precipitate results in more homogeneous deformation and a slower crack growth rate than the shearable GP-zones and η'.

e. The low cycle fatigue parameters, ε_f', C and n', give an accurate indication of the relative crack growth rates. The relative position of the Coffin-Manson plots present the same relative ranking of fatigue resistance as the da/dN versus ΔK plots.

f. Proposed crack growth equations which contain numerical constants that are dependent on the particular alloy system and are based on curve fitting techniques can predict crack growth rates with considerable accuracy. However crack growth tests must be conducted in order to determine these constants.

g. Equations utilizing only measurable monotonic and low cycle fatigue parameters and a microstructural parameter can predict crack growth rates with reasonable accuracy. The best predictive models presently available contain microstructural parameters which can be correlated, in advance, with a metallurgical property of the material.

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 ν-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 ν-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.

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Degrees Granted Under AFOSR Sporsonship

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2. Thomas H. Sanders, Jr., "The Relationship of Microstructure to Monotonic and Cyclic Straining in Two Aluminum-Zinc-Magnesium Precipitation Hardening Alloys," Doctor of Philosophy, February, 1975.

3. Edmund Jung Chen, "Effects of Ion-Plating on Low Cycle Fatigue Behavior of Copper Single Crystals," Doctor of Philosophy, July, 1975.

4. Robert E. Sanders,Jr., "The Effect of Zirconium on the Low Cycle Fatigue Behavior of an Aluminum-Zinc-Magnesium Alloy," Master of Science, June, 1976.

5. Edward J. Coyne, Jr., "The Effect of Microstructure on the Fatigue Crack Propagation Behavior of an Aluminum-Zinc-Magnesium-Zirconium Alloy," Master of Science, March, 1977.

6. Fu-Shiong Lin, "Low Cycle Corrosion Fatigue and Crack Propagation of High Strength 7XXX-Type Aluminum Alloys," Doctor of Philosophy, April, 1978.

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2. E. Y. Chen and E. A. Starke, Jr., "Effects of Ion-Plating on Low Cycle Fatigue Behavior of Copper Single Crystals," <u>Mater. Sci. and Engr</u>., <u>24</u>, No. 2, 209-221 (1976).

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7. E. J. Coyne, Jr. and E. A. Starke, Jr., "The Effect of Microstructure on the Fatigue Crack Growth Behavior of an Al-Zn-Mg(-Zr) Alloy," submitted to <u>Engineering Fracture Mechanics</u>.

8. E. E. Underwood and E. A. Starke, Jr., "Quantitative Stereological Methods for Analyzing Important Microstructural Features in Fatigue of Metals and Alloys," to be published in the Proceedings of the ASTM Symposium on Fatigue Mechanisms, to be held in Kansas City, Missouri, May 22-24, 1978.

9. E. A. Starke, Jr., M. Marek, and B. Sarkar, "A Seperation of the Mechanical and Electrochemical Effects of SCC in High Strength Aluminum Alloys," in preparation.

10. E. A. Starke, Jr., "Cyclic Plastic Deformation and Microstructure," in preparation for the ASM-TMS 1978 Seminar on Fatigue to be held in St. Louis, Mo., October 14-15, 1978.

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1. E. A. Starke, Jr., "The Effects of Microstructure on Stress Corrosion Cracking of Aluminum Alloys," Symposium on Aluminum Alloys, Mechanical Properties and Microstructural Effects, Natcon '74, Detroit, October, 1974.

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Patentable Inventions

No patentable inventions have resulted from the sponsored research.

Respectfully submitted:

Edgar A. Starke, Jr.

Edgar A. Starke, Jr.
Principal Investigator

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20. ABSTRACT (continued)

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