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GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
SPONSORED PROJECT INITIATION

Date: 9/22/78

Project Title: GRA Research Program - The Low Cycle Fatigue and Fatigue Crack Propagation Behavior of High Strength Al Alloys Produced by P/M Fabricating Techniques.

Project No: E-19-671

Project Director: Dr. E. A. Starke, Jr.

Sponsor: Lockheed-Georgia Company

Agreement Period: From 9/1/78 Until 8/31/81

Type Agreement: P. O. No. CT70286

Amount: $25,300

Reports Required: Quarterly Progress Reports

Sponsor Contact Person (s):

Technical Matters	Contractual Matters (thru OCA)
Mr. W. R. Britton, Buyer Dept. 52-25, Zone 383 LOCKHEED-GEORGIA COMPANY Marietta, GA 30063	

Defense Priority Rating: N/A to this order

Assigned to: Chemical Engineering (School/Laboratory)

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CA-3 (3/76)

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION

Date: 5/4/81

Project Title: GRA Research Program - The Low Cycle Fatigue and Fatigue Crack Propagation Behavior of High Strength Al Alloys Produced by P/M Fabricating Techniques.

Project No: E-19-671

Project Director: Dr. E. A. Starke, Jr.

Sponsor: Lockheed-Georgia Company

Effective Termination Date: 5/1/81

Clearance of Accounting Charges: 5/1/81

Grant/Contract Closeout Actions Remaining:

- X Final Invoice ~~and Closing Documents~~
- _ Final Fiscal Report
- _ Final Report of Inventions
- _ Govt. Property Inventory & Related Certificate
- _ Classified Material Certificate
- _ Other ____________

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E-19-671

B-53

FINAL SCIENTIFIC REPORT
LOCKHEED GEORGIA GRANT NUMBER
CT 70286

BASIC RESEARCH IN FATIGUE OF HIGH STRENGTH ALUMINUM ALLOYS

Submitted to

LOCKHEED-GEORGIA COMPANY
86 South Cobb Drive
Marietta, Georgia 30063

by the

FRACTURE AND FATIGUE RESEARCH LABORATORY
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia 30332

Dr. Edgar A. Starke, Jr.
Principal Investigator
Professor of Metallurgy and
Director

14 January 1981

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I. ABSTRACT

The primary objective of this research was to characterize the microstructure, determine the deformation and fatigue behavior of high strength aluminum alloys produced by various processing techniques, and to establish functional relationships between these important interrelated factors. The studies were directed towards understanding fatigue mechanisms in aircraft materials. A multi-task, multi-discipline effort provided a broad research program which included studies of:

1. The effect of intermediate thermomechanical treatments on the fatigue properties of two 7XXX aluminum alloys,

2. The effect of microstructure and moisture on the low cycle fatigue and fatigue crack propagation of two Al-Li-X alloys, and

3. The microstructure and properties of extruded P/M CT91-T7X151.

The material summarized in this report indicates how these objectives were achieved.

II. SUMMARY OF RESEARCH

1. The Effect of Intermediate Thermomechanical Treatments on the Fatigue Properties of Two 7XXX Aluminum Alloys.

The effect of different ingot processing techniques on the microstructural, monotonic, and fatigue properties of 7050 and 7475 aluminum alloys has been investigated. Properties of these alloys after processing by newly developed intermediate thermomechanical treatments (ITMT) were compared with those of hot-rolled materials which received conventional type processing. ITMT materials of the two alloys were studied in both the as-recrystallized (AR) and as-recrystallized plus hot-rolled (AR+HR) conditions. Microstructures of the AR variants were highly recrystallized with very fine equiaxed grains.

AR+HR materials were partially recrystallized with an elongated pancake-type grain morphology. Conventional processing, was used to simulate the commercial-type lamellar, largely unrecrystallized microstructures. The ITMT-7050 materials were more fully recrystallized than their 7475 counterparts due to the presence of different dispersoid phases and slight differences in processing conditions.

The conventionally processed 7050 and 7475 alloys exhibited the best overall combination of fatigue properties of the materials studied. The predominantly unrecrystallized microstructures produced by this processing promoted a high-energy-absorbing transgranular fracture mode and led to superior resistance to fatigue crack propagation and unstable fracture. The more recrystallized ITMT materials experienced a higher degree of intergranular fracture, which contributed to higher fatigue crack growth rates and lower fracture toughness values. The presence of a large volume fraction of Al_2CuMg in ITMT variants of 7050 was particularly detrimental to the fracture resistance of this alloy.

Total low-cycle fatigue and high-cycle fatigue lives of the experimental materials were relatively unaffected by changes in microstructure produced by ingot processing. However, quantitative metallography showed that the crack initiation resistance of the ITMT AR variants was somewhat improved over that of conventionally processed materials. Crack initiation at slip bands, which occurs extensively in the unrecrystallized grains of the conventionally processed materials, is severely limited by the fine grain size and random texture produced by AR-type ITMT processing.

The fatigue crack propagation data of the present investigation showed that the presence of residual stresses in unstretched plate material could markedly affect crack growth rates. A method was developed to correct for residual stresses in edge notched specimens and obtain a rough approximation for an "effective" ΔK. Upon the application of this method, the corrected 7475 fatigue crack propagation data was compared with the results of a predictive equation developed in this laboratory based on low-cycle fatigue and microstructural parameters. The relationship correctly predicted the relative order of fatigue crack propagation resistance for the three 7475 experimental materials.

The results of this research are significant in that they show that microstructure has a large effect on the fatigue behavior of high strength aluminum alloys. More importantly, the microstructural features, which improve fatigue crack initiation resistance in aluminum alloys were identified and found to be different from those that improve fatigue crack propagation resistance. Strain localization should be prevented for FCI resistance, and this goal is approached by reducing the grain size by ITMT and by overaging so that the strengthening precipitates are looped by dislocations. The disperoids present in commercial alloys also aid in homogenizing the deformation. The random texture produced by the

ITMT process enhances the incompatibility of deformation in neighboring grains and causes cracks to initiate at the grain boundaries instead of at persistent slip bands. This delays microcrack link-up and improves FCI resistance, although it lowers FCP resistance. On the other hand, planar slip and an inhomogeneous deformation mode enhances crack branching, which increases the total crack path and lowers the effective stress intensity at the tip of the crack. Large grain sizes and a strong preferred orientation also promote crack propagation by slip-band decohesion and thus crack branching. This research has shown, however, that there is not a simple one-to-one relationship between grain structure and fatigue properties. The problem is much more complicated, since factors such as the cyclic flow stress and slip reversibility also have significant effects on fatigue behavior.

A. Personnel: This task constituted the Ph.D. thesis research of Robert E. Sanders, Jr., Professor Edgar A. Starke, Jr., thesis advisor. Dr. Sanders received his Ph.D. in Metallurgy from Georgia Tech in July, 1978, and is presently employed at the Alcoa Technical Center, Alcoa, PA.

B. Presentations and Publications:

1. Robert E. Sanders, Jr. and E. A. Starke, Jr., "A Comparison of the Low Cycle Fatigue and Crack Propagation Behavior of ITMT - and Commercially-Processed 7050 Aluminum Alloy," paper presented at the AIME Symposium. Fatigue of Aluminum Alloys, 106th AIME Annual Meeting, Atlanta, GA, March 6-10, 1977.

2. Robert E. Sanders, Jr., "The Effect of ITMT on the Fatigue Behavior of Al-Zn-Mg-Cu Alloys," seminar presented at Lockheed-Georgia Company, Marietta, GA, June 21, 1978.

3. Robert E. Sanders, Jr. and E. A. Starke, Jr., "The Effect of Ingot Processing on the Microstructure and Fatigue Properties of 7475-T6 Plate," paper presented at the

AIME Symposium Thermomechanical Processing of Aluminum Alloys, 1978 Fall Meeting of AIME, St. Louis, Missouri, October 15-19, 1978.

4. R. E. Sanders, Jr., "The Effect of ITMT on the Fatigue Properties of Two 7XXX Aluminum Alloys," Ph.D. Thesis, Georgia Institute of Technology, July 1, 1978.

5. R. E. Sanders, Jr. and E. A. Starke, Jr., "The Effect of Intermediate Thermomenchanical Treatment on the Fatigue Properties of a 7050 Al Alloy," Met. Trans. A, 9A 1087-1100 (1978).

6. R. E. Sanders, Jr. and E. A. Starke, Jr., "The Effect of Ingot Processing on the Microstructure and Fatigue Properties of 7475-T6 Plates," in Thermomechanical Processing of Aluminum Alloys, ed. James G. Morris, The Metallurgical Society of AIME, Warrendale, PA, 1979, pp. 50-73.

7. Edgar A. Starke, Jr., "Heat Treatment-Metallurgy," in 1980 Year Book of Science and Technology, McGraw-Hill Company, New York, 1980, pp. 218-221.

2. The Effect of Microstructure and Moisture on the Low Cycle Fatigue and Fatigue Crack Propagation of Two Al-Li-X Alloys.

Al-Li alloys are very attractive for stiffness-critical airframe components, since they have an excellent combination of low density and high modulus. However, their use has been limited by low-fracture toughness and poor fatigue resistance. This research was concerned with the fracture and fatigue behavior of Al-Li alloys, with the primary emphasis being placed on microstructure-fatigue relationships. It is hoped that, once these relationships have been established, modifications can be made in the microstructure to improve these design limiting properties.

The effect of microstructure on the monotonic and fatigue behavior was investigated. The properties of a commercially available aluminum-copper-lithium alloy, 2020-T651, were examined in order to determine a baseline Al-Li alloy for purposes of comparison. The Al-Li-Mn research alloy was studied in an underaged, peak-aged, and overaged condition. The grain structure of the three heat treatments were the same; however, different size precipitates produced by the different heat treatments resulted in differences in deformation characteristics. The underaged and peak-aged alloys deformed by fine and coarse planar slip, respectively. The larger particle size and interparticle spacing of the overaged condition resulted in a combination of coarse planar slip and Orowan looping. The Al-Cu-Li baseline alloy deformed primarily by coarse planar slip.

The overaged condition possessed the best low-cycle-fatigue resistance for the Al-Li-Mn material, consistent with our previous statement. The presence of some degree of homogeneous deformation was responsible for the better properties. With one exception, the Al-Li-Mn alloys exhibited a single-slope, strain-life behavior. This is attributed to the deformation mode remaining the same at both high and low strain amplitudes. The Al-Cu-Li baseline alloy had a discontinuity in the curve which is attributed to homogeneous deformation at high plastic strain amplitudes and planar slip at low strain amplitudes.

The fatigue crack propagation data from this investigation showed that the crack propagation rates of both Al-Li-Mn and Al-Cu-Li (2020) alloys are less than those of other aluminum alloys at low stress intensity factors due to the high modulus and resulting low crack opening displacement. However, as the stress intensity is increased above $\sim$ 12 $MPam^{\frac{1}{2}}$, the crack propagation rates of the lithium bearing alloys exceed those of other aluminum alloys. This is due to their low fracture toughness. The growth rates for the three aging conditions of the Al-Li-Mn alloy were similar. No difference in fatigue behavior was observed between dry air and distilled water environments.

A. Personnel: This task constituted the Ph.D. thesis research of Edward J. Coyne, Jr., Professor Edgar A. Starke, Jr., thesis advisor. Dr. Coyne received his Ph.D. in Metallurgy from Georgia Tech in October, 1979 and is presently employed at Lockheed-Georgia Company, Marietta, GA.

B. Presentation and Publications:

1. E. J. Coyne, Jr., "The Fatigue Behavior of an Al-Cu-Li (2020) Alloy," Seminar presented at Lockheed-Georgia Company, Marietta, GA, July 24, 1978.

2. E. J. Coyne, Jr., "The Microstructure and Fatigue Behavior of Al-Li-X Alloys," Seminar presented at Vanderbilt University, Nashville, TN, January 22, 1979.

3. E. J. Coyne, Jr., "The Low Cycle Fatigue Behavior of Al-Li Alloys," Seminar presented at the Exxon Research Laboratory, Houston, TX, April 3, 1979.

4. E. A. Starke, Jr., "Microstructure-Mechanical Properties of Al-Li Alloys," Seminar presented at German Aerospace Research Institute, (DFVLR) Cologne, Germany, June 22, 1979.

5. Edward J. Coyne, Jr., "The Effect of Microstructure on the Fatigue Behavior of an Aluminum-Lithium, Alloy," Ph.D. Thesis, Georgia Institute of Technology, October, 1979.

6. E. J. Coyne, Jr. and E. A. Starke, Jr., "The Effect of Microstructure on the Fatigue Crack Propagation Behavior of Al-Li-Mn and Al-Cu-Li Alloys," presented at the AIME Annual Meeting, Las Vegas, NV, February 25, 1980.

7. E. J. Coyne, Jr., T. H. Sanders, Jr., and E. A. Starke, Jr., "The Effect of Microstructure and Moisture

on the Low Cycle Fatigue and Crack Propagation of Two Al-Li-X Alloys," presented at the First International Aluminum-Lithium Conference, Stone Mountain, GA, May 21, 1980, and to be published in the Proceedings of the Conference.

3. The Microstructure and Properties of Extruded P/M CT91-T7X151.

The purpose of this investigation was to characterize the microstructure and evaluate the mechanical properties of extruded powder-metallurgical (P/M) CT91-T7X151 in laboratory air at room temperature. Powder metallurgy is one method of microstructure control and when used in conjunction with ITMT, it offers ways of producing ultra-fine grain recrystaillized structures.

The microstructure of the P/M extrusion is more homogeneous than conventionally processed I/M 7XXX alloys. P/M processing creates a partially recrystallized grain structure, orders of magnitude smaller than in I/M alloys. This is due to the ability of the fine distribution of oxides and $(CoFe)_2Al_9$ along the previous P/M particle boundaries to inhibit grain growth. Iron and silicon are not present in P/M materials as clusters of large, brittle secondary intermetallic constituents as they are in I/M alloys.

The variation in texture, degree of recrystallization, grain size and shape which exists as a consequence of non-axisymmetric and non-uniform metal flow creates a subtle difference in tensile properties within the P/M extrusion. Strength is altered by differences in the deformation texture and the degree of recrystallization, which changes the Taylor coefficient. Ductility follows an inverse relationship with strength when the grain size is constant. A finer, less recrystallized grain structure improves the ductility. However, this variation is insignificant when comparisons are made between P/M and I/M processing. At similar ductility the P/M extrusion is $\sim$10 percent stronger than I/M 7050-T76511. The fine grain structure and distribution of $(CoFe)_2Al_9$

in P/M CT91 compensates for the low-energy-absorbing intergranular fracture by uniformly distributing strain before fracture. Large intense slip bands, many times responsible for the low ductility in large grained I/M alloys, are not observed.

The LCF behavior of P/M extrusion is insensitive to the variation in microstructure for the aging conditions tested. The cyclic crack initiation resistance of the P/M extrusion at 13 percent higher strength is similar to the I/M CT91 counterpart overaged ten additional hours at 163^{o}C. However, at low strains and long cyclic-lives, crack initiation resistance of the P/M extrusion is greater due to the fine P/M microstructure's ability to attenuate the deleterious effects of strain localization or environment more effectively than the coarser I/M microstructure. Crack initiation at PSBs was not observed. For all strain amplitudes investigated, crack initiation occurred at grain boundaries. Softening behavior observed in the cyclic stress-response curve indicates that microscopic cracks may form at the grain boundaries as early as ten percent of its life. No significant improvement in total fatigue life associated with I/M or P/M processing exists for the aging conditions considered.

The results of this investigation not only show that the properties of P/M aluminum alloys are sensitive to microstructure, but also point out the need for effective ingot processing to produce homogeneous microstructures on a macroscopic scale. If this is not obtained, the properties and resulting performance of the finished product may vary greatly, depending on the location of the plate from which it was made.

A. <u>Personnel</u>: This task constituted the M.S. thesis research of John Andrew Walker, Professor Edgar A. Starke, Jr., thesis advisor. Mr. Walker received his M.S. in Metallurgy from Georgia Tech in December, 1980, and is presently employed at Alcoa Technical Center, Alcoa Center, PA.

B. Presentations and Publications:

1. J. A. Walker and E. A. Starke, Jr., "High and Low Cycle Fatigue Behavior of CT91-T7," presented at the Annual AIME Meeting, Las Vegas, NV, February 25, 1980.

2. E. A. Starke, Jr., "The Effects of P/M Processing and ITMT on the Fatigue Properties of CT91" Seminar presented at Picatinny Arsenal, Dover, N.J., April 6, 1980.

3. J. A. Walker and E. A. Starke, Jr., "Low Cycle Fatigue Behavior of CT91-T7," Presented at the Fall AIME Meeting, Pittsburgh, PA, October 6, 1980.

4. John Andrew Walker, "The Microstructure and Properties of Extruded P/M CT91-T7X151," M.S. Thesis, Georgia Institute of Technology, December, 1980.