A Progress Report
Grant No. NAG-1-745-4

January 1, 1990 - June 30, 1990

NASA-UVA LIGHT AEROSPACE ALLOY AND STRUCTURES TECHNOLOGY PROGRAM

Submitted to:

National Aeronautics and Space Administration
Acquisition Division
Hampton, VA 23665

Attention:

Mr. J. F. Royall, Jr.
Grants Officer, M/S 126

For review to:

Mr. D. L. Dicus
Grant Monitor
Metallic Materials Branch, M/S 188A

Submitted by:

Richard P. Gangloff
Professor

Report No. UVA/528266/MS90/106
June 1990

DEPARTMENT OF MATERIALS SCIENCE

SCHOOL OF
ENGINEERING
& APPLIED SCIENCE

University of Virginia
Thornton Hall
Charlottesville, VA 22903

UNIVERSITY OF VIRGINIA
School of Engineering and Applied Science

The University of Virginia's School of Engineering and Applied Science has an undergraduate enrollment of approximately 1,500 students with a graduate enrollment of approximately 600. There are 160 faculty members, a majority of whom conduct research in addition to teaching.

Research is a vital part of the educational program and interests parallel academic specialties. These range from the classical engineering disciplines of Chemical, Civil, Electrical, and Mechanical and Aerospace to newer, more specialized fields of Applied Mechanics, Biomedical Engineering, Systems Engineering, Materials Science, Nuclear Engineering and Engineering Physics, Applied Mathematics and Computer Science. Within these disciplines there are well equipped laboratories for conducting highly specialized research. All departments offer the doctorate; Biomedical and Materials Science grant only graduate degrees. In addition, courses in the humanities are offered within the School.

The University of Virginia (which includes approximately 2,000 faculty and a total of full-time student enrollment of about 17,000), also offers professional degrees under the schools of Architecture, Law, Medicine, Nursing, Commerce, Business Administration, and Education. In addition, the College of Arts and Sciences houses departments of Mathematics, Physics, Chemistry and others relevant to the engineering research program. The School of Engineering and Applied Science is an integral part of this University community which provides opportunities for interdisciplinary work in pursuit of the basic goals of education, research, and public service.

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NASA-UVA LIGHT AEROSPACE ALLOY AND STRUCTURES TECHNOLOGY PROGRAM

NASA-LaRC Grant NAG-1-745

Submitted to:

National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia 23665

Attention:

Mr. J.F. Royall, Jr.
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For Review by:

Mr. D.L. Dicus
Grant Monitor
Metallic Materials Branch MS 188A

Submitted by:

Richard P. Gangloff
Professor
Department of Materials Science
School of Engineering and Applied Science
University of Virginia

Report No. UVA/528266/MS90/106
June 1990

Copy No._____

NASA-UVA LIGHT AEROSPACE ALLOY AND STRUCTURES TECHNOLOGY PROGRAM

Program Director:

Richard P. Gangloff

Co-principal Investigators:

Richard P. Gangloff
John K. Haviland
Carl T. Herakovich
Walter D. Pilkey
Marek-Jerzy Pindera
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Robert E. Swanson (VPI)
Earl A. Thornton
Franklin E. Wawner, Jr.
John A. Wert

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NASA-UVA LIGHT AEROSPACE ALLOY AND STRUCTURES TECHNOLOGY PROGRAM

SUMMARY

The NASA-UVa Light Aerospace Alloy and Structures Technology Program (LA^{2}ST) has achieved a substantial level of operation in 1990, with all proposed projects being actively executed by graduate students and faculty advisors. This work is funded by the NASA-Langley Research Center under Grant NAG-1-745. Here, we report on the progress achieved between January 1 and June 30, 1990. This progress report supplements the Grant Review Meeting held on June 13 and 14, 1990 at the Langley Research Center. All visual aids are reproduced in this report without extensive narrative.

The objective of the LA^{2}ST Program is to conduct interdisciplinary graduate student research on the performance of next generation, light weight aerospace alloys, composites and associated thermal gradient structures in close collaboration with Langley researchers. Individual technical objectives are established for each research project. Our efforts aim to produce basic understanding of material behavior, new monolithic and composite alloys, processing methods, solid and fluid mechanics analyses, measurement advances and a pool of educated graduate students.

The accomplishments presented in this report are highlighted as follows:

oo Four research areas are being actively investigated, including: (1) Environment Assisted Degradation Mechanisms in Advanced Light Metals, (2) Aerospace Materials Science, (3) Mechanics of Materials and Composites for Aerospace Structures, and (4) Thermal Gradient Structures.

oo 6 PhD and 5 MS graduate students, 10 faculty members, and 2 research associates from four departments at UVa and VPI are participating in 11 research projects. Each project is in conjunction with a specific branch and technical monitor at LaRC.

oo Eight undergraduate engineering students were incorporated into the LA^{2}ST Program. Four students, recruited from UVa, will work within the various graduate research programs at UVa during the summer and academic months of 1990. Four students, recruited from North Carolina State and California Polytechnic State Universities, will work at the Langley Research Center during the summer of 1990 and under NASA supervision.

oo 5 publications and 9 presentations at technical meetings were accomplished during this reporting period, bringing the totals since 1986 to 15 and 23, respectively.

oo *Research on environmental fatigue of advanced aluminum alloys and metal matrix composites* defined the crack growth behavior of rapidly solidified powder metallurgy Al-Li-Cu-O alloy 644B for vacuum, water vapor, moist air and oxygen. A strong stress ratio effect was traced to substantial and unexpected crack closure. Without the complicating effect of closure, increasing K_{max} at constant near-threshold ΔK resulted in only a small increase in crack growth rate for the water vapor environment. (Program 1)

oo *Research on localized corrosion and stress corrosion cracking of Al-Li-Cu alloys* demonstrates that, in controlled potential constant load time-to-failure experiments, rapid stress corrosion cracking is observed only when the following condition is satisfied:

$$E_{br\,\alpha\text{-}Al} < E_{applied} < E_{br\,T1}$$

$E_{br\,\alpha\text{-}Al}$ is the breakaway potential of the matrix phase and $E_{br\,T1}$ is the breakaway potential of the subgrain boundary phase, T_1. A class of compounds known as hydrotalcites form on crack walls in alkaline solutions and appear to play an important role in accelerated cracking during alternate immersion SCC testing. (Program 4)

oo *Research on zinc effects on the environmental sensitivity of Al-Li-X alloys* demonstrates that the δ' (Al_3Li) precipitate free zone, which often results from grain and subgrain boundary precipitation of Li rich phases, is greatly decreased or eliminated by addition of an intermediate level of zinc to an 8090 composition. Polarization experiments are in progress to investigate the potentially beneficial effect of decreased PFZ size on localized corrosion in aqueous chloride. (Program 5)

oo *Research at VPI on hydrogen embrittlement of aluminum alloys* has developed two charging techniques which provide hydrogen ingress without surface damage. Tensile tests of uncharged Al-Li-Cu alloy 2090 show no significant difference between low and room temperature properties. (Program 6)

oo *Research on the fracture toughness of Al-Li-Cu-In alloys for superplastic forming applications* determined that pilot-scale plates of 2090 and 2090 + In alloys exhibited lower initiation and growth fracture toughness compared to commercial 2090-T81 at 23°C. The latter material exhibited extensive delamination toughening and a microscopic shear mode of fracture, while the pilot-scale alloys exhibited minimal beneficial delamination and fractured by intersubgranular separation. (Program 3)

- oo *Research on elevated temperature fracture of PM Al-Fe-Si-V alloys* demonstrated that the excellent initiation and growth fracture toughness [from $J(\Delta a)$ experiments] for the LT orientation of this alloy at 23°C decreases through a minimum with increasing temperature to 316°C. This behavior is due to the interaction of reduced intrinsic ductility, probably due to strain aging, and reduced delamination toughening. Toughness is low for the TL orientation due to prior ribbon boundary cracking and further declines with increasing temperature. The graduate student on this program successfully passed the comprehensive examinations for the PhD degree. (Program 2)

- oo *Research on elevated temperature subcritical cracking ("creep crack growth") in Al alloys* demonstrated strong time-dependent effects on the fracture behavior of AA 2618 and FVS0812. Subcritical crack propagation occurred in both materials at moderate temperatures (175 to 300°C) and for stress intensities well below K_{IC}. Growth rates correlated with K, however, the C_t integral, which accounts for time dependent plasticity, may better quantify cracking at the higher temperatures. SEM fractography and TEM studies of thin foils from the crack tip and wake regions demonstrate dispersoid debonding and localized Al superplastic flow during cracking of ultrafine grain PM FVS0812. (Program 2)

- oo *Research on elevated temperature deformation* characterized the uniaxial deformation behavior of IM and PM aluminum alloys in terms of Ramberg-Osgood, modified empirical and Bodner-Partom flow rules. Tensile data for FVS0812 confirm a literature report of strain aging due to soluble Fe and V. (Program 2)

- oo *Research on Ti matrix-SiC fiber reinforced composites* demonstrates that the reaction kinetics between several types of SiC fibers and Ti-1100 alloy are appreciably slower than in other popular titanium alloy matrices. Tensile tests on the Ti-1100/SCS-6 fiber composite yielded an ultimate tensile strength of 1490 MPa at 23°C. Predictions from kinetics data suggest that the fiber will retain strength in Ti-1100 for approximately 28,000 hours at 800°C. (Program 7)

- oo *Research on quantifying non-random particle distributions in materials* has further developed the particle distribution software package to include the capability to identify the characteristics of clusters of particles. The graduate student on this program successfully passed the comprehensive examinations for the PhD degree. (Program 8)

- oo *Research on the yielding of SCS-6/Ti-15-3 MMC under biaxial loading* produced yield surfaces and stress-strain curves for a variety of loading conditions using micromechanics. These constitutive descriptions, obtained for silicon carbide-titanium alloy matrix tubes secured from McDonnell Douglas Corporation, are now available for comparison with experimental results. (Program 9) oo *Research on cryogenic tankage* has analyzed several computer models for buckling and demonstrates that proposed superplastically formed stringers are adequate. It has not been shown whether the same sections can be used as rings. Effective properties of the stringers were calculated for use in tank analyses and for comparison with test data. Several models needed to complete the study exceed the capabilities of the NASA computer which was used. (Program 10)

oo *Research on the thermoviscoplastic behavior* of high temperature alloys demonstrates that unsupported "Heldenfels" panel specimens exhibit significant out-of-plane bending, or thermal buckling, due to imperfections. A thermoviscoplastic finite element program for predicting thermal stresses in an unbuckled panel has been validated for elastic panel behavior and simple viscoplastic behavior, and is being used to examine in-plane stresses for test panels under thermal loading. (Program 11)

INTRODUCTION

Background

Since 1986, the Metallic Materials Branch in the Materials Division of the NASA-Langley Research Center has sponsored graduate student engineering-science research at the University of Virginia and at Virginia Polytechnic Institute and State University. This work has emphasized the mechanical and corrosion behavior of light aerospace alloys, particularly Al-Li based compositions, in aggressive environments [1]. Results are documented in a series of progress reports [2-4]. In the Fall of 1988 this program was increased to incorporate research at UVa on the development and processing of advanced aerospace materials [5]. In early 1989 the program was further increased in scope to include interdisciplinary work on solid mechanics and thermal structures, as funded by several Divisions within the Structures Directorate at NASA-LaRC [6]. With this growth, the NASA-UVA LIGHT AEROSPACE ALLOY AND STRUCTURES TECHNOLOGY PROGRAM (LA^2ST) was initiated within the School of Engineering and Applied Science at UVa.

The first progress report for the LA^2ST program was published in August of 1989 [7]. Research efforts in solid mechanics were in a state of infancy and were not represented at that time. Since then, graduate students have been recruited into the structural mechanics programs and several new projects have been initiated. Since July of 1989, the LA^2ST program has been operating with full participation from all faculty and student as outlined in the year-end 1989 progress report [8].

LA^2ST research planning for 1990 is presented in a recent renewal proposal [9]. This report summarizes the progress of this work for the period from January 1st to June 31, 1990. The first Grant Review Meeting was held on June 13 and 14, 1990 at the Langley Research Center, with over 20 faculty and graduate students from UVa and 1 faculty and graduate student from VPI participating. The main body of this report contains the slides and overhead projections from each presentation with no narrative.

Problem and Needs

Future aerospace missions require advanced light alloys and composites with associated processing and fabrication methods; new structural design methods and concepts with experimental evaluations; component reliability/durability/damage tolerance prediction procedures; and a pool of doctoral level engineers and scientists. Work on advanced materials and structures must be fully integrated. The NASA-UVa Technology Program addresses these needs.

LA^{2}ST Program

As detailed in the original proposal [6] and confirmed in the most recent renewal document [9], faculty from the Departments of Materials Science, Mechanical and Aerospace Engineering, and Civil Engineering at UVa are participating in the LA^{2}ST research and education program focused on high performance, light weight, aerospace alloys and structures. We aim to develop long term and interdisciplinary collaborations between graduate students, UVa faculty, and NASA-Langley researchers.

Our research efforts will produce basic understanding of materials performance, new monolithic and composite alloys, advanced processing methods, solid and fluid mechanics analyses, and measurement advances. A major product of the LA^{2}ST program is graduate students with interdisciplinary education and research experience in materials science, mechanics and mathematics. These advances should enable various NASA technologies.

The scope of the LA^{2}ST Program is broad. Four research areas are being investigated, including:

oo Environment Assisted Degradation Mechanisms in Advanced Light Metals,

oo Aerospace Materials Science,

oo Mechanics of Materials and Composites for Aerospace Structures, oo Thermal Gradient Structures.

Eleven specific research projects are ongoing within these areas. These projects, which form the basis for the dissertation requirement of graduate studies, currently involve ten faculty, two research associates and eleven graduate students. The majority of the graduate students are at the doctoral level and are citizens of the United States. Research is conducted at either UVa or LaRC, and under the guidance of UVa faculty and NASA staff. Each project is developed in conjunction with a specific LaRC researcher. Participating students and faculty are closely identified with a NASA-LaRC branch.

A primary goal of the LA^2ST Program is to foster interdisciplinary research. To this end, many of the research projects share a common focus on light and reusable aerospace structures which will be subjected to aggressive terrestrial and space environments; with emphasis on both cryogenic and elevated temperature conditions with severe thermal gradients typical of tankage structures.

Organization of Progress Report

This progress report provides organizational and administrative information (viz., statistics on the productivity of faculty and student participants, a history of current and graduated students, and a list of ongoing projects with NASA and UVa advisors). Twelve sections summarize the specific technical accomplishments of each research project for the period from January 1st to June 30th of 1990, and as presented at the First Grant Review Meeting held on June 13th and 14th. Appendices document grant sponsored publications and conference participation, and provide abstracts of technical papers.

References

1. R.P. Gangloff, G.E. Stoner and M.R. Louthan, Jr., "Environment Assisted Degradation Mechanisms in Al-Li Alloys", University of Virginia, Proposal No. MS-NASA/LaRC-3545-87, October, 1986.

2. R.P. Gangloff, G.E. Stoner and R.E. Swanson, "Environment Assisted Degradation Mechanisms in Al-Li Alloys", University of Virginia, Report No. UVA/528266/MS88/101, January, 1988.

3. R.P. Gangloff, G.E. Stoner and R.E. Swanson, "Environment Assisted Degradation Mechanisms in Advanced Light Metals", University of Virginia, Report No. UVA/528266/MS88/102, June, 1988.

4. R.P. Gangloff, G.E. Stoner and R.E. Swanson, "Environment Assisted Degradation Mechanisms in Advanced Light Metals", University of Virginia, Report No. UVA/528266/MS89/103, January, 1989.

5. T.H. Courtney, R.P. Gangloff, G.E. Stoner and H.G.F. Wilsdorf, "The NASA-UVa Light Alloy Technology Program", University of Virginia, Proposal No. MS NASA/LaRC-3937-88, March, 1988.

6. R.P. Gangloff, "NASA-UVa Light Aerospace Alloy and Structures Technology Program", University of Virginia, Proposal No. MS NASA/LaRC-4278-89, January, 1989.

7. R.P. Gangloff, "NASA-UVa Light Aerospace Alloy and Structures Technology Program", University of Virginia, Report No. UVA/528266/MS90/104, August, 1989.

8. R.P. Gangloff, "NASA-UVa Light Aerospace Alloy and Structures Technology Program", University of Virginia, Report No. UVA/528266/MS90/105, December, 1989.

9. R.P. Gangloff, "NASA-UVa Light Aerospace Alloy and Structures Technology Program", University of Virginia, Proposal No. MS NASA/LaRC-4512-90, November, 1989.

SUMMARY STATISTICS

Table I documents the numbers of students and faculty who participated in the LA^{2}ST Program, both during this reporting period and since the program inception in 1986. Academic and research accomplishments are indicated by the degrees awarded, and by publications and presentations. Specific graduate students and research associates who participated in the LA^{2}ST Program are named in Tables II and III, respectively.

TABLE I: LA^2ST Program Statistics

	Current 1/1 to 6/30/90	Cumulative 1986 to 6/30/90
PhD Students--UVa:	5	7
--NASA-LaRC:	1	1
MS Students--UVa:	3	3
--NASA:	1	1
--VPI:	1	1
Faculty--UVa:	9	9
--VPI:	1	1
Research Associates--UVa:	2	2
PhD Awarded:	0	2
MS Awarded:	0	0
Employers--NASA:	0	1
--Federal:	0	1
--University:	0	0
--Industry:	0	0
Publications:	5	15
Presentations:	9	23
Dissertations/Theses:	0	2
NASA Reports:	1	7

TABLE II

GRADUATE STUDENT PARTICIPATION IN THE NASA-UVa LA^2ST PROGRAM

POS #	GRADUATE STUDENT EMPLOYER	ENTERED PROGRAM	DEGREE COMPLETED	LANGLEY RESIDENCY	RESEARCH TOPIC	UVa/NASA-LaRC ADVISORS
1.	R. S. Piascik NASA-Langley	6/86	Ph.D. 10/89		Damage Localization Mechanisms in Corrosion Fatigue of Aluminum-Lithium Alloys	R. P. Gangloff D. L. Dicus
2.	J. A. Wagner NASA-Langley	6/87	Ph.D. (12/91)	PhD Research @ LaRC	Deformation and Fracture of Thin Sheet Aluminum-Lithium Alloys: The Effect of Cryogenic Temperatures	R. P. Gangloff W. B. Lisagor J. C. Newman
3.	R. G. Buchheit	6/87	Ph.D. (1/91)		Measurements and Mechanisms of Localized Aqueous Corrosion in Aluminum-Lithium Alloys	G. E. Stoner D. L. Dicus
4.	W. C. Porr, Jr.	1/88	Ph.D. (12/91)		Elevated Temperature Crack Growth in Advanced Powder Metallurgy Aluminum Alloys	R. P. Gangloff C. E. Harris
5.	D. B. Gundel	9/88	M.S. (5/90)		Investigation of the Reaction Kinetics Between SiC Fibers and Titanium Matrix Composites	F. E. Wawner W. Brewer
6.	F. Rivet (VPI)	9/88	M.S. (12/90)		Deformation and Fracture of Aluminum-Lithium Alloys: The Effect of Dissolved Hydrogen	R. E. Swanson (VPI) D. L. Dicus
7.	J. B. Parse	9/88	Ph.D. (5/91)		Quantitative Characterization of Spatial Distribution of Particles in Materials	J. A. Wert D. R. Tenney
8.	J. P. Moran NIST	9/88	Ph.D. 12/89		An Investigation of the Localized Corrosion and Stress Corrosion Cracking Behavior of Alloy 2090	G. E. Stoner W. B. Lisagor

TABLE II (continued)

GRADUATE STUDENT PARTICIPATION IN THE NASA-UVa LA^{2}ST PROGRAM

(continued)

POS #	GRADUATE STUDENT EMPLOYER	ENTERED PROGRAM	DEGREE COMPLETED	LANGLEY RESIDENCY	RESEARCH TOPIC	UVa/NASA-LaRC ADVISORS
9.	C. Copper	4/89	M.S. 12/90		Design of Cryogenic Tanks for Launch Vehicles	W. D. Pilkey J. K. Haviland D. R. Rummler
10.	D. C. Slavik	9/89	Ph.D. 12/92		Near Threshold Corrosion Fatigue of Advanced Aluminum Alloys and Composites	R. P. Gangloff D. L. Dicus
11.	C. L. Lach	9/89	M.S. (12/91)	MS Research @LaRC	To Be Selected	R.P. Gangloff
12.	R. J. Kilmer	11/89	Ph.D. (12/92)		Microstructure and Localized Corrosion of Al-Li-X Alloys	G. E. Stoner W. B. Lisagor
13.	M. F. Coyle	12/89	M.S. (12/92)		Visoplastic Response of High Temperature Structures	E. A. Thornton D. R. Rummler

Updated 6/90

TABLE III

Post-Doctoral Research Associate Participation in NASA-UVA LA^2ST Program

Pos #	Res. Assoc. Employer	Tenure	Research	Supervisor
1.	Yang Leng	3/89 to 3/91	Elevated Temperature Deformation and Fracture of PM Al Alloys and Composites	R. P. Gangloff
2.	Farshad Mizadeh	7/89 to 12/90	Deformation of Metal Matrix Composites	C. T Herakovich and Marek-Jerzy Pindera

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CURRENT PROJECTS

ENVIRONMENT ASSISTED DEGRADATION MECHANISMS IN ADVANCED LIGHT METALS

1. ENVIRONMENT-ENHANCED FATIGUE OF ADVANCED ALUMINUM ALLOYS AND METAL MATRIX COMPOSITES
   Faculty Investigator: R.P. Gangloff
   Graduate Student: Donald C. Slavik; PhD Candidate
   Research Associate: Yang Leng
   UVa Department: Materials Science
   NASA-LaRC Contact: D.L. Dicus (Metallic Materials)
   Start Date: September, 1989
   Anticipated Completion Date: December, 1992
   Supplementary Funding Support: Virginia Center for Innovative Technology

2. ELEVATED TEMPERATURE CRACK GROWTH IN ADVANCED RAPIDLY SOLIDIFIED, POWDER METALLURGY ALUMINUM ALLOYS
   Faculty Investigator: R.P. Gangloff
   Graduate Student: William C. Porr, Jr.; PhD candidate
   Research Associate: Yang Leng
   UVa Department: Materials Science
   NASA-LaRC Contact: C.E. Harris (Mechanics of Matls.)
   Start Date: January, 1988
   Anticipated Completion Date: December, 1991
   Supplementary Funding Support: UVa Academic Enhancement Program

3. DEFORMATION AND FRACTURE OF THIN SHEET ALUMINUM-LITHIUM ALLOYS: THE EFFECT OF CRYOGENIC TEMPERATURES
   Faculty Investigator: R.P. Gangloff
   Graduate Student: John A. Wagner; PhD candidate
   UVa Department: Materials Science
   NASA-LaRC Contacts: W.B. Lisagor (Metallic Materials)
   J.C. Newman (Mechanics of Materials)
   Start Date: June, 1987
   Anticipated Completion Date: December, 1991

4. MEASUREMENTS AND MECHANISMS OF LOCALIZED AQUEOUS CORROSION IN ALUMINUM-LITHIUM ALLOYS
   Faculty Investigator: Glenn E. Stoner
   Graduate Student: Rudolph G. Buchheit; PhD candidate
   UVa Department: Materials Science
   NASA-LaRC Contact: Dennis L. Dicus (Metallic Matls.)
   Start Date: June, 1987
   Anticipated Completion Date: January, 1991
   Supplementary Funding Support: ALCOA

5. THE EFFECTS OF ZINC ADDITION ON THE ENVIRONMENTAL STABILITY OF ALUMINUM-LITHIUM ALLOYS
   Faculty Investigator: Glenn E. Stoner
   Graduate Student: Raymond J. Kilmer; PhD candidate
   Department: Materials Science
   NASA-LaRC Contact: W.B. Lisagor (Metallic Materials)
   Start Date: September, 1989
   Anticipated Completion Date: December, 1992
   Co-Sponsor: ALCOA

6. DEFORMATION AND FRACTURE OF ALUMINUM-LITHIUM ALLOYS: THE EFFECT OF DISSOLVED HYDROGEN
   Faculty Investigator: R.E. Swanson (VPI)
   Graduate Student: Frederic C. Rivet; MS candidate
   VPI Department: Materials Engineering at VPI
   NASA-LaRC Contact: D.L. Dicus (Metallic Materials)
   Start Date: September, 1988
   Anticipated Completion Date: December, 1990

AEROSPACE MATERIALS SCIENCE

7. INVESTIGATION OF THE REACTION KINETICS BETWEEN SiC FIBERS AND SELECTIVELY ALLOYED TITANIUM MATRIX COMPOSITES AND DETERMINATION OF THEIR MECHANICAL PROPERTIES
   Faculty Investigator: F.E. Wawner
   Graduate Student: Douglas B. Gundel; MS candidate
   UVa Department: Materials Science
   NASA-LaRC Contact: D.L. Dicus and W.B. Brewer (Metallic Materials)
   Start Date: January, 1989
   Anticipated Completion Date: May, 1990

8. QUANTITATIVE CHARACTERIZATION OF SPATIAL DISTRIBUTION OF PARTICLES IN MATERIALS: APPLICATION TO MATERIALS PROCESSING
   Faculty Investigator: John A. Wert
   Graduate Student: Joseph Parse; PhD candidate
   UVa Department: Materials Science
   NASA-LaRC Contact: D.R. Tenney (Materials Division)
   Start Date: September, 1988
   Anticipated Completion Date: May, 1991
   Supplementary Funding Support: UVa Academic Enhancement Program

MECHANICS OF MATERIALS FOR AEROSPACE STRUCTURES

9. INELASTIC RESPONSE OF METAL MATRIX COMPOSITES UNDER BIAXIAL LOADING
   Faculty Investigators: Carl T. Herakovich and Marek-Jerzy Pindera
   Research Associate: Farshad Mirzadeh
   UVa Department: Civil Engineering
   NASA-LaRC Contact: W.S. Johnson (Mechanics of Materials)
   Start Date: June, 1989
   Anticipated Completion Date: To be determined

THERMAL GRADIENT STRUCTURES

10. DESIGN OF CRYOGENIC TANKS FOR LAUNCH VEHICLES
    Faculty Investigators: W.D. Pilkey and J.K. Haviland
    Graduate Student: Charles Copper; MS candidate
    UVa Department: Mechanical and Aerospace Engineering
    NASA-LaRC Contact: Donald R. Rummler (Thermal Structures)
    Start Date: April, 1989
    Anticipated Completion Date: December, 1990
    Supplementary Funding Support: UVa Academic Enhancement Program

11. EXPERIMENTAL STUDY OF THE VISCOPLASTIC RESPONSE OF HIGH TEMPERATURE STRUCTURES
    Faculty Investigator: Earl A. Thornton
    Graduate Student: Marshall F. Coyle; MS Candidate
    UVa Department: Mechanical and Aerospace Engineering
    NASA-LaRC Contact: Donald R. Rummler (Thermal Structures)
    Start Date: January, 1990
    Anticipated Completion Date: December, 1992
    Supplementary Funding Support: UVa Academic Enhancement Program

COMPLETED PROJECTS

1. DAMAGE LOCALIZATION MECHANISMS IN CORROSION FATIGUE OF ALUMINUM-LITHIUM ALLOYS
   Faculty Investigator: R.P. Gangloff
   Graduate Student: Robert S. Piascik; PhD candidate
   UVa Department: Materials Science
   NASA-LaRC Contact: D. L. Dicus (Metallic Materials)
   Start Date: June, 1986
   Completion Date: November, 1989

2. AN INVESTIGATION OF THE LOCALIZED CORROSION AND STRESS CORROSION CRACKING BEHAVIOR OF ALLOY 2090 (Al-Li-Cu)
   Faculty Investigator: Glenn E. Stoner
   Graduate Student: James P. Moran; PhD candidate
   UVa Department: Materials Science
   NASA-LaRC Contact: W.B. Lisagor (Metallic Materials)
   Start Date: September, 1988
   Completion Date: December, 1989
   Co-Sponsor: ALCOA

ADMINISTRATIVE PROGRESS AND PLANS

Student Recruitment

No new graduate students were recruited into the LA^{2}ST Program during the period from January to June of 1990. Only one opening currently exists, with graduate enrollment being outstanding.

Undergraduates were incorporated into the LA^{2}ST Program for this first time this reporting period. This increase in program scope was suggested by W.B. Lisagor of the Metallic Materials Branch and was detailed in a proposal to NASA-LaRC in April of 1990 [1]. Since April, eight undergraduate engineering students have been incorporated into the LA^{2}ST Program. Four students, recruited from UVa, will work within the various graduate research programs at UVa during the summer and academic months of 1990. Four students, recruited from North Carolina State and California Polytechnic State University, will work at the Langley Research Center during the summer of 1990 and under NASA supervision. These undergraduates have typically completed three years of course work in metallurgy and materials science departments, have cumulative grade point averages between 3.0 and 3.5 (A = 4.0) and are extremely enthused about the opportunity to assist in aerospace related research. We hope that this program will provide both immediate engineering and research results, and a source for future graduate students.

Brochure

A brochure describing the LA^{2}ST Program has not been developed to date because we have had excellent success in recruiting a sufficient number of high quality graduate students. Rather, our efforts have been focused on developing the technical excellence of the various projects.

We will develop a brochure during the next reporting period. The purpose of this will be to facilitate graduate student recruitment by describing the educational and technical opportunities provided by the LA^{2}ST Program. A secondary objective will be to advertise our research programs to the technical community worldwide.

Grant Meeting

We conducted the First Grant Review Meeting in June of 1990 at the Langley Research Center. The objective of this meeting was to provide graduate students with a presentation opportunity, to review and improve research directions, to promote interdisciplinary research and to spawn new technical ideas for incorporation in the LA^2ST Program. We plan to conduct this meeting at eighteen month intervals.

Complementary Programs at UVa

The School of Engineering and Applied Science has targeted materials and structures research for aerospace applications as an important area for broad future growth. The LA^2ST Program is an element of this thrust. Several additional programs are of benefit to LA^2ST work.

The Board of Visitors at UVa awarded SEAS an Academic Enhancement Program Grant in the area of Thermal Structures. The aim is to use University funding to seed the establishment of a world-class center of excellence which incorporates several SEAS Departments. This program is lead by Professors Wilsdorf, Herakovich, Pilkey and Thornton. Professor Thornton is establishing a Thermal Structures Laboratory.

The Light Metals Center has existed within the Department of Materials Science for the past several years under the direction of Professor H.G.F. Wilsdorf.

A Virginia Center for Innovative Technology Development Center, The Center for Electrochemical Science and Engineering, was established in 1988 with Professor G.E. Stoner as Director.

Professors Pilkey, Thornton and Gangloff have recently been awarded a NASA-Headquarters Grant to examine "Advanced Concepts for Metallic Cryo-thermal Space Structures". Research within this program will complement LA^2ST studies.

References

1. R.P. Gangloff, "NASA-UVa Light Aerospace Alloy and Structures Technology Program: A Supplementary Proposal", University of Virginia, Proposal No. MS NASA/LaRC-4677-90, April, 1990.

2. W.P. Pilkey, "Advanced Concepts for Metallic Cryo-thermal Space Structures", University of Virginia Proposal No. MAE-NASA/HQ-4462-90, August, 1989.

MEETING INTRODUCTION AND AGENDA

Introduction to the NASA-UVa Light Alloy and Structures Technology Program

Richard P. Gangloff
Department of Materials Science
University of Virginia

and

Dennis L. Dicus
Metallic Materials Branch
NASA-Langley Research Center

NASA-UVa LIGHT AEROSPACE ALLOY
and
STRUCTURES TECHNOLOGY PROGRAM

$\underline{\underline{LA^2ST}}$

D.L. Dicus	NASA Monitor
R.P. Gangloff	UVa Director

Co-principal investigators

R.P. Gangloff

J.K. Haviland

C.T. Herakovich

W.D. Pilkey

M.-J. Pindera

G.E. Stoner

R.E. Swanson (VPI)

E.A. Thornton

F.E. Wawner

J.A. Wert

History of LA^2ST

1986: Program on light alloy behavior in aggressive environments

Lisagor and Dicus--NASA
Gangloff and Stoner--UVa
Louthan--VPI

1988: Program expanded to elevated temperature fracture, composites, microstructure models

Harris--NASA   Swanson--VPI
Wert--UVa   Wawner--UVa

1989: LA^2ST established to integrate materials and mechanics

Herakovich and Pindera--UVa
Thornton--UVa
Haviland and Pilkey--UVa

3 Proposals and 6 Progress Reports

Needs---New aerospace components in aggressive environments require:

Advanced light alloys and composites

Novel processing and joining methods

New structural design concepts with analysis methods and evaluations

Reliability and durability predictions from fundamental material behavior

Interdisciplinary approach

Pool of PhD engineers and scientists

LA^2ST Objective---

Deliver educated students, publications, and technology in above areas

Operations

<u>BASIS</u>: UVa faculty and NASA investigator identify graduate research project and branch/cost sharing support for Fall renewal

<u>EDUCATION</u>:

UVa courses; UVa (LaRC) research

UVa courses (TV); LaRC research

UVa advisor; NASA committeeman

Undergraduate summer program at UVa and LaRC

Staff interchanges for unique work

	Current 1/1 to 6/30/90	Cumulative 1986 to 6/30/90
PhD Students--UVa:	5	7
--NASA-LaRC:	1	1
MS Students--UVa:	3	3
--NASA:	1	1
--VPI:	1	1
Faculty--UVa:	9	9
--VPI:	1	1
Research Associates--UVa:	2	2
PhD Awarded:	0	2
MS Awarded:	0	0
Employers--NASA:	0	1
--Federal:	0	1
--University:	0	0
--Industry:	0	0
Publications:	5	15
Presentations:	9	23
Dissertations/Theses:	0	2
NASA Reports:	1	7

Research Areas

<u>Environmental Degradation Mechanisms in Advanced Light Metals and Composites</u>

3 faculty   1 research associate
5 PhD students   2 MS students
Materials Science--UVa and VPI

<u>Aerospace Materials Science</u>

2 faculty
1 PhD student   1 MS student
Materials Science

<u>Mechanics of Materials and Composites for Aerospace Structures</u>

2 faculty   1 research associate
Civil Engineering (Solid Mechanics)

<u>Thermal Gradient Structures</u>

3 faculty   2 MS students
Mechanical and Aerospace Engineering

COMPLETED PROJECTS

1. DAMAGE LOCALIZATION MECHANISMS IN CORROSION FATIGUE OF ALUMINUM-LITHIUM ALLOYS

    Faculty Investigator: R.P. Gangloff
    Graduate Student: Robert S. Piascik; PhD
    UVa Department: Materials Science
    NASA-LaRC Contact: D. L. Dicus (Metallic Materials)

2. AN INVESTIGATION OF THE LOCALIZED CORROSION AND STRESS CORROSION CRACKING BEHAVIOR OF ALLOY 2090 (Al-Li-Cu)

    Faculty Investigator: Glenn E. Stoner
    Graduate Student: James P. Moran; PhD
    UVa Department: Materials Science
    NASA-LaRC Contact: W.B. Lisagor (Metallic Materials)
    Co-Sponsor: ALCOA

CURRENT PROJECTS

ENVIRONMENT ASSISTED DEGRADATION MECHANISMS IN ADVANCED LIGHT METALS

1. ENVIRONMENT-ENHANCED FATIGUE OF ADVANCED ALUMINUM ALLOYS AND METAL MATRIX COMPOSITES
   Faculty Investigator: R.P. Gangloff
   Graduate Student: Donald C. Slavik; PhD Candidate
   Research Associate: Yang Leng
   UVa Department: Materials Science
   NASA-LaRC Contact: D.L. Dicus (Metallic Materials)
   Supplementary Funding Support: Virginia CIT

2. ELEVATED TEMPERATURE CRACK GROWTH IN ADVANCED RAPIDLY SOLIDIFIED POWDER METALLURGY ALUMINUM ALLOYS
   Faculty Investigator: R.P. Gangloff
   Graduate Student: William C. Porr, Jr.; PhD candidate
   Research Associate: Yang Leng
   UVa Department: Materials Science
   NASA-LaRC Contact: C.E. Harris (Mechanics of Matls.)
   Supplementary Funding Support: UVa AEP

3. DEFORMATION AND FRACTURE OF THIN SHEET ALUMINUM-LITHIUM ALLOYS: THE EFFECT OF CRYOGENIC TEMPERATURES
   Faculty Investigator: R.P. Gangloff
   Graduate Student: John A. Wagner; PhD candidate
   UVa Department: Materials Science
   NASA-LaRC Contacts: W.B. Lisagor (Metallic Materials)
   J.C. Newman (Mechanics of Materials)

CURRENT PROJECTS

ENVIRONMENT ASSISTED DEGRADATION MECHANISMS IN ADVANCED LIGHT METALS

4. MEASUREMENTS AND MECHANISMS OF LOCALIZED AQUEOUS CORROSION IN ALUMINUM-LITHIUM ALLOYS
   Faculty Investigator: Glenn E. Stoner
   Graduate Student: Rudolph G. Buchheit; PhD candidate
   UVa Department: Materials Science
   NASA-LaRC Contact: Dennis L. Dicus (Metallic Materials)
   Supplementary Funding Support: ALCOA

5. THE EFFECTS OF ZINC ADDITION ON THE ENVIRONMENTAL STABILITY OF ALUMINUM-LITHIUM ALLOYS
   Faculty Investigator: Glenn E. Stoner
   Graduate Student: Raymond J. Kilmer; PhD candidate
   Department: Materials Science
   NASA-LaRC Contact: W.B. Lisagor (Metallic Materials)
   Co-Sponsor: ALCOA

6. DEFORMATION AND FRACTURE OF ALUMINUM-LITHIUM ALLOYS: THE EFFECT OF DISSOLVED HYDROGEN
   Faculty Investigator: R.E. Swanson (VPI)
   Graduate Student: Frederic C. Rivet; MS candidate
   VPI Department: Materials Engineering
   NASA-LaRC Contact: D.L. Dicus (Metallic Materials)

CURRENT PROJECTS

AEROSPACE MATERIALS SCIENCE

7. INVESTIGATION OF THE REACTION KINETICS BETWEEN SiC FIBERS AND SELECTIVELY ALLOYED TITANIUM MATRIX COMPOSITES AND DETERMINATION OF THEIR MECHANICAL PROPERTIES

   Faculty Investigator: F.E. Wawner
   Graduate Student: Douglas B. Gundel; MS candidate
   UVa Department: Materials Science
   NASA-LaRC Contact: D.L. Dicus and W.B. Brewer (Metallic Materials)

8. QUANTITATIVE CHARACTERIZATION OF SPATIAL DISTRIBUTION OF PARTICLES IN MATERIALS: APPLICATION TO MATERIALS PROCESSING

   Faculty Investigator: John A. Wert
   Graduate Student: Joseph Parse; PhD candidate
   UVa Department: Materials Science
   NASA-LaRC Contact: D.R. Tenney (Materials Division)
   Supplementary Funding Support: UVa AEP

CURRENT PROJECTS

MECHANICS OF MATERIALS AND COMPOSITES FOR AEROSPACE STRUCTURES

9. INELASTIC RESPONSE OF METAL MATRIX COMPOSITES UNDER BIAXIAL LOADING

   Faculty Investigators: Carl T. Herakovich and
   Marek-Jerzy Pindera
   Research Associate: Farshad Mirzadeh
   UVa Department: Civil Engineering
   NASA-LaRC Contact: W.S. Johnson (Mechanics of Materials)

THERMAL GRADIENT STRUCTURES

10. DESIGN OF CRYOGENIC TANKS FOR LAUNCH VEHICLES

    Faculty Investigators: W.D. Pilkey and J.K. Haviland
    Graduate Student: Charles Copper; MS candidate
    UVa Department: Mechanical and Aerospace Engineering
    NASA-LaRC Contact: Donald R. Rummler (Thermal Structures)
    Supplementary Funding Support: UVa AEP

11. EXPERIMENTAL STUDY OF THE VISCOPLASTIC RESPONSE OF HIGH TEMPERATURE STRUCTURES

    Faculty Investigator: Earl A. Thornton
    Graduate Student: Marshall F. Coyle; MS Candidate
    UVa Department: Mechanical and Aerospace Engineering
    NASA-LaRC Contact: Donald R. Rummler (Thermal Structures)
    Supplementary Funding Support: UVa AEP

AGENDA FOR FIRST ANNUAL NASA-UVa LA^{2}ST MEETING

NASA-Langley Research Center

June 13 and 14, 1990

Wednesday, June 13, 1990

9:00-9:30 am	Introductions and LA^{2}ST program overview D.L. Dicus R.P. Gangloff
9:30-10:15	Stress Corrosion of Al-Li-Cu: Role of Localized Corrosion in the Subgrain Boundary Region R.G. Buchheit and G.E. Stoner
10:15-10:30	Break
10:30-11:00	The Effects of Zinc Additions on the Environmental Stability of Alloy 8090 R.J. Kilmer and G.E. Stoner
11:00-11:45	Hydrogen Effects on Mechanical Behavior of Al-Li Alloys F.C. Rivet and R.E. Swanson
11:45-1:00 pm	Lunch
1:00-1:30	Near-Threshold Environmental Fatigue in Advanced Aluminum Alloys and Composites D.C. Slavik and R.P. Gangloff

1:30-2:15	Investigation of the Reaction Kinetics Between SCS-6 Fibers and Ti-1100 Titanium Matrices and Determinations of Their Mechanical Properties D.B. Gundel and F.E. Wawner
2:15-3:00	A Method for Analyzing How Uniformly Particles or Fibers are Dispersed in a Material J.B. Parse and J.A. Wert
3:00-3:20	Break
3:20-4:00	Fracture of Al-Li-Cu-X Alloys at Cryogenic Temperatures J.A. Wagner and R.P. Gangloff
4:00-4:40	Fracture of Powder Metallurgy Al-Fe-Si-V at Elevated Temperatures W.C. Porr and R.P. Gangloff
4:40-5:30	Elevated Temperature Deformation and Time-Dependent Crack Growth in Aluminum Alloys Yang Leng and R.P. Gangloff
6:45	Group Dinner

Thursday, June 14, 1990

9:00-9:45 am	Yielding of SCS6/Ti MMC Under Biaxial Loading C.T. Herakovich, Marek Pindera and Farshad Mirzadeh
9:45-10:30	Computational and Experimental Studies of Thermoviscoplastic Panels J.D. Kolenski, Marshall Coyle and E.A. Thornton
10:30-10:45	Break
10:45-11:30	Design of Cryogenic Tanks for Launch Vehicles J.K. Haviland, W.D. Pilkey and Charles Copper
11:30-1:00 pm	Lunch
1:00-2:00	Group discussions between UVa PIs and LaRC technical contacts on the health and direction of the grant.
2:00-	Individual discussions between UVa PIs and LaRC technical contacts on the direction and finances for the 1991 renewal to be written in August of 1990.
1:00-	Tour of LaRC for graduate students.

RESEARCH PROGRESS AND PLANS (January 1 to June 30, 1990)

Research progress, recorded during the period from January 1, 1990 to June 30, 1990 is summarized and future plans are described here for each of the eleven projects.

N90-22652

Program 1 **Environment Enhanced Fatigue of Advanced Aluminum Alloys and Composites**

Donald C. Slavik and Richard P. Gangloff

Objective

The objective of this PhD research is to characterize and understand the environmental fatigue crack propagation behavior of advanced, high stiffness and strength, aluminum alloys and metal matrix composites. Those gases and aqueous electrolytes which are capable of producing atomic hydrogen by reactions on clean crack surfaces are emphasized. We seek quantitative characterizations of the behavior of new materials to provide data for damage tolerant component life prediction. We seek mechanistic models of crack tip damage processes which are generally applicable to structural aluminum alloys. Such models will enable predictions of cracking behavior outside of the data, metallurgical improvements in material cracking resistance, and insight on hydrogen compatibility.

Environmental and Mean Stress Interactions
in Fatigue Crack Growth of P/M Aluminum Alloy 644B

Don C. Slavik and Richard P. Gangloff
Department of Materials Science

Abstract

The near-threshold fatigue crack propagation behavior of advanced aluminum alloys and metal matrix composites, in gaseous and aqueous environments that produce embrittling hydrogen, is poorly understood. The general objective of this research is to characterize material microstructure-chemical environment-fatigue crack propagation properties, to understand crack tip damage mechanisms, and to develop predictive models.

An immediate challenge is to isolate environmental effects on extrinsic crack closure and on intrinsic hydrogen damage which govern crack growth rates (da/dN). High R-ratio (K_{min}/K_{max}) environmental fatigue crack growth experiments can establish intrinsic crack propagation resistance above crack closure levels and as affected by stress intensity range (ΔK) and K_{max}, however, limited results are recorded in this regard. Such information is important in damage tolerant design and for understanding the relative contributions of maximum stress and cyclic strain within the crack tip process zone. The objective of our initial experiments is to examine the effect of R on intrinsic near-threshold crack growth in an Al-Li based alloy in water vapor.

The fine grained powder metal alloy, 644B (Al-2.6Li-1.0Cu-0.5Mg-0.5Zr by wt % and donated by Allied Signal), was selected for study. Crack closure loads are monitored with a crack mouth mounted displacement gauge. Intrinsic fatigue crack growth rate experiments with programmed ΔK and K_{max} are performed in water vapor, moist air, oxygen, and dynamic vacuum. The water vapor environment and fine grain size were selected for reduced roughness induced closure. Experiments in water vapor employ two constant K_{max} levels of 17 MPa√m and 8.5 MPa√m with decreasing ΔK. A constant ΔK of 2 MPa√m with decreasing K_{max} is also employed. Crack growth rate data are reproducible and consistent with literature results. Crack closure is surprisingly important at stress intensities of 5 to 6.5 MPa√m, presumably due to unexpected faceted cracking in the P/M alloy. Above this closure level, intrinsic crack growth rates increase mildly for a two-fold increase in K_{max}. This result is consistent with limited literature data. The mild effect of K_{max} on da/dN can be rationalized with analytical stress distributions around a crack tip. Significant variations in K_{max} may not alter the opening stress distribution within the process zone.

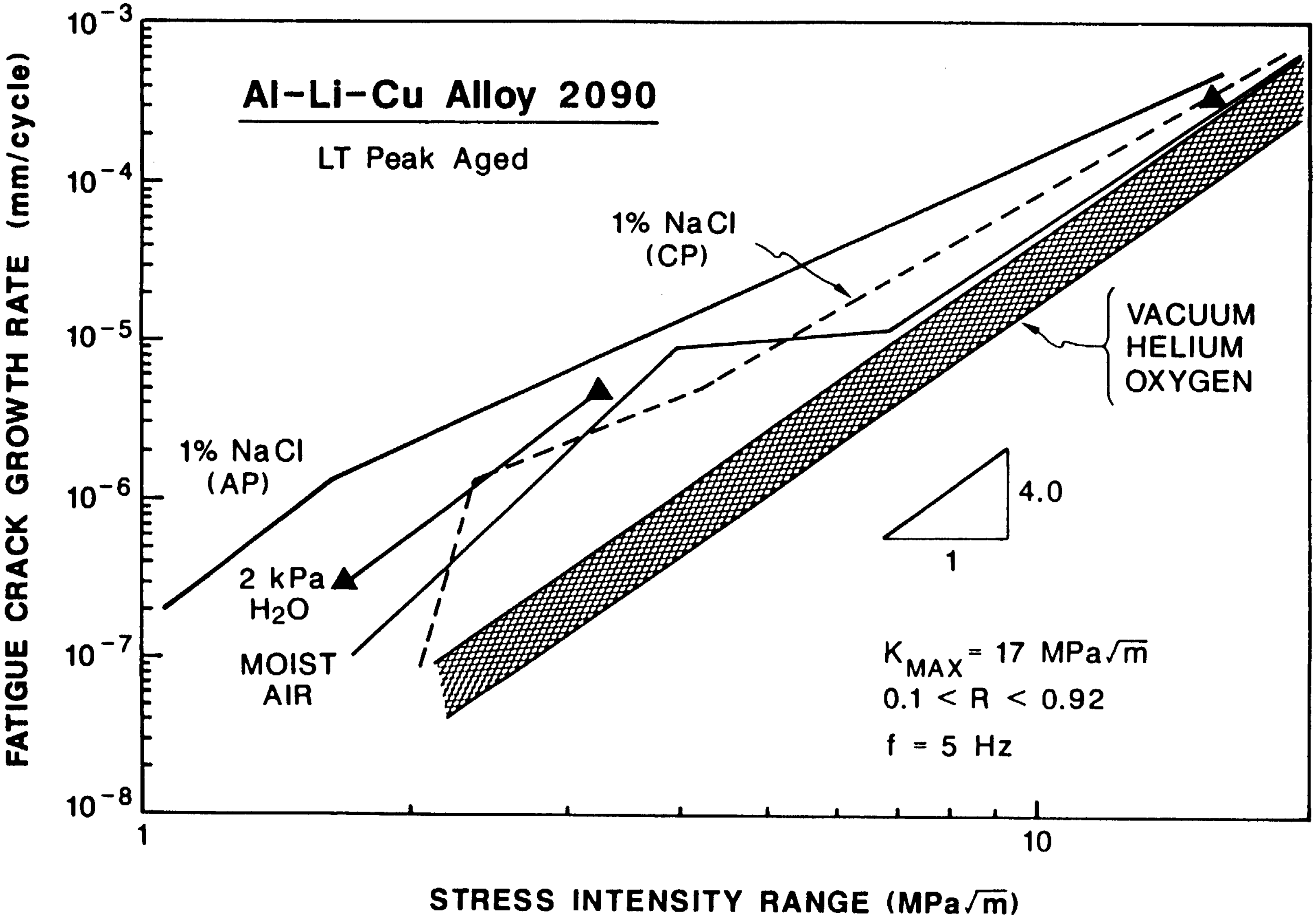
Future work aims to broadly characterize crack growth in a variety of aluminum alloys and composites in both gaseous and aqueous NaCl environments; to further examine the interaction of cyclic strain, maximum stress and hydrogen within the crack tip process zone; and to design experiments to elucidate crack tip damage mechanisms.

Environmental and Mean Stress Interactions in Fatigue Crack Growth of P/M 644B

Don C. Slavik and Richard P. Gangloff
University of Virginia

Support Provided by NASA
Langley Research Center

D. L. Dicus Project Monitor



Al-Li-Cu Alloy 2090
LT Peak Aged
1% NaCl (CP)
VACUUM
HELIUM
OXYGEN
1% NaCl (AP)
2 kPa H_2O
MOIST AIR
4.0
1
K_{MAX} = 17 MPa$\sqrt{m}$
0.1 < R < 0.92
f = 5 Hz
FATIGUE CRACK GROWTH RATE (mm/cycle)
STRESS INTENSITY RANGE (MPa$\sqrt{m}$)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
1
10

Background

- Intrinsic 2090 & 7075 corrosion fatigue established

- Vacuum, He, & Oxygen
  - Faceted cracking along {111} slip planes in 2090

- Water Vapor & Air
  - Cleavage cracking at low ΔK along {100}
  - Inter-subgranular cracking at high ΔK
  - Transition related to sub-boundary size to cyclic process zone

Questions on the Environmental Effect Near ΔK_{th}

- What is the environmental fatigue crack growth rate behavior of advanced alloys and composites?
  - Intrinsic
  - Extrinsic

- What are the relevant crack tip mechanistic parameters controlling environmental fracture?
  - $\Delta\varepsilon_p$
  - σ_{normal}
  - Dislocation structures
  - Dissolved Hydrogen

- How does stress ratio contribute to crack tip damage?
  - Closure issue
  - Damage issue
  - Technological issue

Available Materials

- Allied Signal Alloy 644 B

- 2009 with SiC Reinforcement
  - 15 vol % whisker
  - 20 vol % particulate
  - Powder Matrix

- 2090 and 2091
  - Recrystallized
  - Unrecrystallized

- High Purity Al-Cu Alloy

- 7075 and 2024

Alloy 644B

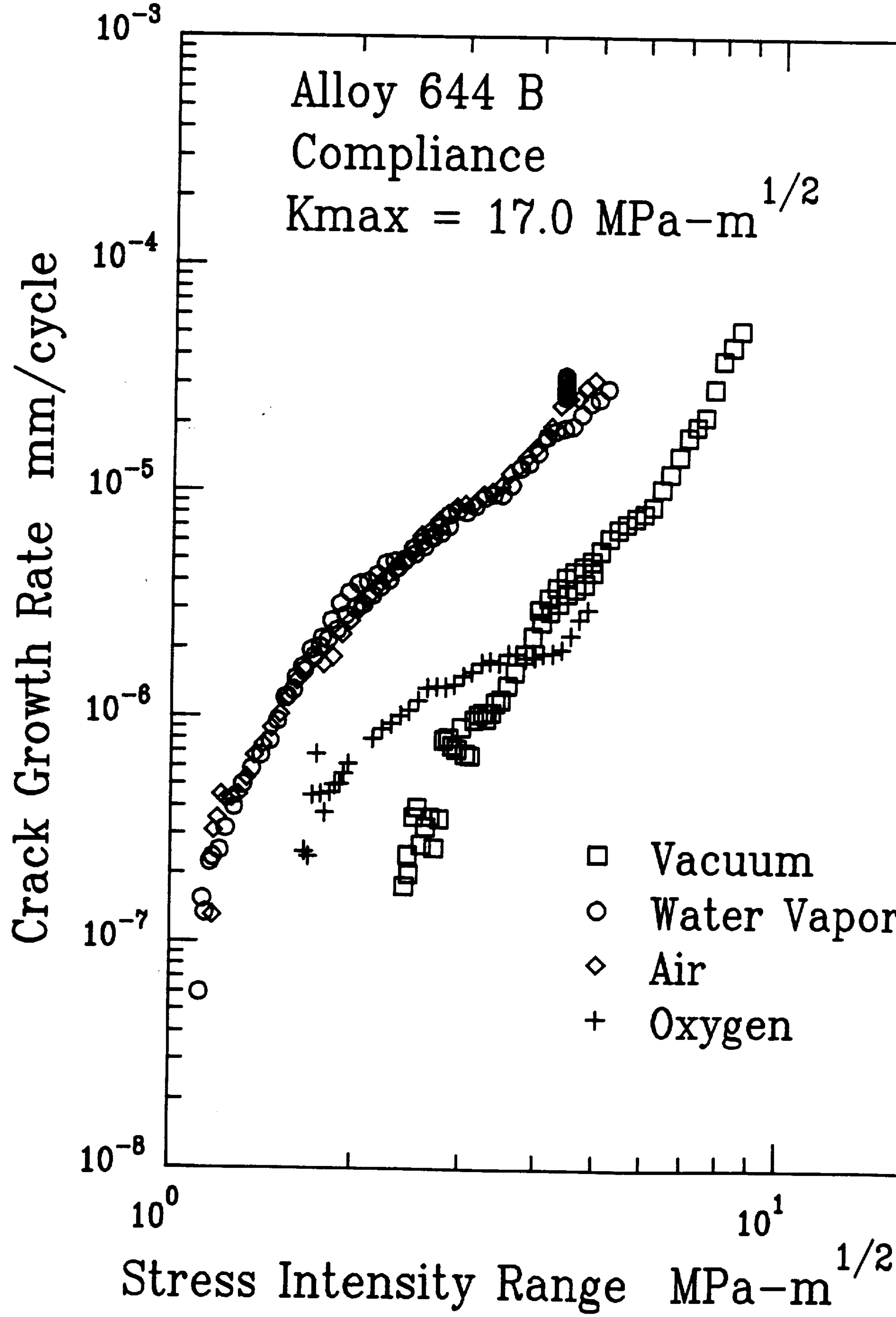
- Al-2.6Li-1.0Cu-0.5Mg-0.5Zr (weight %)
- Major strengthening phases δ' and Al_3Zr
- Rapidly solidified process
- Ribbons 100μm - 25μm - 500μm
- Grains 2μm - 2μm - 10μm
- Fine grain size material to minimize roughness induced crack closure

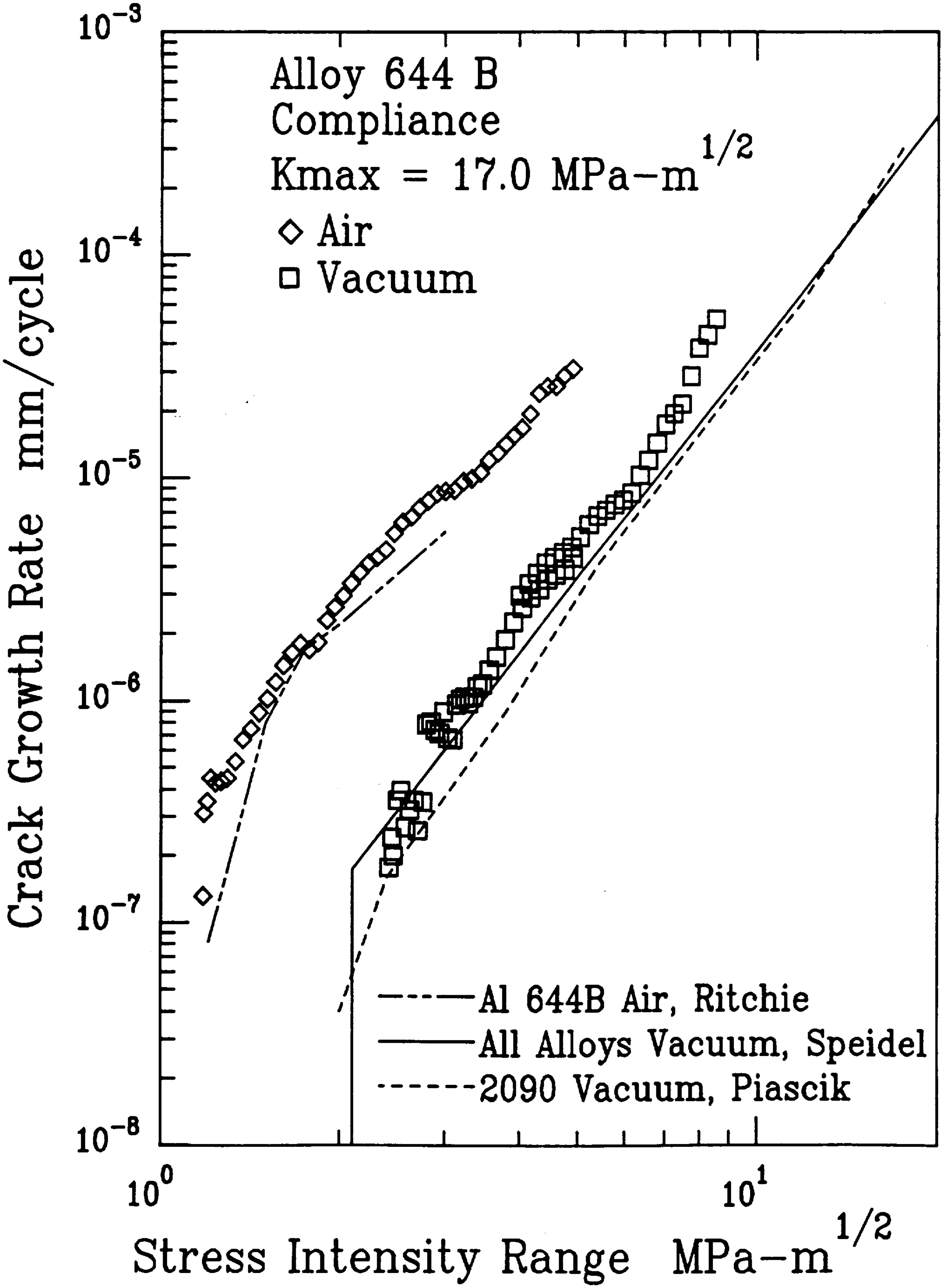
Objectives of 644B Experiments

- Perform environmental fatigue experiments and learn issues

- Measure crack closure levels
  - Compact tension specimen geometry
  - Introduce compliance to gas/vacuum system

- Examine mean stress damage effects
  - Identify closure behavior
  - Examine R effect on intrinsic crack growth

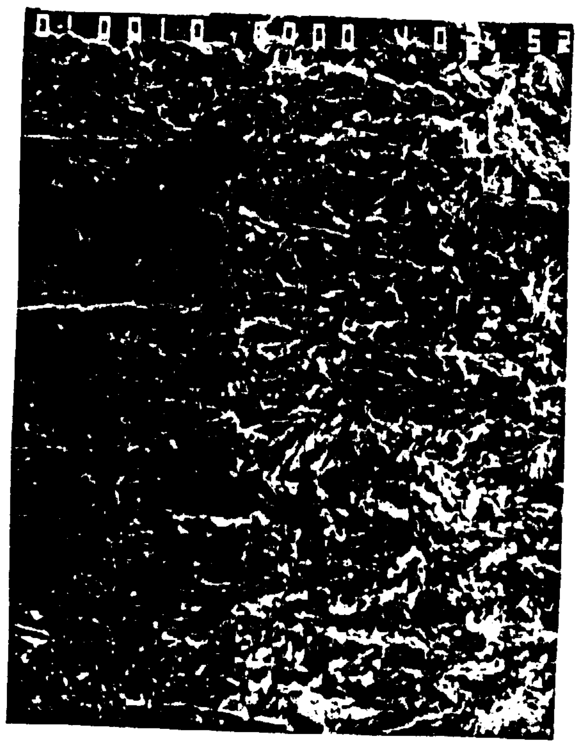

Alloy 644 B
Compliance
Kmax = 17.0 MPa-m^1/2
Crack Growth Rate mm/cycle
Stress Intensity Range MPa-m^1/2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^0
10^1
Vacuum
Water Vapor
Air
Oxygen



Alloy 644 B
Compliance
Kmax = 17.0 MPa-m^1/2
◇ Air
□ Vacuum
Al 644B Air, Ritchie
All Alloys Vacuum, Speidel
2090 Vacuum, Piascik
Crack Growth Rate mm/cycle
Stress Intensity Range MPa-m^1/2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^0
10^1

644B Fracture Surface

Water Vapor to Vacuum Test



0.1 mm

Mean Stress Effects

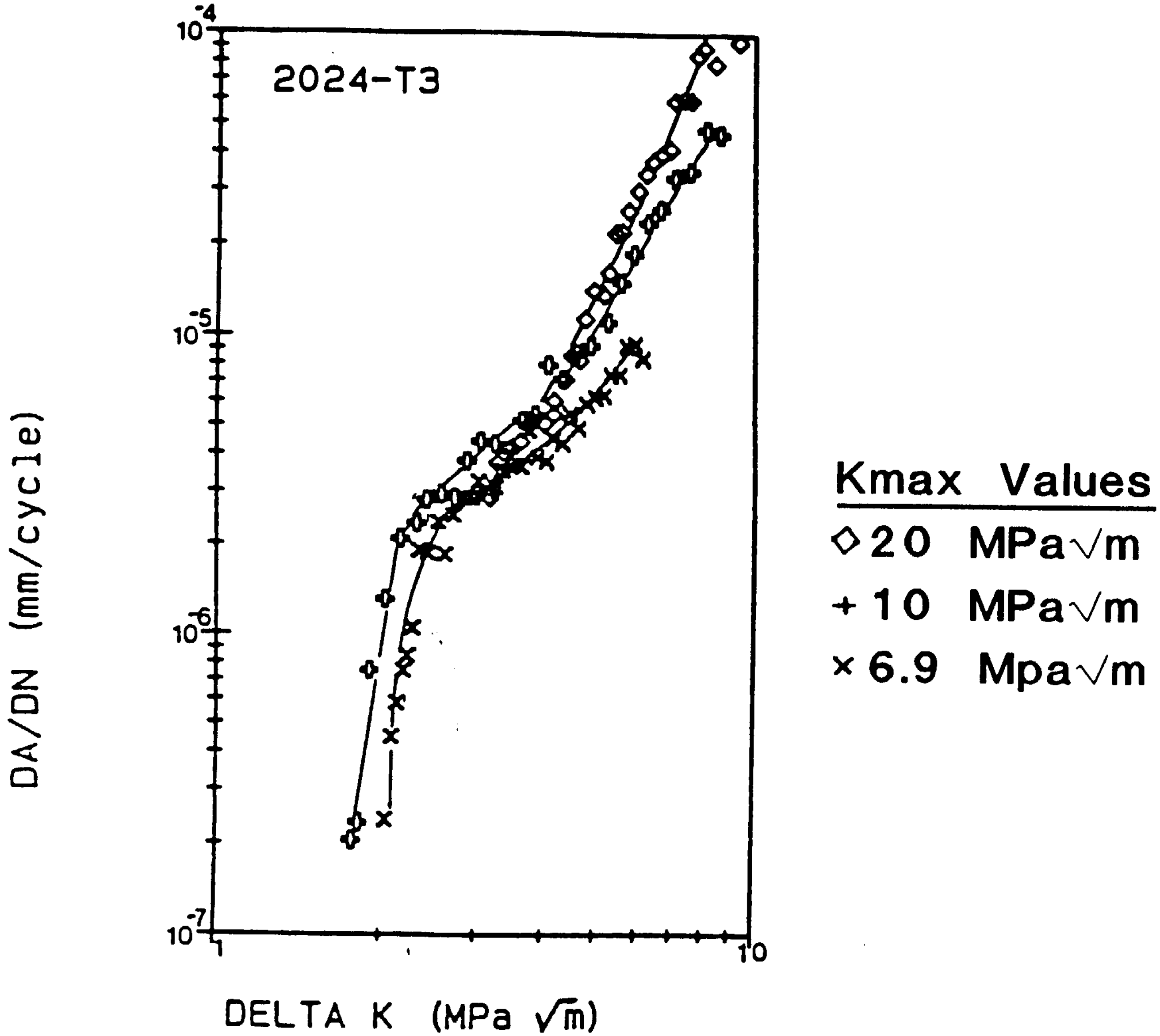
- Literature
  - What has been done done apart from crack closure to examine mean stress damage?

- Mechanisms
  - How do crack tip parameters change with Kmax?

- Alloy 644B
  - Is roughness induced crack closure limited due to the alloys small grain size?

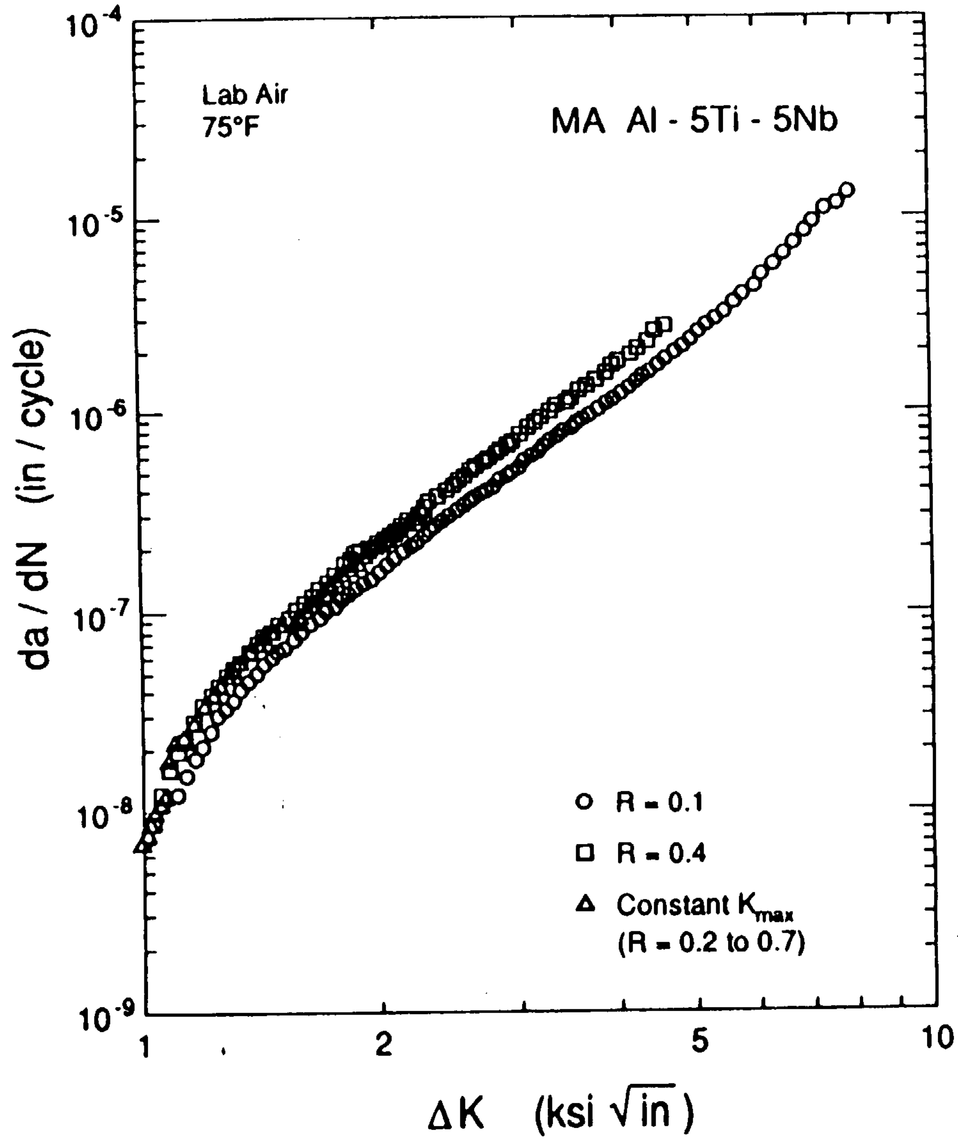
Intrinsic Crack Growth?

(Herman, Hertzberg, and Jaccard)



Intrinsic Crack Growth?

(Bray and Wilsdorf)



Why A Mean Stress Effect

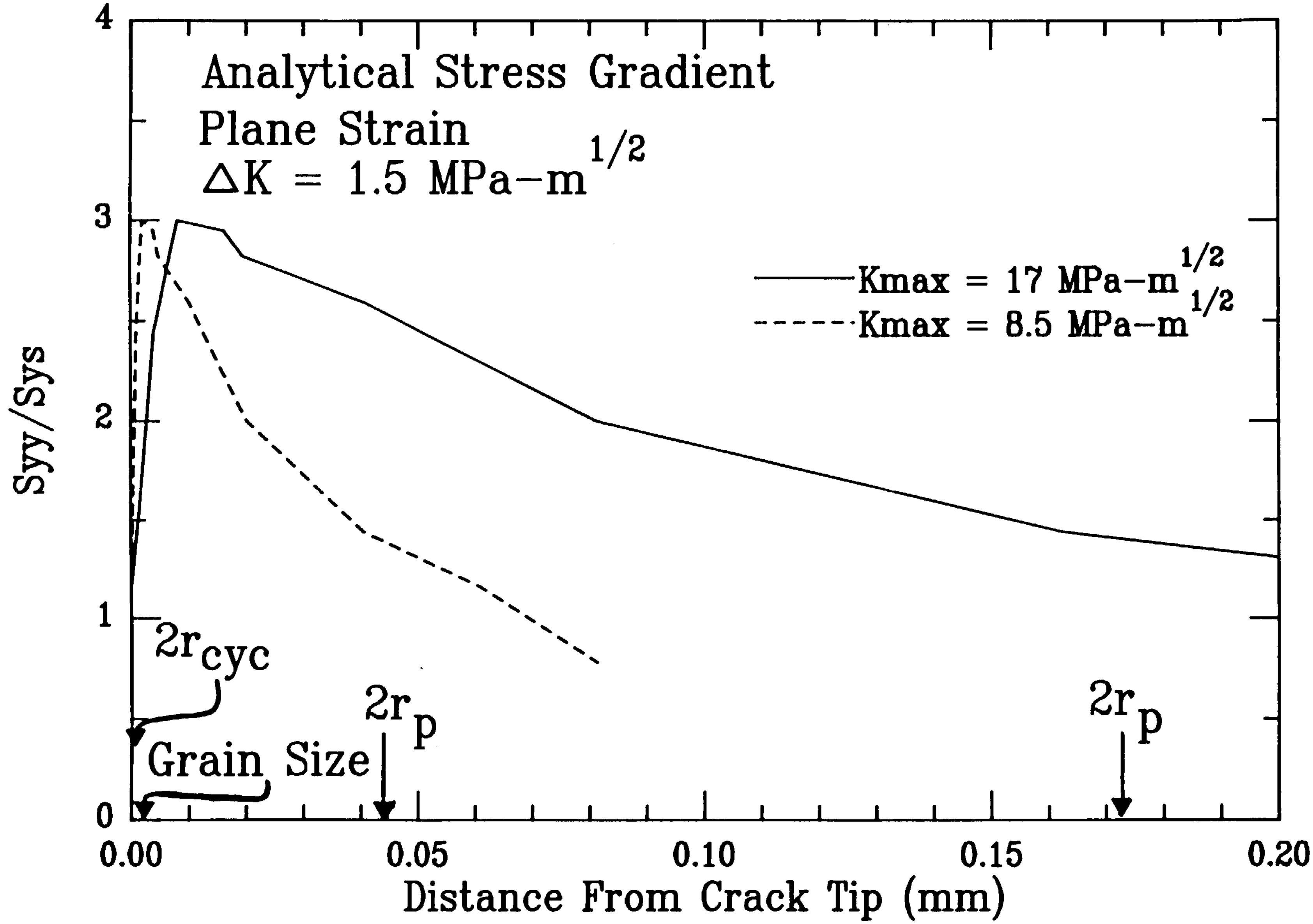
- Increased σmax increases mechanical damage
- Increased σmax increases hydrogen accumulation

Why Not A Mean Stress Effect

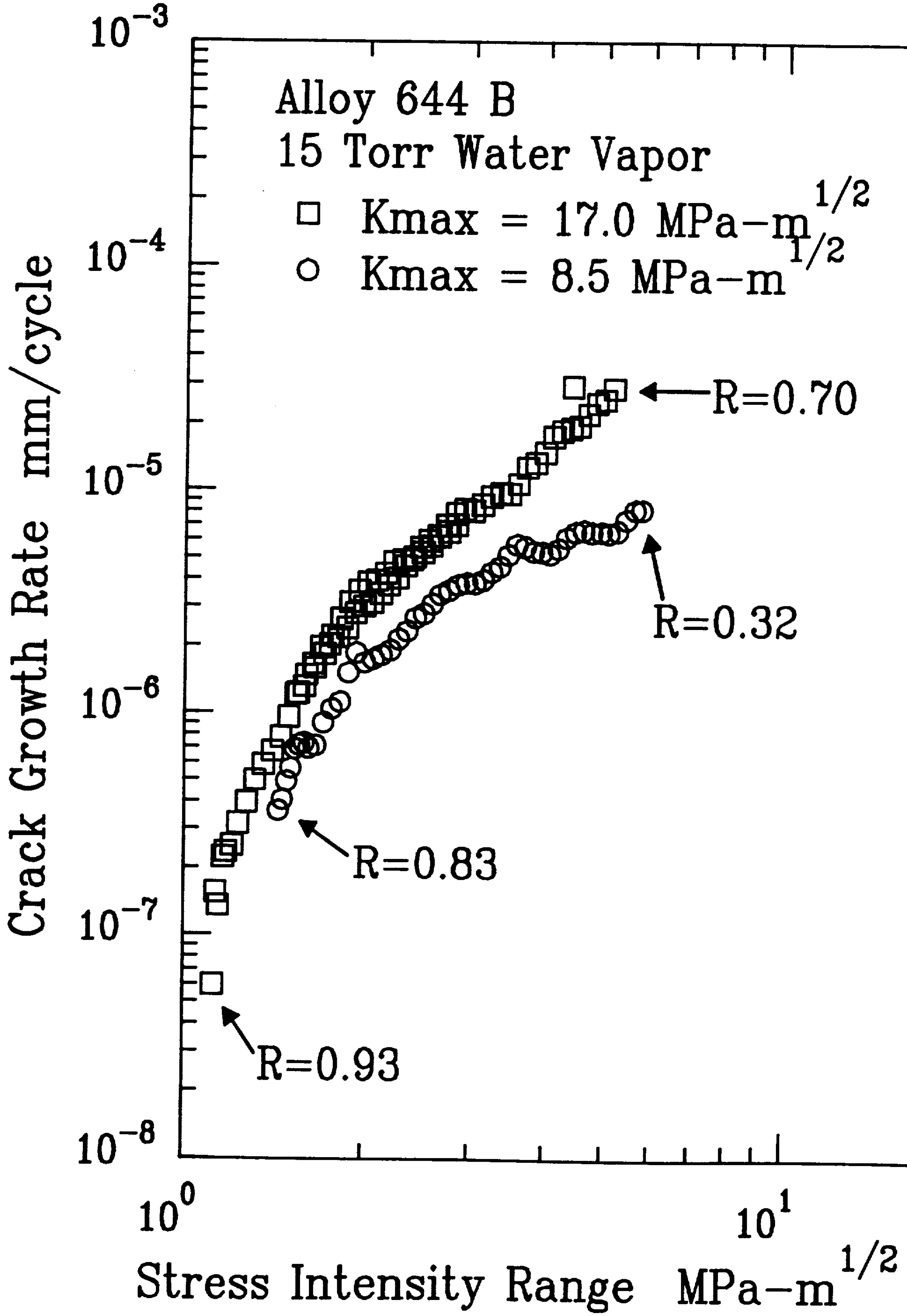
- Increased R does not appreciably change stress distribution in the process zone

Problems

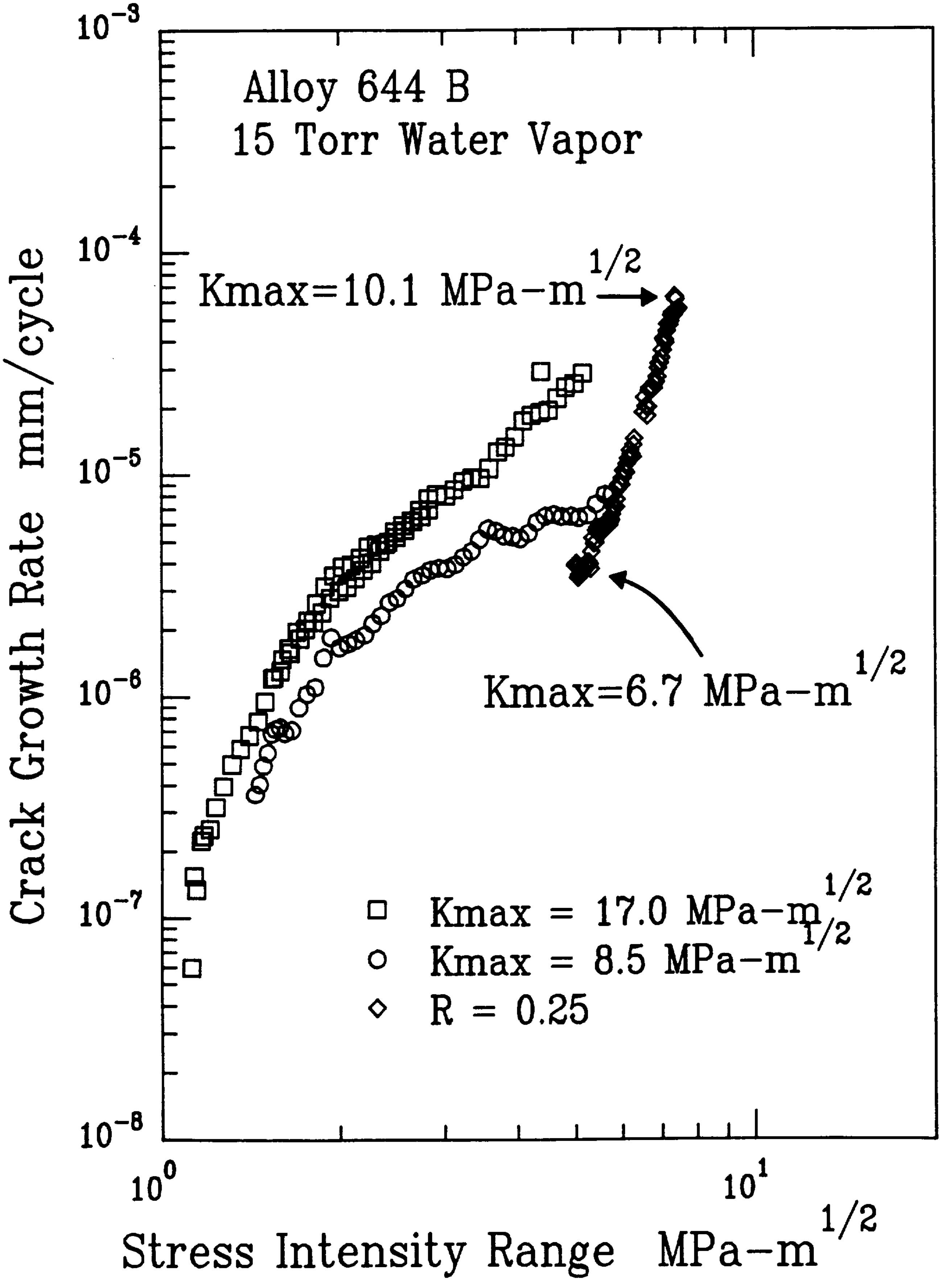
- What are $\Delta\varepsilon p$ and σmax in the process zone?
- What is the effect of R on the microscopic stress distribution?



Analytical Stress Gradient
Plane Strain
ΔK = 1.5 MPa-m^1/2
Kmax = 17 MPa-m^1/2
Kmax = 8.5 MPa-m^1/2
2r_cyc
Grain Size
2r_p
2r_p
Syy/Sys
Distance From Crack Tip (mm)
0
1
2
3
4
0.00
0.05
0.10
0.15
0.20



Alloy 644 B
15 Torr Water Vapor
Kmax = 17.0 MPa-m^1/2
Kmax = 8.5 MPa-m^1/2
R=0.70
R=0.32
R=0.83
R=0.93
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^0
10^1
Crack Growth Rate mm/cycle
Stress Intensity Range MPa-m^1/2

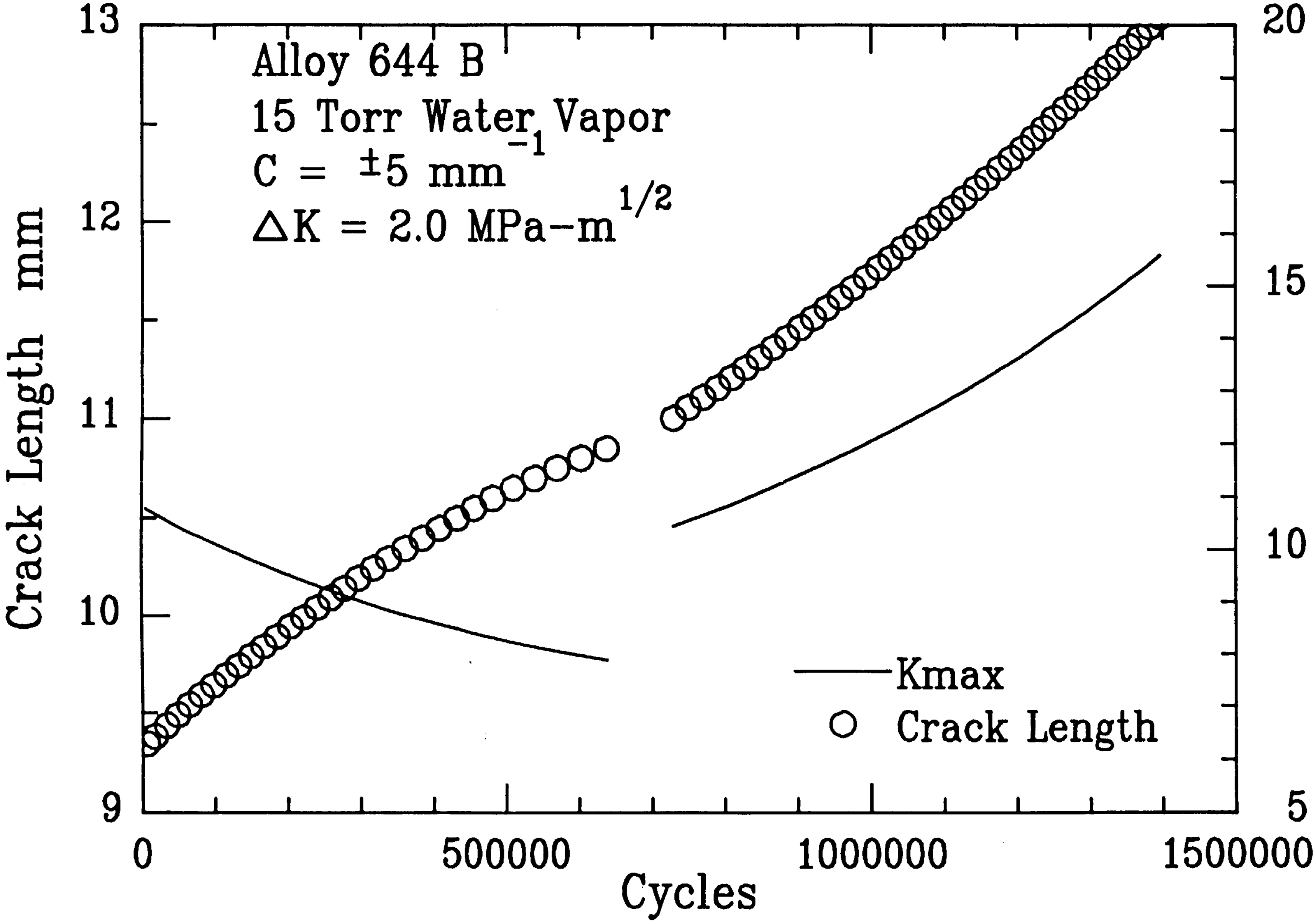

Alloy 644 B
15 Torr Water Vapor
Kmax=10.1 MPa-m^1/2
Kmax=6.7 MPa-m^1/2
Kmax = 17.0 MPa-m^1/2
Kmax = 8.5 MPa-m^1/2
R = 0.25
Crack Growth Rate mm/cycle
Stress Intensity Range MPa-m^1/2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^0
10^1

Need for Appropriate Experiment

- Constant $\Delta K = 2.0$ MPa$\sqrt{m}$
- Variable Kmax = 15.6 MPa$\sqrt{m}$ to 8.0 MPa$\sqrt{m}$

Experimental Difficulties

- Slow crack growth rates make experiment difficult
- Unexpected roughness of 644B
  - Kopen = 5-6.5 MPa$\sqrt{m}$
- Is a Clip gage opening load an appropriate measure of the crack tip opening?



Alloy 644 B
15 Torr Water Vapor
C = ±5 mm^-1
ΔK = 2.0 MPa-m^1/2
Kmax
Crack Length
Crack Length mm
Kmax MPa-m^1/2
Cycles
13
12
11
10
9
20
15
10
5
0
500000
1000000
1500000

Conclusions

- Kmax has limited influence on the intrinsic damage of Alloy 644B in water vapor.

- Kclose of 5-6.5 MPa$\sqrt{m}$ was observed in Alloy 644B. Roughness induced closure may be significant.

- Kmax may have a small effect on the stress distributions very near the crack tip. This can explain the limited influence of Kmax on the intrinsic crack growth rates.

- Determining the effect of Kmax on intrinsic rates in hydrogen environments is a complex experiment.

Future Work

What is the near threshold fatigue crack growth behavior of composites and advanced Al alloys in aggressive hydrogen environments?

- Experimental
  - Gripping system and closure monitoring for aqueous environments

  - Consider novel alloys
    + Aluminum-Lithium Alloys
    + Metal Matrix Composites
    + Conventional Aluminum Alloys

Future Work

$\boxed{\text{What is the crack tip process zone damage mechanism and associated da/dN-}\Delta\text{K model?}}$

- "Large" cracks in a fine grain alloy
  - Closure measurements

- "Small" cracks in a large grain alloy
  - Al-Cu model alloys

- Fractographic characterization for crack path micromechanism determinations

- Review crack tip stress/strain fields
  - Cyclic loading analytical results
  - SEM/fatigue loading stage observations

N90-22653

Program 2 **Elevated Temperature Crack Growth in Advanced Powder Metallurgy Aluminum Alloys**

William C. Porr, Jr. and R.P. Gangloff

Objective

The goal of this PhD research is to characterize subcritical crack growth and fracture toughness in advanced aluminum alloys at elevated temperatures, with emphasis on crack tip damage mechanisms. As an extension of this goal, the effects of microstructure and the components of the moist air environment on crack growth and mechanisms will be examined.

Fracture of PM Al-Fe-V-Si at Elevated Temperature

William C. Porr, Jr. and Richard P. Gangloff
Department of Materials Science

Abstract

Rapidly solidified Al-Fe-V-Si powder metallurgy alloy FVS0812, produced by Allied-Signal, is among the most promising of the elevated temperature aluminum alloys developed in recent years. The ultra fine grain size and high volume fraction of thermally stable dispersoids enable the alloy to maintain tensile properties at elevated temperatures. In contrast, this alloy displays complex and potentially deleterious damage tolerant and time dependent fracture behavior that varies with temperature.

J-Integral fracture mechanics were used to determine fracture toughness (K_{IC}) and crack growth resistance (tearing modulus, T) of extruded FVS0812 as a function of temperature. The alloy exhibits high fracture properties at room temperature (K_{IC} = 36.6 MPa√m, T=20.1) when tested in the LT orientation, due to extensive delamination of prior ribbon particle boundaries perpendicular to the crack front. Delamination results in a loss of through thickness constraint along the crack front, raising the critical stress intensity necessary for precrack initiation. The fracture toughness and tensile ductility of this alloy decrease with increasing temperature, with minima observed at 200°C (K_{IC}=14.6 MPa√m, T=2.1). This behavior results from minima in the intrinsic toughness of the material, due to dynamic strain aging, and in the extent of prior particle boundary delaminations. (Dynamic strain aging, a dislocation-solute interaction, increases yield strength and decreases ductility and fracture toughness, only at intermediate temperatures.) At 200°C FVS0812 fails at K levels that are insufficient to cause through thickness delamination. As temperature increases beyond the minimum, strain aging is reduced and delamination returns. For the TL orientation, K_{IC} decreased (16.1 MPa√m to 9.5 MPa√m) and T increased slightly (0 to 1.4) with increasing temperature from 25°C to 316°C. Fracture in the TL orientation is governed by prior particle boundary toughness; increased strain localization at these boundaries may result in lower toughness with increasing temperature. Preliminary results demonstrate a complex effect of loading rate on K_{IC} and T at 175°C, and indicate that the combined effects of time dependent deformation, environment, and strain aging may play a role. Fractography showed that microvoid coalescence was the microscopic mode of fracture in FVS0812 under all testing conditions. However, the nature of the microvoids varied with test temperature and loading rate, and is complex for the fine grain and dispersoid sizes of FVS0812.

Future work will focus on determining the fracture behavior of FVS0812 as a function of temperature, loading rate, microstructure, stress state, and environment. Additionally, there will be an effort to determine the mechanism for the influence of strain aging on fracture.

FRACTURE OF POWDER METALLURGY Al-Fe-V-Si AT ELEVATED TEMPERATURES

William C. Porr, Jr. and Richard P. Gangloff

Funded by NASA Langley Research Center
C. E. Harris, Project Monitor

OUTLINE

A. Background / Objective
B. Materials
C. Procedure
D. Results and Discussion
E. Conclusions
F. Future Work

Background

- Much effort has gone into the development of elevated temperature aluminum alloys to replace titanium alloys with similar specific properties in aerospace applications.

- Among the most promising alloys developed include the Al-Fe-V-Si PM alloys produced by Allied-Signal, Inc.

- Before consideration for service, the unique damage tolerant and time dependent fracture behavior of these alloys as a function of temperature must be understood.

PROJECT OBJECTIVE

- ▪▪▪ Characterize subcritical crack growth and fracture toughness in advanced aluminum alloys as a function of temperature

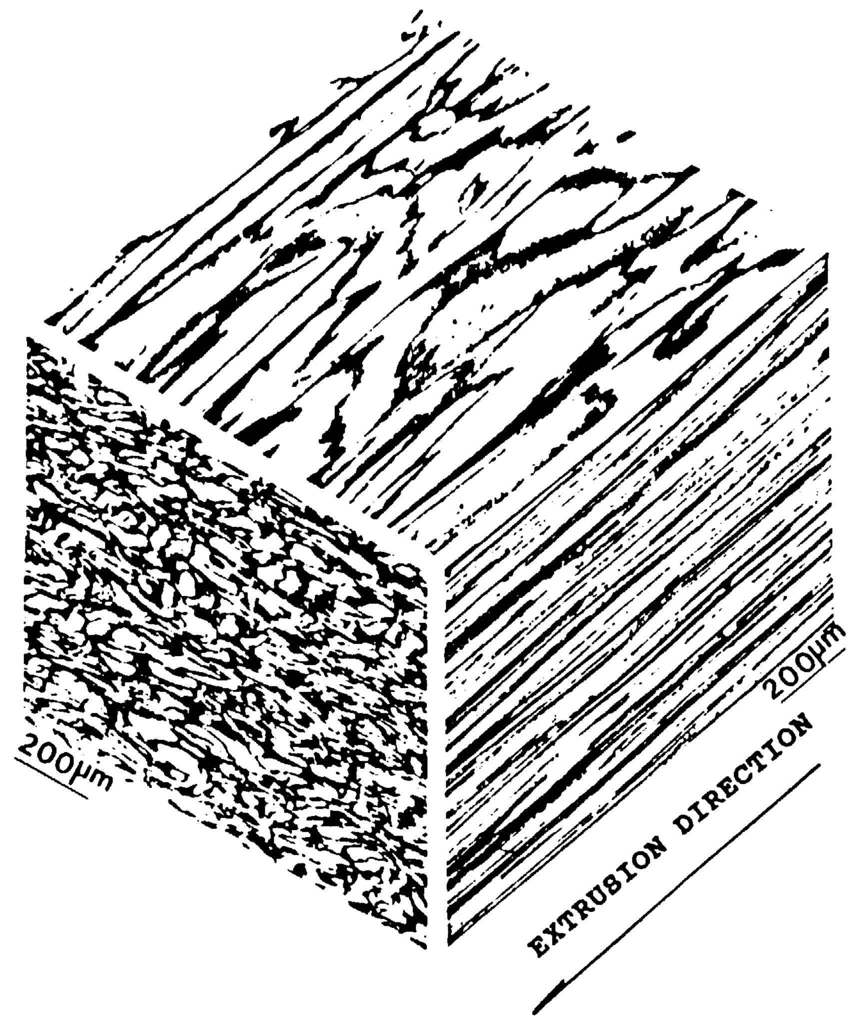
  - ▪▪ crack tip damage mechanisms

    - ▪ microstructure / metallurgy
    - ▪ components of moist air environment

MATERIAL

FVS0812

- Powder metallurgy, Al-8.5Fe-1.3V-1.7Si
  - Rapidly solidified, planar flow casting process
    - ribbon mechanically comminuted
    - extruded, final particle dimensions:
      1000 μm x 100 μm x 20 μm
  - Ultra fine dispersion strengthened microstructure
    - 300nm grain size
    - 24 v/o Al(Fe,V)Si dispersoids less than 100nm in size
  - Provided by Allied-Signal, Inc.



Optical micrographs (Bright field) of FVS0812 Al alloy

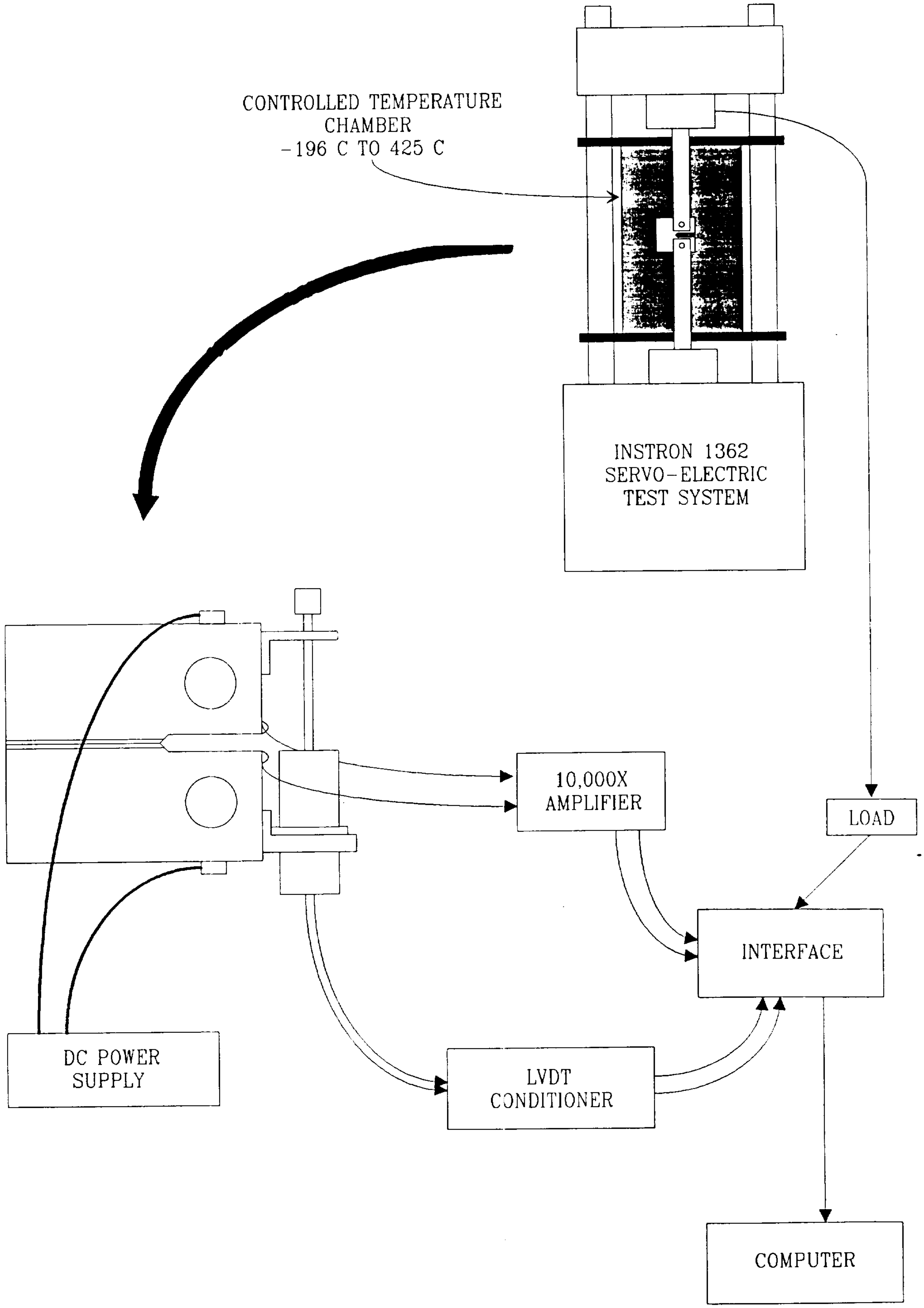
TEM micrograph of FVS0812 Al alloy

PROCEDURE

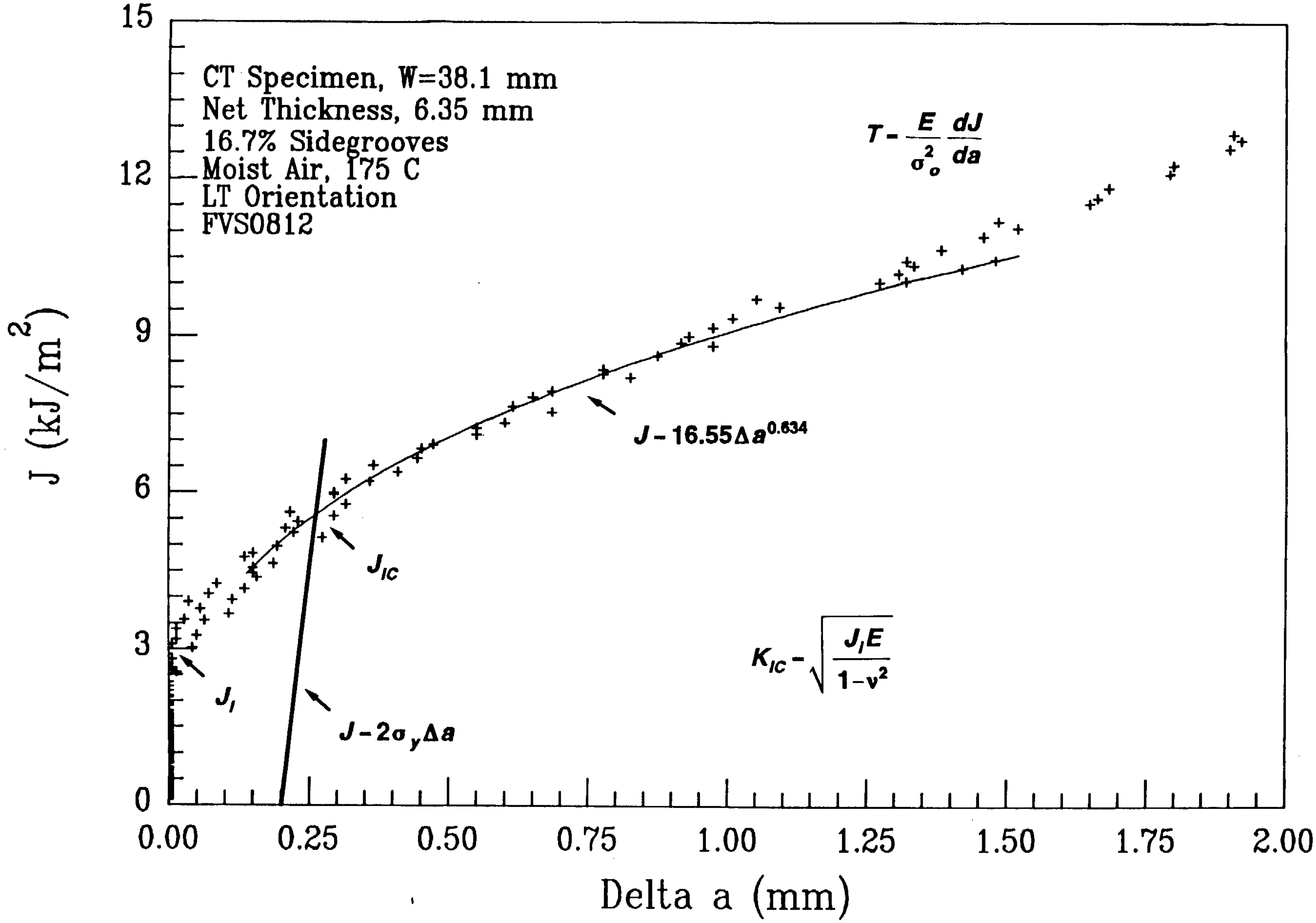
- J integral fracture mechanics used for fracture toughness testing
    - Plane strain requirements not as stringent
    - Valid under both linear elastic and elastic-plastic conditions

- Determined J-Δa curves by measuring load, load-line displacement, and crack length (from DCPD)
    - J from P, δ, and calculated compliance (from a) using area method
    - Δa from DCPD

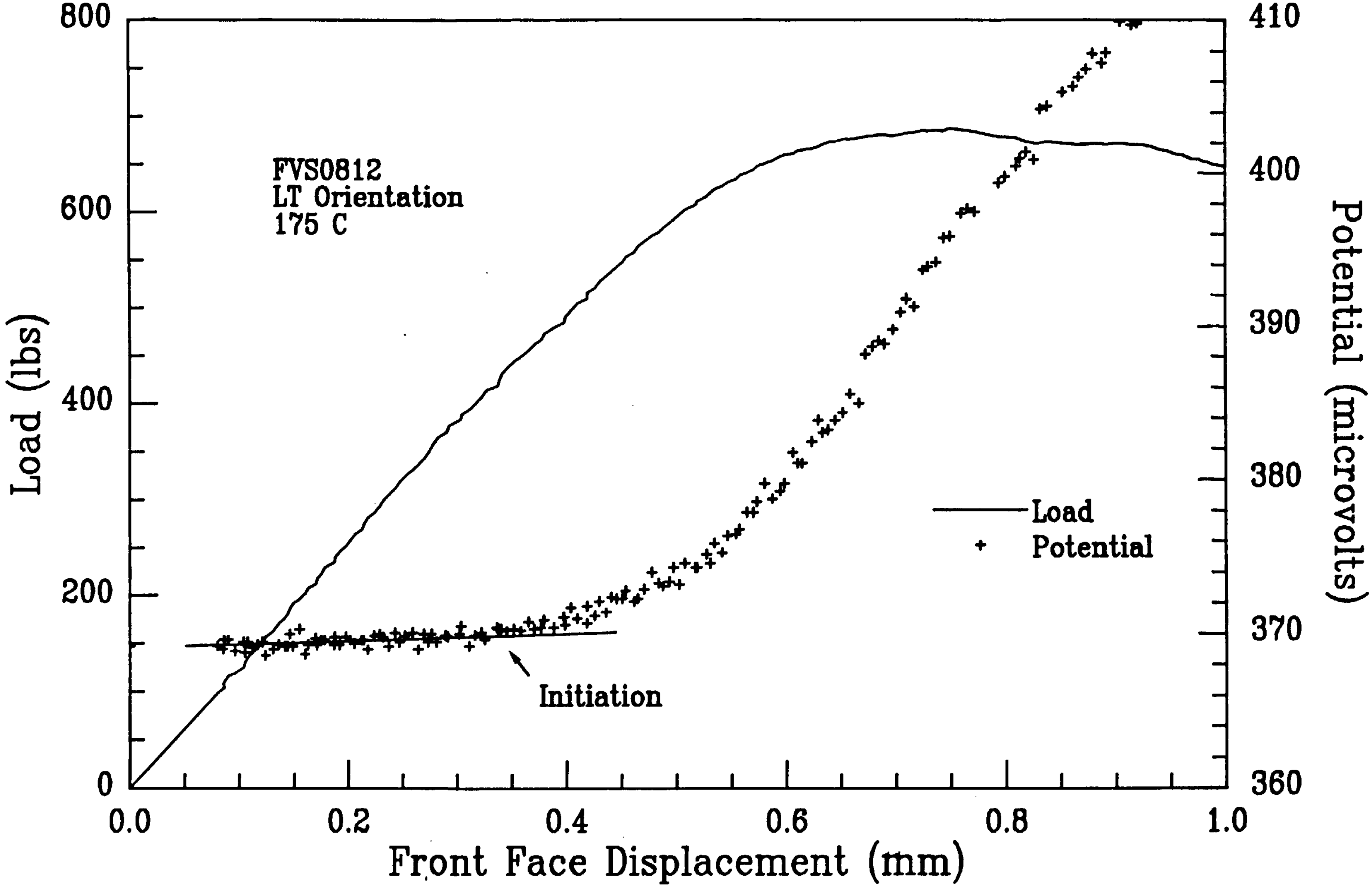
- Determined initiation J according to:
    - ASTM E813-89 (J_{IC})
    - Alternative (J_i)



CONTROLLED TEMPERATURE
CHAMBER
-196 C TO 425 C
INSTRON 1362
SERVO-ELECTRIC
TEST SYSTEM
10,000X
AMPLIFIER
LOAD
INTERFACE
DC POWER
SUPPLY
LVDT
CONDITIONER
COMPUTER



CT Specimen, W=38.1 mm
Net Thickness, 6.35 mm
16.7% Sidegrooves
Moist Air, 175 C
LT Orientation
FVS0812
$T = \frac{E}{\sigma_o^2} \frac{dJ}{da}$
$J = 16.55 \Delta a^{0.634}$
J_{IC}
J_I
$J = 2\sigma_y \Delta a$
$K_{IC} = \sqrt{\frac{J_I E}{1-\nu^2}}$
J (kJ/m²)
Delta a (mm)
0
3
6
9
12
15
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00

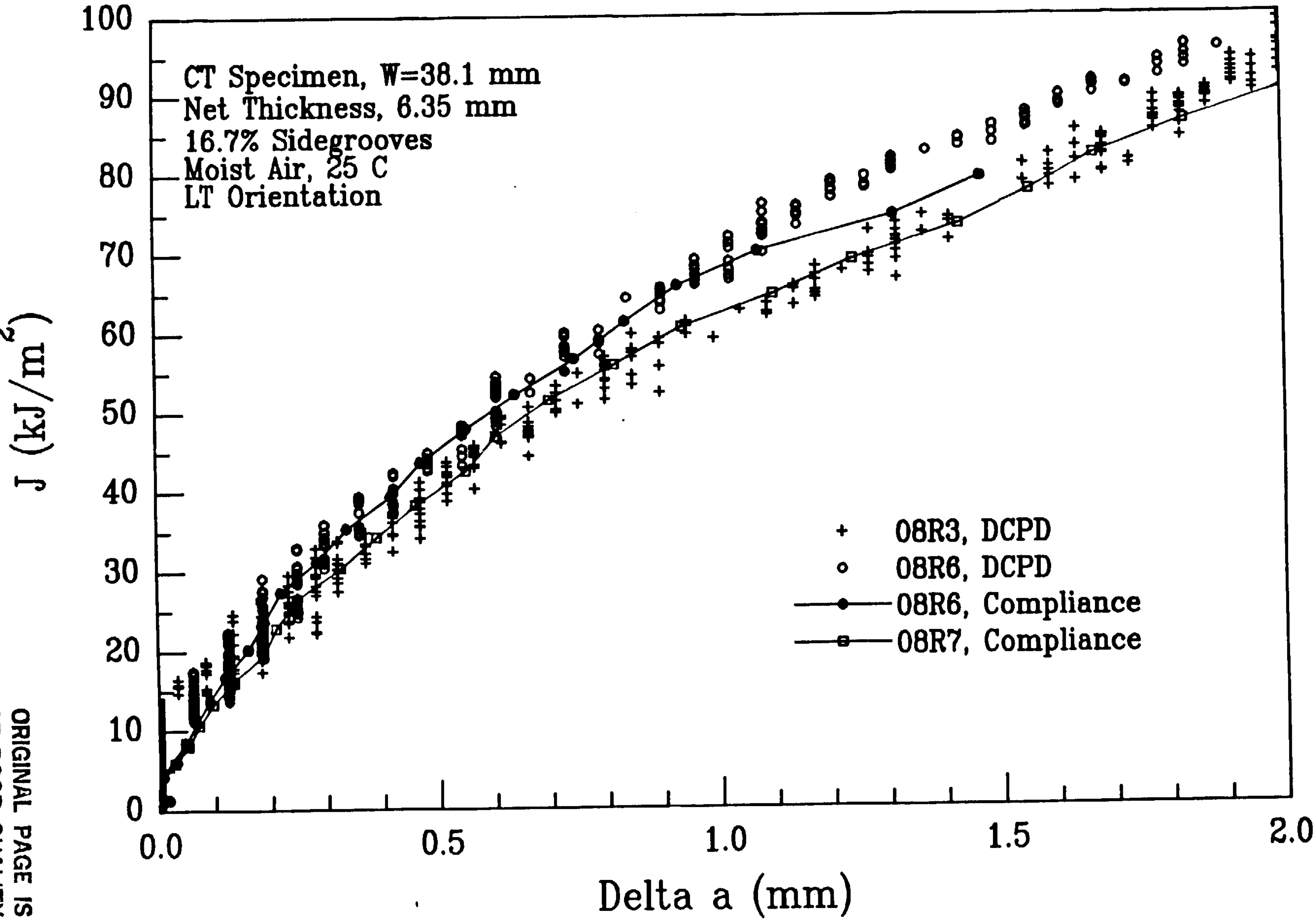

FVS0812
LT Orientation
175 C
Load
Potential
Initiation
Load (lbs)
Potential (microvolts)
Front Face Displacement (mm)
0
200
400
600
800
360
370
380
390
400
410
0.0
0.2
0.4
0.6
0.8
1.0

Advantage of DCPD for crack length determination

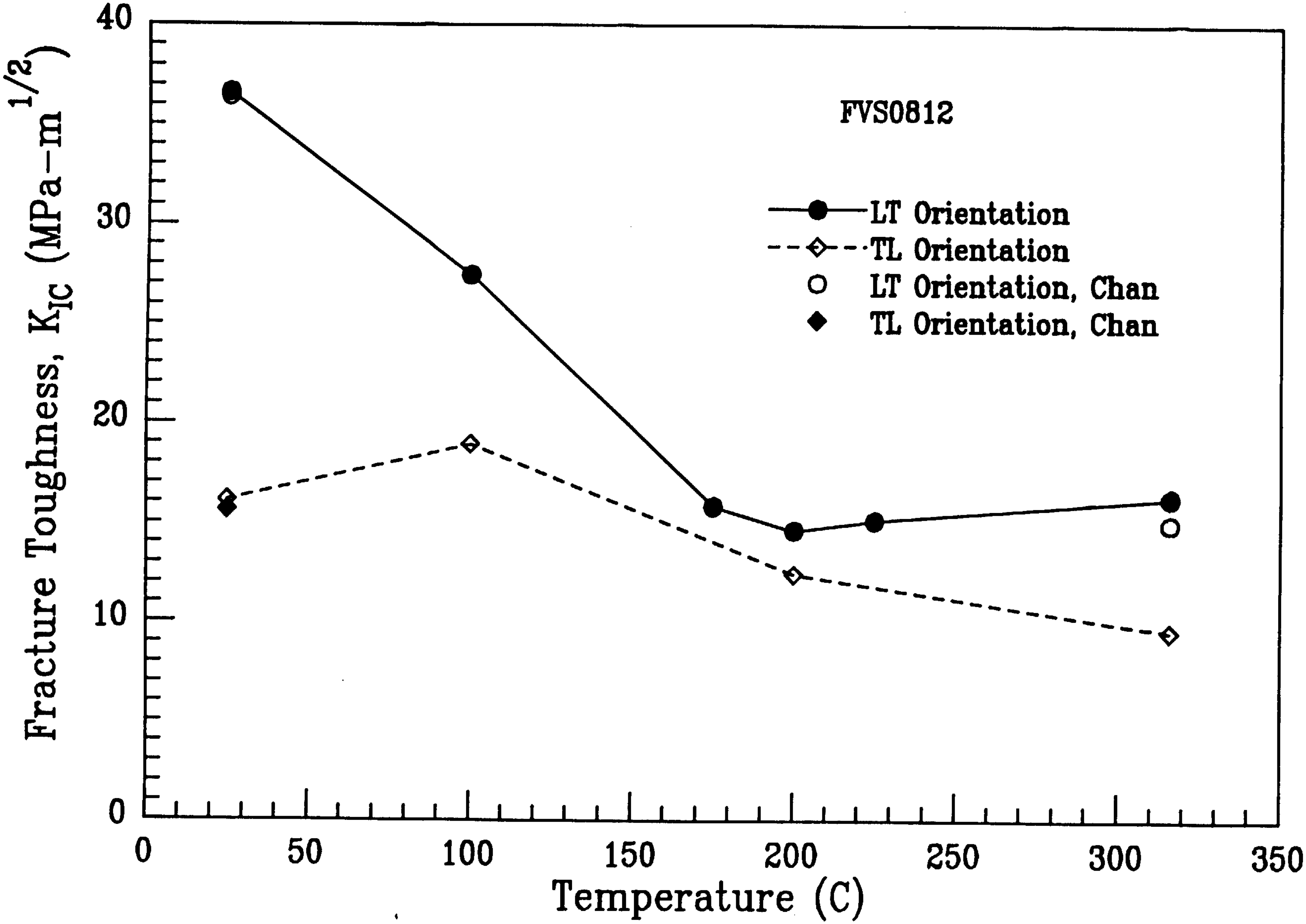
- No need to unload
- More accurate determination of crack growth initiation
  - K_{IC} determined from initiation J_i

Verification of Procedure Accuracy

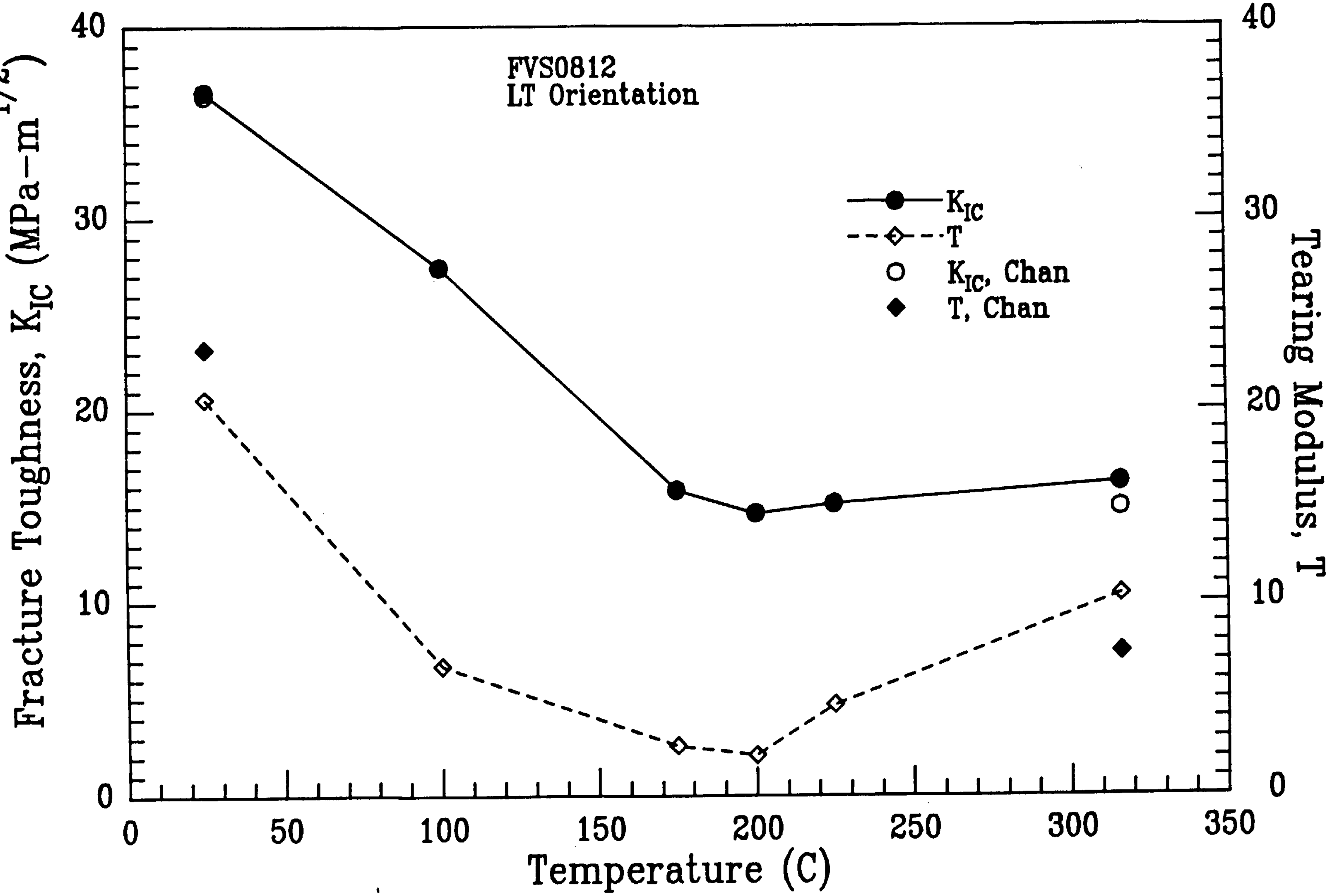
- Compared to standardized unloading compliance technique
- Excellent agreement and reproducibility



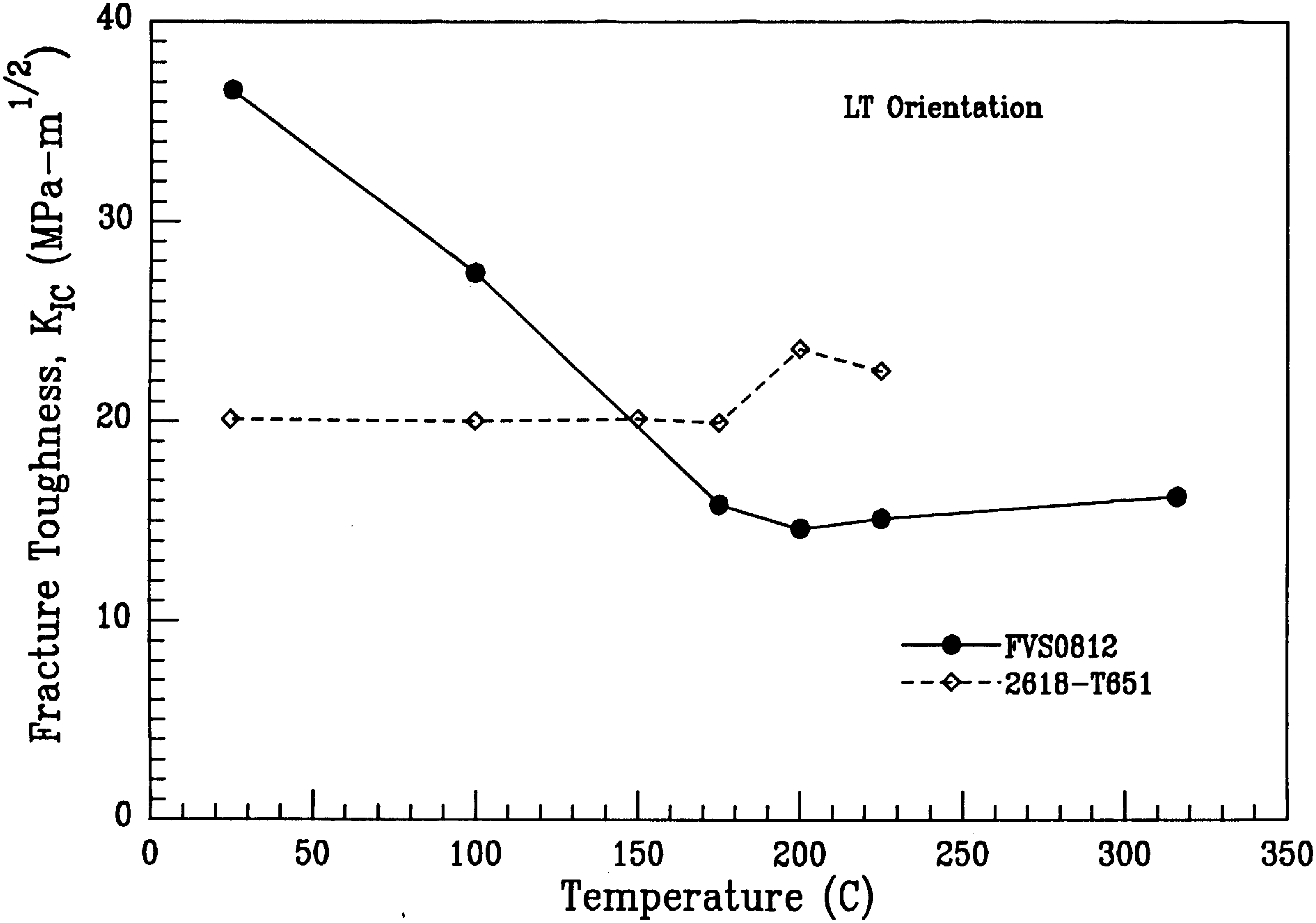
CT Specimen, W=38.1 mm
Net Thickness, 6.35 mm
16.7% Sidegrooves
Moist Air, 25 C
LT Orientation
08R3, DCPD
08R6, DCPD
08R6, Compliance
08R7, Compliance
J (kJ/m²)
Delta a (mm)
0
10
20
30
40
50
60
70
80
90
100
0.0
0.5
1.0
1.5
2.0

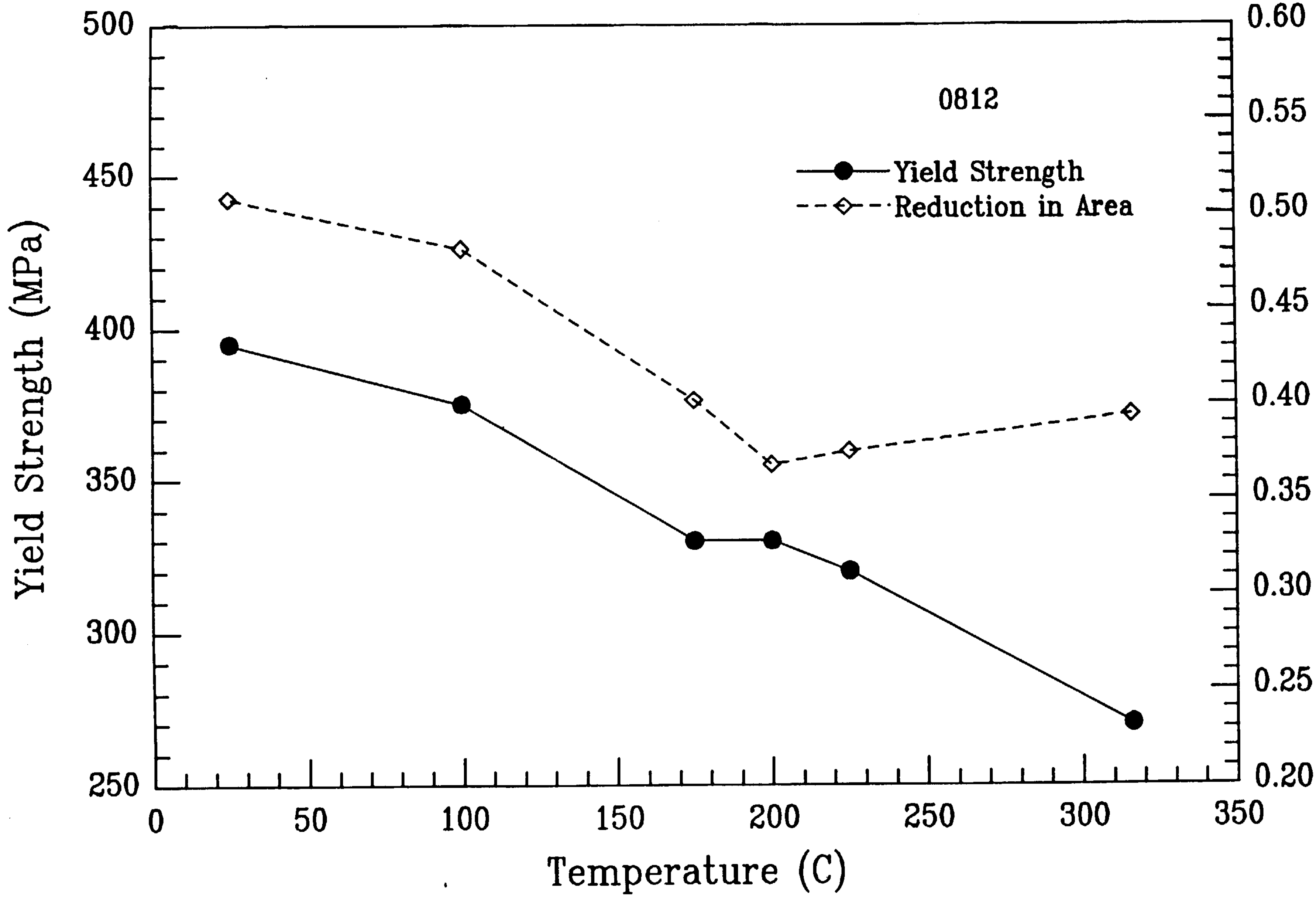


FVS0812
LT Orientation
TL Orientation
LT Orientation, Chan
TL Orientation, Chan
Fracture Toughness, K_{IC} (MPa-m$^{1/2}$)
Temperature (C)
0
10
20
30
40
0
50
100
150
200
250
300
350

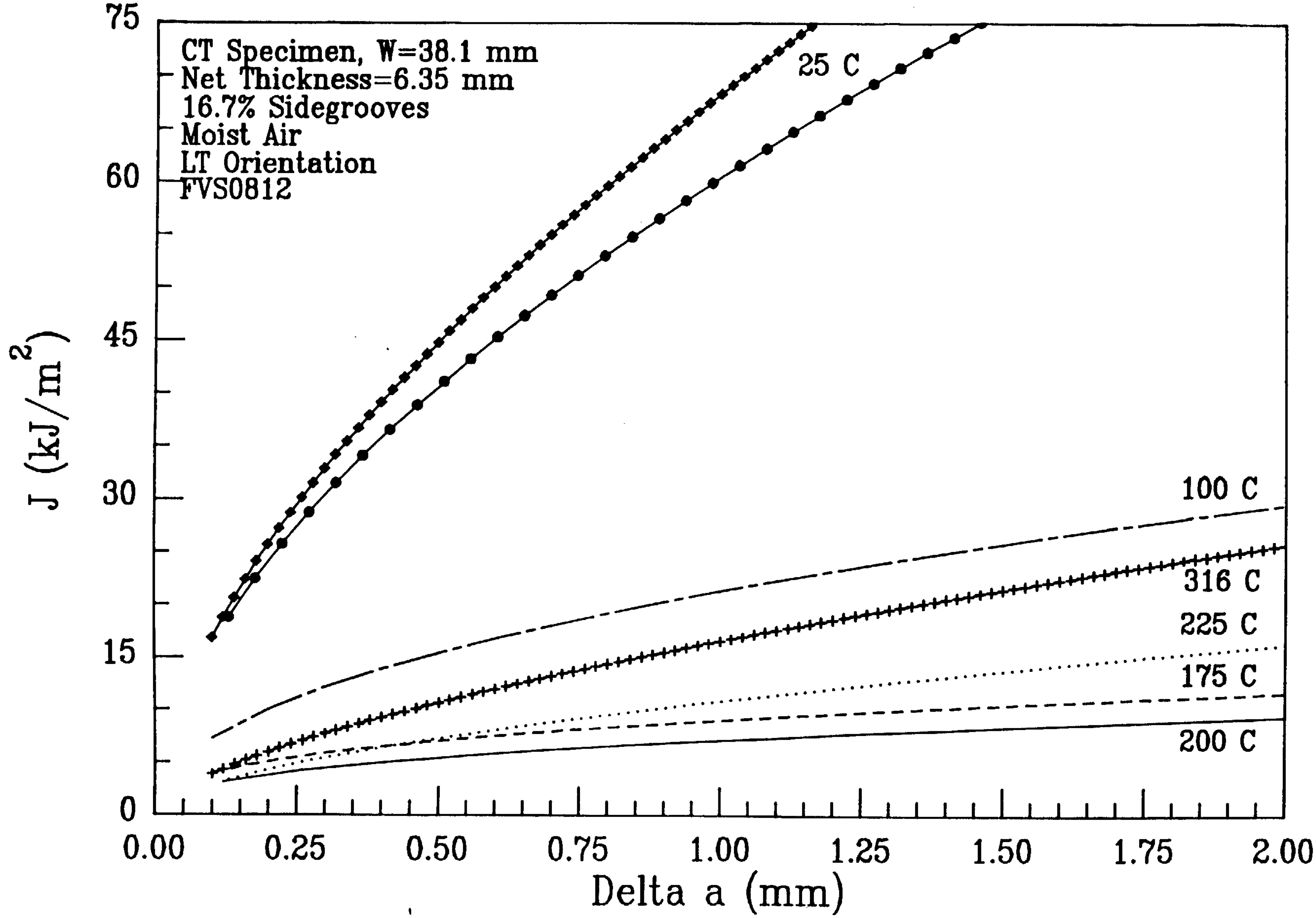


FVS0812
LT Orientation
K_{IC}
T
K_{IC}, Chan
T, Chan
Fracture Toughness, K_{IC} (MPa-m$^{1/2}$)
Tearing Modulus, T
Temperature (C)
0
10
20
30
40
0
50
100
150
200
250
300
350

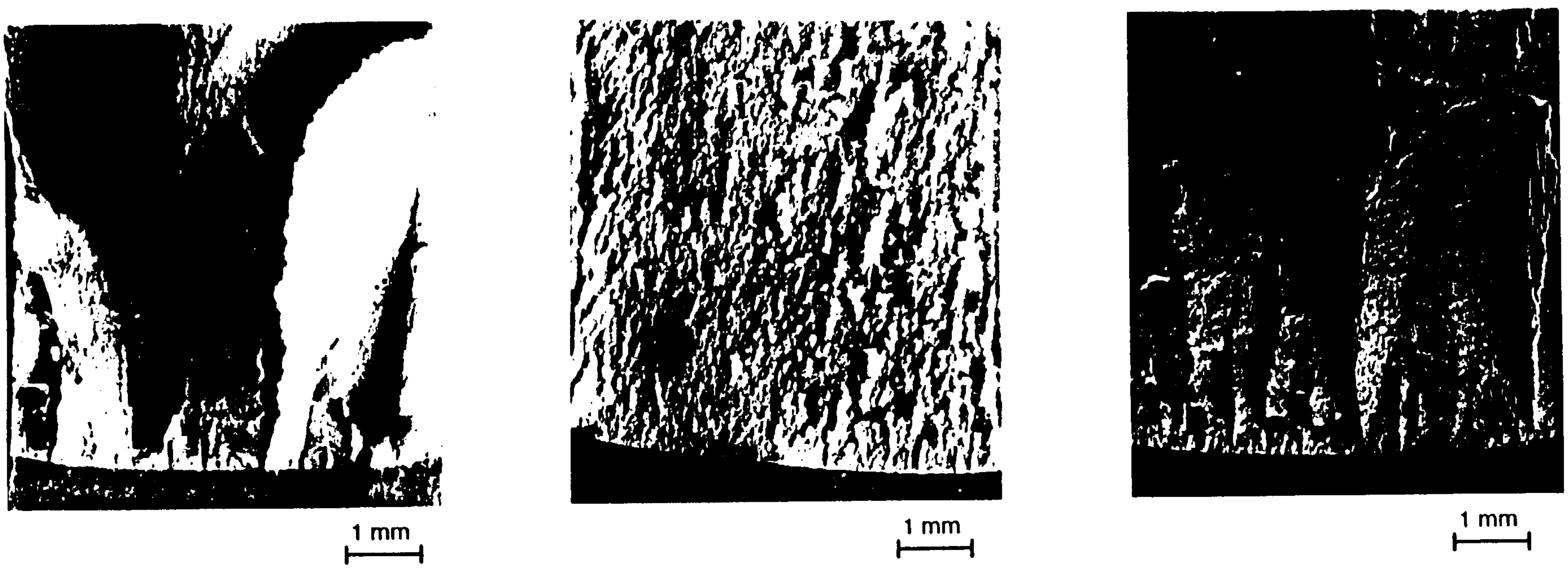

LT Orientation
FVS0812
2618-T651
Fracture Toughness, K_{IC} (MPa-m$^{1/2}$)
Temperature (C)
0
10
20
30
40
0
50
100
150
200
250
300
350



0812
Yield Strength
Reduction in Area
Yield Strength (MPa)
Reduction in Area
Temperature (C)
500
450
400
350
300
250
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0
50
100
150
200
250
300
350

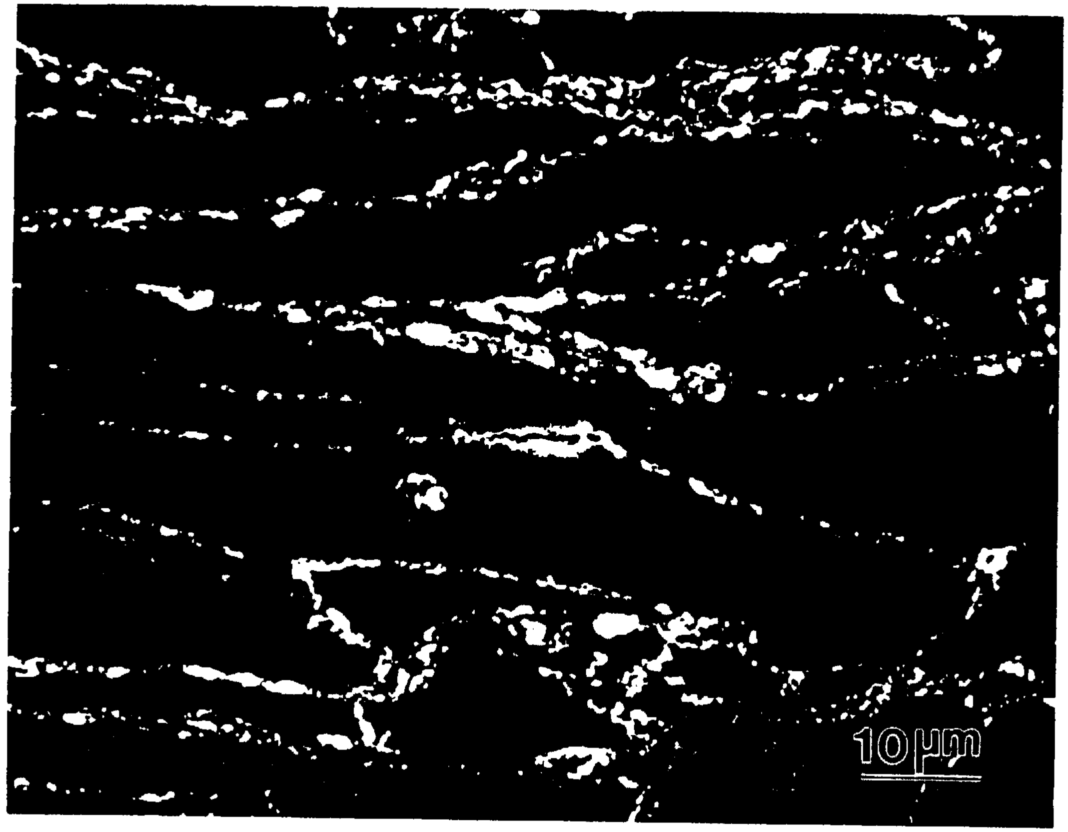


CT Specimen, W=38.1 mm
Net Thickness=6.35 mm
16.7% Sidegrooves
Moist Air
LT Orientation
FVS0812
25 C
100 C
316 C
225 C
175 C
200 C
J (kJ/m2)
Delta a (mm)
0
15
30
45
60
75
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00

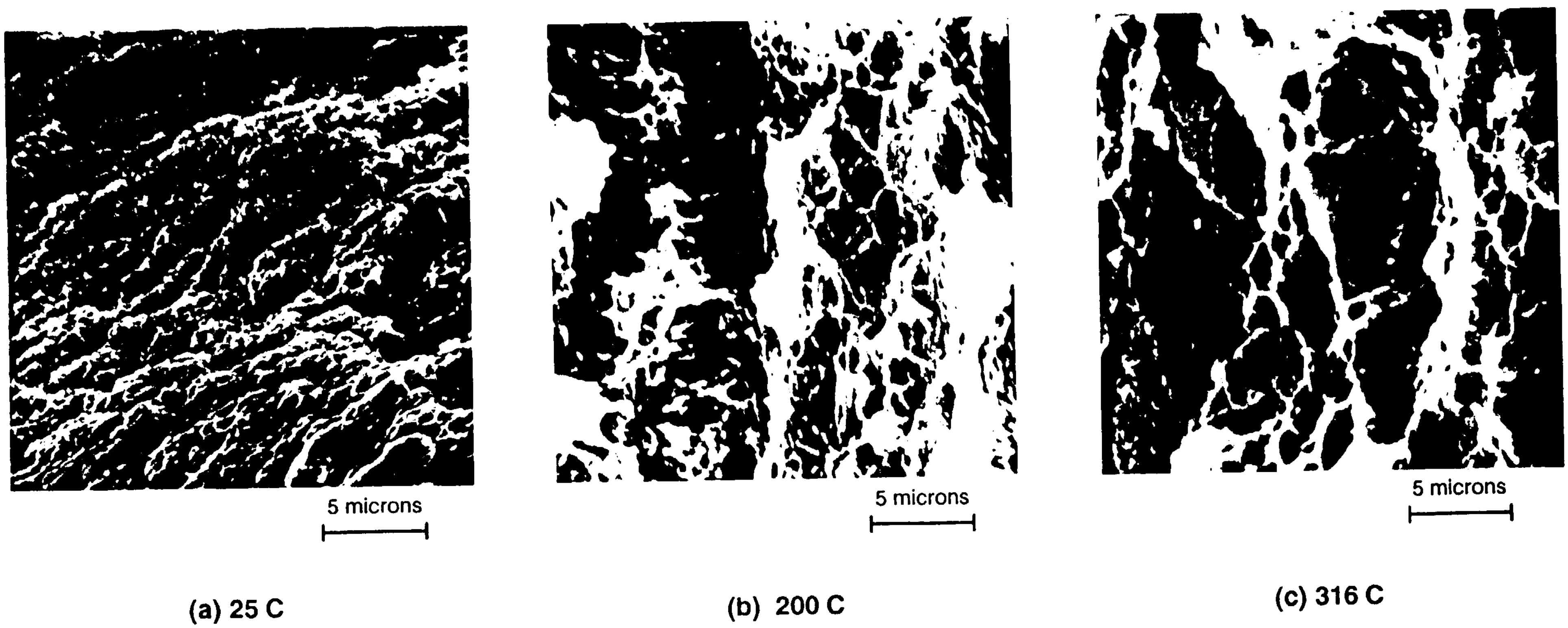


(a) 25 C (b) 200 C (c) 316 C

Low magnification SEM photographs of FVS0812 fracture surfaces for different test temperatures.



SEM micrograph of FVS0812 Al alloy (S-T surface)



High magnification SEM photographs of FVS0812 fracture surfaces for different test temperatures.

DISCUSSION

- Why, in the L-T orientation, does FVS0812 exhibit a high K_{IC} and T at room temperature?

  - Thin sheet toughening mechanism:

    Delamination perpendicular to the crack front along prior particle boundaries results in a loss of through thickness constraint.

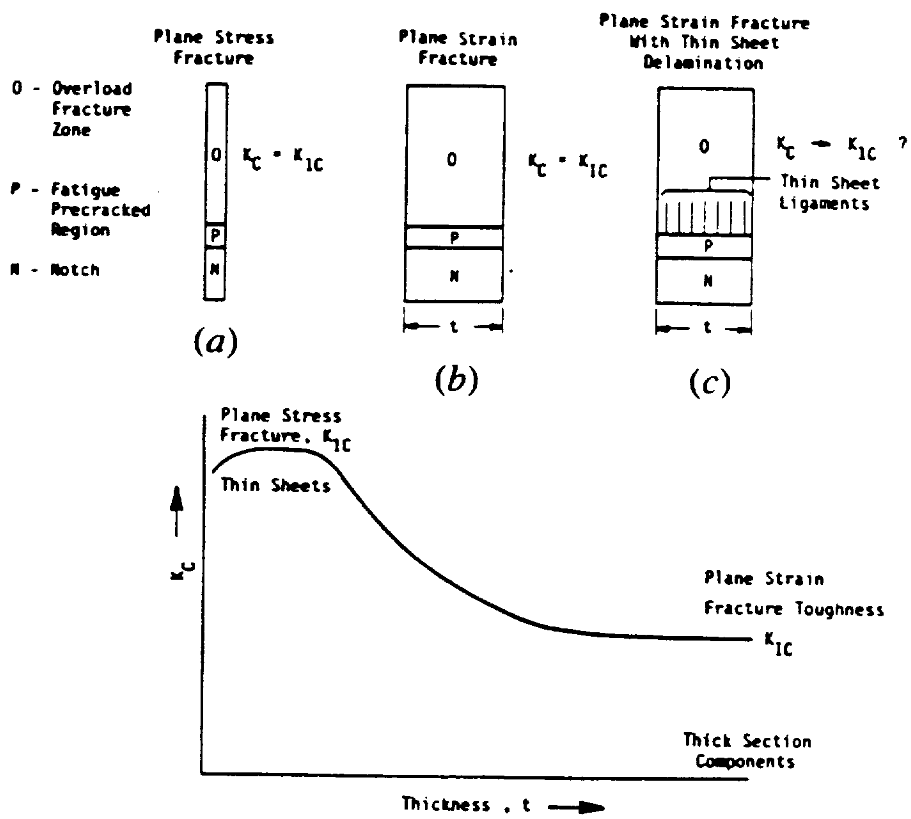


Fig. 1—A schematic showing the dependence of K_c on thickness: (*a*) a plane stress fracture toughness of K_{IC} for thin sheets; (*b*) a plane strain fracture toughness of K_{IC} for thick-section components; (*c*) a potential toughness value of K_{IC} for plane strain fracture with thin sheet ligament formations in the process zone.

ORIGINAL PAGE IS OF POOR QUALITY

- Why, in the L-T orientation, do K_{IC} and T *decrease* with increasing temperature, reaching a minimum at 200°C?

    - Decreased intrinsic toughness

        - dynamic strain aging
        - other?

    - Decreases in prior particle boundary delaminations up to 200°C

        - decrease in intrinsic toughness leads to failure of the matrix at lower K levels than necessary to develop tranverse stresses for delamination to occur.

- Why, in the L-T orientation, do K_{IC} and T increase again above 200°C?
    - Intrinsic toughness increases
        - dynamic strain aging effects are lessened; solute no longer impedes dislocation motion
    - Delaminations return
        - prior particle boundaries weaken as temperature increases; K levels rise sufficiently prior to crack growth for delamination to occur, raising K_{IC} and T.

- Why, in the T-L orientation, does K_{IC} decrease with increasing temperature, while T increases slightly?

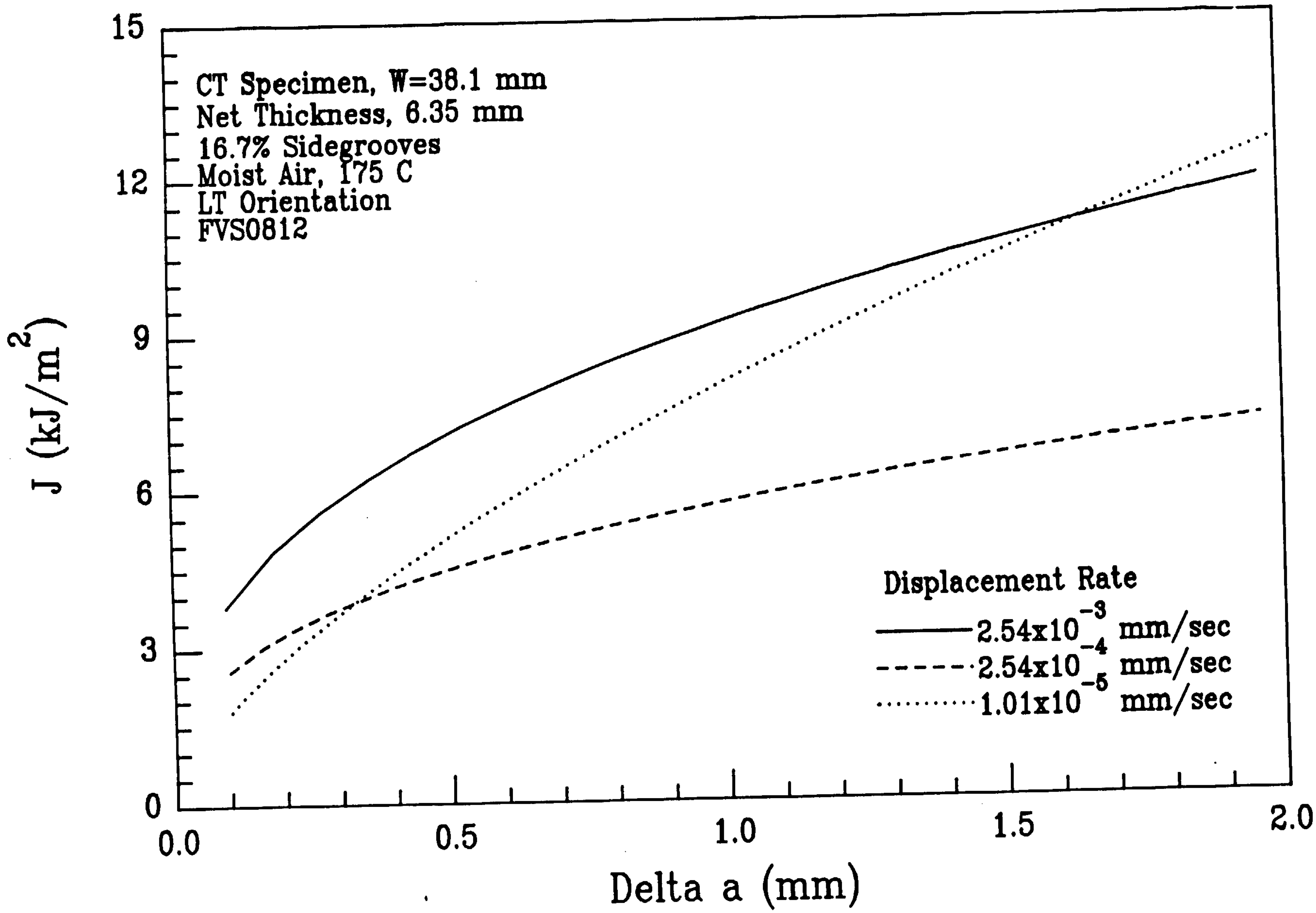
  - Represents a measure of prior particle boundary toughness

  - Strain localization at prior particle boundaries may result in lower toughness with increasing temperature

Strain Rate Effects

- K_{IC} decreases with decreasing displacement rate, while T exhibits a minimum over the range tested at 175°C.

    - combined effects of time dependent deformation, environment, and dynamic strain aging may be playing a role



CT Specimen, W=38.1 mm
Net Thickness, 6.35 mm
16.7% Sidegrooves
Moist Air, 175 C
LT Orientation
FVS0812
Displacement Rate
2.54x10^{-3} mm/sec
2.54x10^{-4} mm/sec
1.01x10^{-5} mm/sec
J (kJ/m^2)
Delta a (mm)
0
3
6
9
12
15
0.0
0.5
1.0
1.5
2.0

CONCLUSIONS

- PM alloy FVS0812 shows very high fracture toughness and tearing modulus at room temperature due to thin sheet toughening mechanism.

- Fracture toughness and tearing modulus of 0812 decrease with increasing temperature, with minima at 200°C, due to dynamic strain aging and decreased delamination.

- Toughness of prior particle boundaries, as measured by T-L toughness, decreases with increasing temperature as a result of strain localization at boundaries.

FUTURE RESEARCH

- Two questions:

  - What is the fracture behavior of FVS0812 in terms of J-Δa versus:
    Temperature, loading rate, microstructure, stress state, and environment.

    Tasks: Continue fracture testing, fractographic analysis, and micromechanical modelling

    - cryogenic temperatures
    - rolled plate
    - thinned specimens
    - vacuum

- What is the mechanism by which dynamic strain aging contributes to fracture?

  Tasks: Develop mechanical testing, microscopy, and metallurgical techniques to explore this.

  - interrupted tests
  - sectioning, TEM studies
  - lower Fe,V chemistry
  - heat treatments

ACADEMIC TIMETABLE

- April 1990; Completed comprehensive exam.
- Mid-summer 1990; Present and defend a PhD. dissertation proposal.
- Late summer 1991; Present and defend PhD. dissertation.

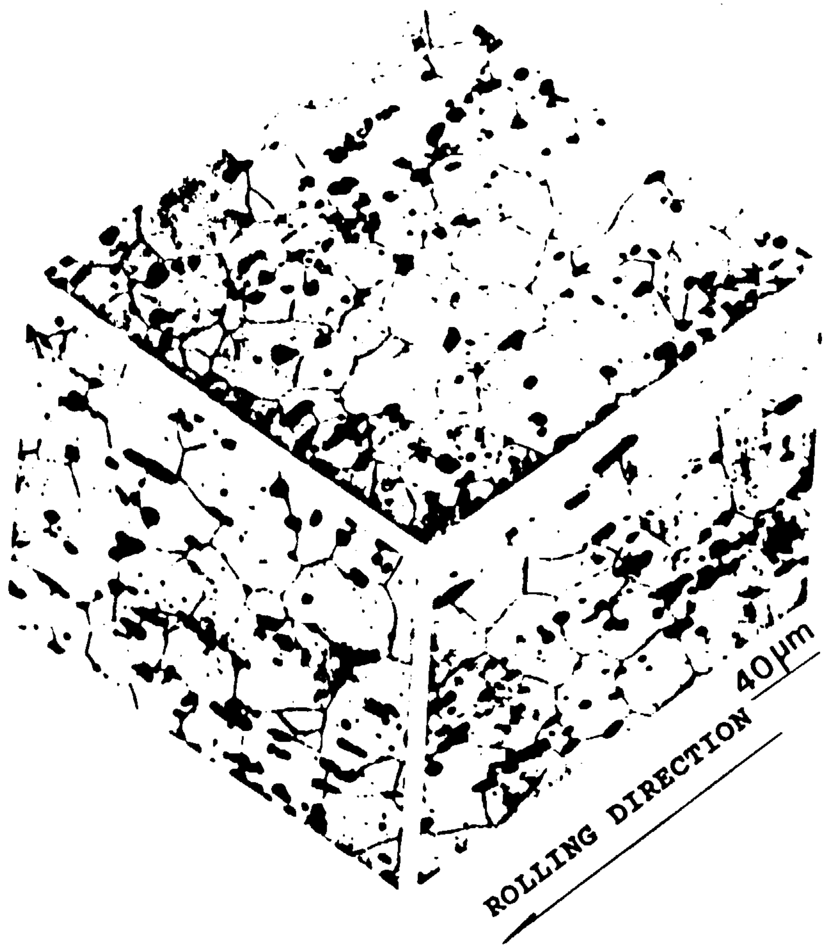
APPENDIX

Results of Fracture Toughness Testing of Aluminum Alloy 2618

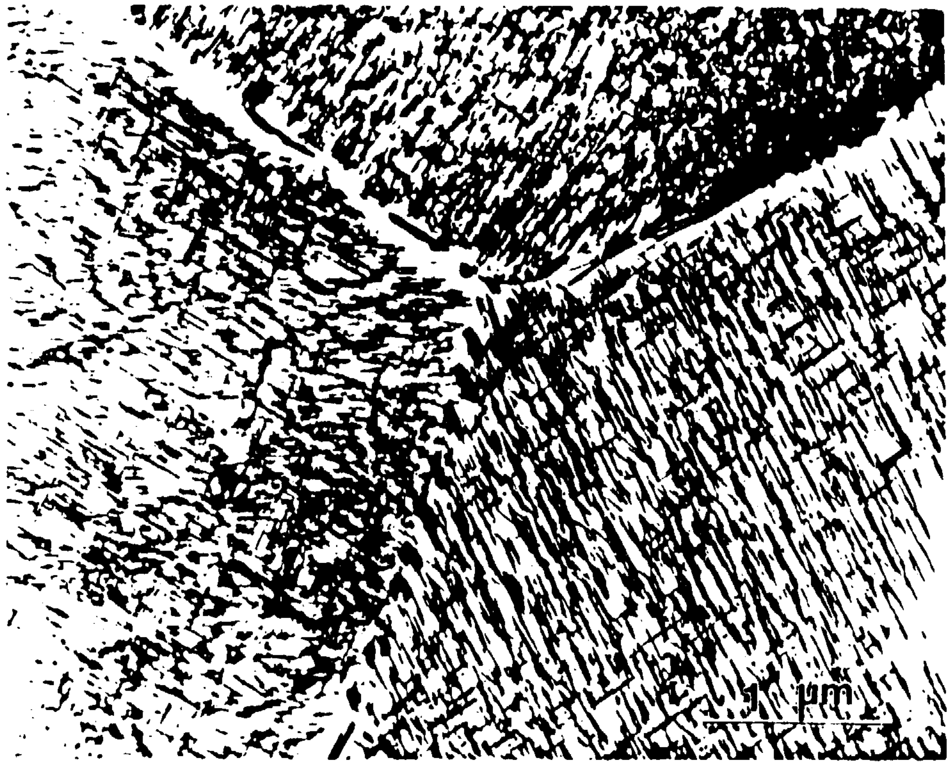
MATERIAL

2618

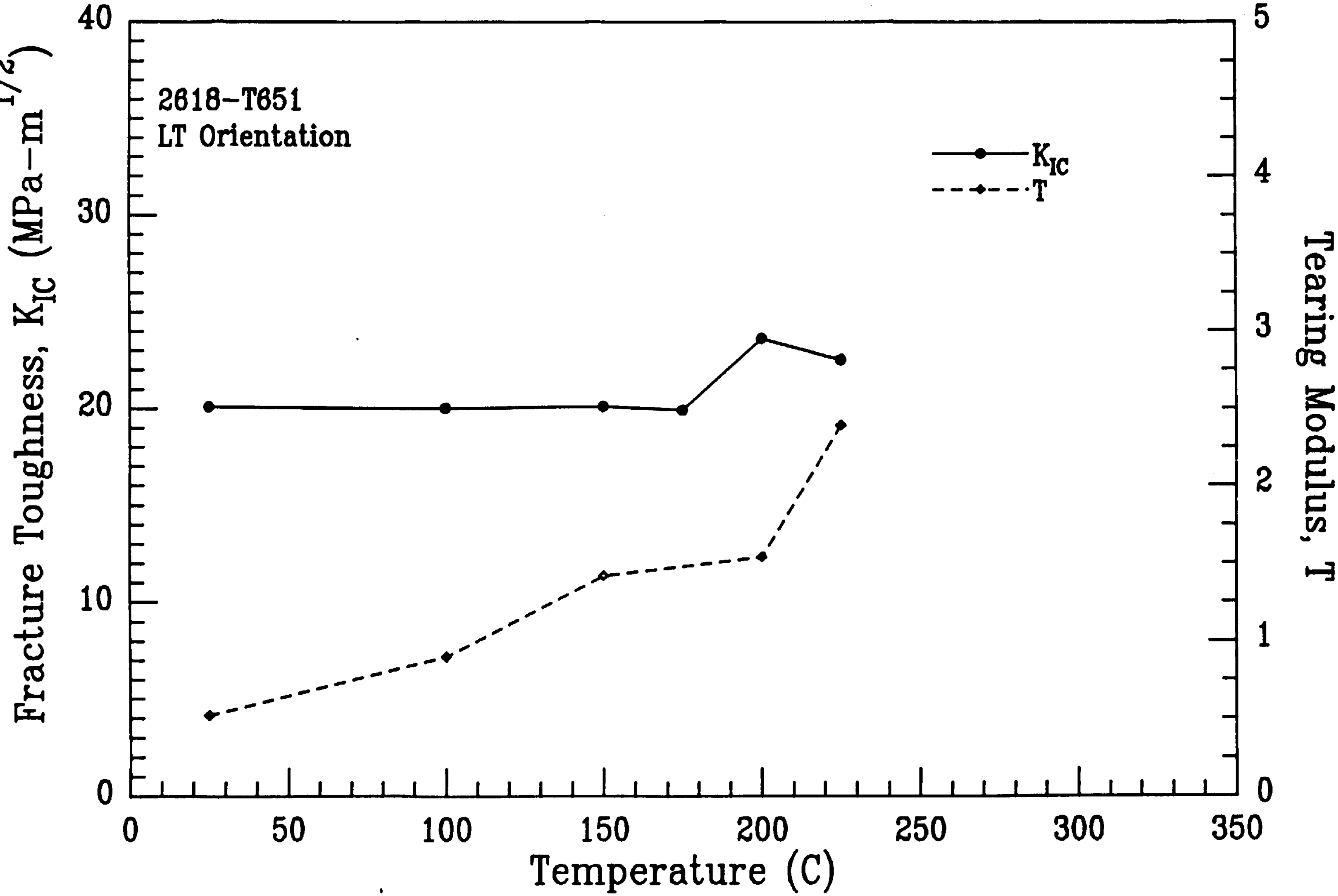
- Ingot metallurgy, Al-Cu-Mg with substantial Fe, Ni, and Si
    - S' primary strengthening phase
    - 5-10 μm Fe-Ni-Al particles for mechanical property retention at elevated temperatures
    - 30-50 μm equiaxed grain structure
- Provided by Cegedur Pechiney



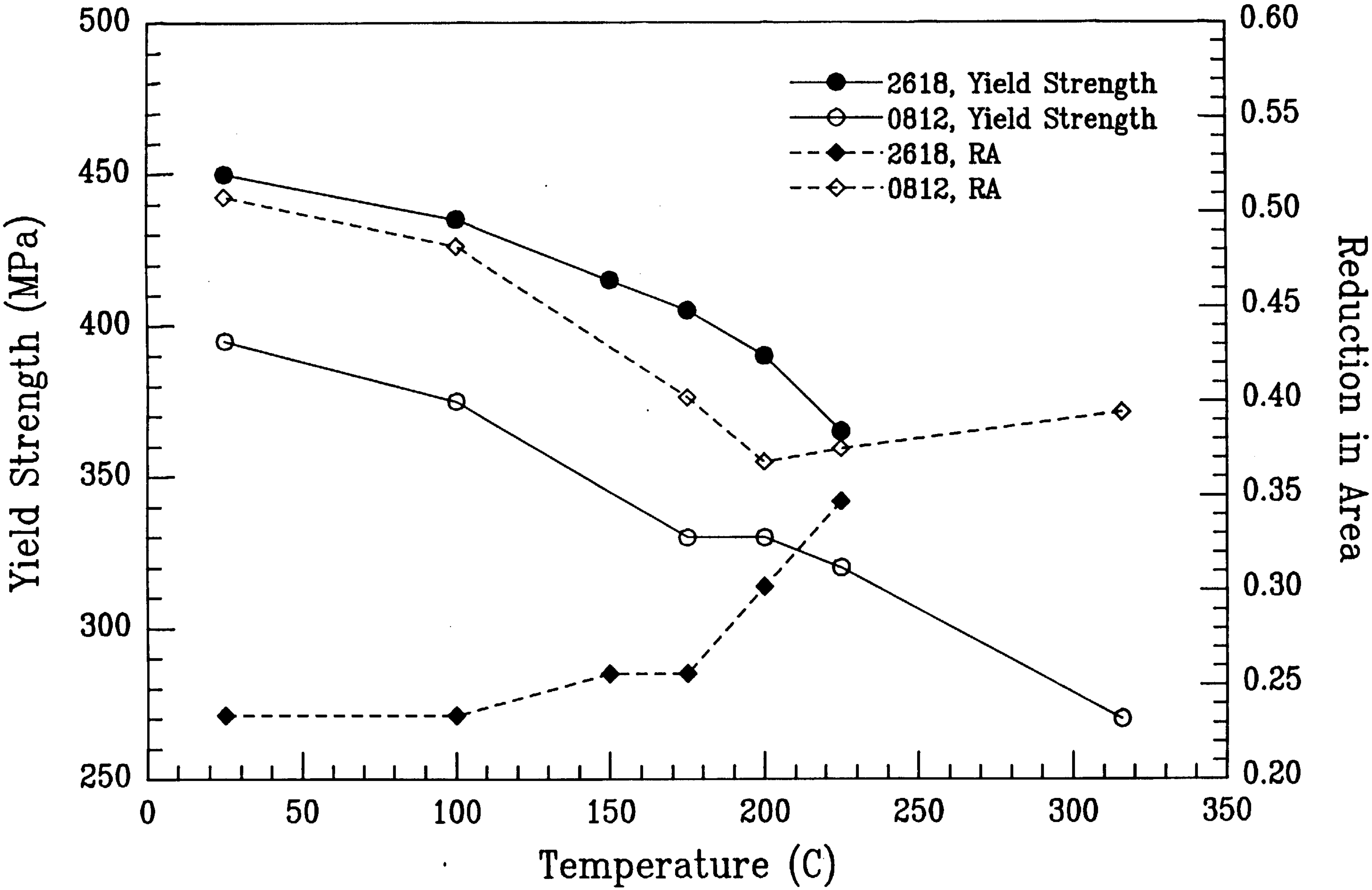
Optical micrograph of 2618 Al alloy



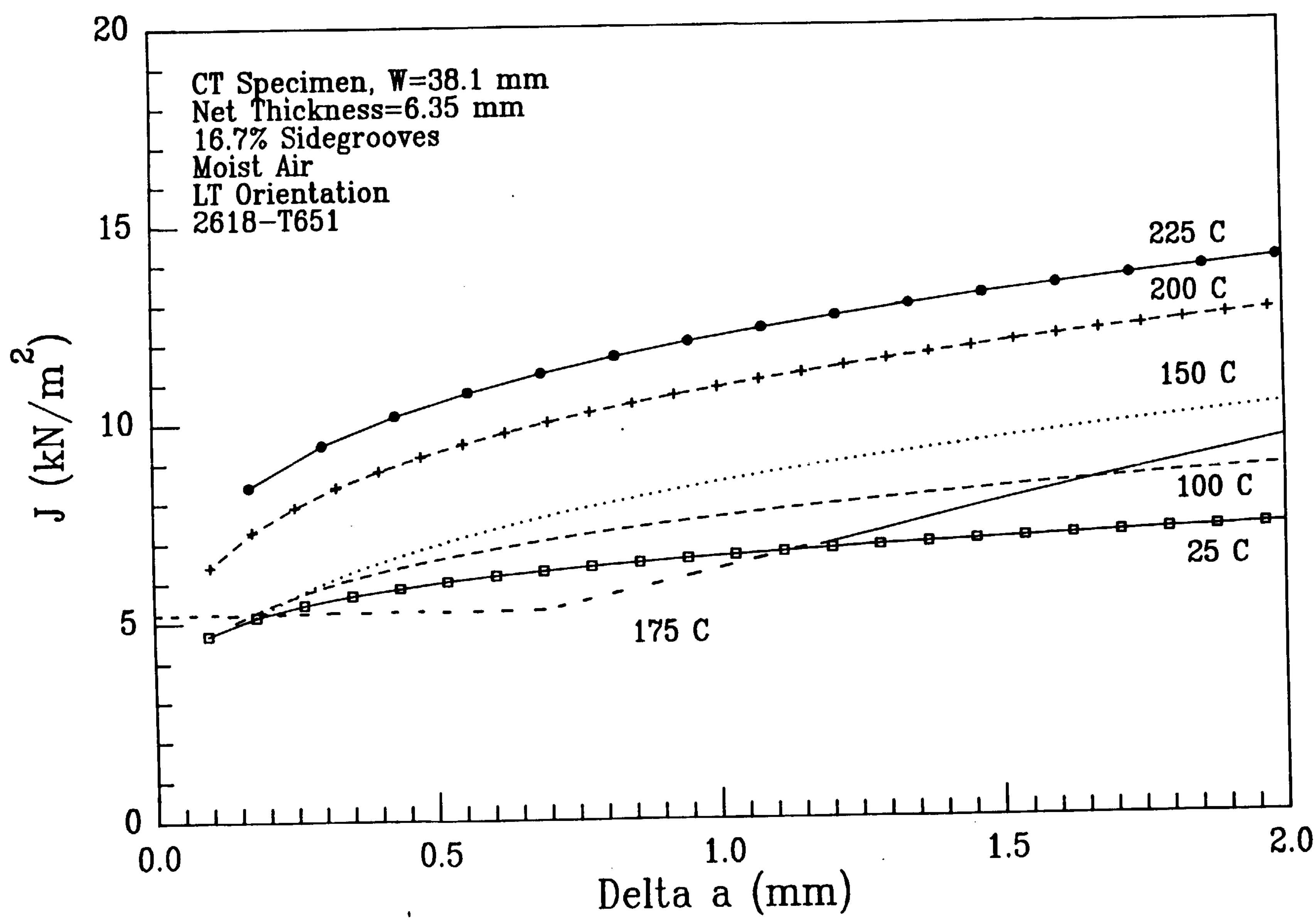
TEM micrograph of 2618 Al alloy



2618-T651
LT Orientation
K_{IC}
T
Fracture Toughness, K_{IC} (MPa-m$^{1/2}$)
Tearing Modulus, T
Temperature (C)
0
10
20
30
40
0
1
2
3
4
5
0
50
100
150
200
250
300
350



2618, Yield Strength
0812, Yield Strength
2618, RA
0812, RA
Yield Strength (MPa)
Reduction in Area
Temperature (C)
500
450
400
350
300
250
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0
50
100
150
200
250
300
350



CT Specimen, W=38.1 mm
Net Thickness=6.35 mm
16.7% Sidegrooves
Moist Air
LT Orientation
2618-T651
225 C
200 C
150 C
100 C
25 C
175 C
20
15
10
5
0
0.0
0.5
1.0
1.5
2.0
J (kN/m2)
Delta a (mm)

RESULTS

2618

- K_{IC} increases slightly with increasing temperature

- Tearing modulus, T, increases with increasing temperature

- Insufficient stable crack growth at 175°C for valid J-Δa curve

- Fractography showed microvoid coalescence to be the mode of fracture in all specimens

Implications: The increase of fracture toughness with increasing temperature is consistent with the decrease in yield strength.

The inability to sustain stable crack growth at 175°C may be from dynamic strain aging due to solid solution Fe.

N90-22654

Program 2 **Elevated Temperature Crack Growth in Aluminum Alloys: Tensile Deformation of 2618 and FVS0812 Aluminum Alloys**

Yang Leng and Richard P. Gangloff

Objectives

The objectives of this portion of the project are:

1) to characterize the elastic-plastic deformation behavior of ingot metallurgy 2618 and powder metallurgy Al-Fe-V-Si alloys as function of temperature.

2) to investigate the correlation between tensile behavior and microstructure.

Program 2 **Elevated Temperature Crack Growth in Aluminum Alloys: Time Dependent Crack Growth Behavior of Alloy 2618**

Yang Leng and Richard P. Gangloff

Objectives

The objectives of this program are to investigate the subcritical crack growth behavior of aluminum alloy 2618 at elevated temperatures, to determine the dominant damage mechanism and to correlate macroscopic crack growth with microstructure.

Time Dependent Crack Growth in Aluminum Alloys at Elevated Temperature

Yang Leng and Richard P. Gangloff
Department of Materials Science

Abstract

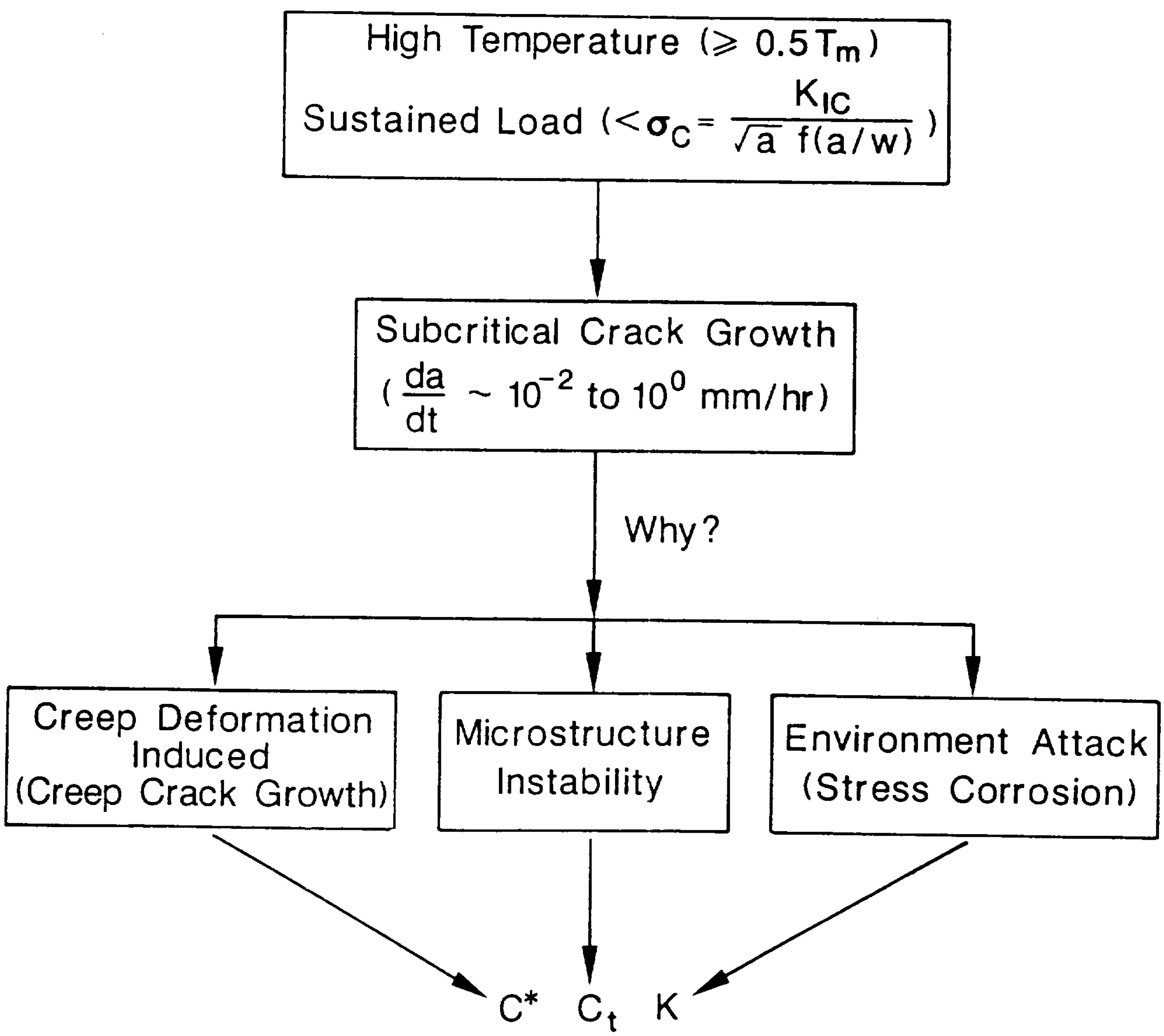
Understanding the damage tolerance of aluminum alloys at elevated temperatures is essential for safe applications of advanced materials. The objective of this project is to investigate the time dependent subcritical cracking behavior of powder metallurgy FVS0812 and ingot metallurgy 2618 aluminum alloys at elevated temperatures.

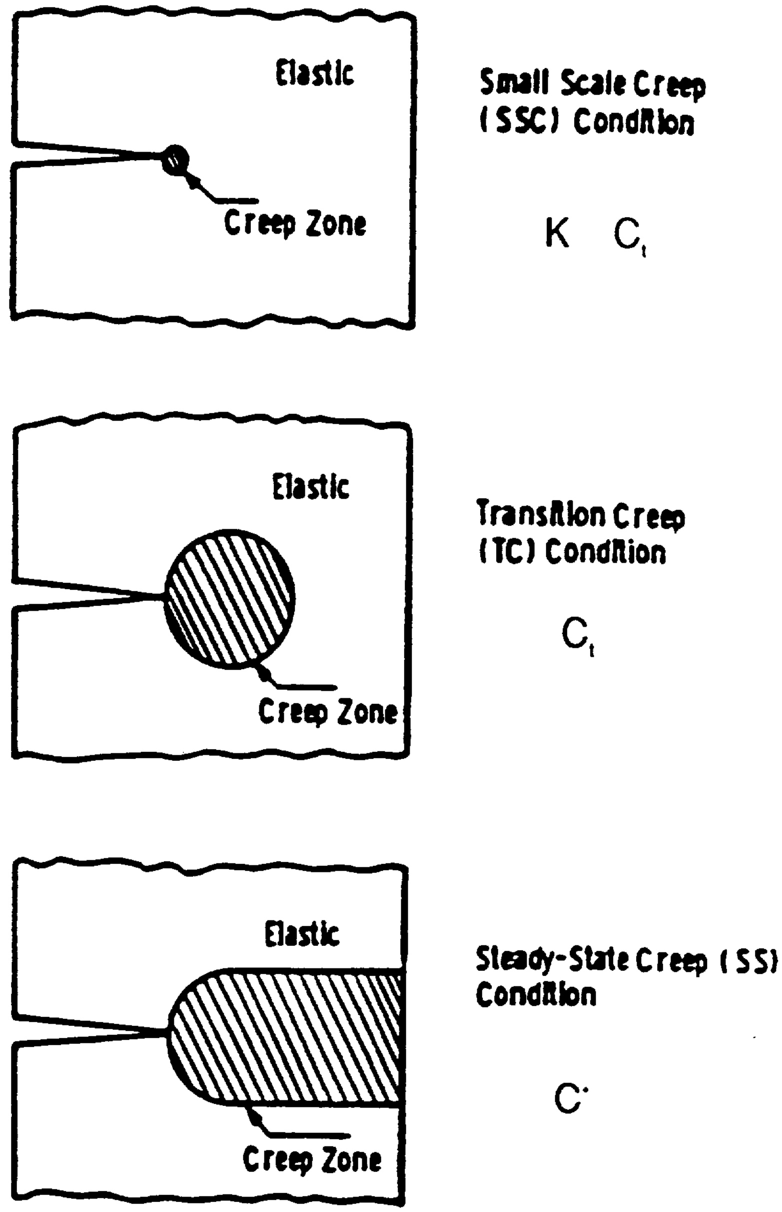
The fracture mechanics approach was applied in this study. Sidegrooved compact tension specimens were tested at 175, 250 and 316°C under constant load. Subcritical crack growth occurred in each alloy at applied stress intensity levels (K) of between about 14 and 25 MPa$\sqrt{m}$, well below K_{IC}. Measured load, crack opening displacement and displacement rate, and crack length and growth rate (da/dt) were analyzed with several continuum fracture parameters including, the C^*-integral, C_t and K. Since extensive creep conditions are not met according to the transition time criterion and for the load levels which produce crack growth, the C^*-integral is not a relevant parameter for these aluminum alloys. Elevated temperature growth rate data suggest that K is a controlling parameter during time dependent cracking. For FVS0812, da/dt is highest at 175°C when rates are expressed as a function of K. While crack growth rate is not controlled by C_t at 175°C, da/dt appears to better correlate with C_t at higher temperatures. Here, "creep brittle" cracking at intermediate temperatures, and perhaps related to strain aging, is augmented by time dependent transient creep plasticity at higher temperatures. The C_t analysis is, however, complicated by the necessity to measure small differences in the elastic crack growth and creep contributions to the crack opening displacement rate.

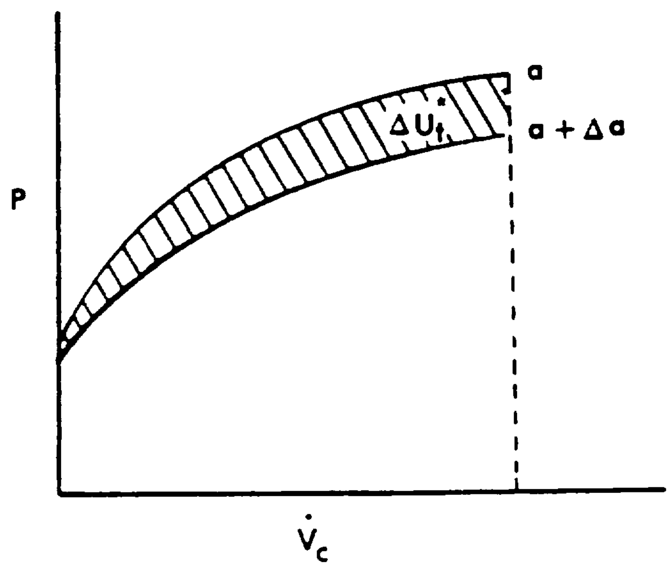
A microstructural study indicates that 2618 and FVS0812 are likely to be creep brittle materials, consistent with the results obtained from the fracture mechanics study. Time dependent crack growth of 2618 at 175°C is characterized by mixed transgranular and intergranular fracture. Delamination along the ribbon powder particle boundaries occurs in FVS0812 at all temperatures. The fracture mode of FVS0812 changes with temperature. At 175°C, it is characterized as dimpled rupture, and at 316°C as mixed matrix superplastic rupture and matrix-dispersoid debonding.

Further study will concentrate on revealing the correlation between macromechanical behavior and microstructure, investigating possible environmental effects and exploring mechanisms of time dependent crack growth in these advanced aluminum alloys.

Damage Tolerance of Advanced Aluminum Alloys




Elastic
Creep Zone
Small Scale Creep
(SSC) Condition
K C_t
Elastic
Creep Zone
Transition Creep
(TC) Condition
C_t
Elastic
Creep Zone
Steady-State Creep (SS)
Condition
C^*



The C_t is an instantaneous energy rate dissipation rate
which can characterize CCG from small scale to steady state creep

$$C_t = -\frac{1}{B}\frac{\partial \dot{U}_t}{\partial a}$$

For compact tension specimens

$$(C_t)_{ssc} = \frac{P\,\dot{V}_c}{B\,W}\frac{F'}{F}$$

F' and F are geometric factors and

$$\frac{F'}{F} = f(a/w)$$

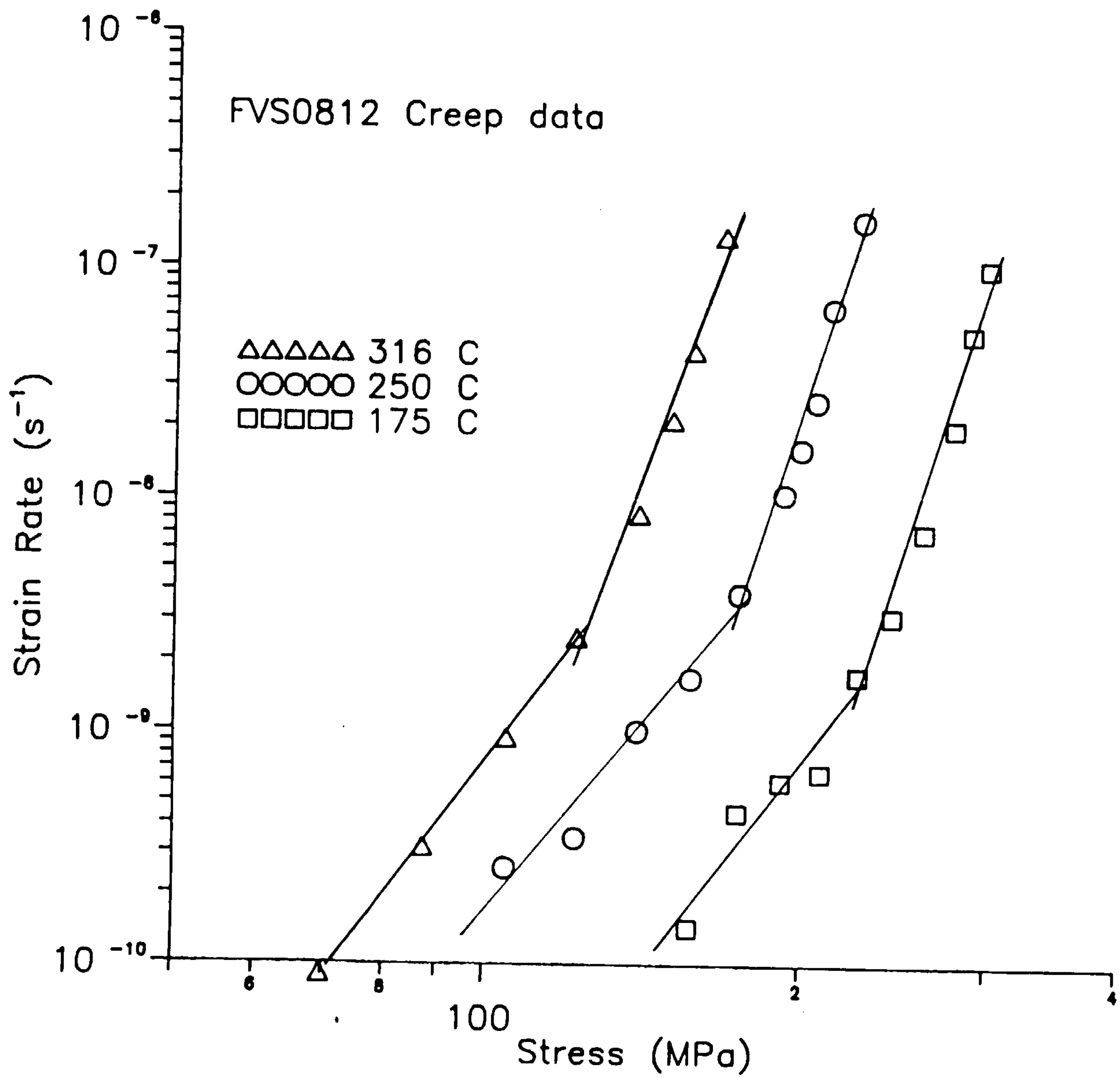
TRANSITION TIME CRITERIA

$$t_T = \frac{K^2(1-\nu^2)}{E(n+1)C^*}$$

$$C^* = A_1 \frac{\sigma_o^2}{E}(W-a)\,h_1\left(\frac{P}{P_o}\right)^{n+1}$$

$$\dot{\varepsilon} = A_1\left(\frac{\sigma}{\sigma_o}\right)^n$$

The transition time can be used to justify the validity of C^*.
There is no analytical criteria to justify C_t and K.



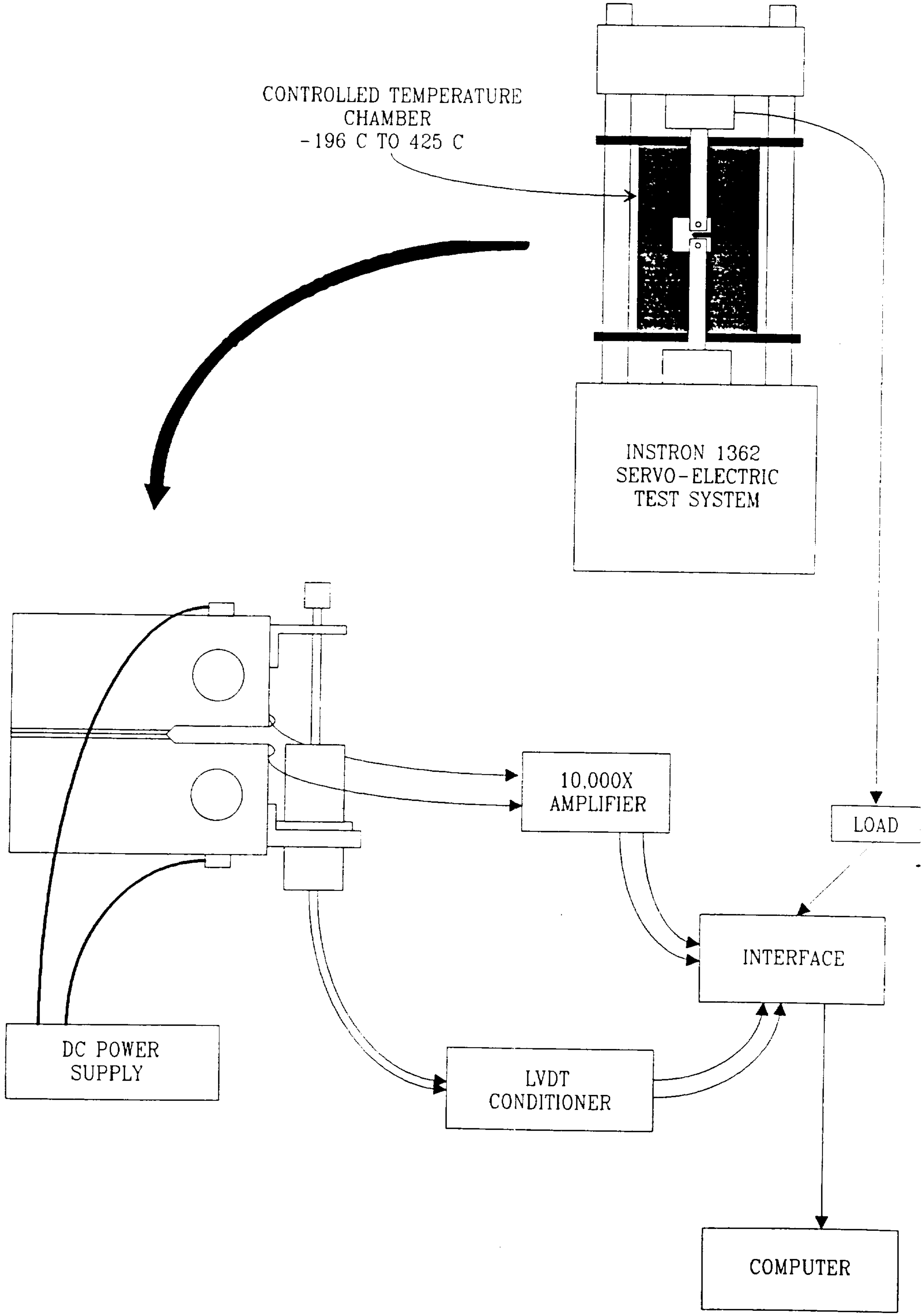
FVS0812 Creep data
316 C
250 C
175 C
Strain Rate (s^{-1})
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
6
8
100
2
4
Stress (MPa)

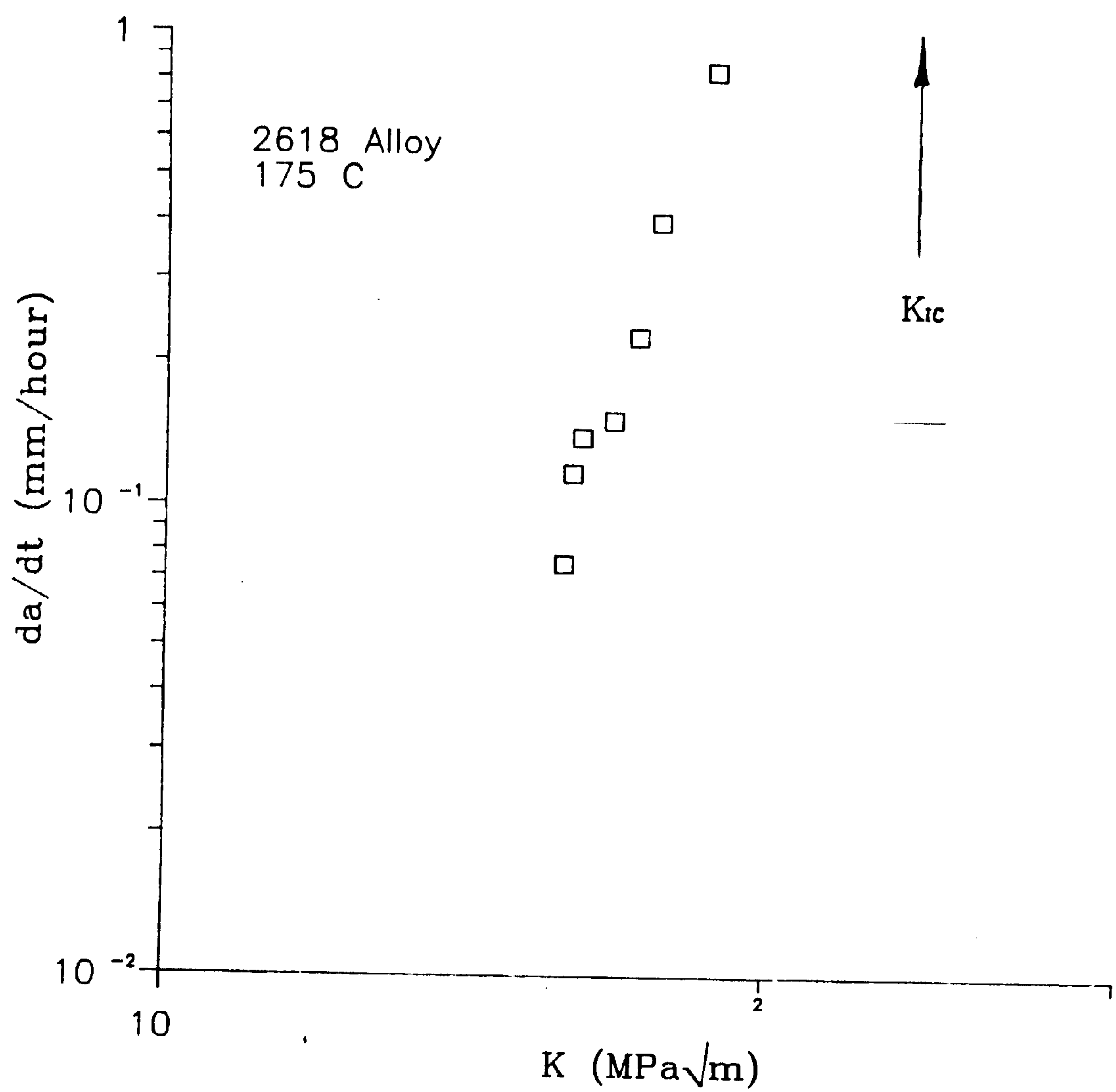
TRANSITION TIME FOR ALLOY ALLOYS

Material	temperature(°C)	n	t_T (year) a/W=0.5	t_T (year) a//W=0.6
2618	175	6.1	$1.7x10^2$	2.4
0812	175	5.9	$1.3x10^2$	19
0812	175	15	$1.2x10^6$	$3.2x10^3$
0812	250	5.4	12	2.2
0812	250	14	$7.8x10^3$	28
0812	316	5.9	3.9	.59
0812	316	12	84	.64

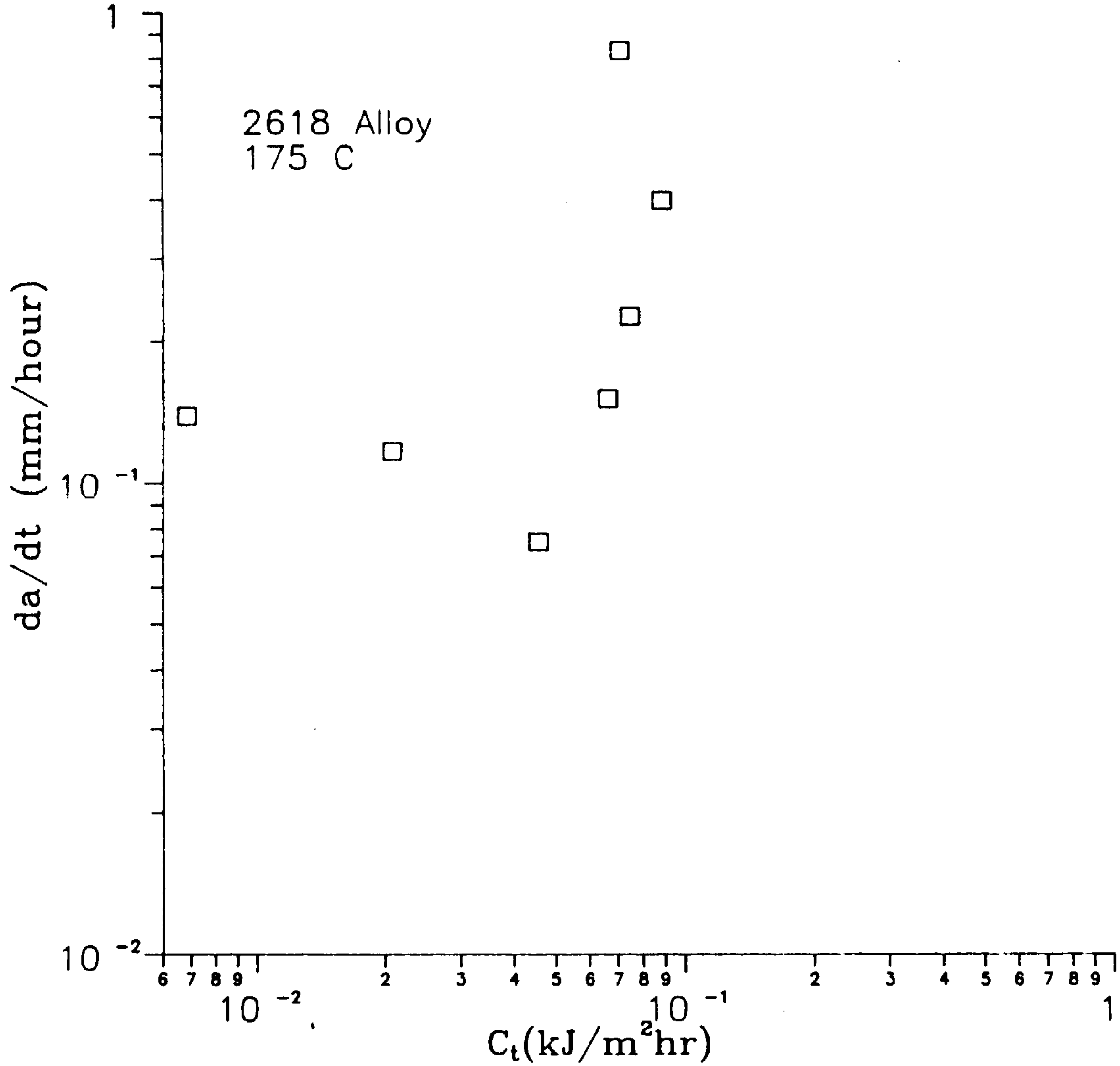
Applied load = 2.2 kN

The ratio of applied stress on ligament to yield strength is only about 4% to 8 %.


CONTROLLED TEMPERATURE
CHAMBER
-196 C TO 425 C
INSTRON 1362
SERVO-ELECTRIC
TEST SYSTEM
10,000X
AMPLIFIER
LOAD
INTERFACE
DC POWER
SUPPLY
LVDT
CONDITIONER
COMPUTER



2618 Alloy
175 C
K_{IC}
da/dt (mm/hour)
1
10^{-1}
10^{-2}
10
2
K (MPa√m)



2618 Alloy
175 C
da/dt (mm/hour)
1
10 ⁻¹
10 ⁻²
6 7 8 9
10 ⁻²
2 3 4 5 6 7 8 9
10 ⁻¹
2 3 4 5 6 7 8 9
1
Ct(kJ/m²hr)

For compact tension specimens

$$(C_t)_{ssc} = \frac{P\,\dot{V}_c}{B\,W}\frac{F'}{F}$$

Load line deflection rate, $\dot{V}$, can be partitioned into two components

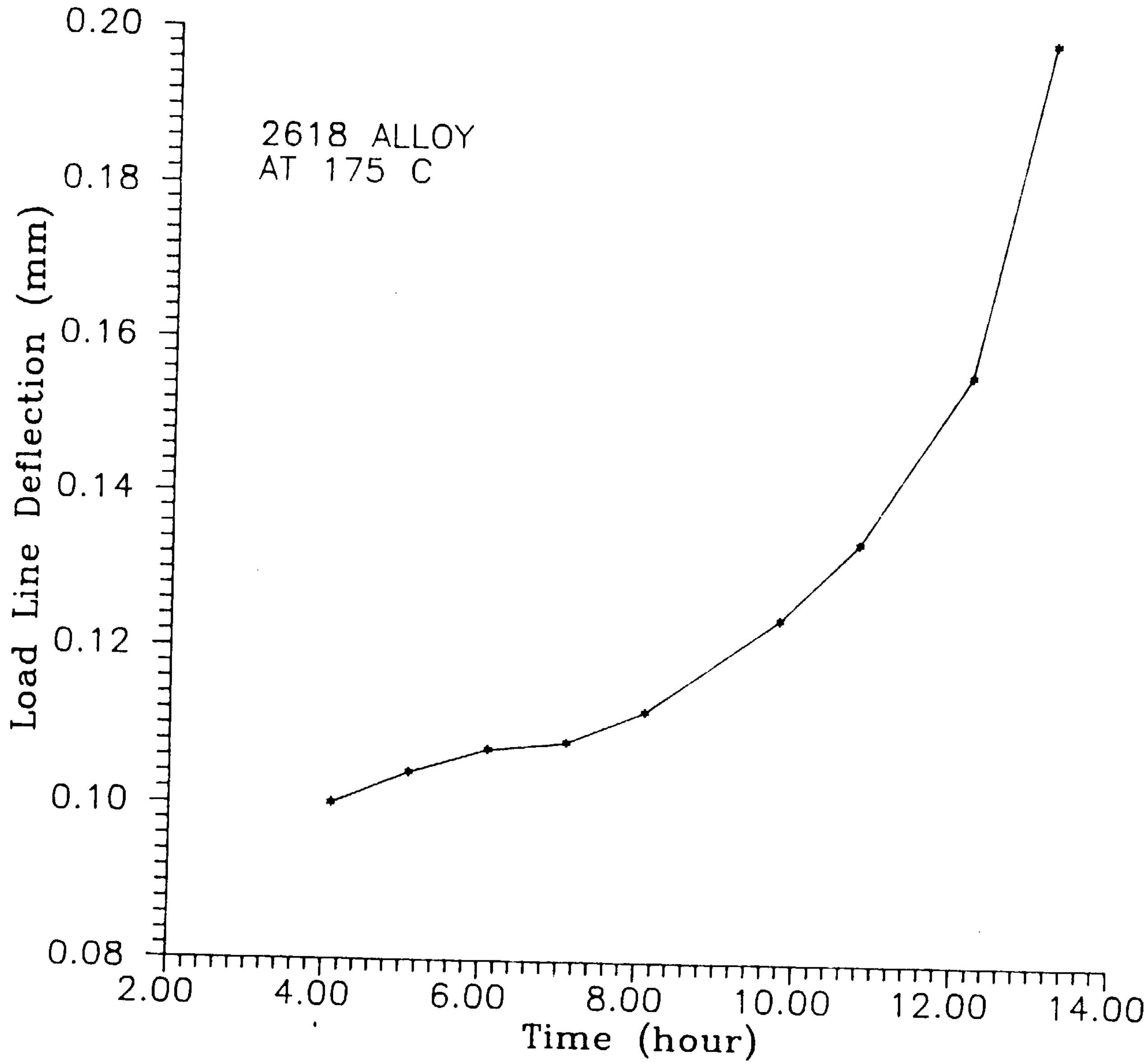
$$\dot{V} = \dot{V}_e + \dot{V}_c$$

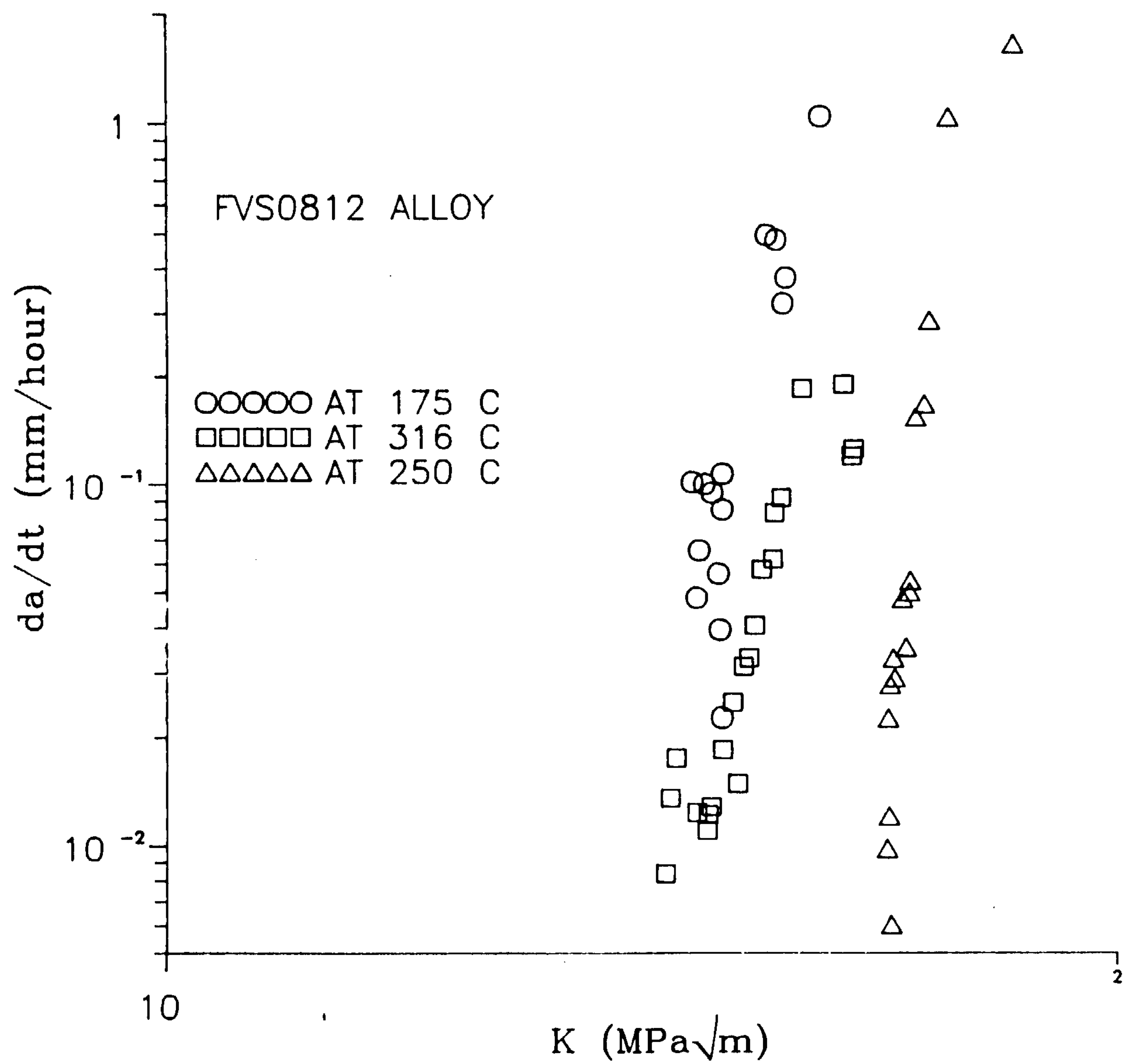
$\dot{V}_e$ = deflection rate corresponding to change in elastic compliance with crack growth

$\dot{V}_c$ = deflection rate due to development of creep deformation

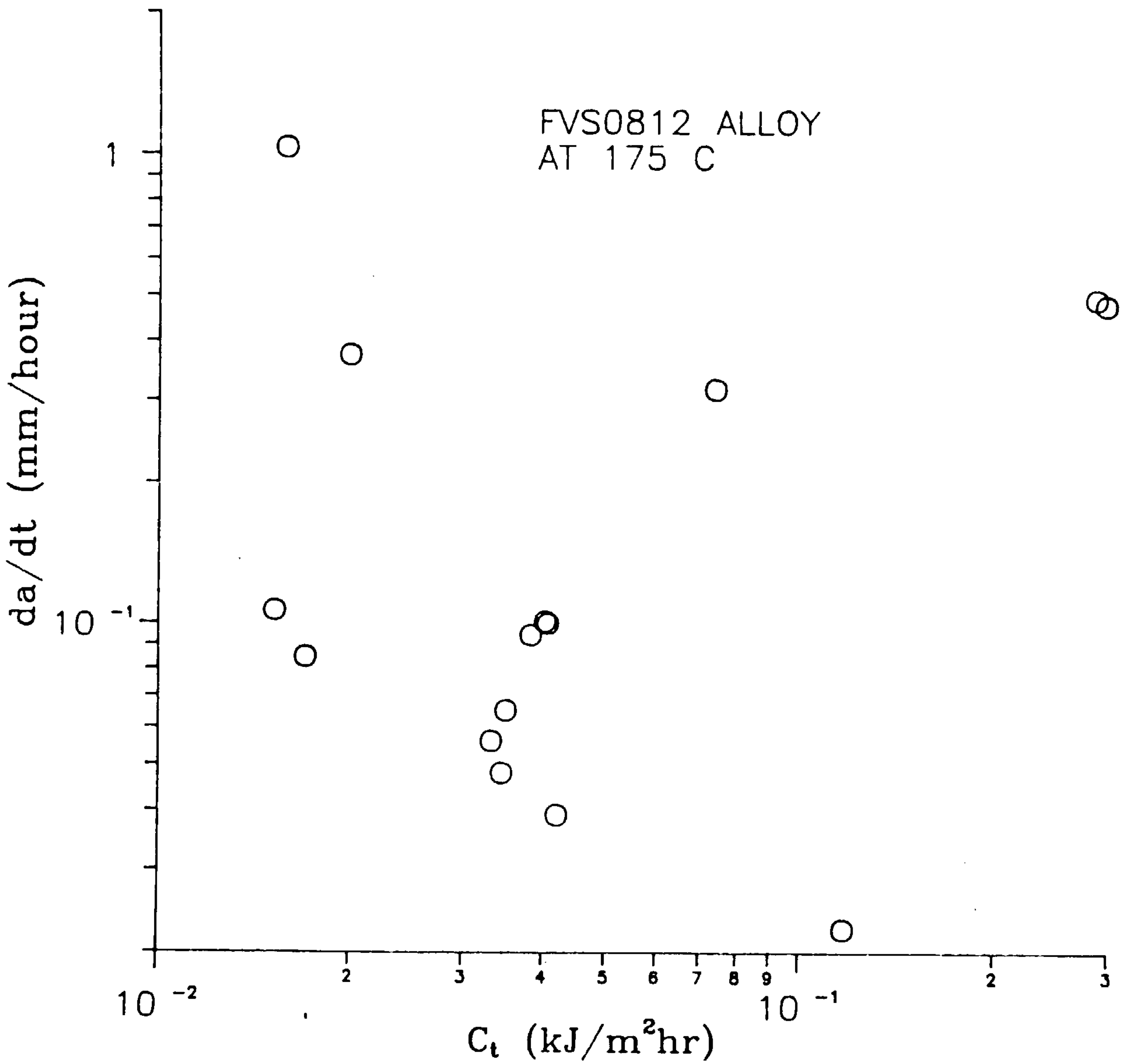
Under constant load condition

$$\dot{V}_c = \dot{V} - \frac{\dot{a}B}{P}\left[\frac{2K^2}{E}\right]$$

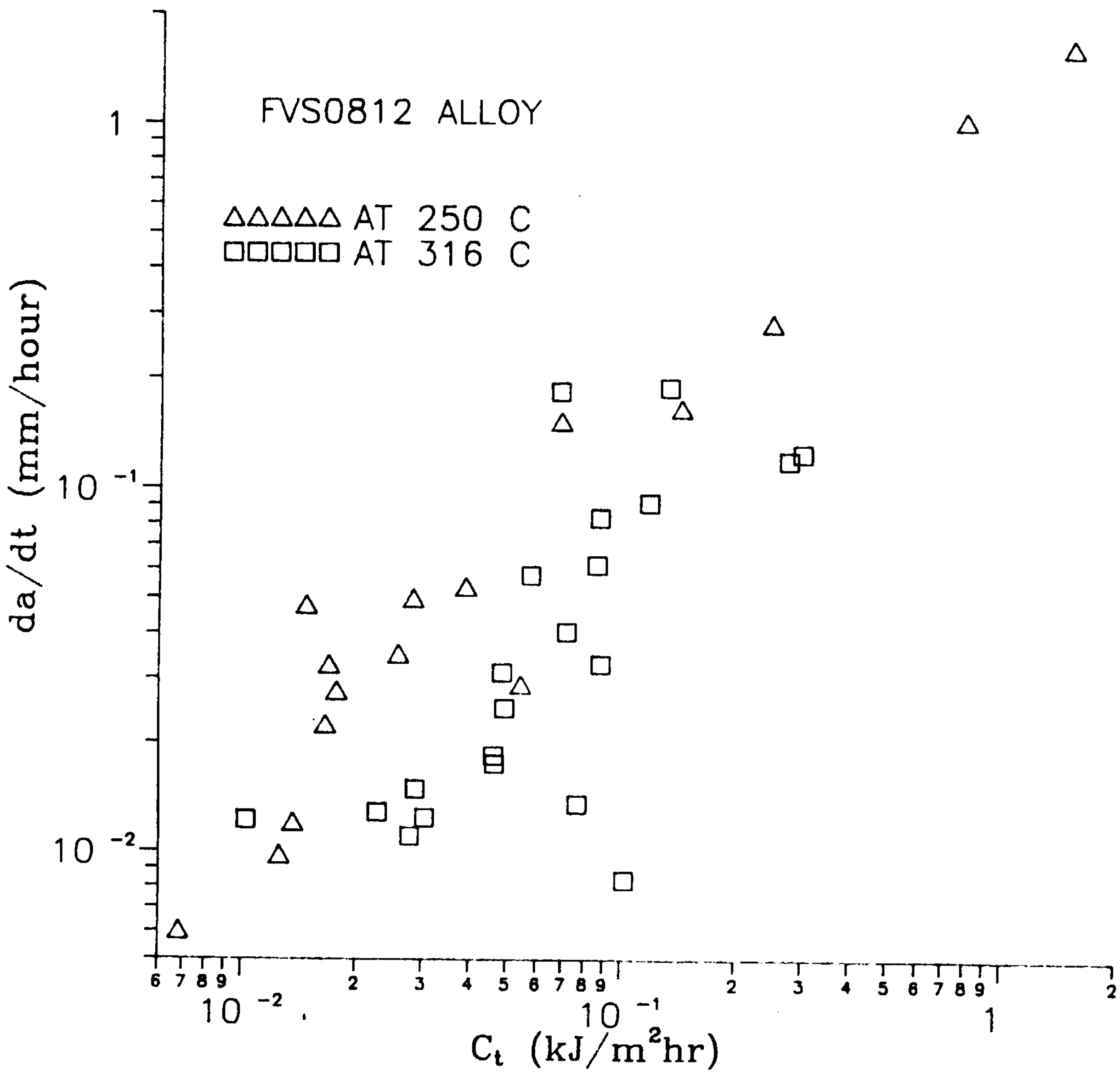

2618 ALLOY
AT 175 C
Load Line Deflection (mm)
0.20
0.18
0.16
0.14
0.12
0.10
0.08
2.00
4.00
6.00
8.00
10.00
12.00
14.00
Time (hour)



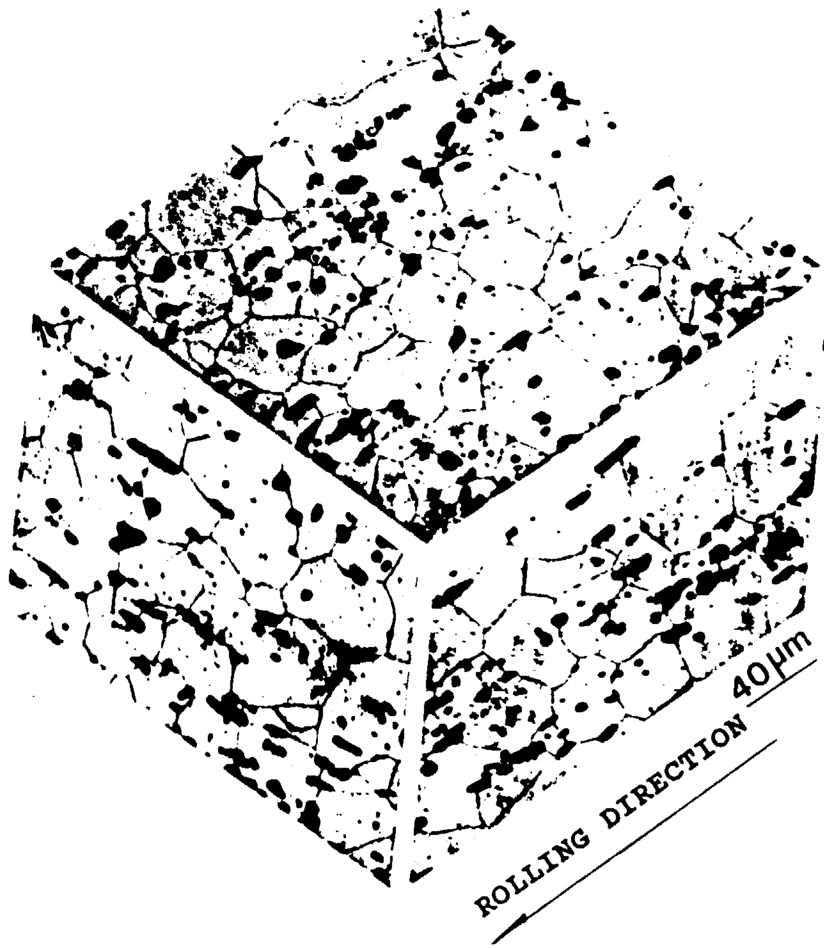
FVS0812 ALLOY
OOOOO AT 175 C
□□□□□ AT 316 C
△△△△△ AT 250 C
1
10 ⁻¹
10 ⁻²
da/dt (mm/hour)
10
2
K (MPa√m)



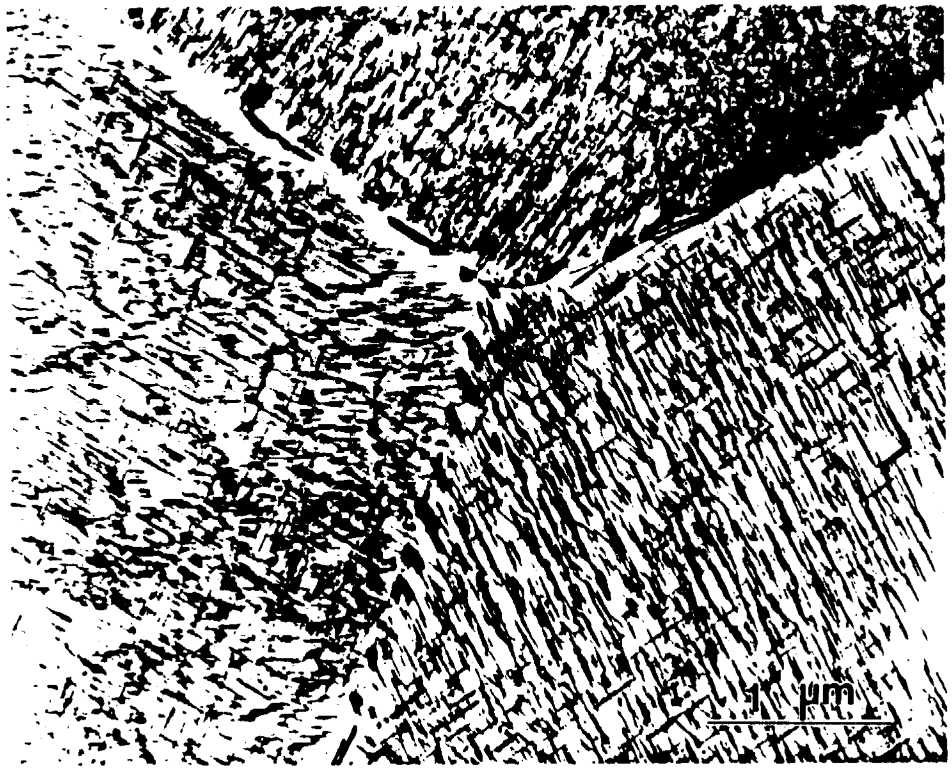
FVS0812 ALLOY
AT 175 C
da/dt (mm/hour)
1
10 ⁻¹
2
3
4
5
6
7
8
9
10 ⁻²
10 ⁻¹
C_t (kJ/m²hr)



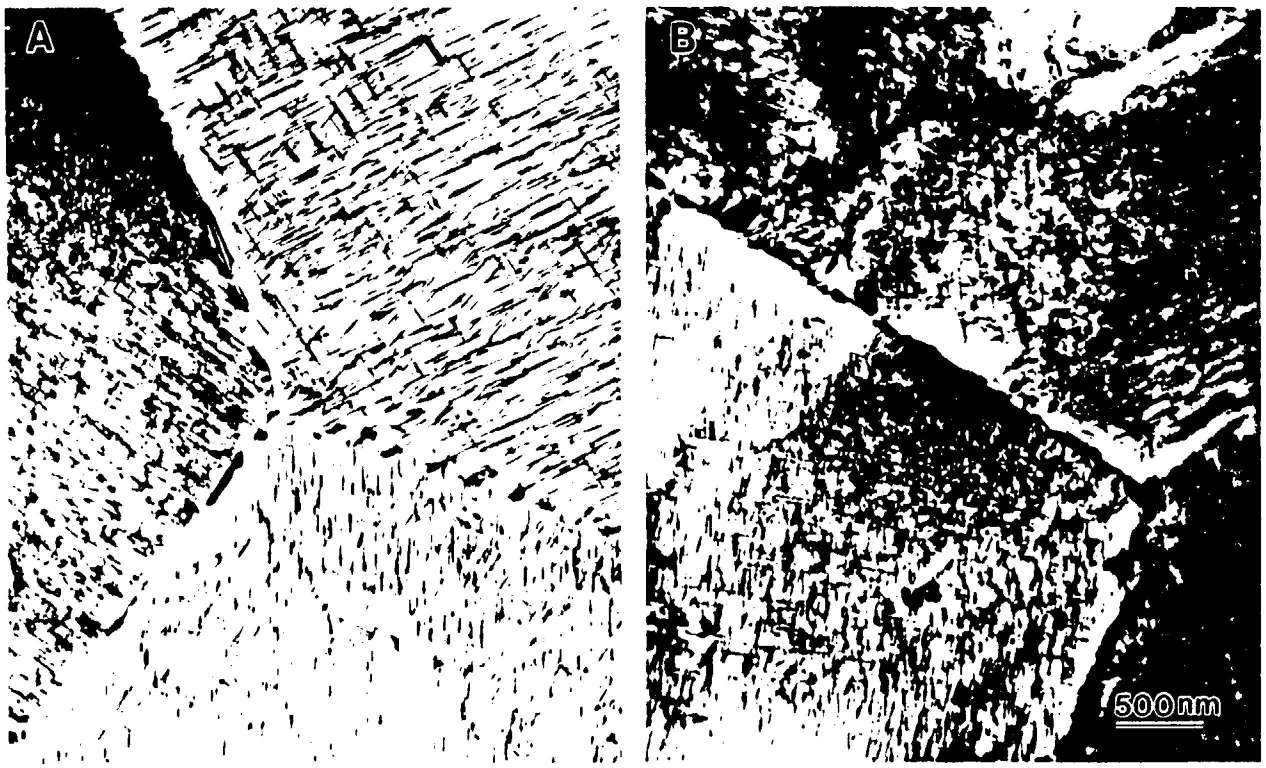
FVS0812 ALLOY
ΔΔΔΔΔ AT 250 C
□□□□□ AT 316 C
da/dt (mm/hour)
1
10^{-1}
10^{-2}
6 7 8 9
2
3
4
5
6 7 8 9
2
3
4
5
6 7 8 9
2
10^{-2}
10^{-1}
1
C_t (kJ/m^2hr)



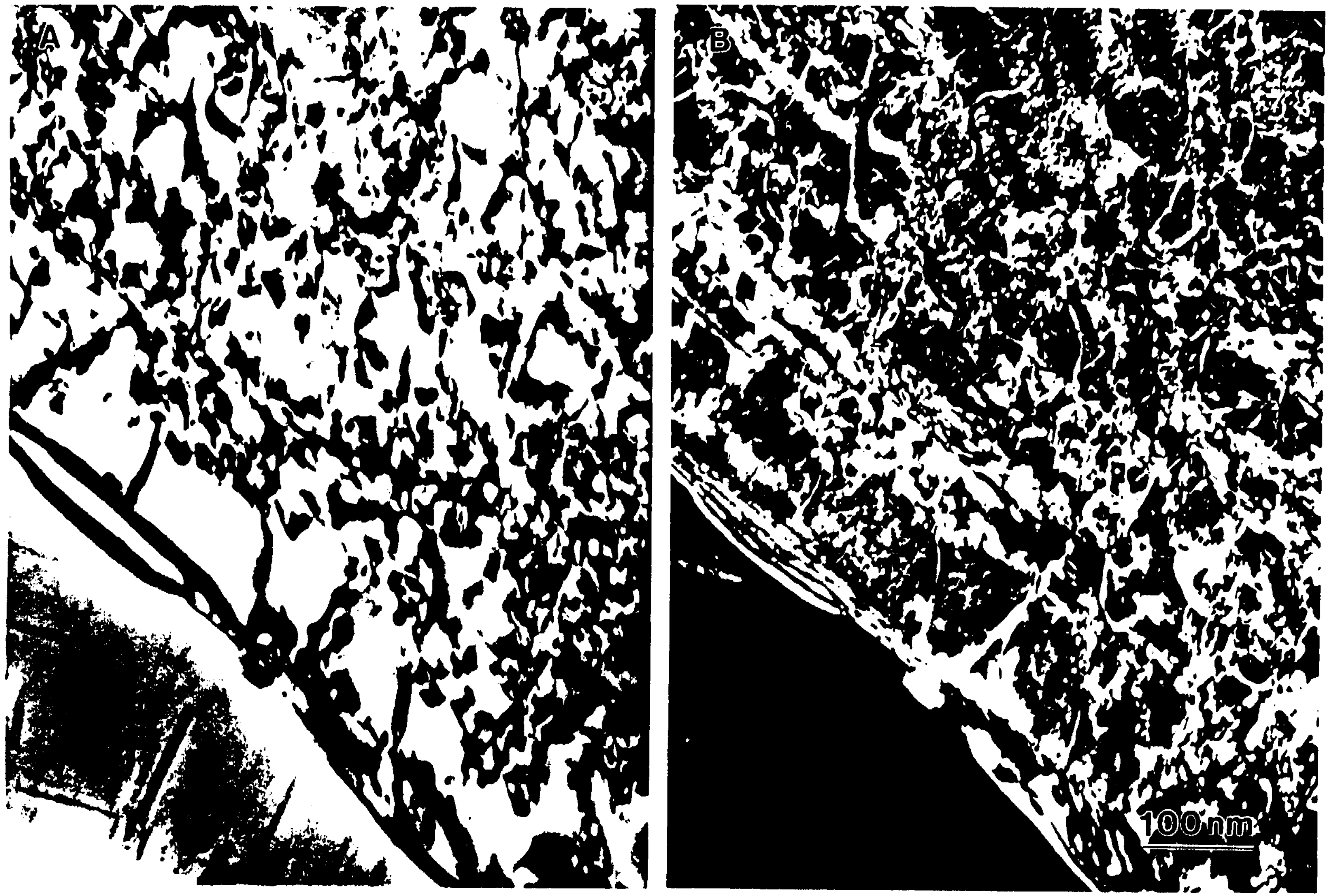
Optical micrograph of 2618 Al alloy



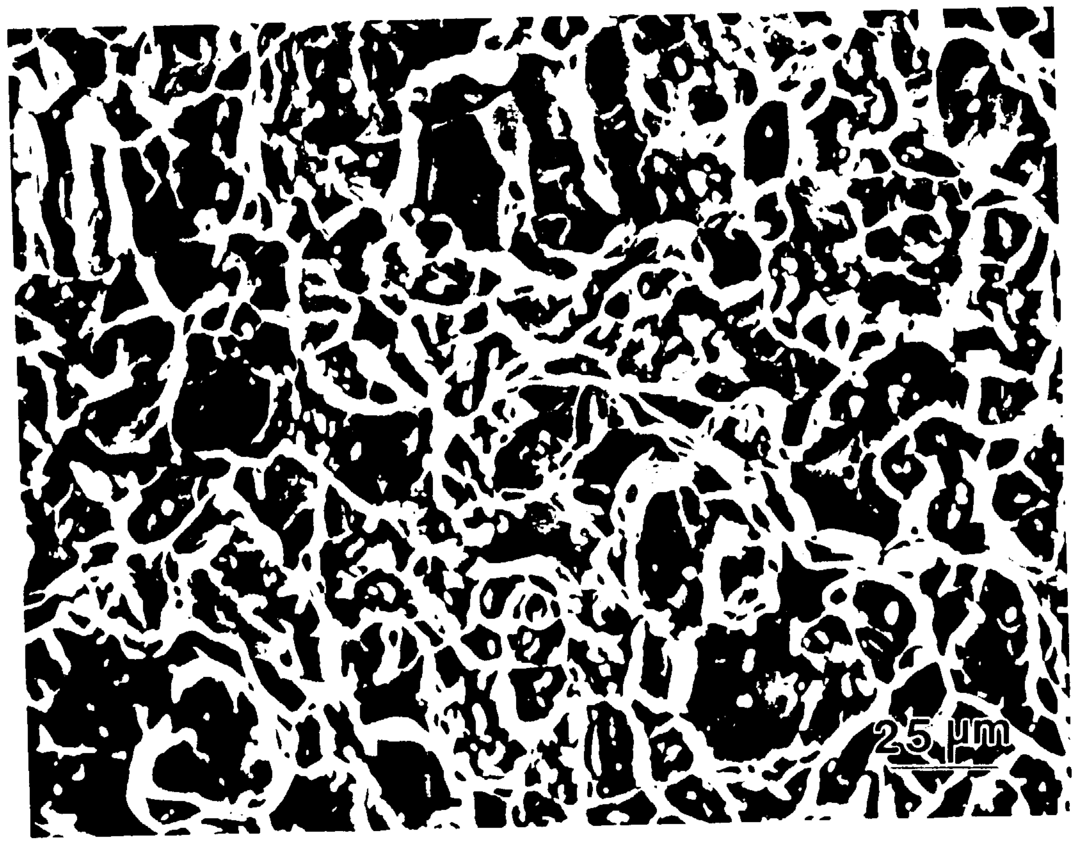
TEM micrograph of 2618 Al alloy



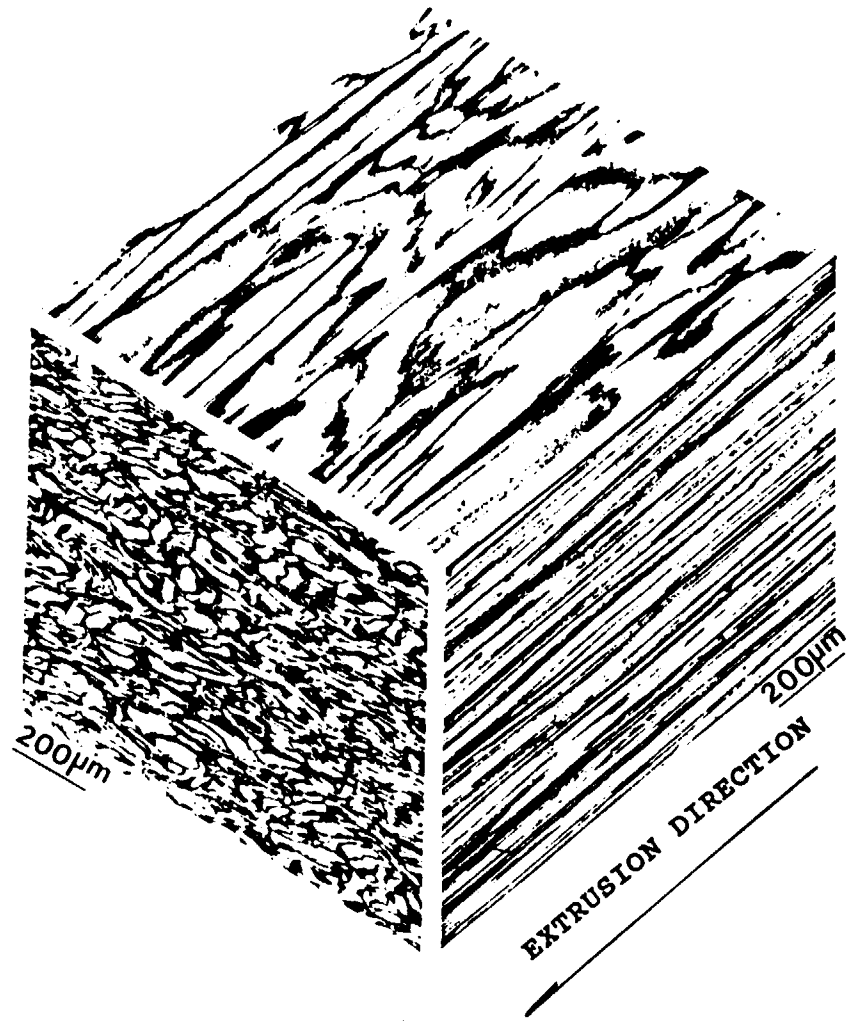
TEM micrographs of 2618 Al alloy a) room temperature
b) after heated to 300 °C for one hour



TEM micrographs of 2618 Al alloy after stretched to strain of 2%.
The zone is [001]. a) bright field, b) weak beam dark field.

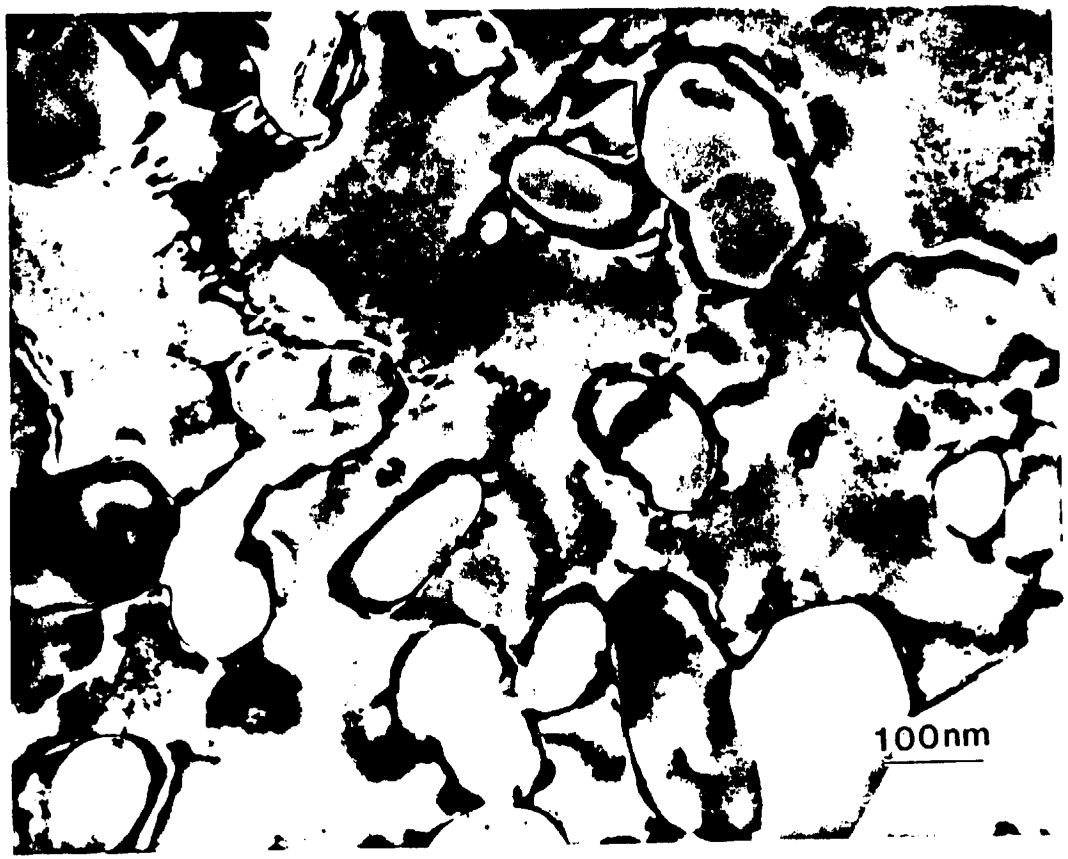


Creep crack growth fracture surface of 2618 Al alloy (175 °C)

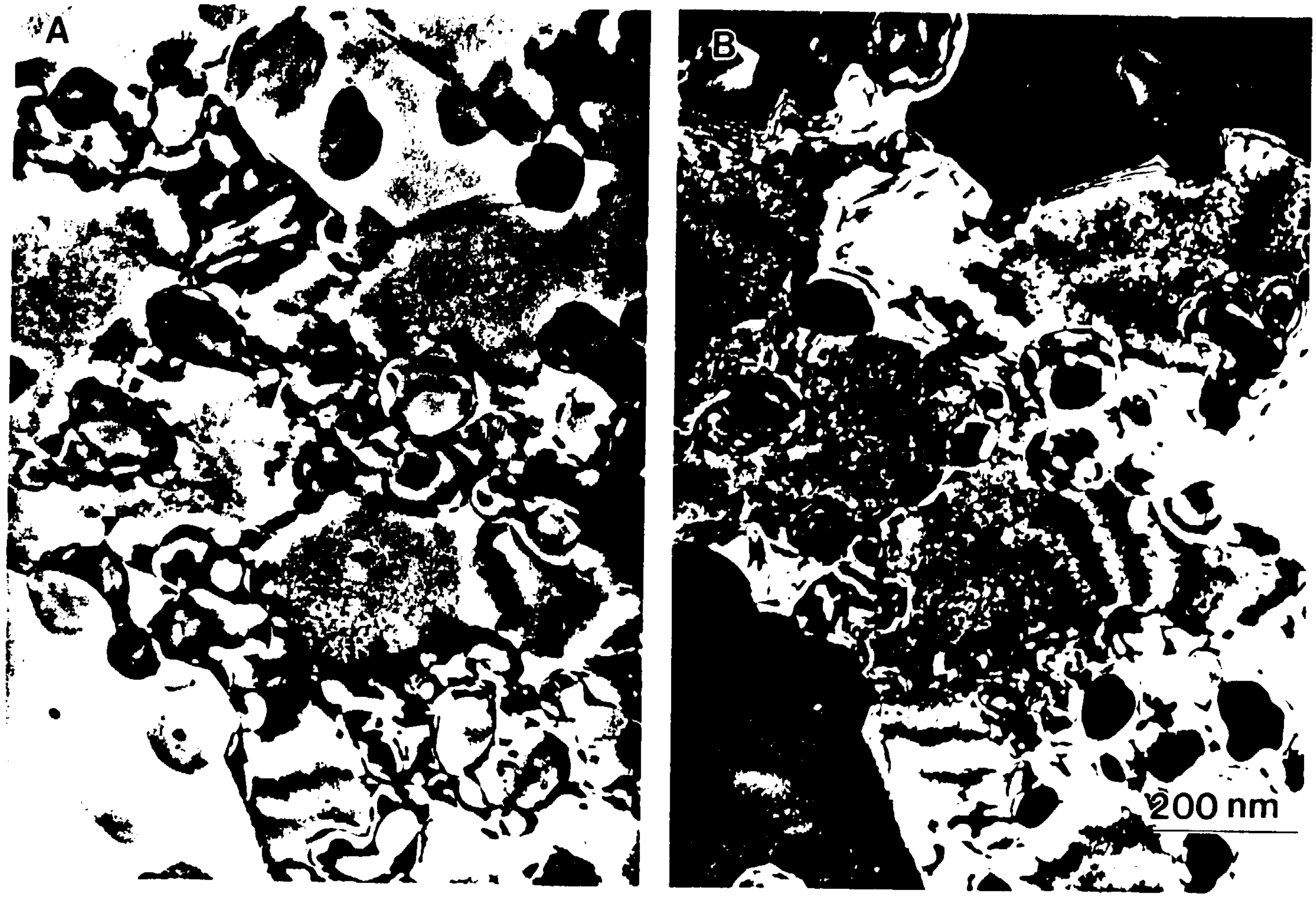


Optical micrographs (Bright field) of FVS0812 Al alloy

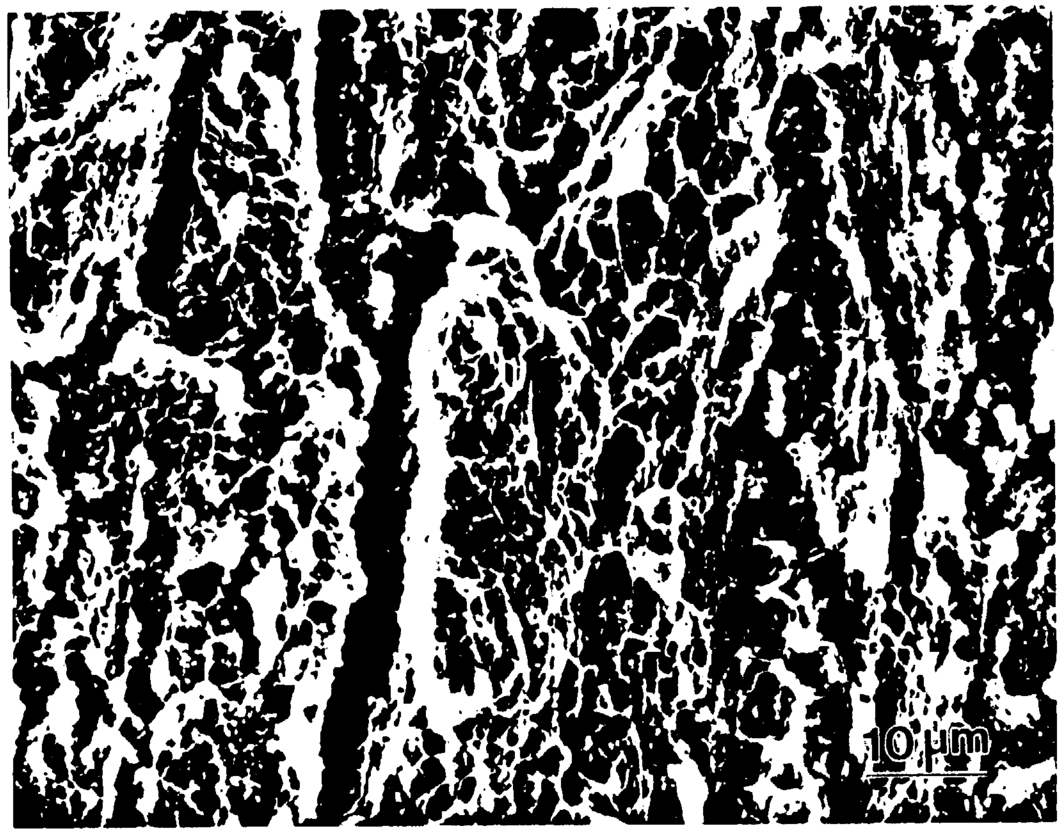
TEM micrograph of FVS0812 Al alloy



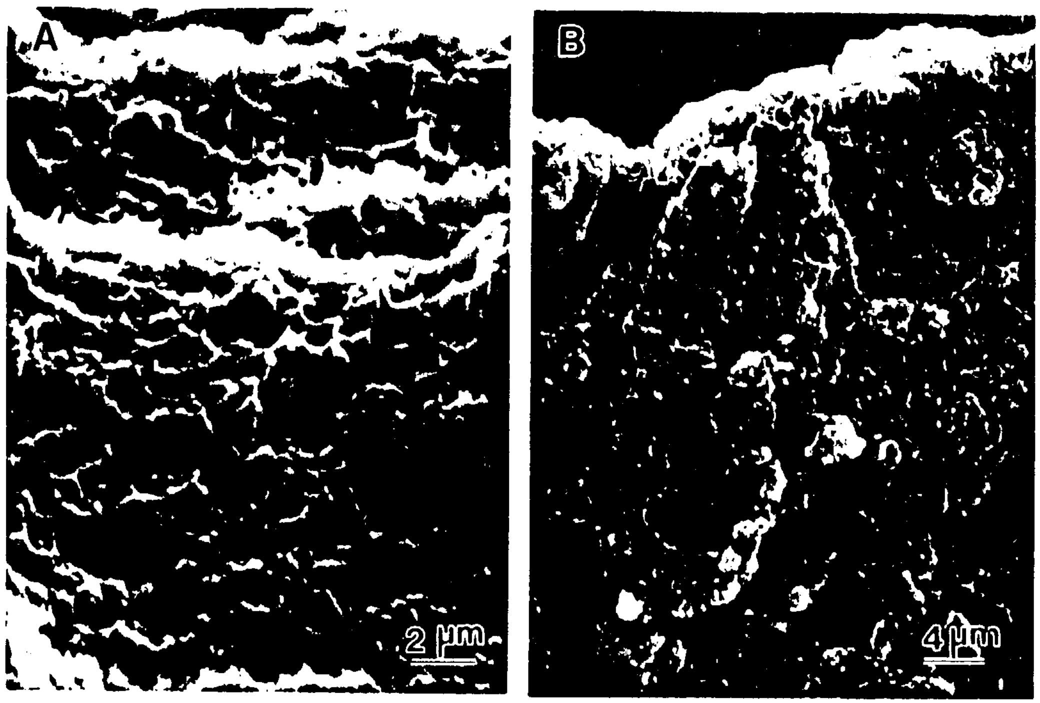
TEM micrograph of FVS0812 Al alloy after stretched to strain of 2%.



TEM micrographs of FVS0812 Al alloy after stretched to strain of 2%. a) bright field, b) weak beam dark field.

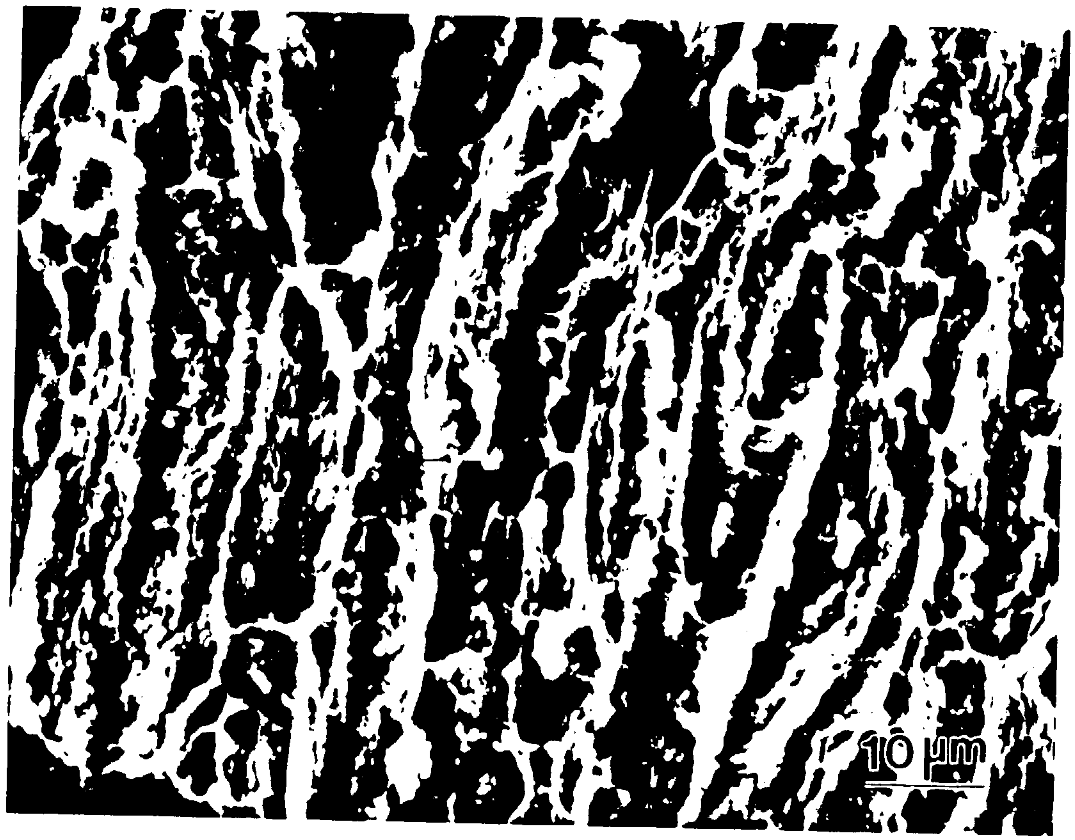


Creep crack growth fracture surface of FVS0812 (175 °C)

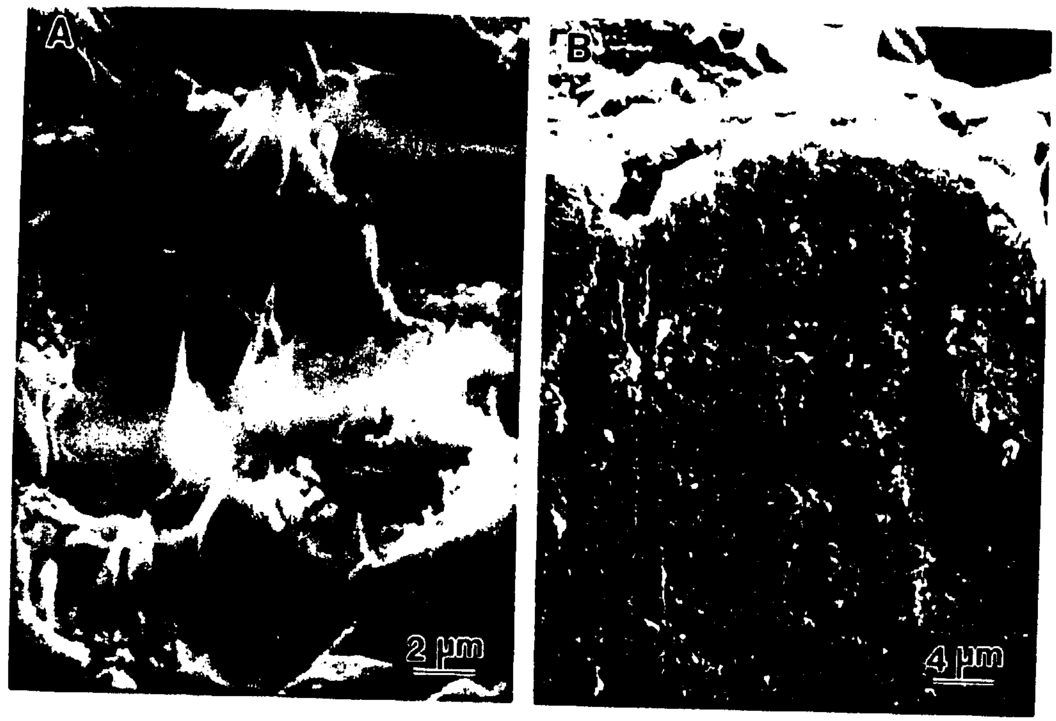


Side views of CCG fracture surface of FVS0812 (175 °C)
a) dimple fracture region   b) delamination region

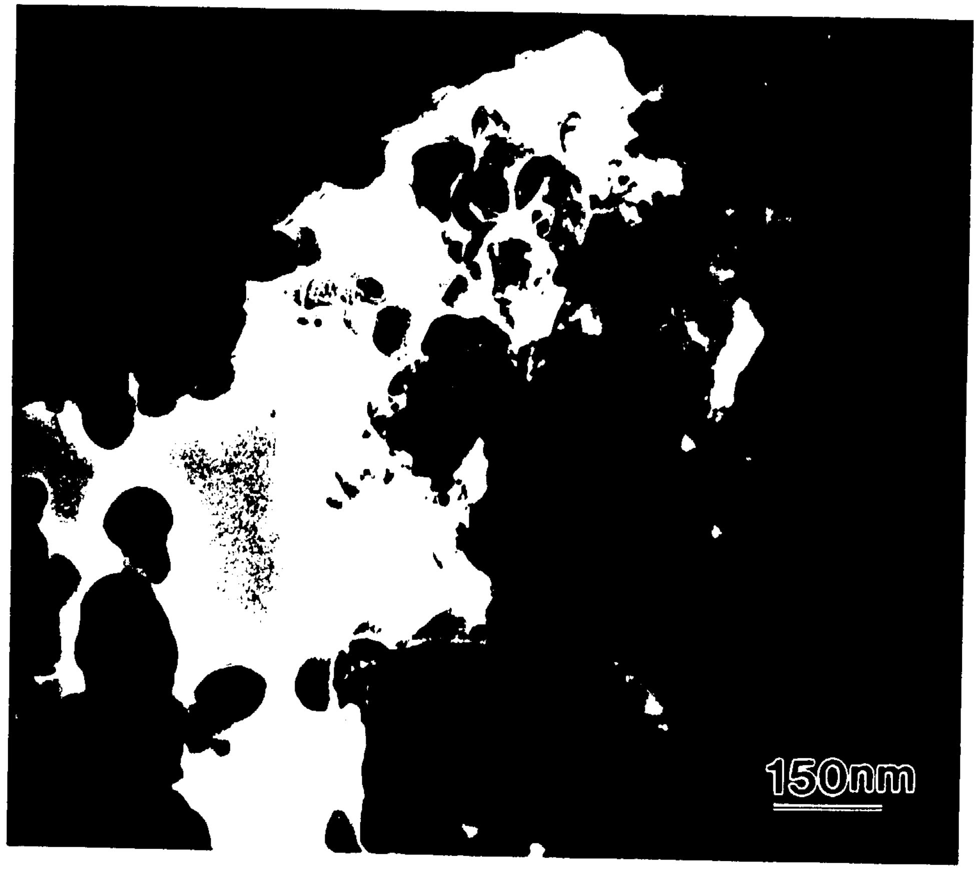
Nomarski contrast micrograph of the crack path profile of FVS0812 Al alloy after creep crack growth tested at 316 °C



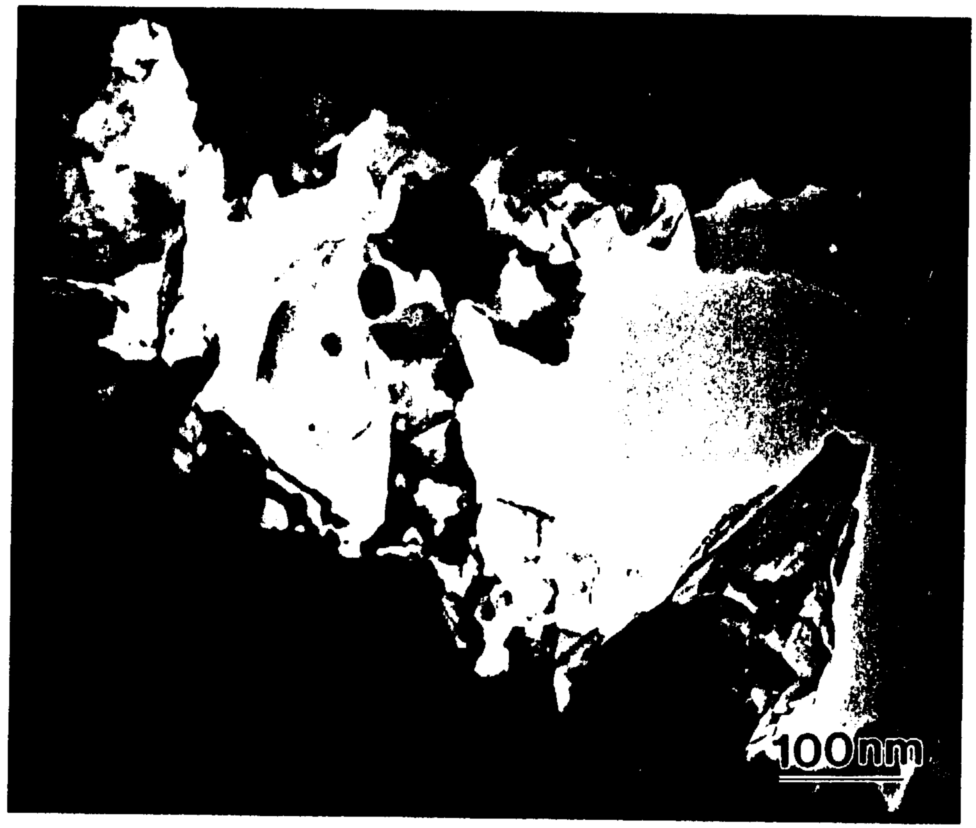
Creep crack growth fracture surface of FVS0812 (316 °C)



Side views of CCG fracture surface of FVS0812 (316 °C)
a) superplastic deformed and interdispersoid fracture region
b) delamination region



TEM micrograph of the crack tip of FVS0812 Al alloy after CCG tested at 316 °C



TEM micrograph of the crack tip of FVS0812 Al alloy after CCG tested at 316 °C

N90-22655

Program 3 **Deformation and Fracture of Thin Sheet Aluminum-Lithium Alloys: The Effect of Cryogenic Temperatures**

John A. Wagner and R.P. Gangloff

Objective

The objective of this PhD research program is to characterize and optimize the fracture resistance of Al-Cu-Li and Al-Cu-Li-In alloys, processed for thin sheet cryogenic tank applications, and through emphasis on micromechanical mechanisms for crack tip damage.

Fracture of Al-Li-Cu-Zr-X Alloys at Cryogenic Temperatures

John A. Wagner[1] and Richard P. Gangloff[2]

[1]Metallic Materials Branch, NASA-Langley Research Center
[2]Department of Materials Science

Abstract

The objective of this investigation is to characterize the fracture behavior and to define the fracture mechanisms for new Al-Li-Cu alloys, with emphasis on the role of indium additions and cryogenic temperatures. Three alloys have been investigated in rolled product form: 2090 baseline and 2090 + indium produced by Reynolds Metals, and commercial AA 2090-T81 produced by Alcoa. The experimental 2090 + In alloy exhibited increases in hardness and ultimate strength, but no change in tensile yield strength, compared to the baseline 2090 composition in the unstretched T6 condition. The reason for this behavior is not understood. Based on hardness and preliminary Kahn Tear fracture experiments, a nominally peak-aged condition (75 hours at 160°C) was employed for detailed fracture studies. Crack initiation and growth fracture toughnesses were examined as a function of stress state and microstructure using $J(\Delta a)$ methods applied to precracked compact tension specimens in the LT orientation. To date, $J(\Delta a)$ experiments have been limited to 23°C. Alcoa 2090-T81 exhibited the highest toughness regardless of stress state. Fracture was accompanied by extensive delamination associated with high angle grain boundaries normal to the fatigue precrack surface and progressed microscopically by a transgranular shear mechanism. In contrast the two peak-aged Reynolds alloys had lower toughnesses and fracture was intersubgranular without substantial delamination.

The influences of cryogenic temperature, microstructure, boundary precipitate structure, and deformation mode in governing the competing fracture mechanisms will be determined in future experiments. Results from this study will contribute to the development of predictive micromechanical models for fracture modes in Al-Li alloys, and to fracture resistant materials.

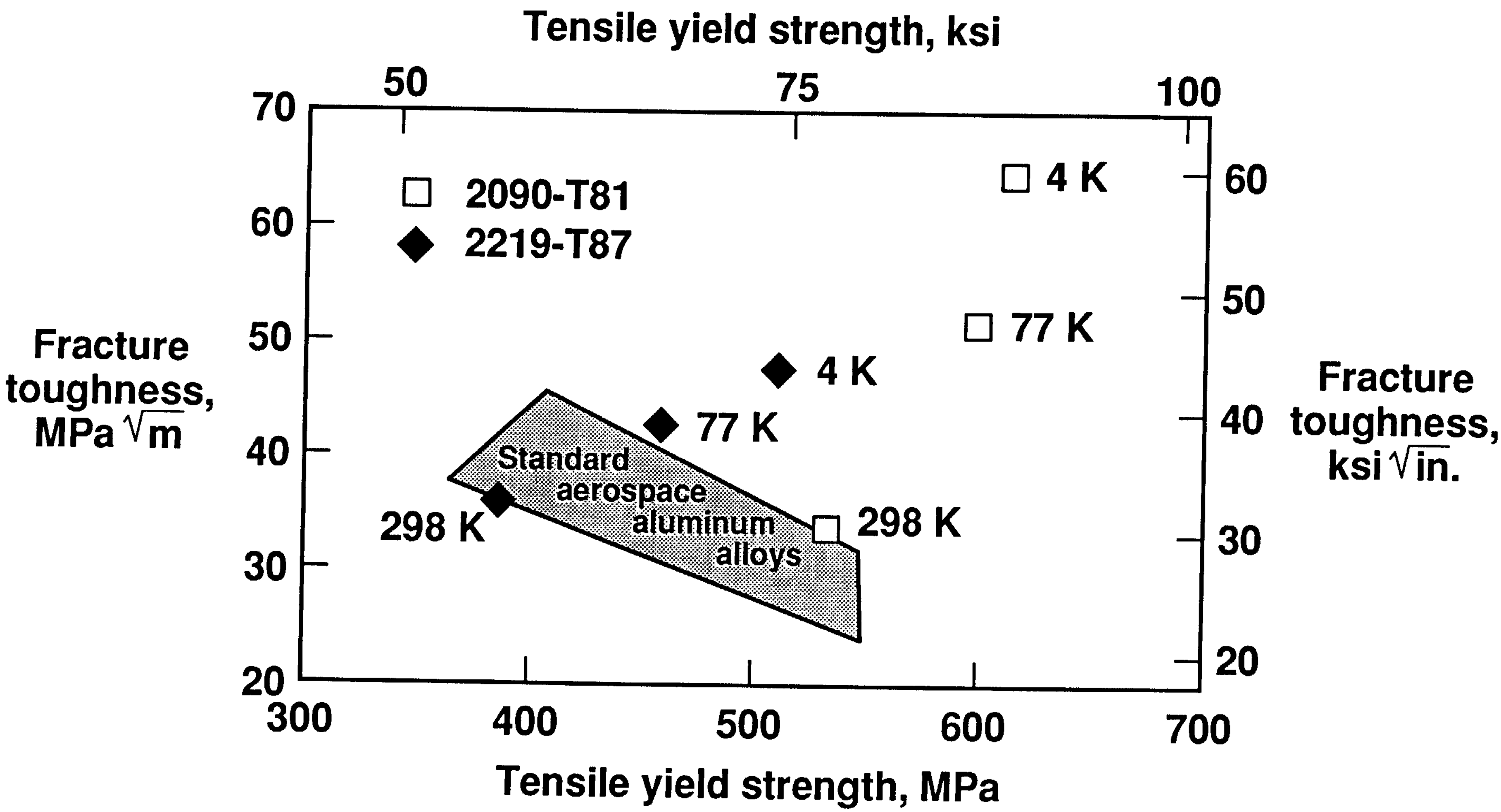
FRACTURE OF Al-Li-Cu-Zr-X ALLOYS AT CRYOGENIC TEMPERATURES

John A. Wagner

LA^2ST Program Review
NASA Langley Research Center

June 13-14, 1990

Al-Li ALLOYS FOR CRYOGENIC APPLICATIONS



al-li alloys

FRACTURE OF Al-Li-Cu-Zr-X ALLOYS AT CRYOGENIC TEMPERATURES

Problem

- No systematic investigation conducted to determine the interactive effects of:
  - Temperature
  - Delamination
  - Indium addition
  - Microstructure

  on the deformation and fracture of Al-Li-Cu-Zr-X alloys

Objective

- Determine the influences of intragranular features & grain boundary structure in governing the occurrence of various fracture mechanisms in Al-Li-Cu-X alloys at ambient and cryogenic temperatures.

FRACTURE OF Al-Li-Cu-Zr-X ALLOYS AT CRYOGENIC TEMPERATURES

Outline

- Initial experimentation (sheet)
- Proposed experiments (plate)
- Progress
- Future direction

fal-i/2

CHEMICAL COMPOSITIONS AND PROCESS HISTORIES OF AVAILABLE ALLOYS

R2090: Al-2.65Cu-2.17Li-0.13Zr-0.06Fe-0.05Si (wt%)
R2090+In: Al-2.60Cu-2.34Li-0.16Zr-0.05Fe-0.04Si-017In (wt%)

Material available:

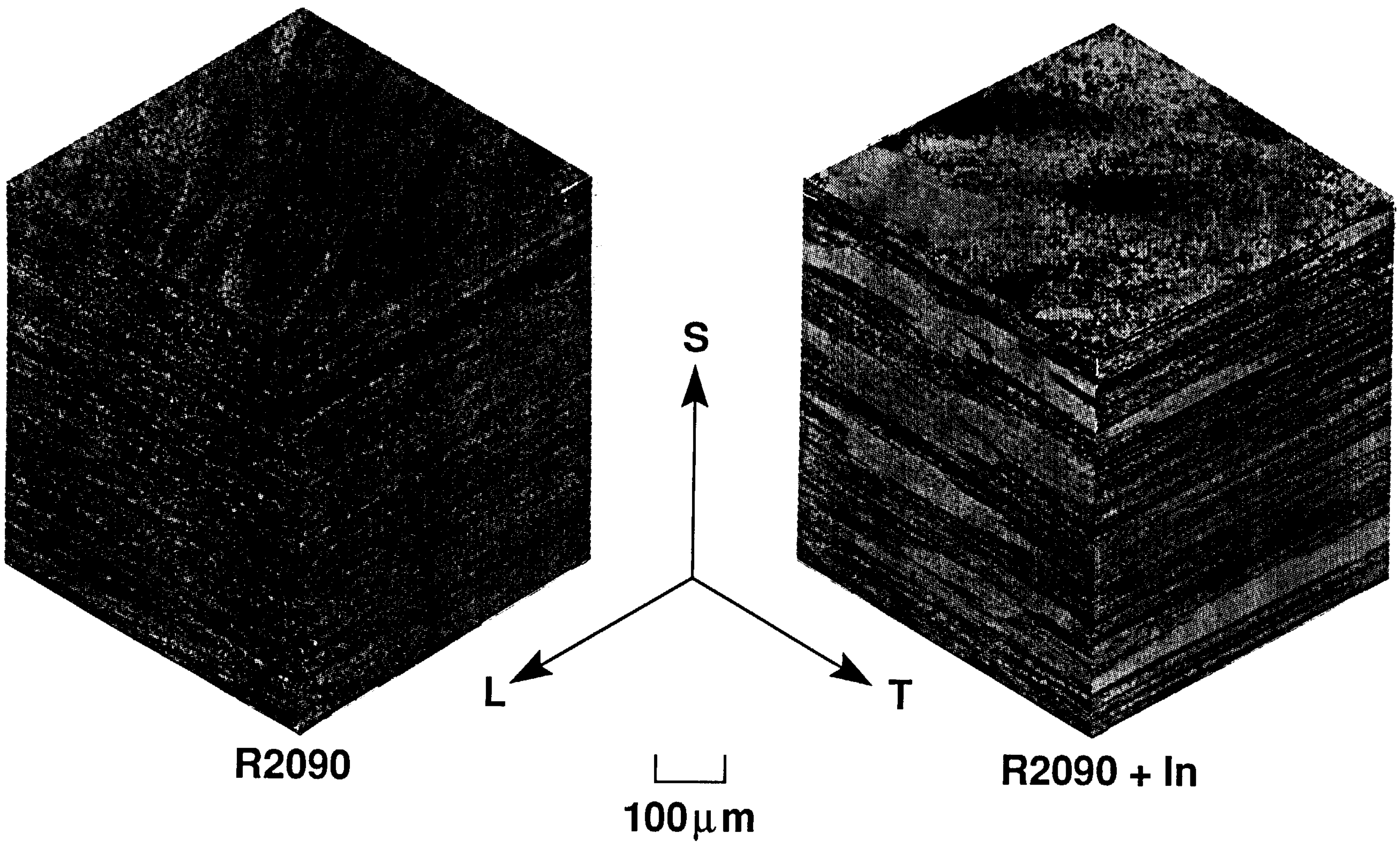
1. R2090 Base chemistry

⟶	0.125 in. sheet	TMTC	SHT	3% stretch
⟶	0.125 in. sheet		TMT C	SHT @ LaRC
	0.500 in. plate		SHT	3% stretch

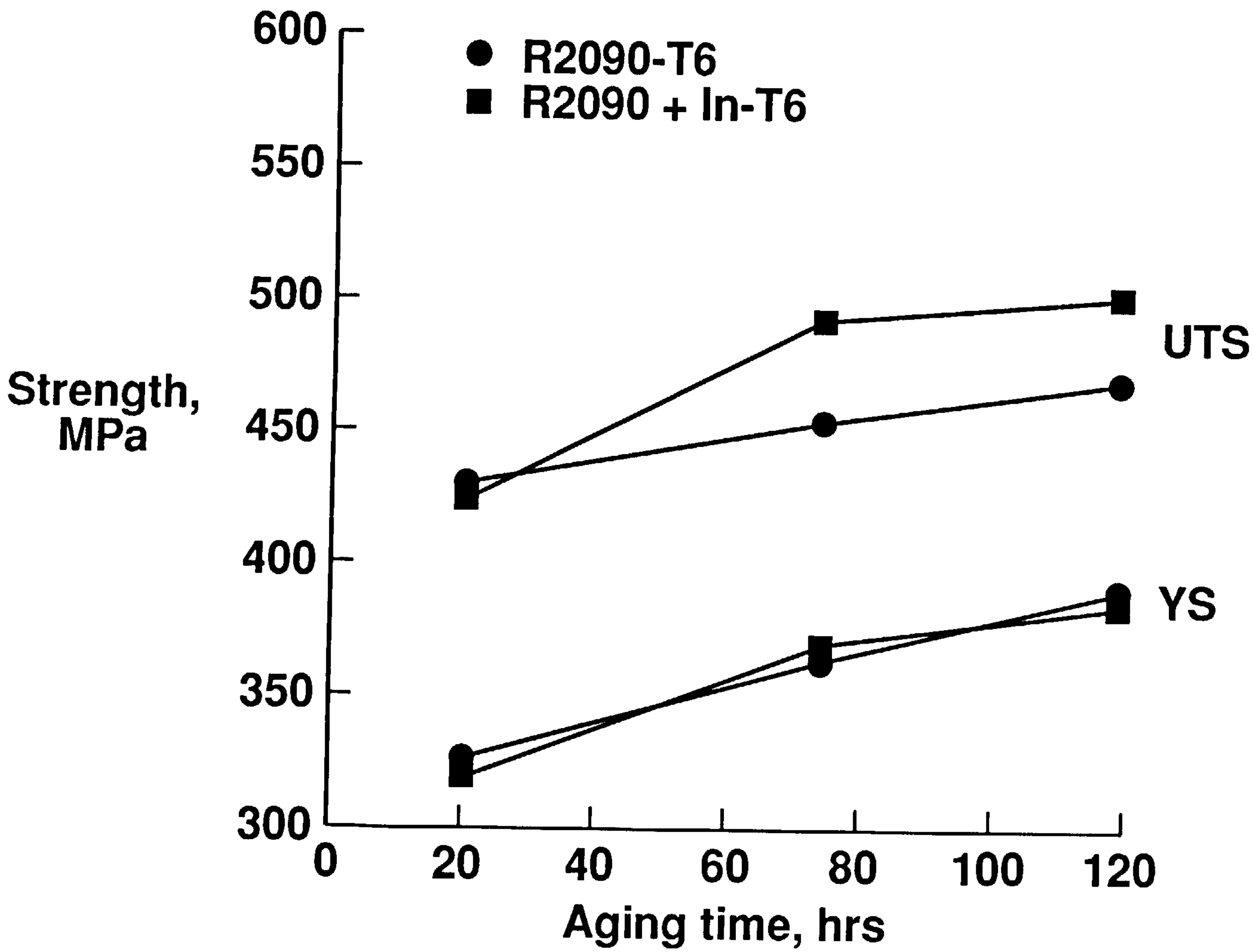
2. R2090+In

	0.125 in. sheet	TMTC	SHT	3% stretch
⟶	0.125 in. sheet		TMT C	SHT @ LaRC
	0.500 in. plate		SHT	3% stretch
	0.500 in. plate		SHT	0% stretch

SHEET MICROSTRUCTURES AFTER SOLUTION HEAT TREATMENT AND AGING



VARIATION OF ROOM TEMPERATURE STRENGTH WITH AGING TIME AT 160°C

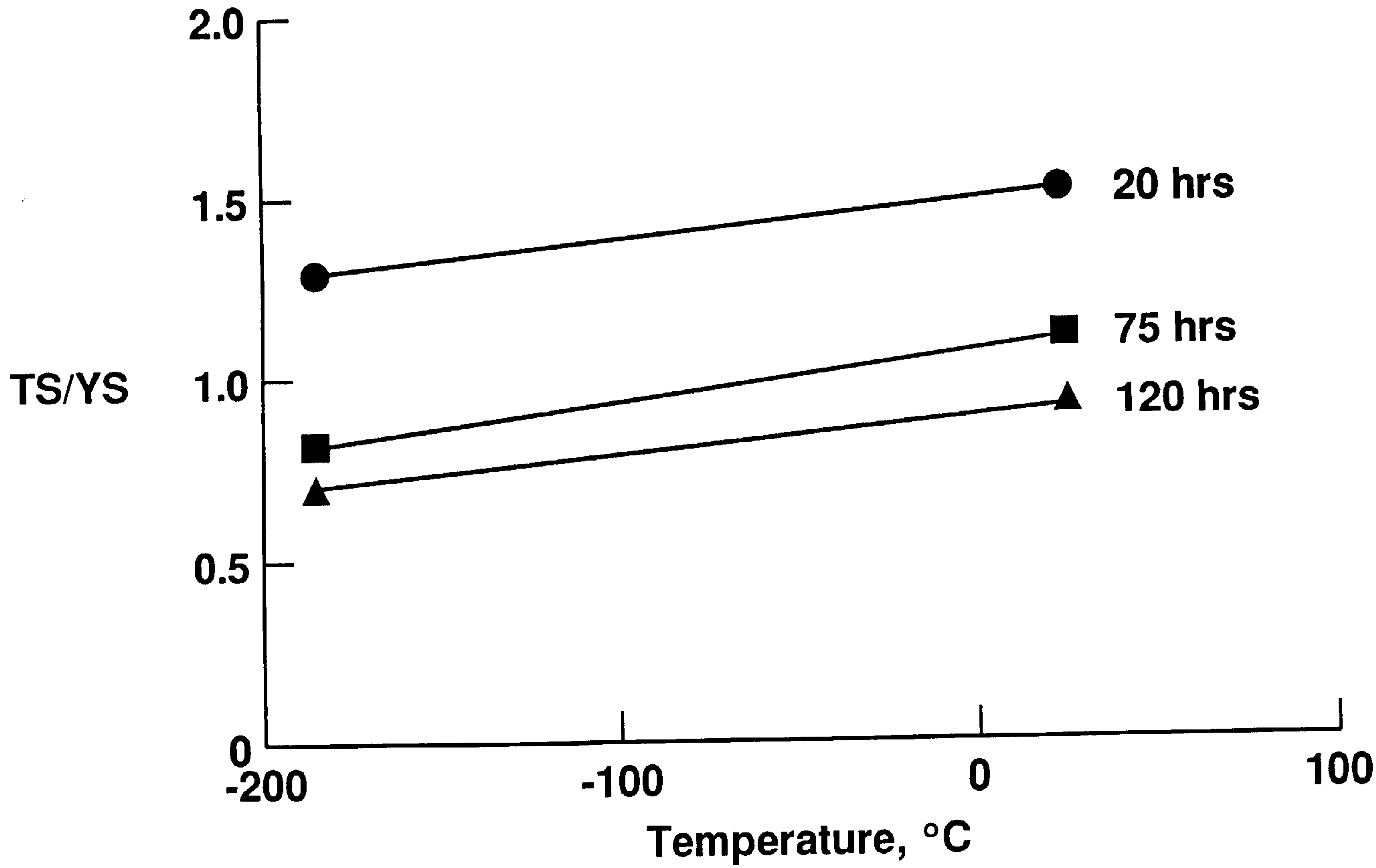


INDIUM ADDITIONS TO Al-Li-Cu-Zr ALLOYS

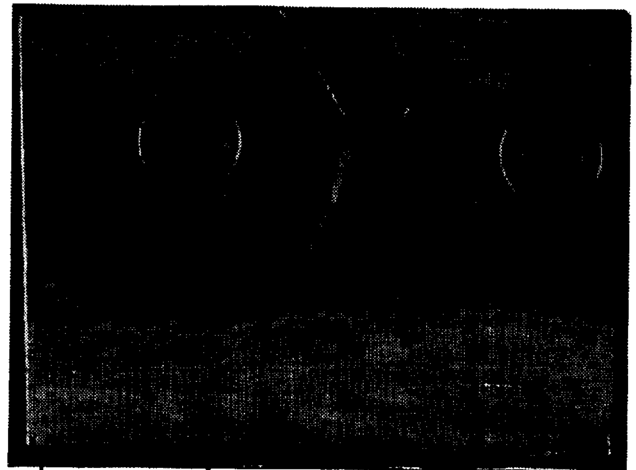
Observations

- Increased in σ_{ys} + σ_{ult} observed for 30 lb laboratory permanent mold casting attributed to increase number density of T_1
- For 350 lb DC castings indium additions increased σ_{ult} but had no effect on σ_{ys} regardless of product form
- Variation in recrystallization with processing variables requires further investigation

TEAR STRENGTH TO YIELD STRENGTH RATIO OF 2090 + In-T6

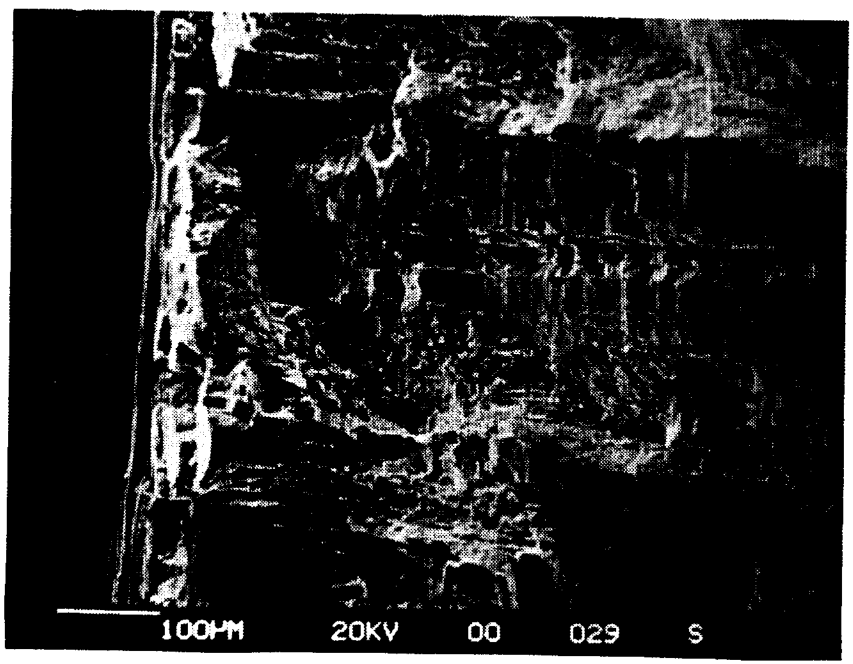


FRACTURE PATH AND FRACTURE SURFACE MORPHOLOGY OF R2090 BASELINE TESTED AT ROOM TEMPERATURE

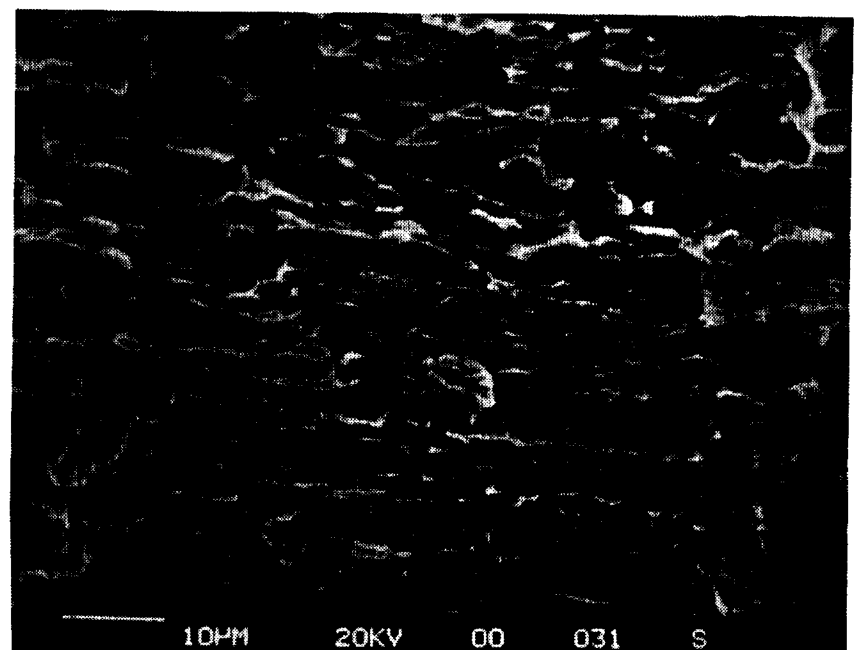


0.562 in.

A



B



C

CHEMICAL COMPOSITIONS AND PROCESS HISTORIES OF AVAILABLE ALLOYS

R2090: Al-2.65Cu-2.17Li-0.13Zr-0.06Fe-0.05Si (wt%)
R2090+In: Al-2.60Cu-2.34Li-0.16Zr-0.05Fe-0.04Si-017In (wt%)

Material available:

1. R2090 Base chemistry

	0.125 in. sheet	TMTC	SHT	3% stretch
	0.125 in. sheet		TMT C	SHT @ LaRC
⟶	0.500 in. plate		SHT	3% stretch

2. R2090+In

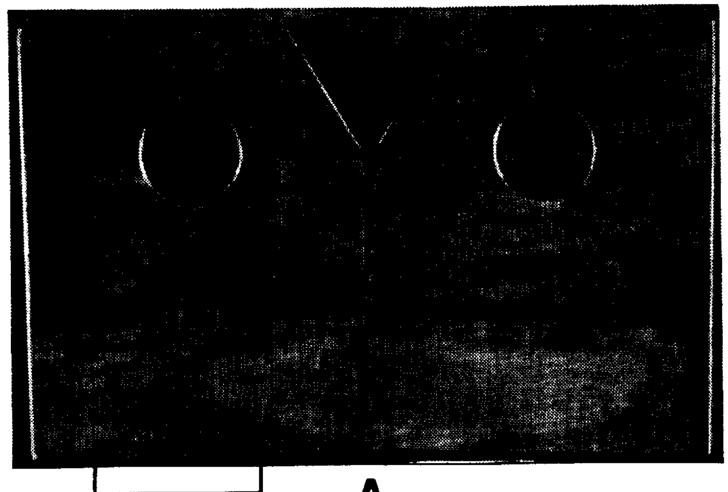
	0.125 in. sheet	TMTC	SHT	3% stretch
	0.125 in. sheet		TMT C	SHT @ LaRC
	0.500 in. plate		SHT	3% stretch
⟶	0.500 in. plate		SHT	0% stretch

3. A2090

⟶	0.750 in. sheet		T81 (T8E41)	

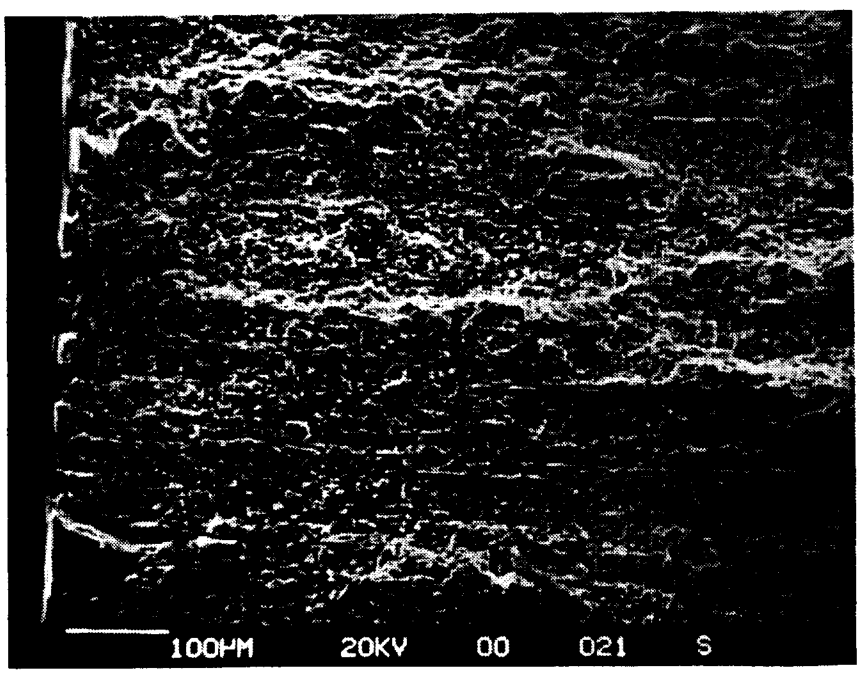
ccppr.2

FRACTURE PATH AND FRACTURE SURFACE MORPHOLOGY OF R2090 BASELINE TESTED AT CRYOGENIC TEMPERATURES

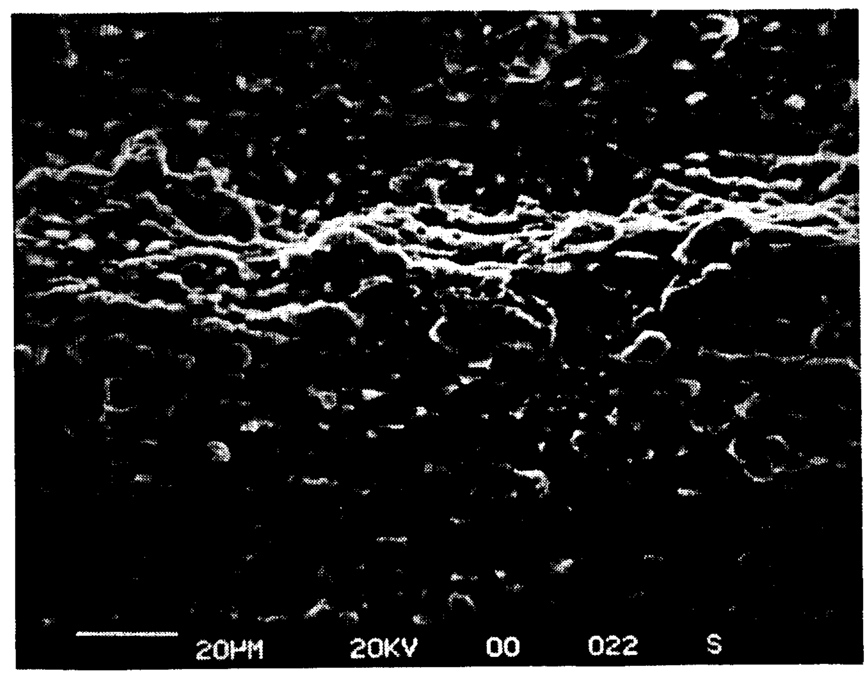


0.562 in.

A

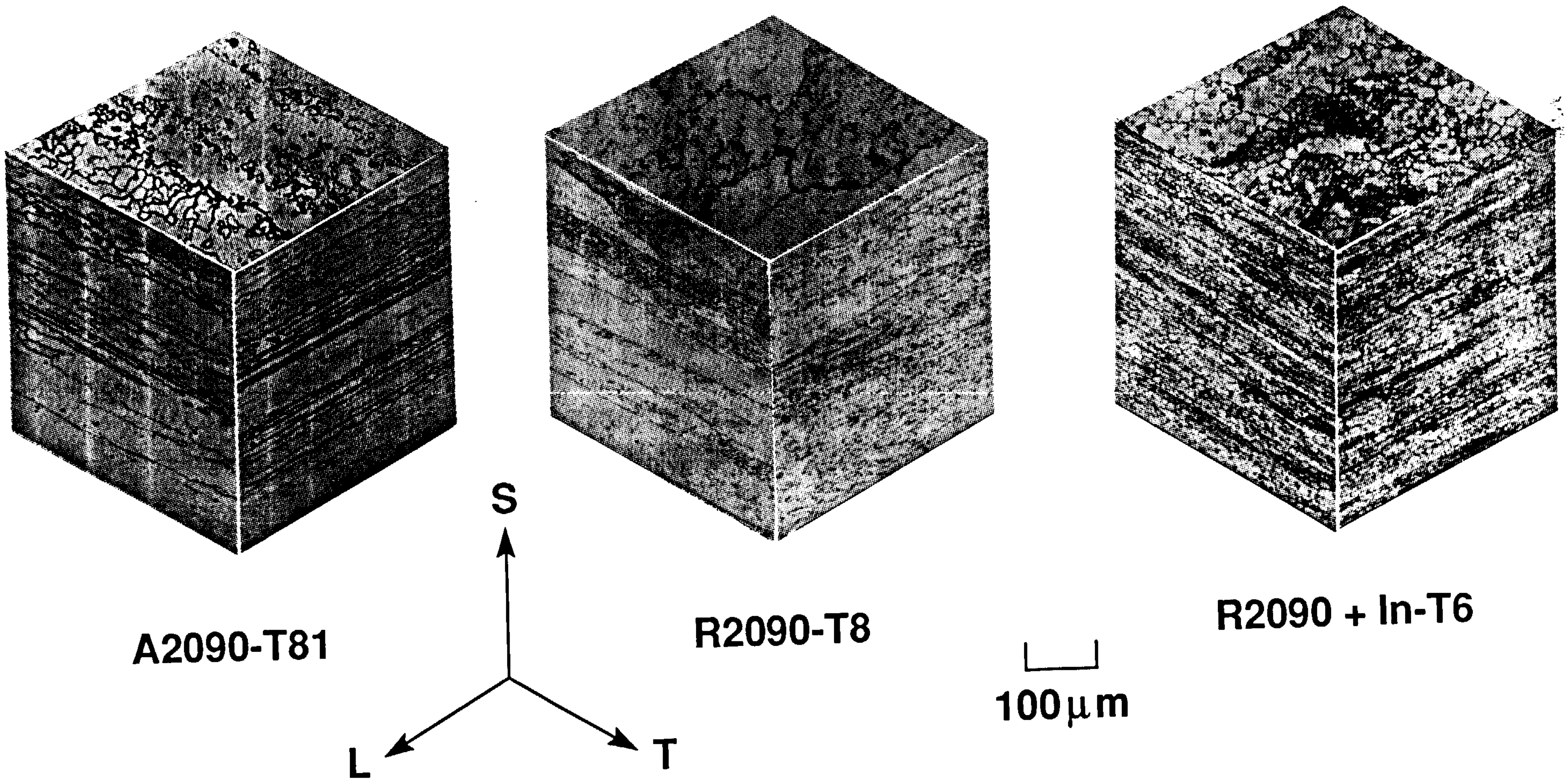


B



C

MICROSTRUCTURES OF PLATE ALLOYS



OBJECTIVES OF EXPERIMENTAL TEST MATRIX

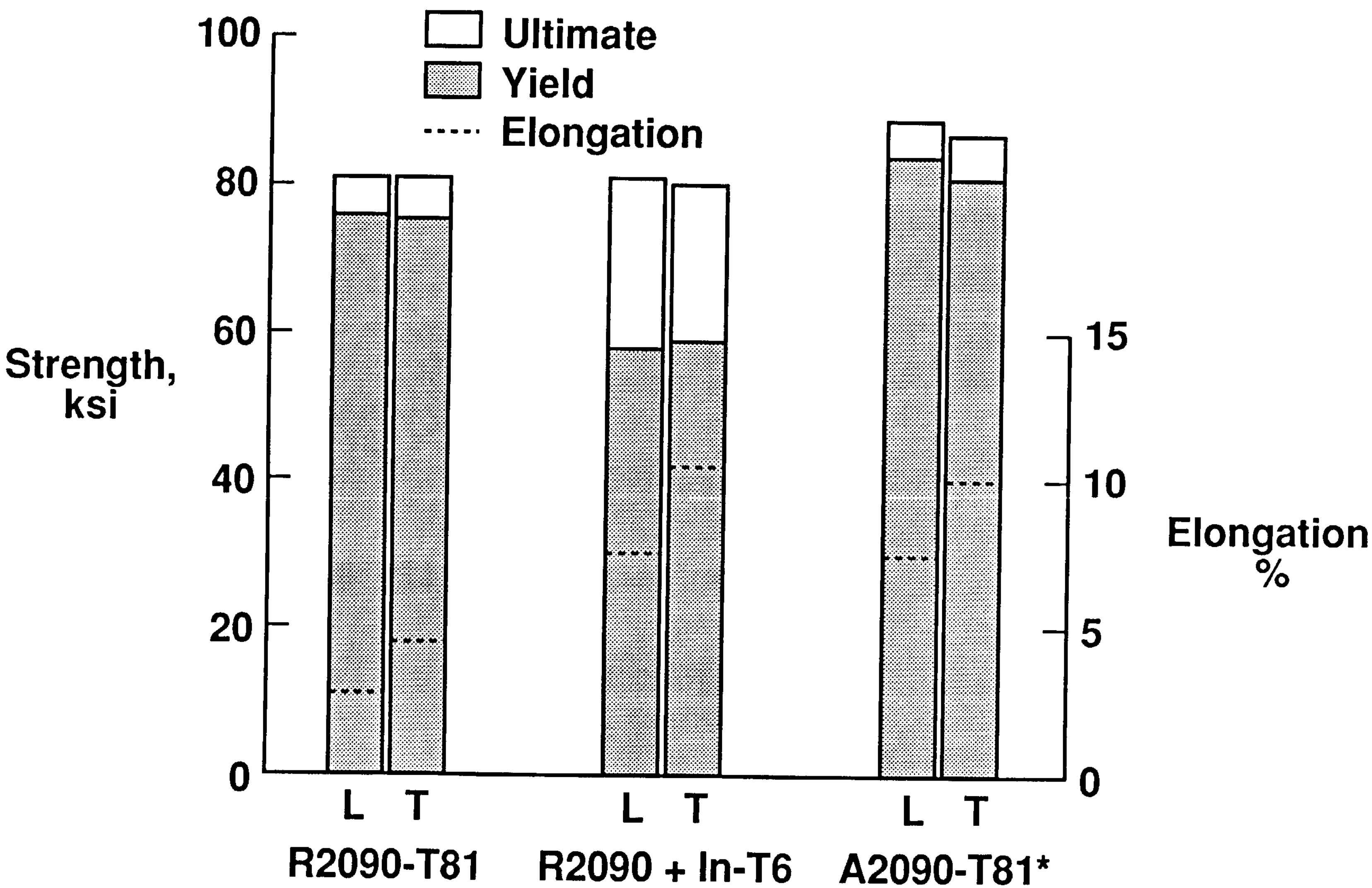
Primary objective

- Determine the effect of key variables on J (Δa) behavior, fracture path and fracture mode of Al-Li-Cu-Zr-X alloys
    - Temperature
    - Constraint
    - In addition

Secondary objective

- Examine the general deformation & fracture behavior of Al-Li-Cu-Zr-X alloys with respect to:
    - Orientation
    - Process history
    - Material vendor

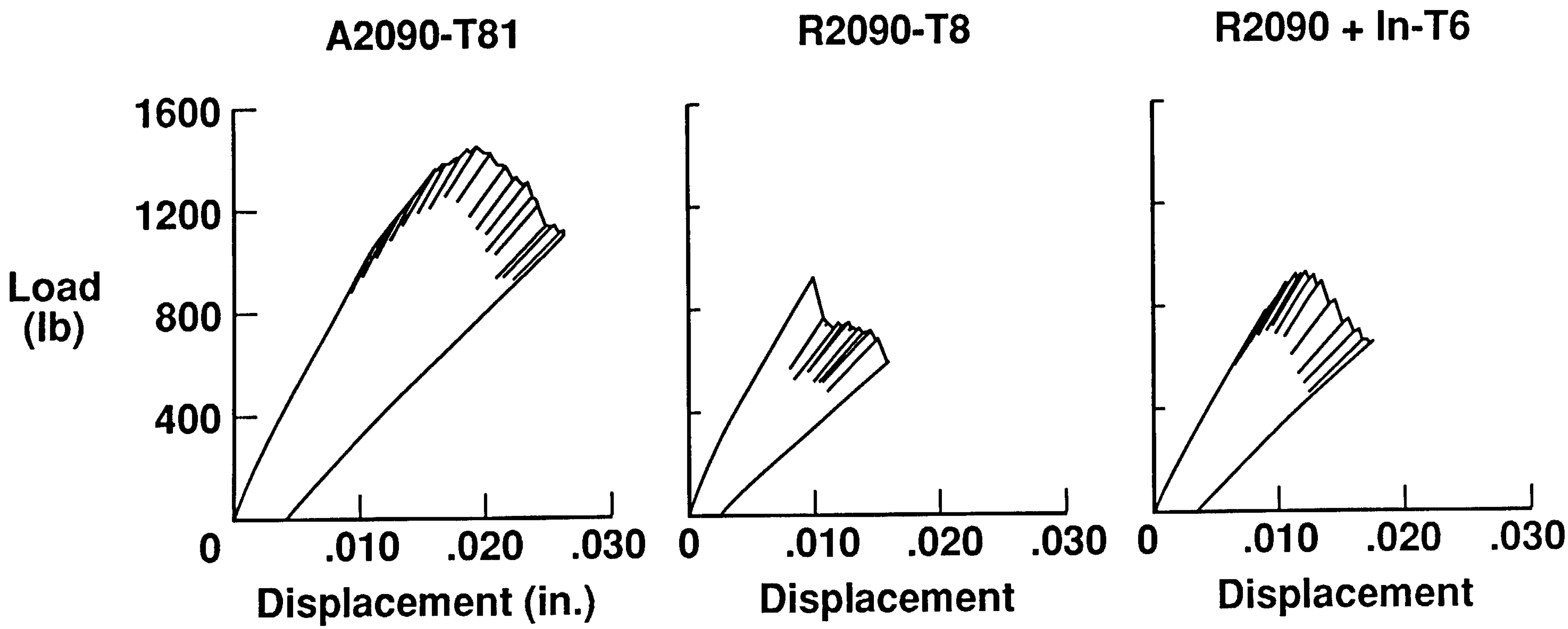
TENSILE PROPERTIES Al-Li-Cu-Zr ALLOYS



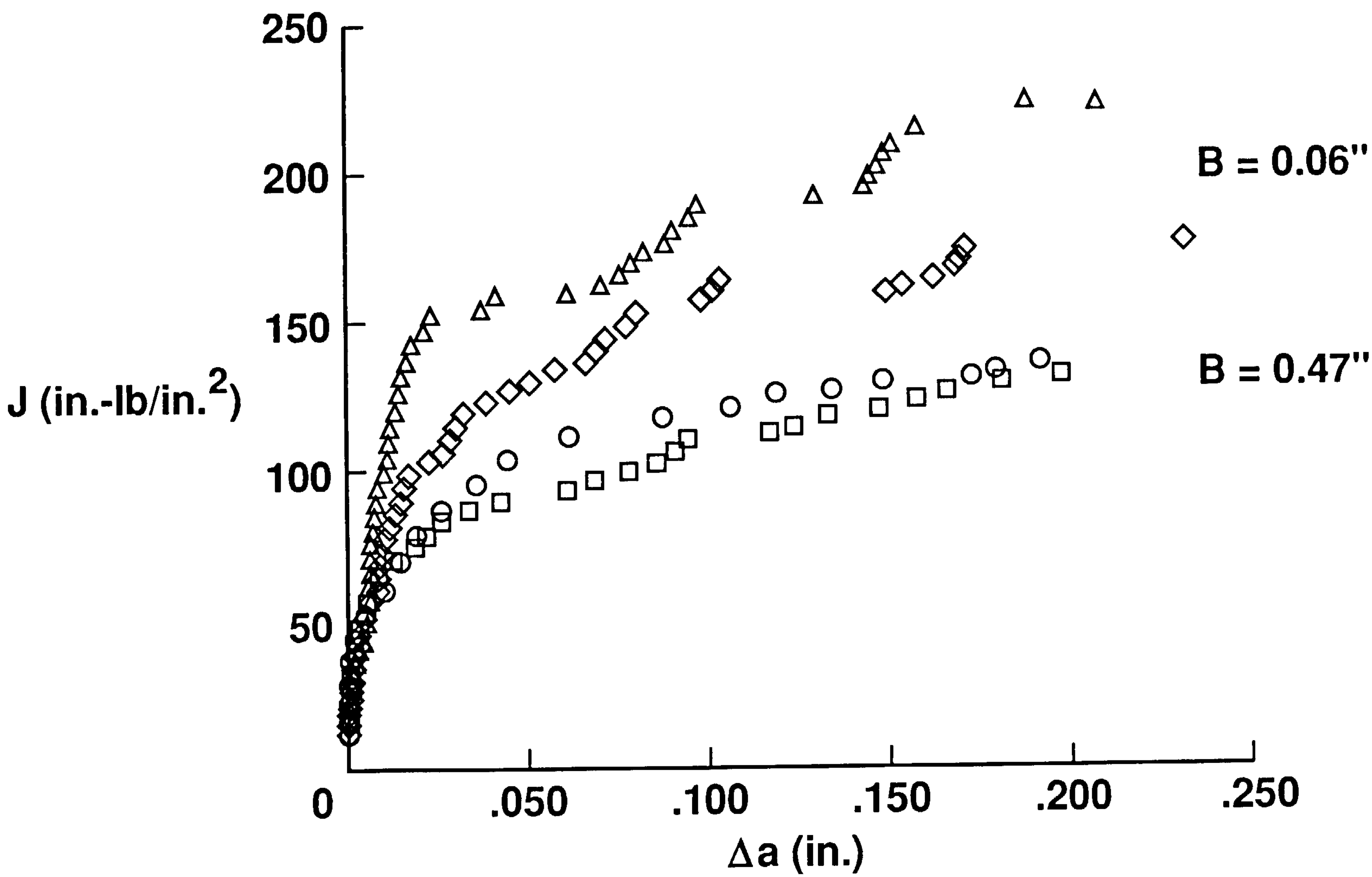
* Values from NIST

TYPICAL LOAD VERSUS DISPLACEMENT CURVES FOR 0.473 IN. SPECIMENS WITH SIDEGROOVES

LT orientation
Compact tension

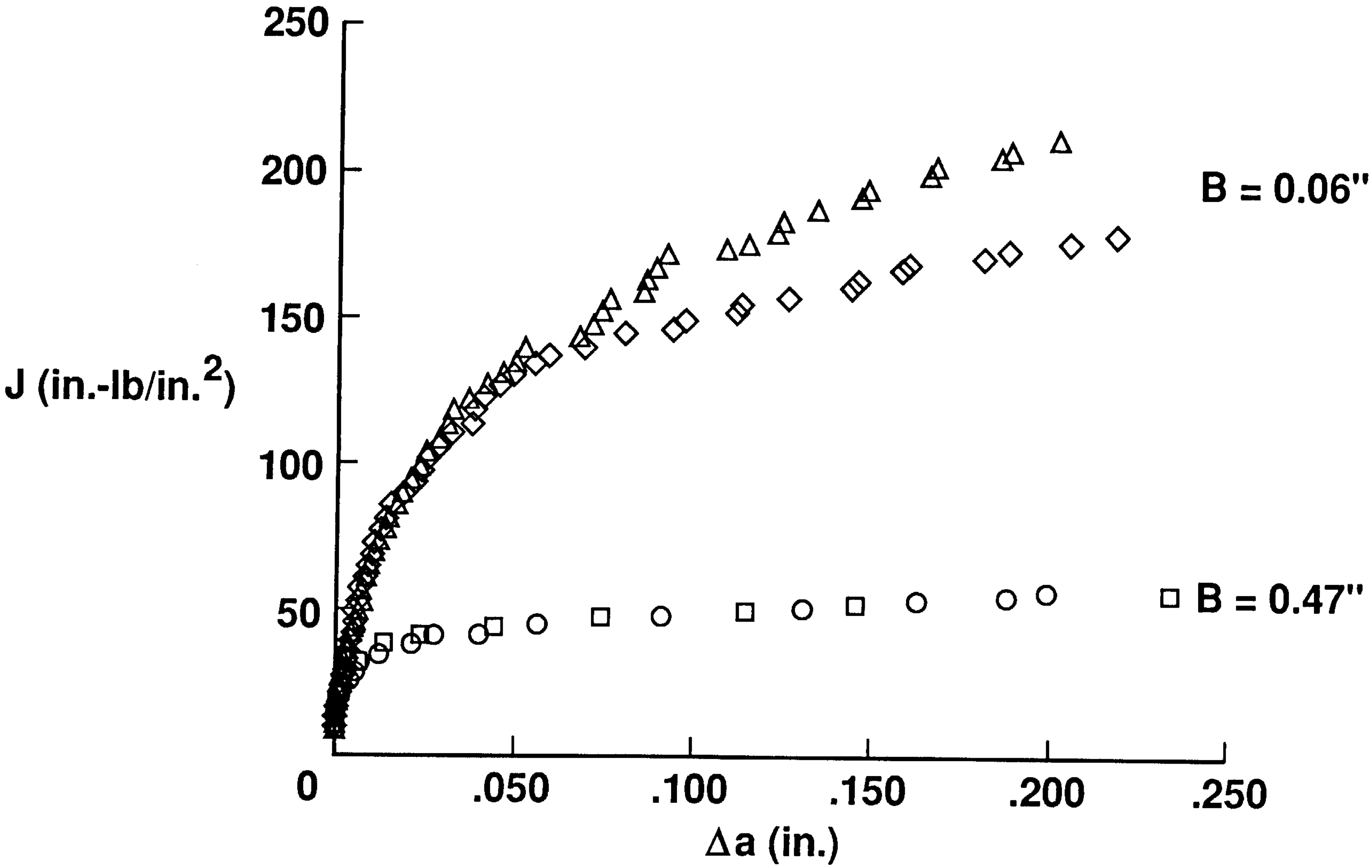


J-R CURVE FOR A2090-T81



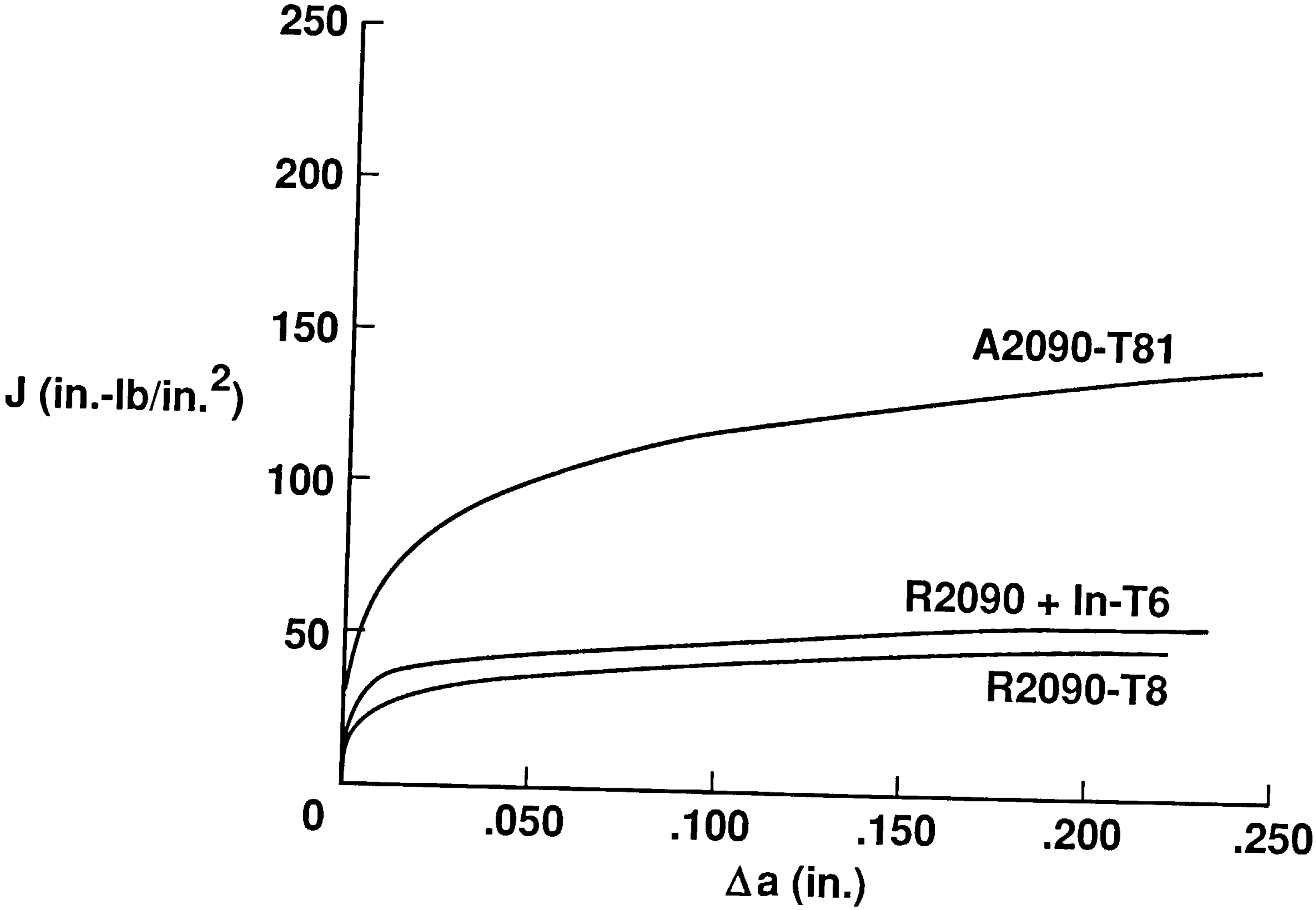
j-r curve a2090

J-R CURVE FOR R2090 + In-T6

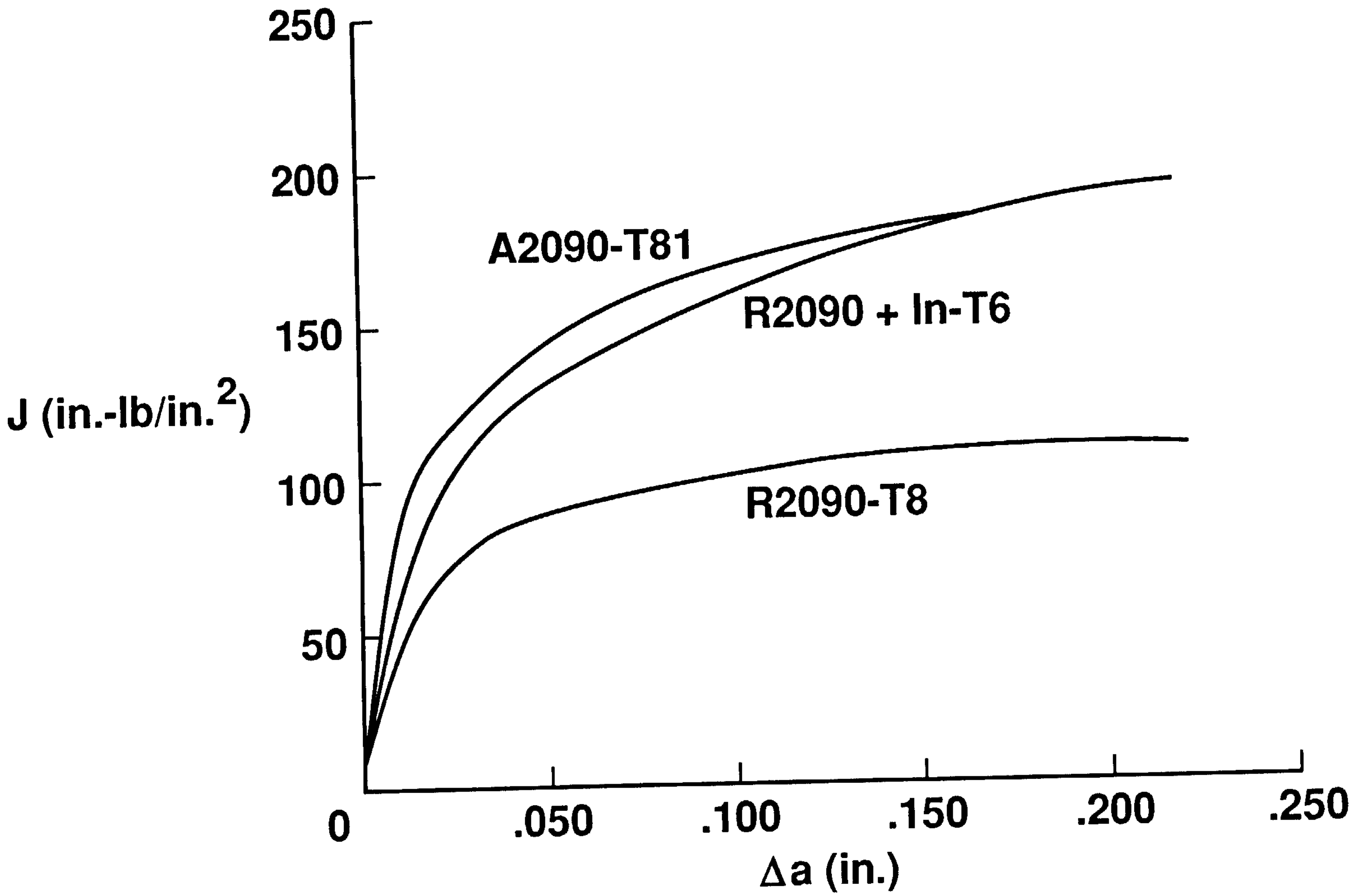


j-r curve

FRACTURE TOUGHNESS R-CURVE FOR 0.47" THICK SPECIMENS

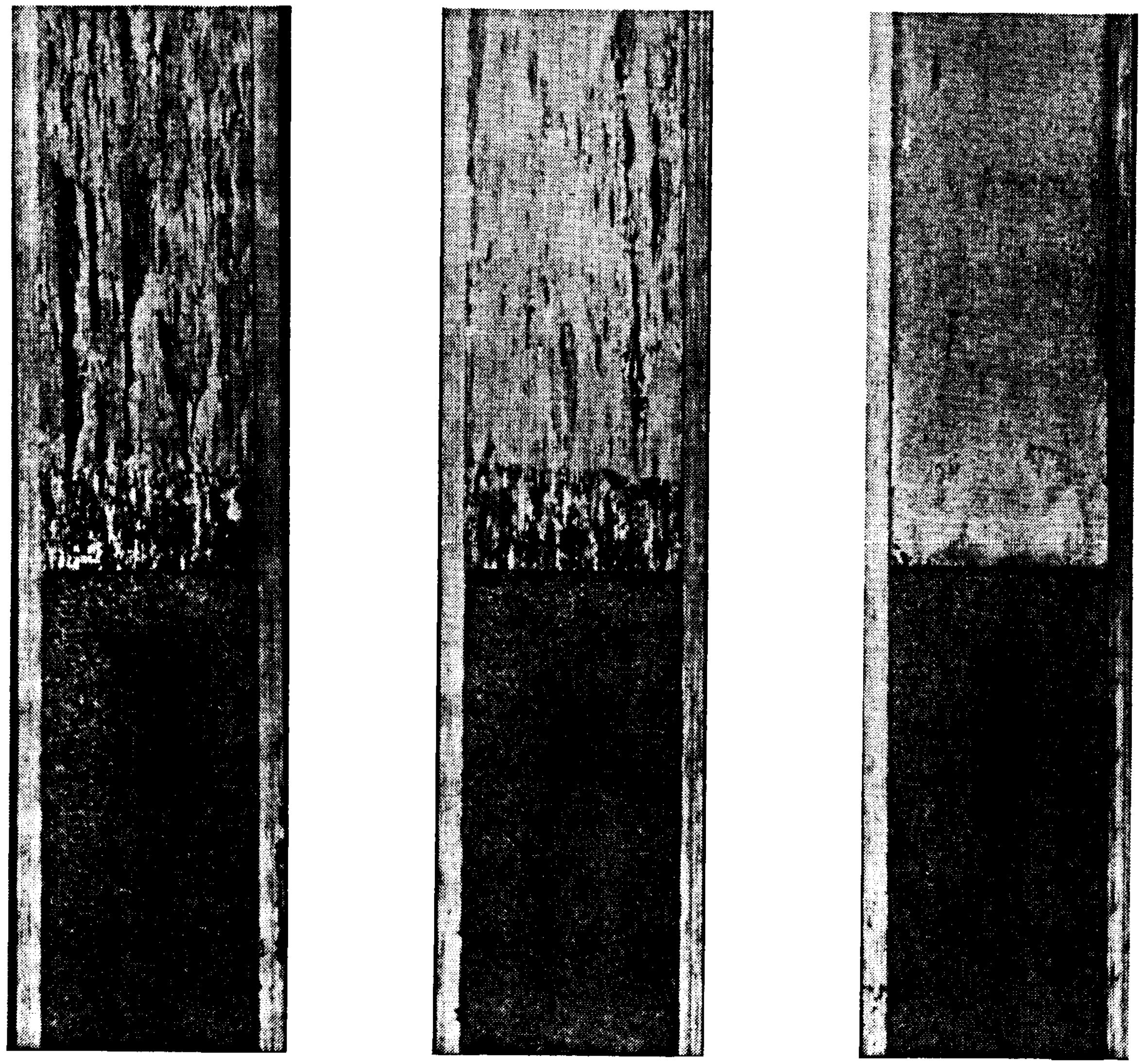


FRACTURE TOUGHNESS R-CURVE FOR 0.06" THICK SPECIMENS



ftr-curve 0.06

FRACTURE MORPHOLOGY OF 0.47" THICK COMPACT TENSION SPECIMENS



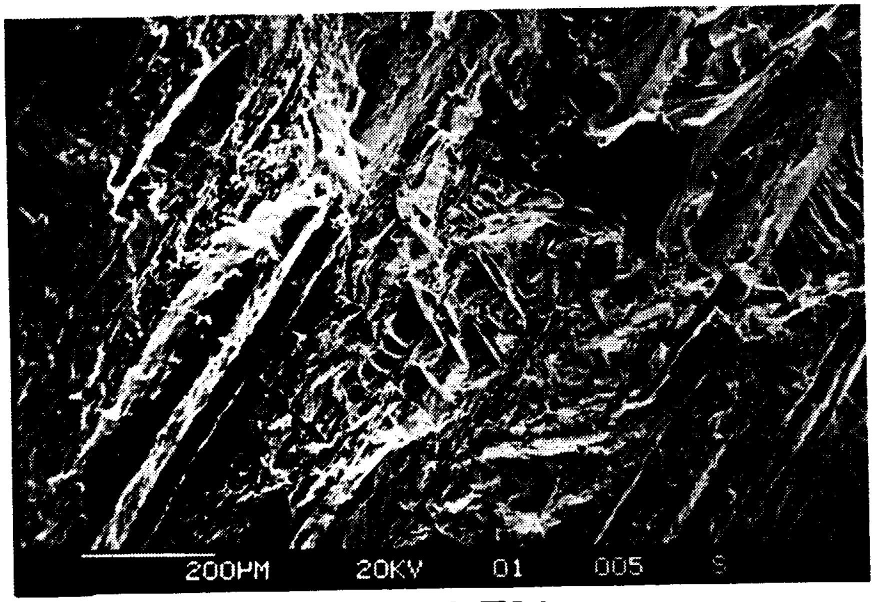
A2090-T81 R2090-T8 R2090 + In-T6

FRACTURE MODE AND AVERAGE J_{Ic} FOR PLATE 2090

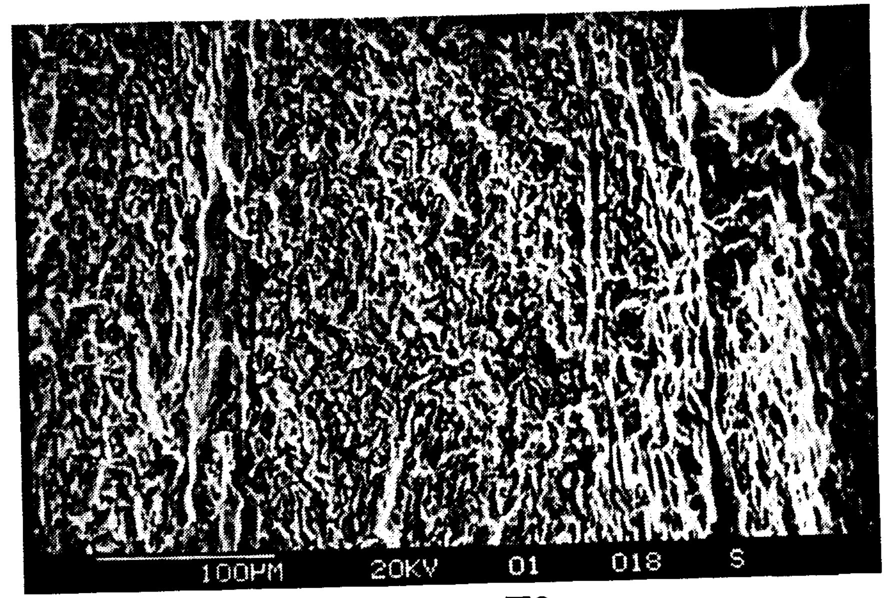
Material	Thickness (in.)	J_{Ic} (in.-lb/in.^{2})	K_{Ic} (ksi $\sqrt{in.}$)	$\frac{\text{Plastic zone}}{\text{thickness}}$	Amount of delamination	Primary fracture mode
A2090-T81	0.06	75	31	0.37	Medium	TGS/min. ISG
	0.47	56	27	0.03	High	TGS/min. ISG
R2090-T8	0.06	44	24	0.25	Low	ISG
	0.47	30*	20	0.02	Medium	ISG
R2090 + In-T6	0.06	55	27	0.57	Low	ISG
	0.47	32	21	0.05	Low	ISG

TGS $\equiv$ transgranular shear
ISG $\equiv$ intersubgranular
* Invalid according to ASTM E813

FRACTURE SURFACE MORPHOLOGY OF PRECRACK/FAST FRACTURE TRANSITION REGION

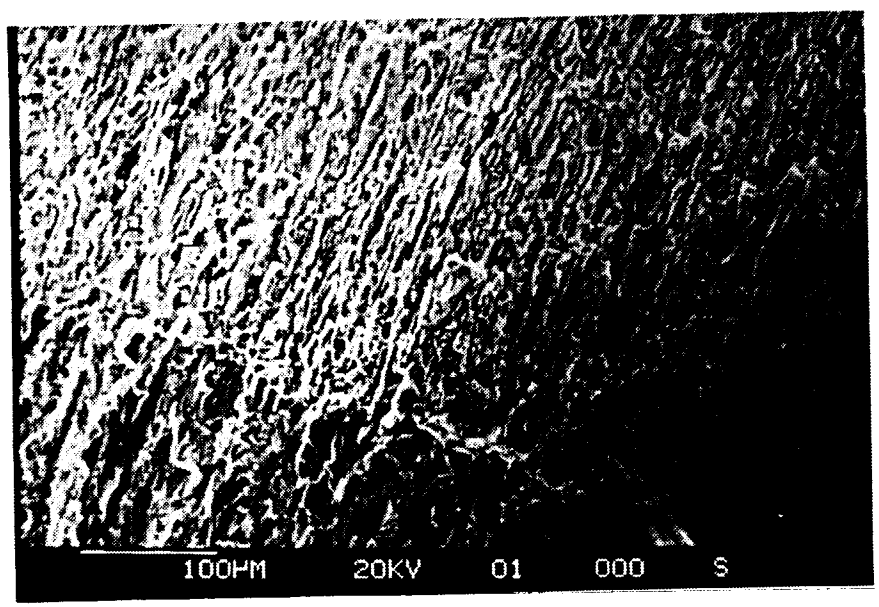


A2090-T81



R2090-T8

R2090 + In-T6



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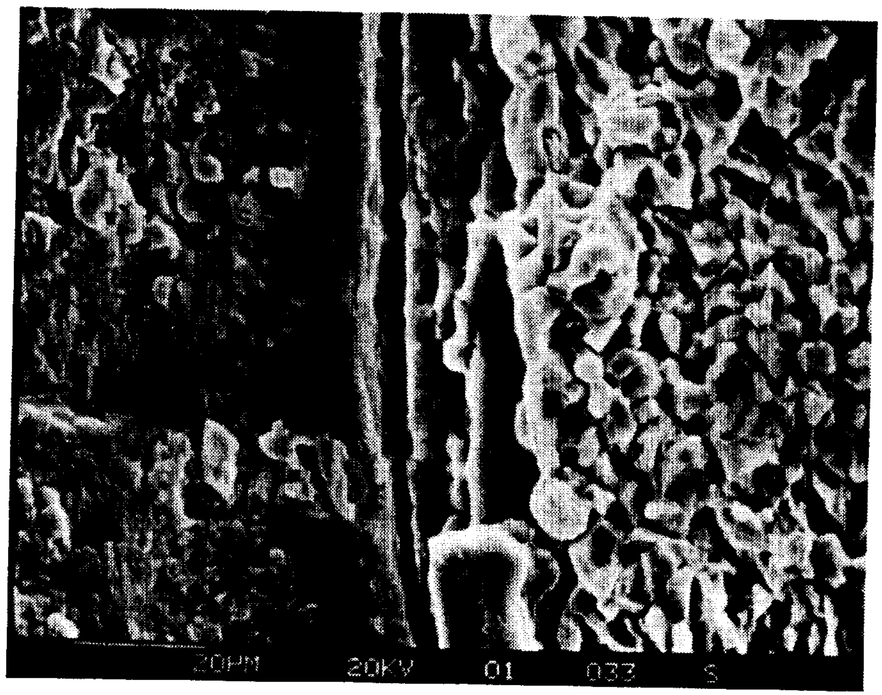
SEM PHOTOMICROGRAPH OF REGION ADJACENT TO DELAMINATION IN R2090-T8



SUMMARY

- Increase in σ_{ult} and no change in σ_{ys} observed for both sheet and plate alloys of R2090 + In-T6
- Alcoa 2090-T81 0.75" plate exhibited excellent tensile properties with moderate toughness
- Moderate toughness associated with A2090-T81 associated with large amount of delamination and transgranular shear
- Fracture toughness was lower in R2090 + In-T6 and R2090-T8 and characterized by intersubgranular fracture
- Difference in toughness between A2090-T81 and R2090 + In-T6 decreases in plane stress regime

FUTURE PLANS

What is the influence of microstructure and stress state in controlling the toughness and fracture mode of Al-Li-Cu-Zr-X alloys at cryogenic temperatures? Specifically, what promotes transgranular shear mode of failure?

- Grain structure
- Temperature
- Delamination
- Stress state
- In addition

N90-22656

Program 4 **Measurements and Mechanisms of Localized Aqueous Corrosion in Aluminum-Lithium Alloys**

Rudolph G. Buchheit, Jr. and Glenn E. Stoner

Objectives

The objective of this research is to characterize the localized corrosion and stress corrosion crack initiation behavior of Al-Li-Cu alloy 2090, and to gain an understanding of the role of local corrosion and occluded cell environments in the mechanisms of pitting and initiation and early-stage propagation of stress corrosion cracks.

Stress Corrosion in 2090: The Role of Localized Corrosion in the Subgrain Boundary Region

R. G. Buchheit
G. E. Stoner

Department of Materials Science

Like most heat treatable aluminum alloys, localized corrosion and stress corrosion of Al-Li-Cu alloys is strongly dependent on the nature and distribution of second phase particles. To develop a mechanistic understanding of the role of localized corrosion in the stress corrosion process, bulk samples of T_1 (Al_2CuLi) and a range of Al-Cu-Fe impurity phases were prepared for electrochemical experiments. Potentiodynamic polarization and galvanic couple experiments were performed in standard 0.6 M NaCl and in simulated crevice solutions to assess corrosion behavior of these particles with respect to the α-Al matrix.

A comparison of time to failure versus applied potential using a constant load, smooth bar SCC test technique in Cl^-, Cl^-/CrO_4^{2-} and Cl^-/CO_3^{2-} environments shows that rapid failures are to be expected when applied potentials are more positive than the breakaway potential (E_{br}) of T_1 (crack tip) but less than E_{br} of α-Al (crack walls). It is shown that this criterion is not satisfied in aerated Cl^- solutions. Accordingly, SCC resistance is good. This criterion is satisfied, however, in an alkaline isolated fissure exposed to a CO_2 containing atmosphere. Rapid failure induced by these fissures has recently been termed "preexposure embrittlement."

Anodic polarization shows that the corrosion behavior of T_1 is relatively unaffected in alkaline CO_3^{2-} environments but the α-Al phase is rapidly passivated. X-ray diffraction of crevice walls from artificial crevices suggests that passivation of α-Al occurs as Bayerite ($Al(OH)_3$) imbibes solvated lithium and carbonate ions to form a hydrotalcite-type compound $[LiAl_2(OH)_6]_2^+ \cdot CO_3^{2-} \cdot nH_2O$.

Stress Corrosion of 2090: The Role of Localized Corrosion in the Subgrain Boundary Region

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G.E. Stoner

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Charlottesville, Virginia 22901

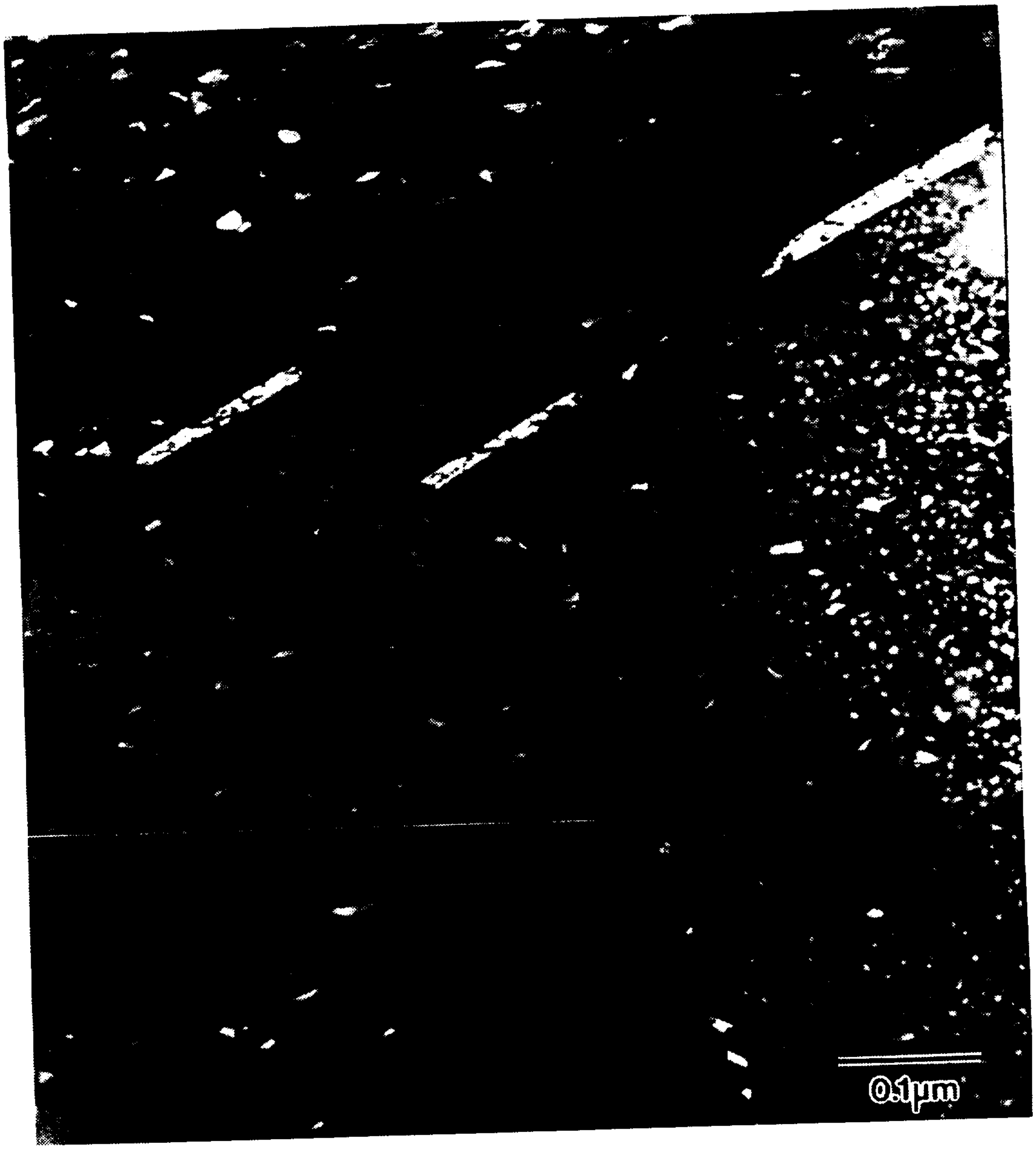
Sponsored by NASA, Langley Research Center, Hampton, Virginia

Outline

* Microstructural Heterogeneity and Localized Corrosion

* Time to Failure vs. Applied Potential in Cl^- and Cl^-/CrO_4^{2-}

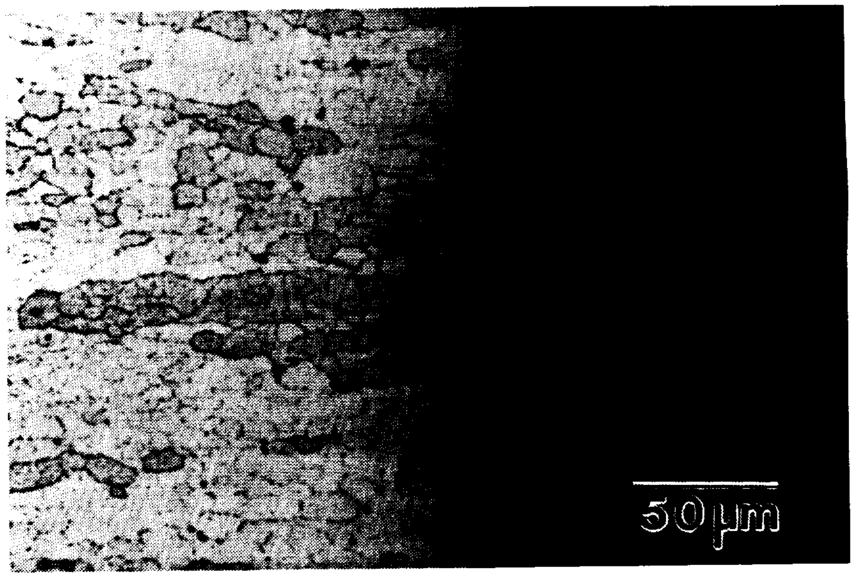
* SCC in CO_3^{2-} Environments, "Pre-Exposure Embrittlement"

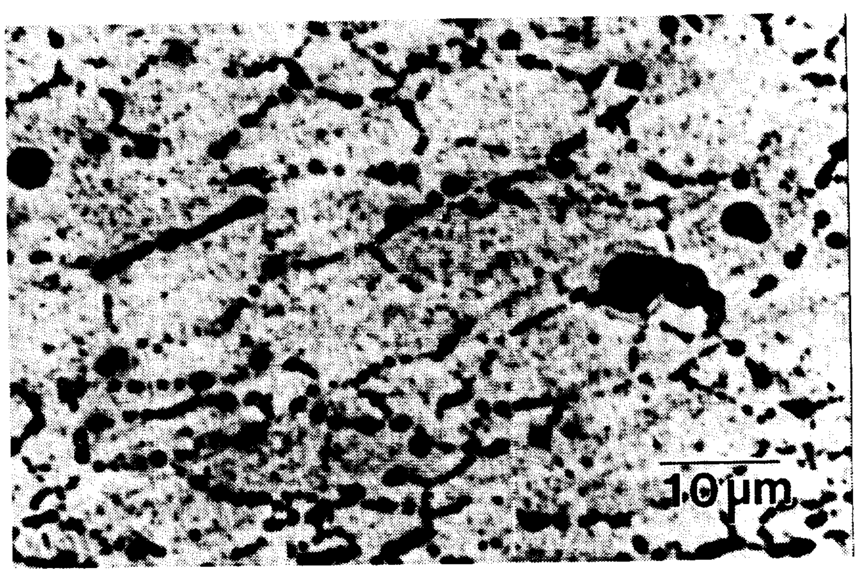


Centered dark field transmission electron micrograph of the subgrain boundary region showing the precipitation of T_1 on boundaries and in subgrains.

Corrosion Behavior in Aerated 0.6 M NaCl

Phase	Model Material	Corrosion Potential (mV_{sce})	Galvanic Couple Current Density (ua/cm^2)
α - Al	SHT 2090	-720	----
Al-14Cu	as cast	-620	-0.5
Al18-Cu-5Fe	as cast	-670	-7.0
Al-24Cu-5Fe	as cast	-675	-3.0
T_1	Al-26Cu-21Li	-1100	+500
PA 2090	Al-3Cu-2Li	-720	----





A. Optical micrograph of pitting associated with Al-Fe-Cu impurity particles.

B. Optical micrograph of discontinuous subgrain boundary pitting associated with T_1 precipitated on subgrain boundaries.

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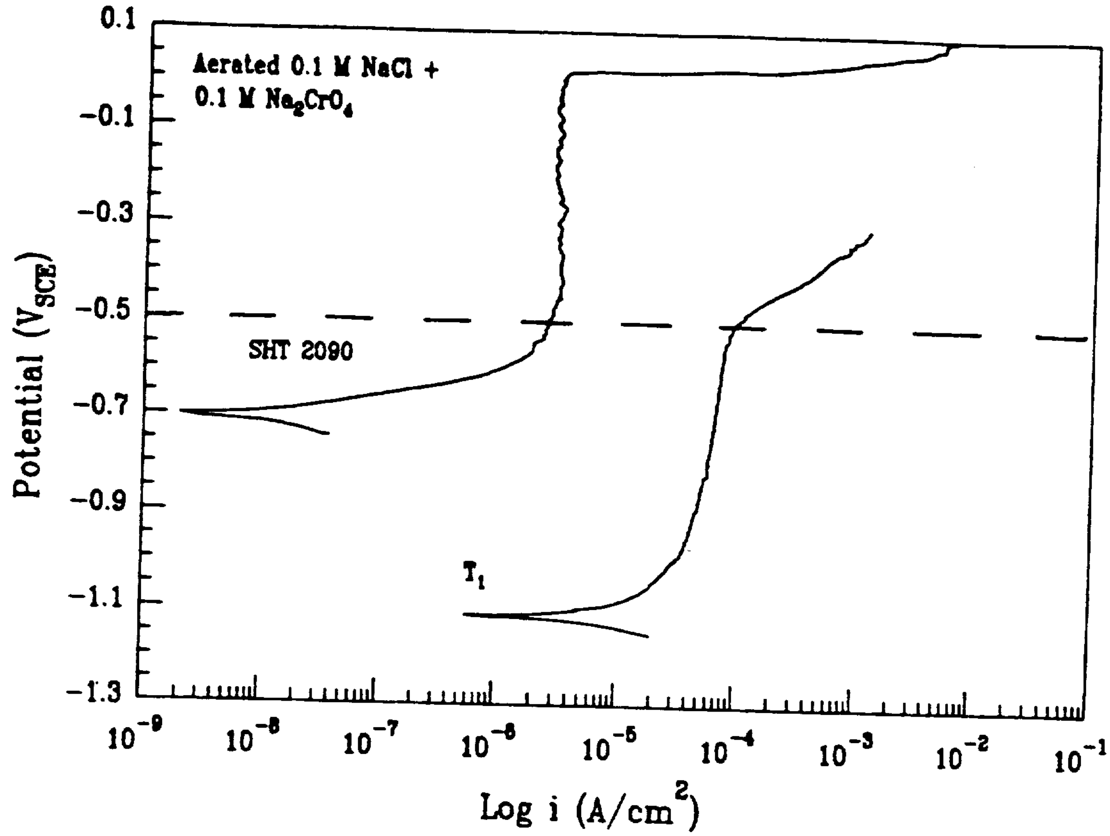
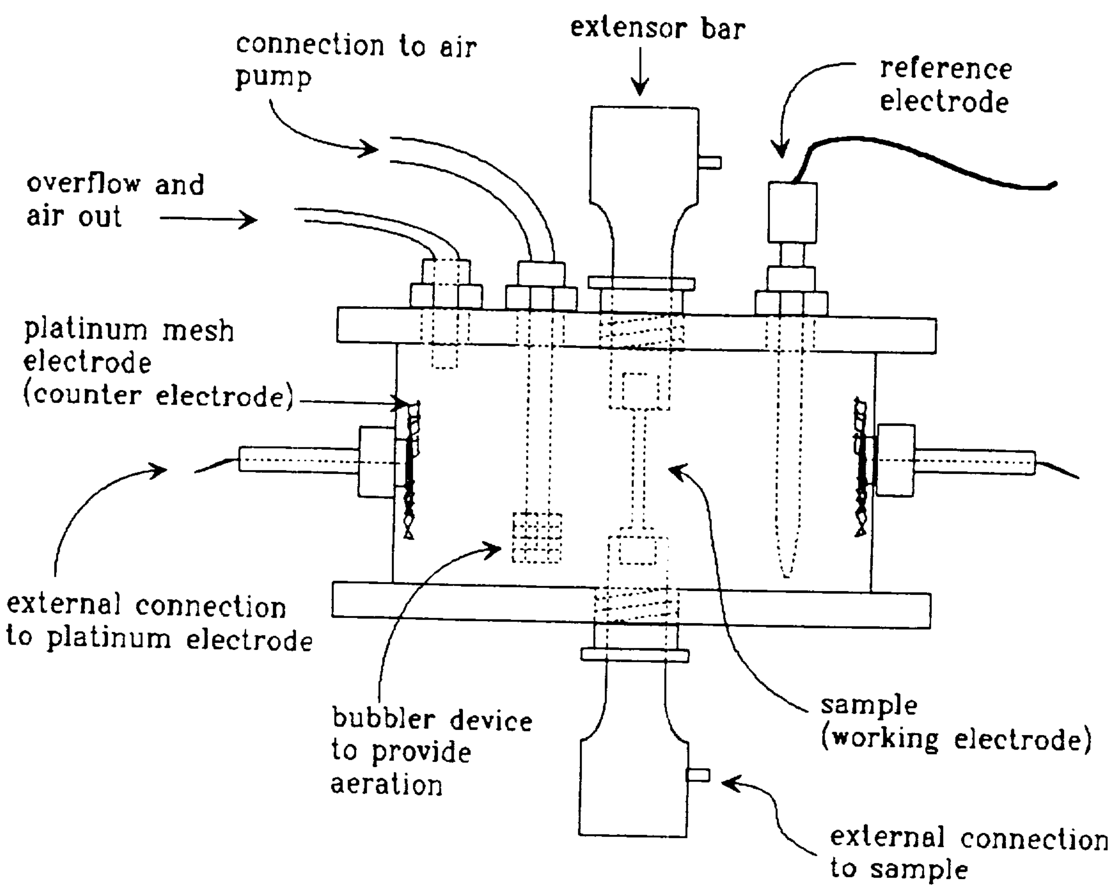
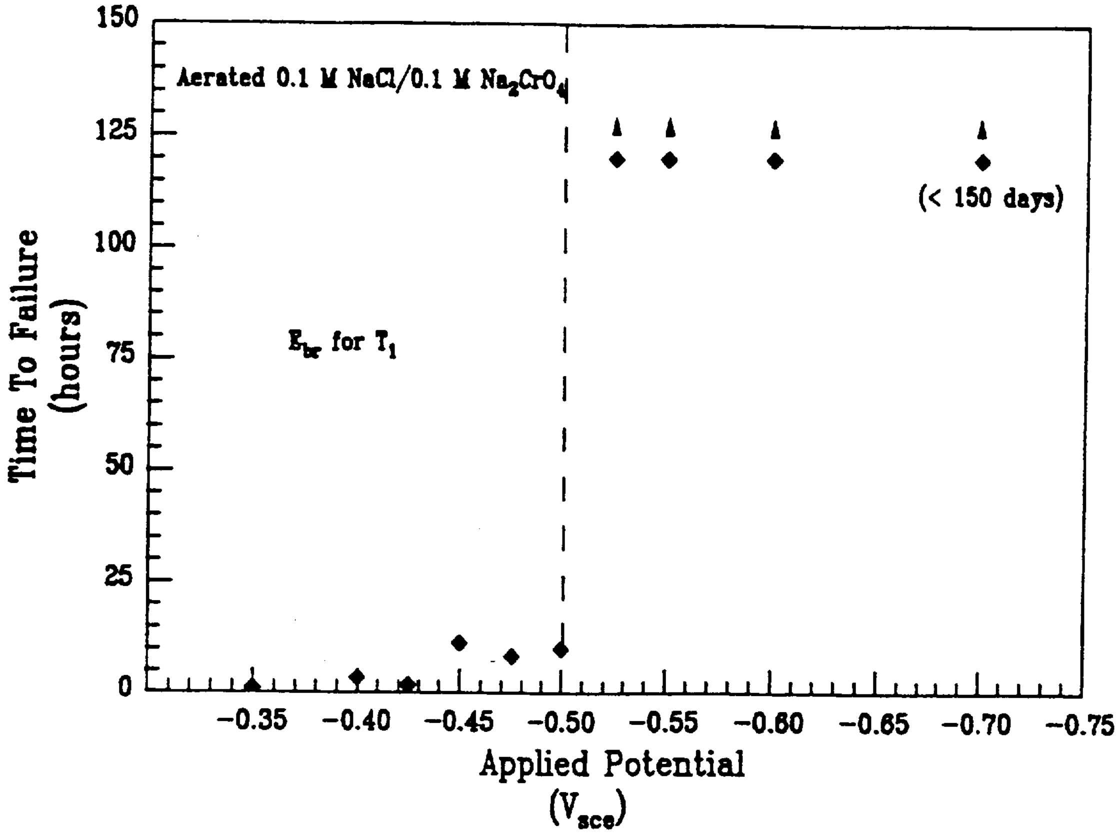


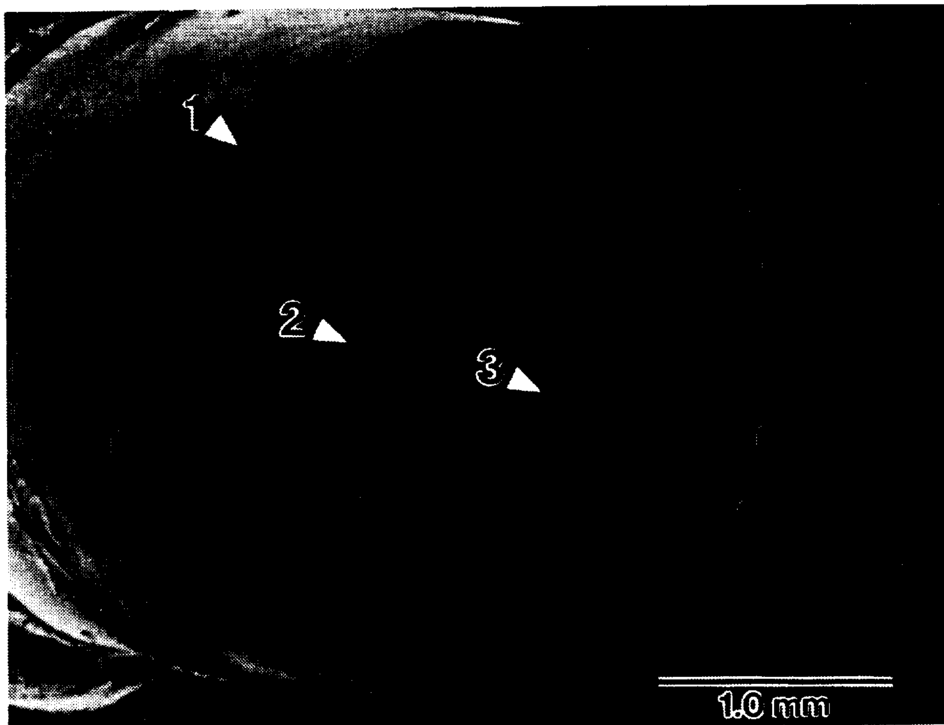
Anodic polarization in Cl^-/CrO_4^{2-}



Schematic of the cell used for constant load TTF experiments.

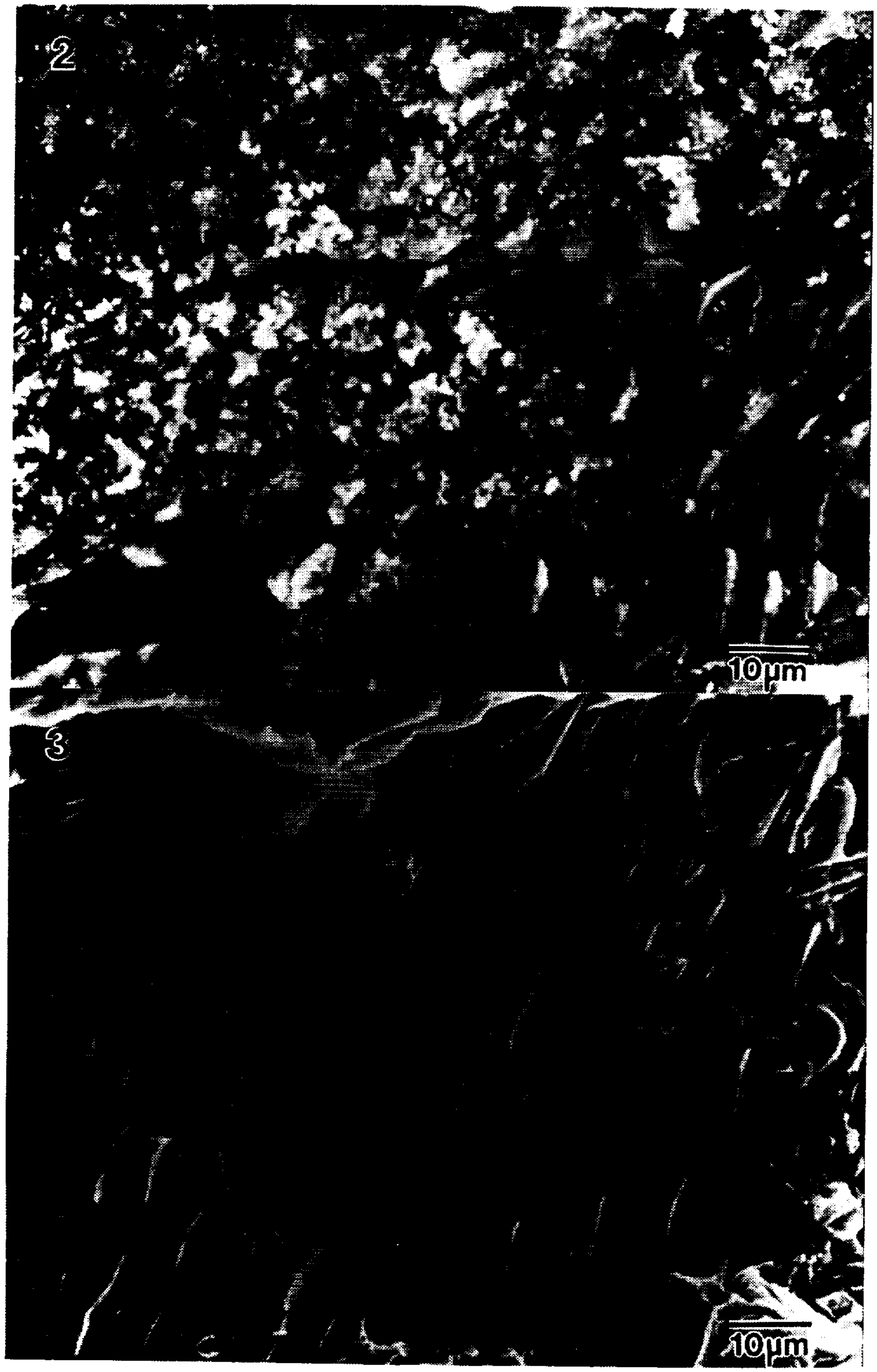


Time to failure versus applied potential in Cl^-/CrO_4^{2-}



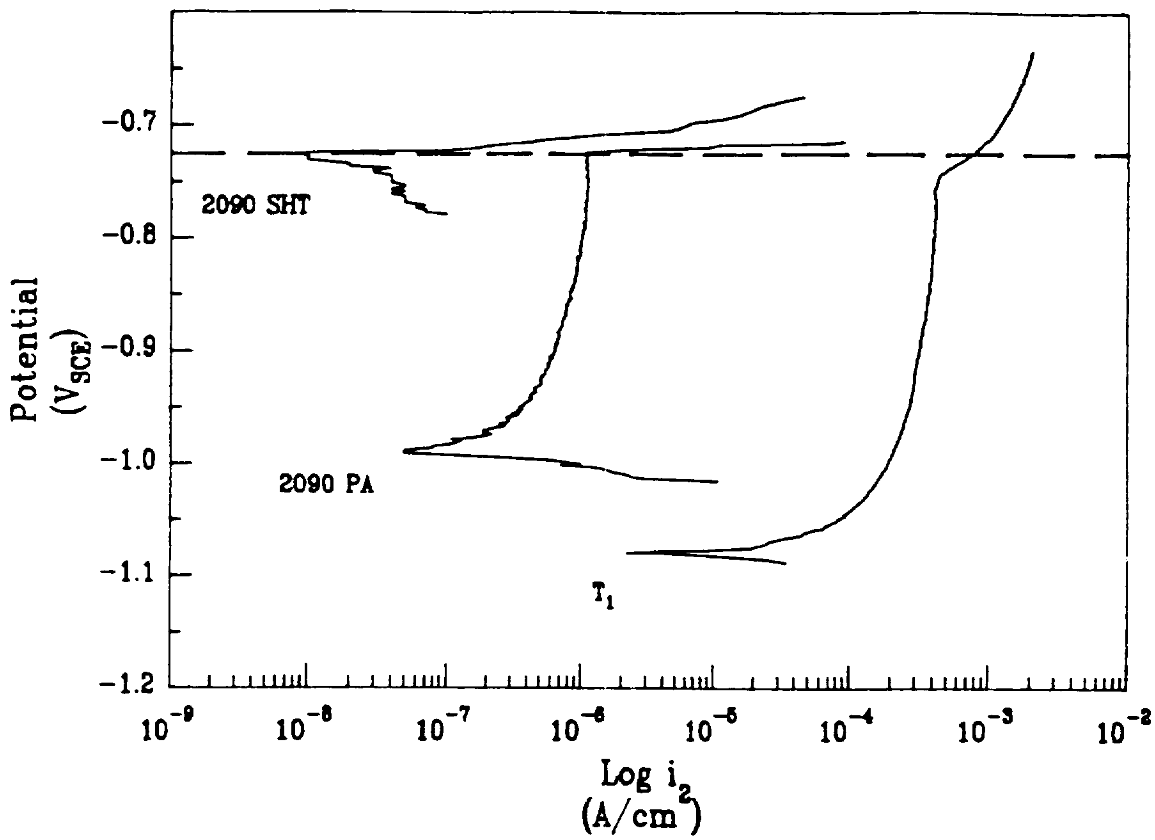
A. Scanning electron micrograph of the fracture surface of a 2090 tensile specimen subjected to a time to failure experiment at 55 % of the S-T yield strength in 0.1 M NaCl + 0.1 M Na_2CrO_4 at an applied potential greater than E_{br} of T_1.

B. Scanning electron micrograph from the rim of the failure initiating pit.



C. Scanning electron micrograph of the SCC propagation region 200 micrometers below the base of the pit.

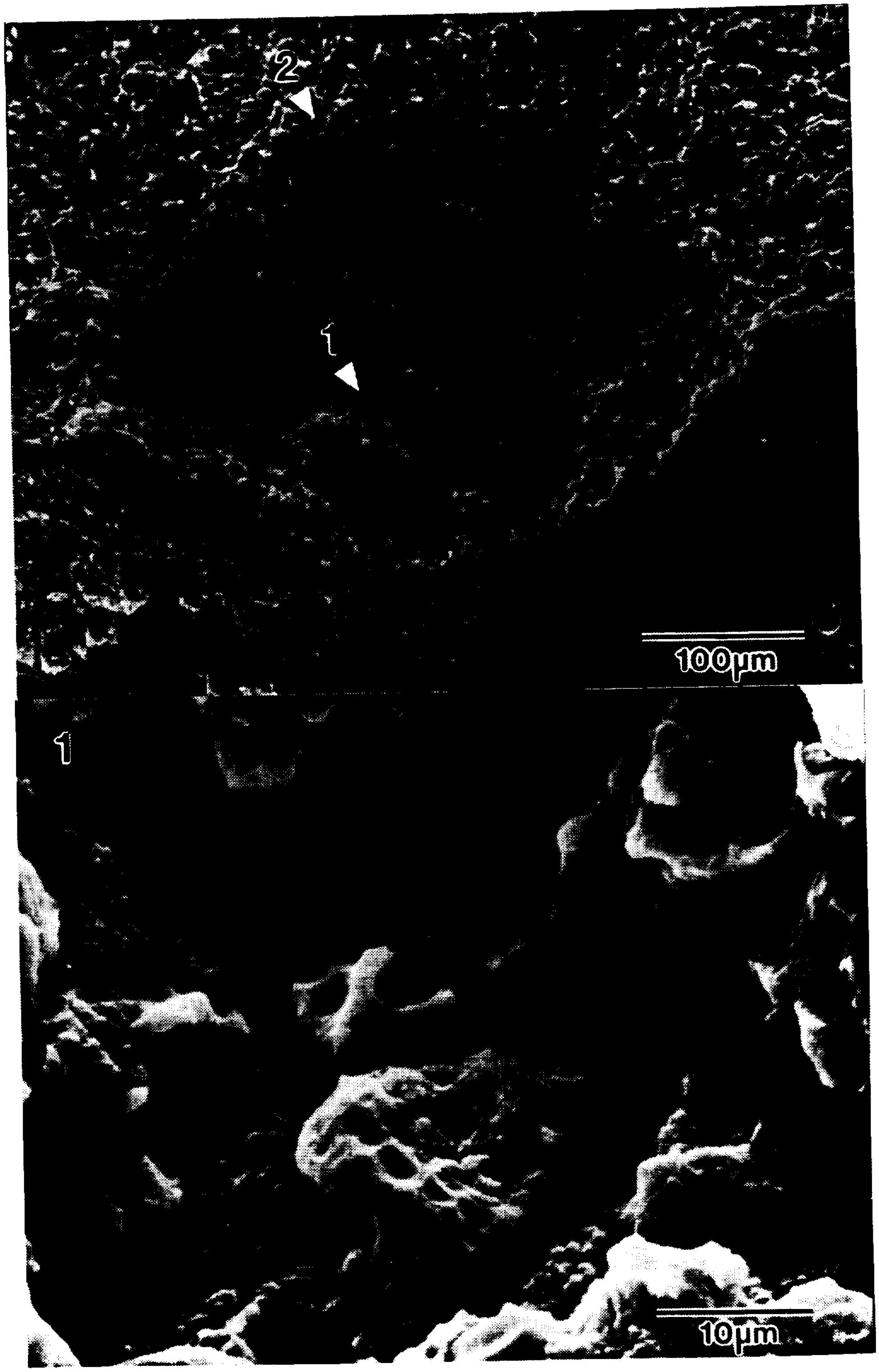
D. Scanning electron micrograph of the tensile overload region.



Anodic polarization in 0.6 M NaCl solution

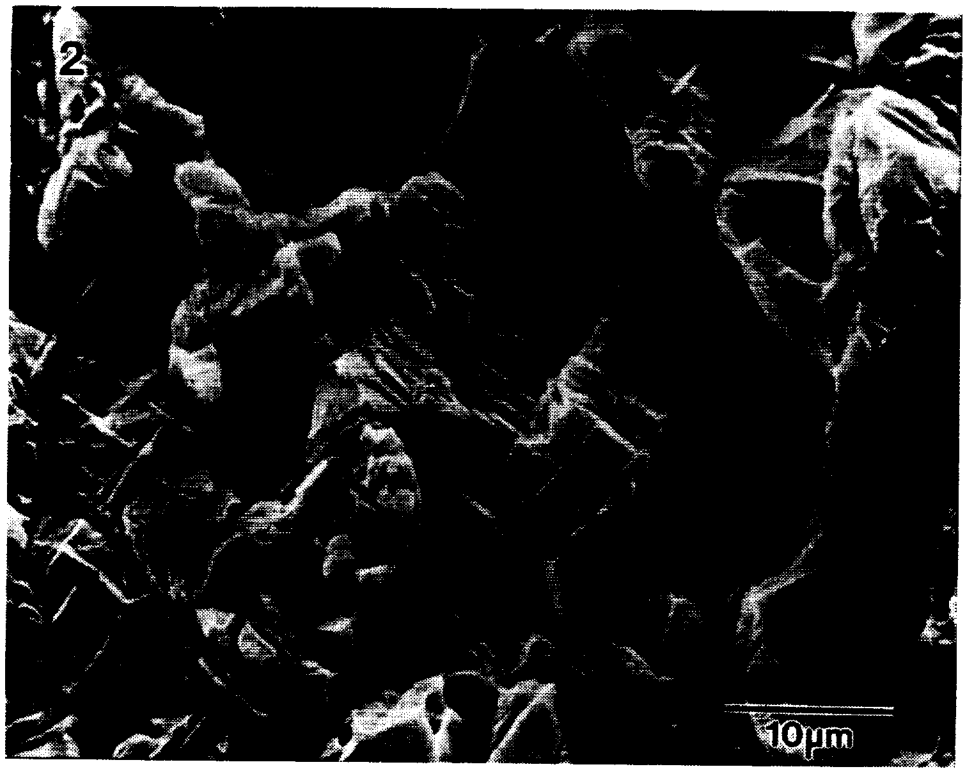
Time to Failure vs. Applied Potential
in Aerated 0.6 M NaCl

Applied Potential (mV_{sce})	Time to Failure (days)
-720 (E_{corr})	3 @ > 75 5 @ > 30
-715	2 @ > 45
-1150	2 @ > 45



A. Scanning electron micrograph of the fracture surface of a 2090 specimen loaded to 55% of the S-T yield and immersed in 0.6 M NaCl solution under free corrosion conditions for 7 days then removed from solution and pulled to fracture in air.

B. Scanning electron micrograph of the failure initiating pit.



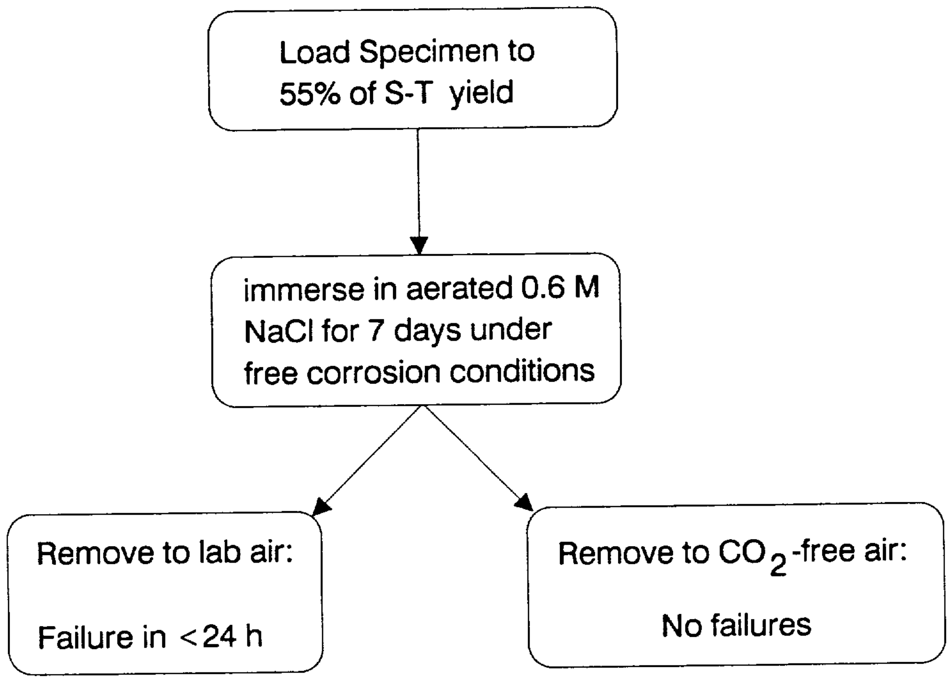
C. Scanning electron micrograph of the overload region directly below the base of the pit.

Necessary Conditions for Rapid SCC Failure Appear to be:

* α - Al passive (below E_{br})

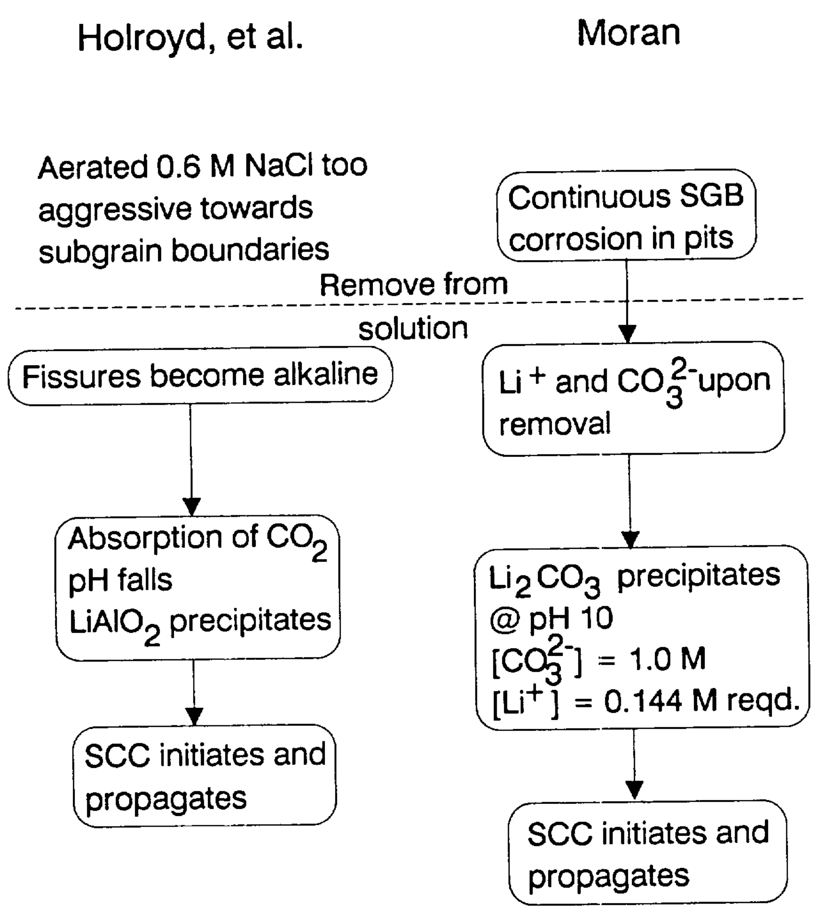
* T_1 transpassive (above E_{br})

Pre-Exposure Embrittlement



* Alloy 8090, Holroyd, et al. (1987)

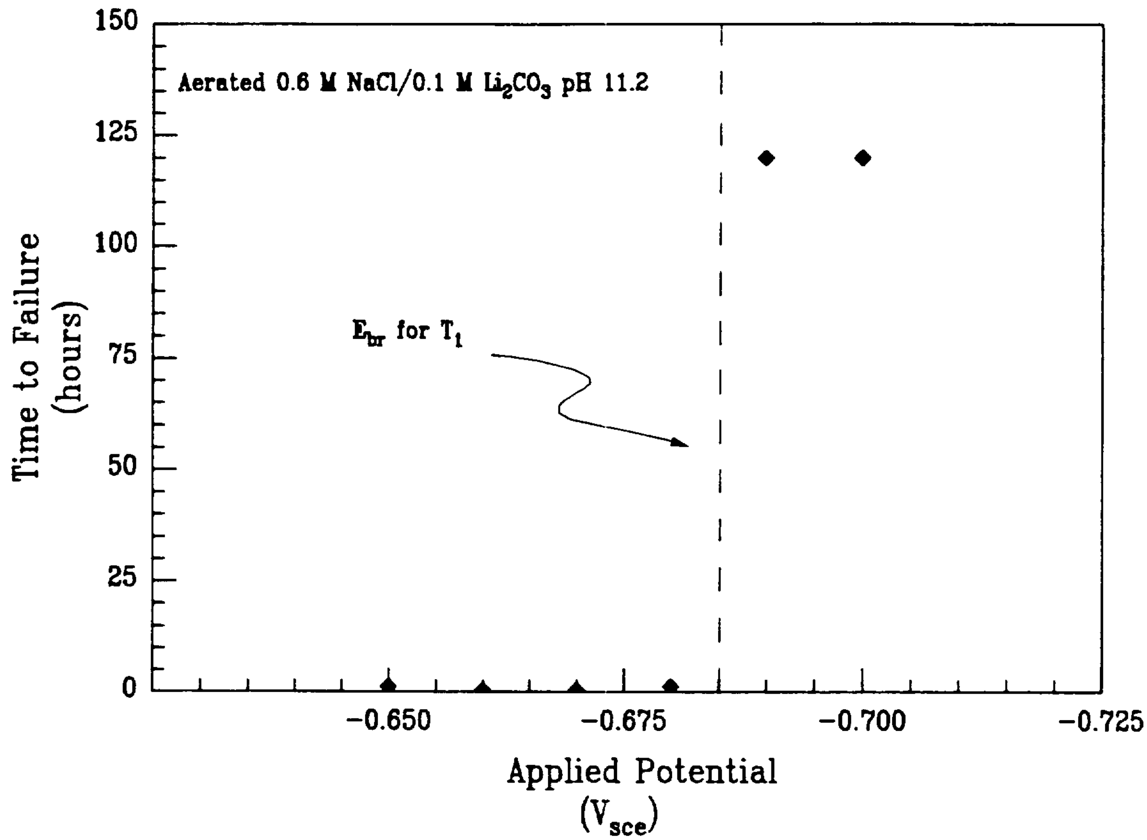
* Alloy 2090, Moran (1989)


Holroyd, et al.
Moran
Aerated 0.6 M NaCl too aggressive towards subgrain boundaries
Continuous SGB corrosion in pits
Remove from solution
Fissures become alkaline
Li + and CO_3^{2-} upon removal
Absorption of CO_2
pH falls
$LiAlO_2$ precipitates
Li_2CO_3 precipitates
@ pH 10
$[CO_3^{2-}]$ = 1.0 M
$[Li^+]$ = 0.144 M reqd.
SCC initiates and propagates
SCC initiates and propagates

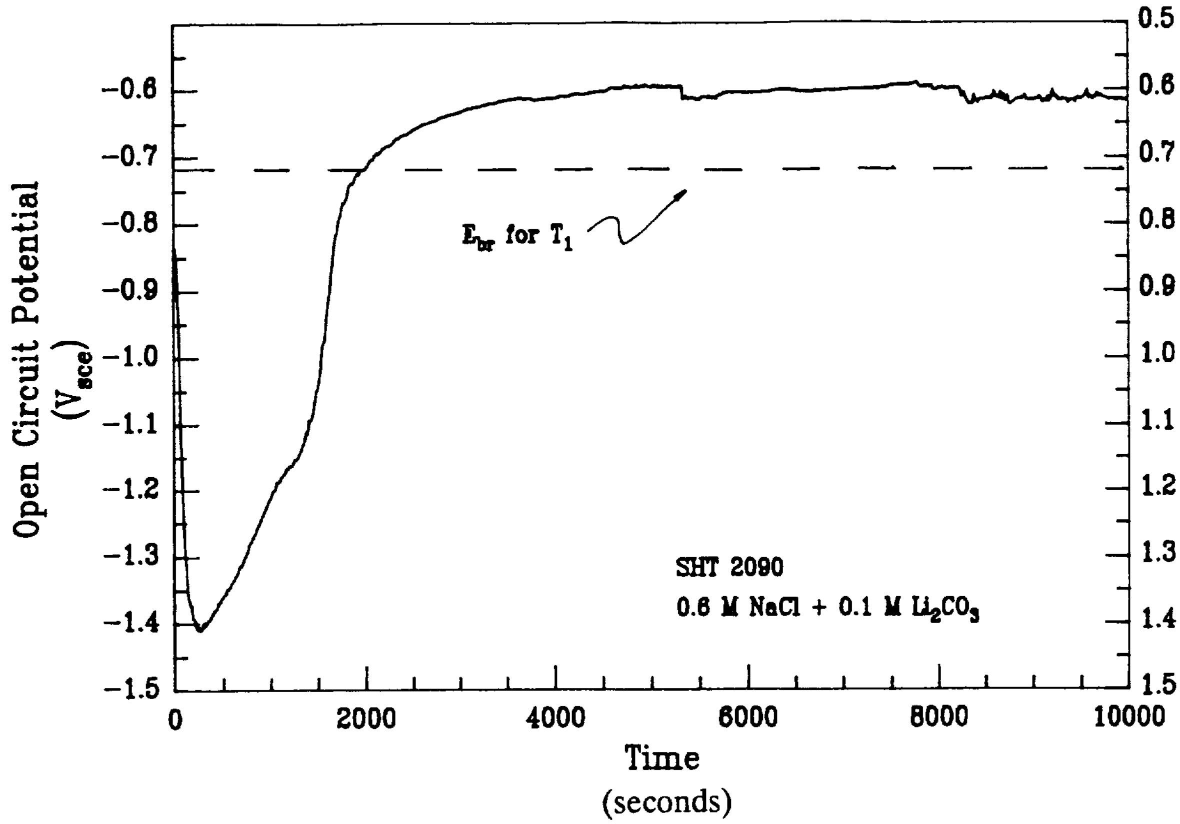
Corrosion Behavior in Cl^- and Cl^- / CO_3^{2-}

	phase	i_{pass} (ua/cm^2)	E_{br} (mV$_{sce}$)
0.6 M NaCl pH = 7 - 8	α - Al T_1	1.0 200	-690 -720
0.6 M NaCl + 0.1 M Li_2CO_3 pH = 10	α - Al T_1	0.75 550	-590 -720

-590 mV > Rapid Failure Window > -720 mV

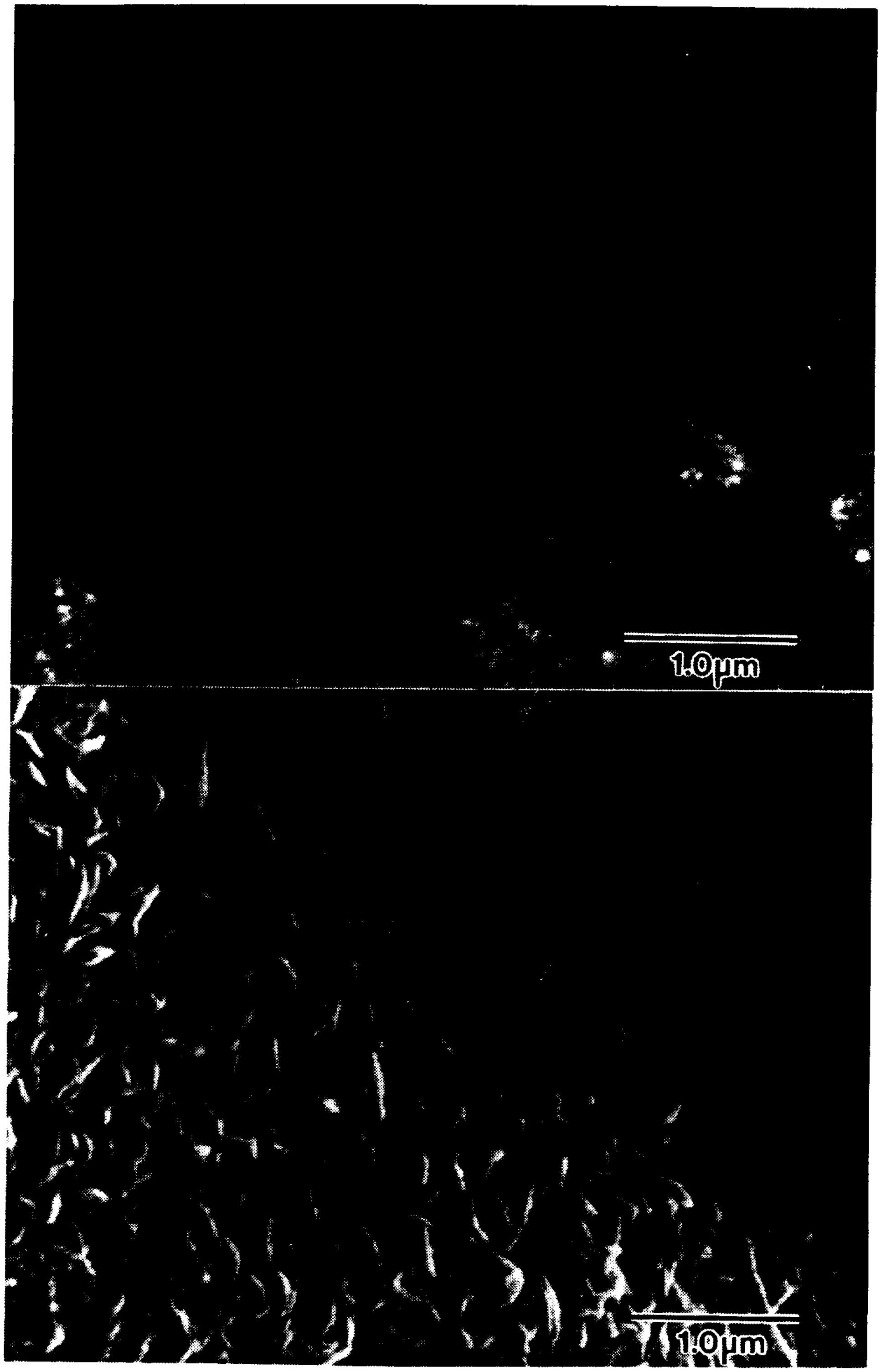


Time to failure versus applied potential in Cl^-/CO_3^{2-}



Open circuit potential versus time in Cl^{-}/CO_3^{2-}

N.P.



A. Scanning electron micrograph of the film that forms in the SCC region of a 2090 tensile specimen where the specimen is immersed in aerated 0.6 M NaCl for 7 days then removed to CO_2 -free air.

B. Scanning electron micrograph of the film that forms in the SCC region of a 2090 tensile specimen that is immersed in aerated 0.6 M NaCl for 7 days then removed to laboratory air.

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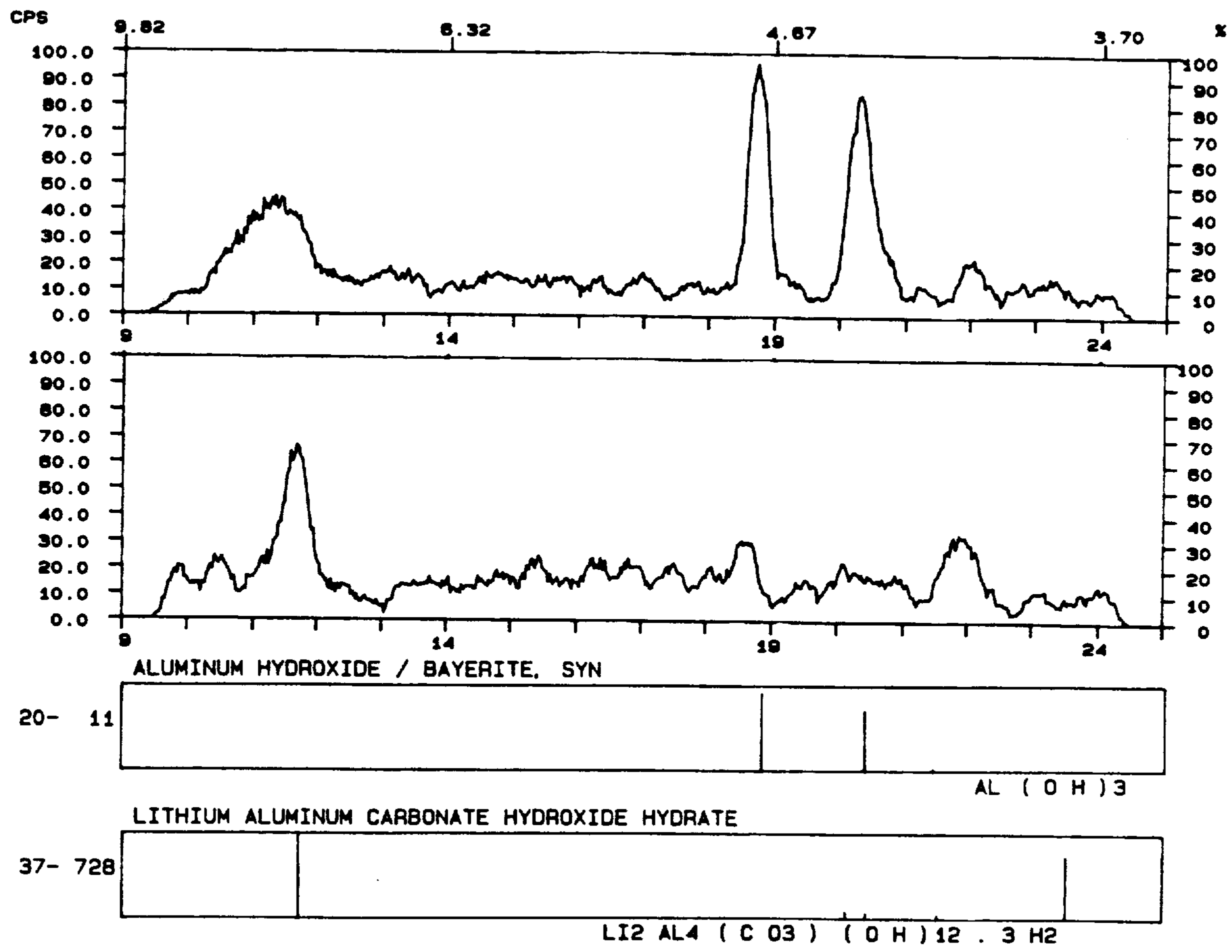


* hydrotalcite -type compound $[LiAl_2(OH)_6]_2^+ \cdot CO_3^{2-} \cdot nH_2O$

* derived from bayerite $Al(OH)_3$

Hydrotalcites

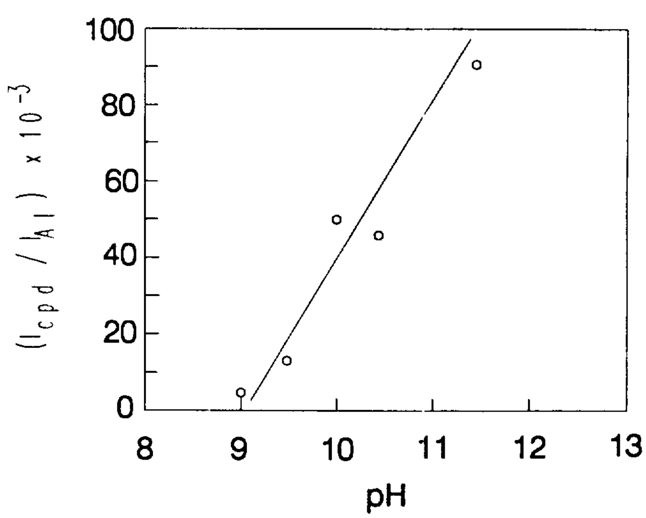
* Alumina Gels + Lithium Salts $\longrightarrow$ $(LiX_x)_y \cdot 2(AlOH)_3 \cdot nH_2O$

* Several anions produce isomorphous compounds

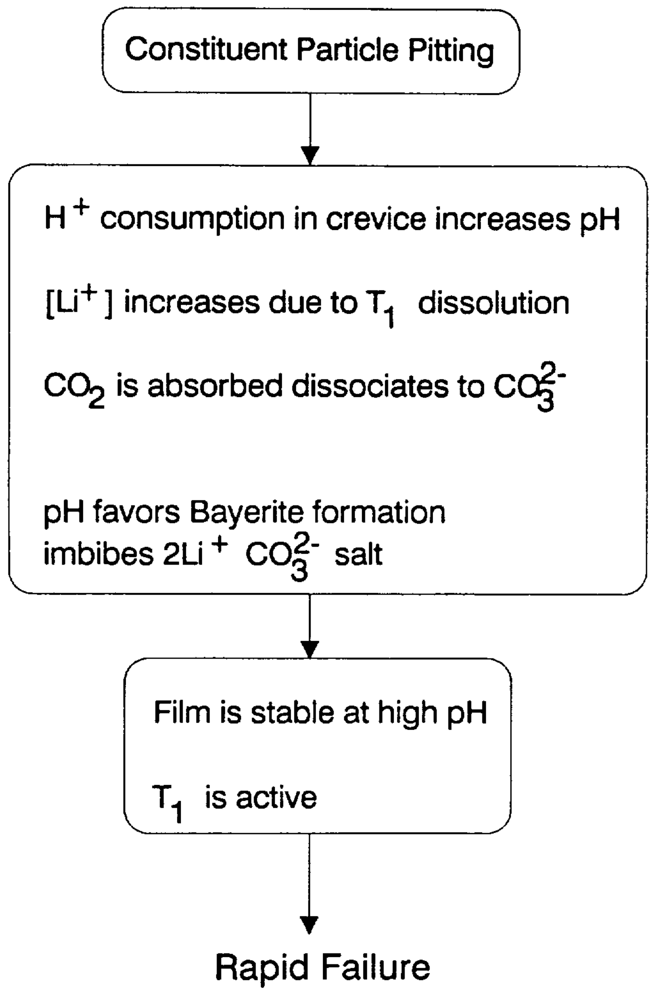
OH^- Cl^-

* Passivating effects associated with its presence (Perrota, 1990)

* Insoluble in alkaline solutions



Ammended Pre-Exposure Embrittlement Mechanism



Summary

* In order of increasing nobility:
  $T_1 < \alpha$ - Al $<$ Al-Cu-Fe

* Rapid SCC ensues when:
  $E_{br} T_1 > E_{applied} > E_{br} \alpha$ - Al

* In 0.6 M NaCl, $E_{br} T_1 = E_{br} \alpha$ - Al
  rapid SCC criterion is not satified

* In isolated fissures, rapid SCC criterion is satisfied

* α - Al is passivated by a hydrotalcite-type compound

The following pages are from a presentation given at the CORROSION/90 Meeting, April 23-27, Las Vegas, Nevada

The Role of Hydrolysis in Crevice Corrosion of Aluminum-Lithium-Copper Alloys

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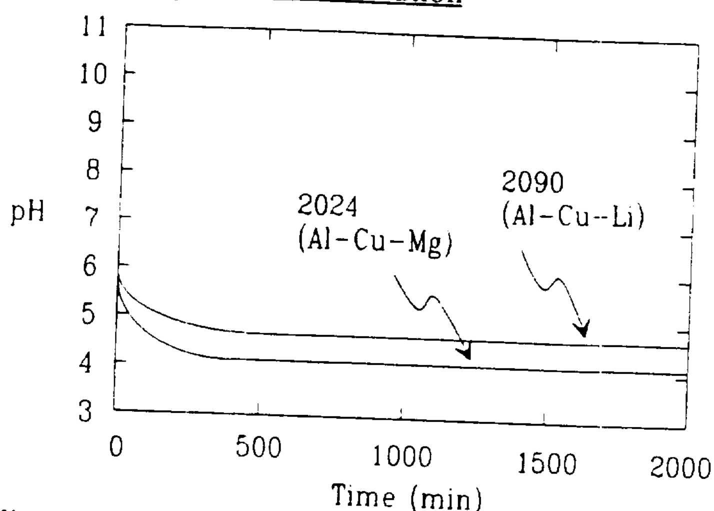
Sponsored by NASA, Langley Research Center, Hampton, VA under Contract No. NAG-745-2, D.L. Dicus Contract Monitor.

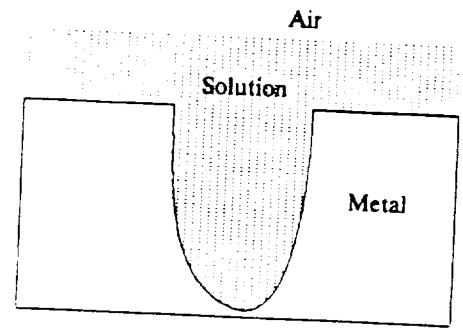
Overview

* Background
* Objectives
* Approach
* Results
* Summary

Background

Crevice coupled to Bulk Solution

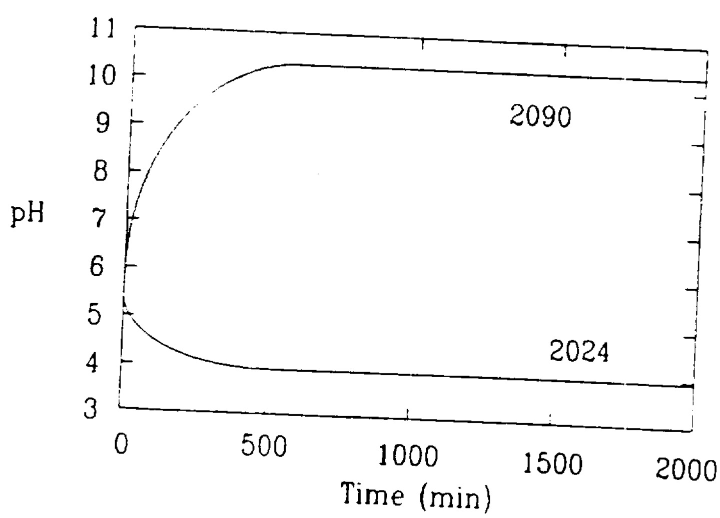


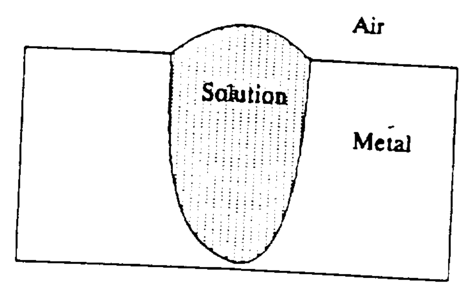


dissolution in the crevice

reduction reactions outside the crevice

Isolated Crevice





dissolution in the crevice

reduction reactions inside crevice

Objectives

Separate and identify the roles of:

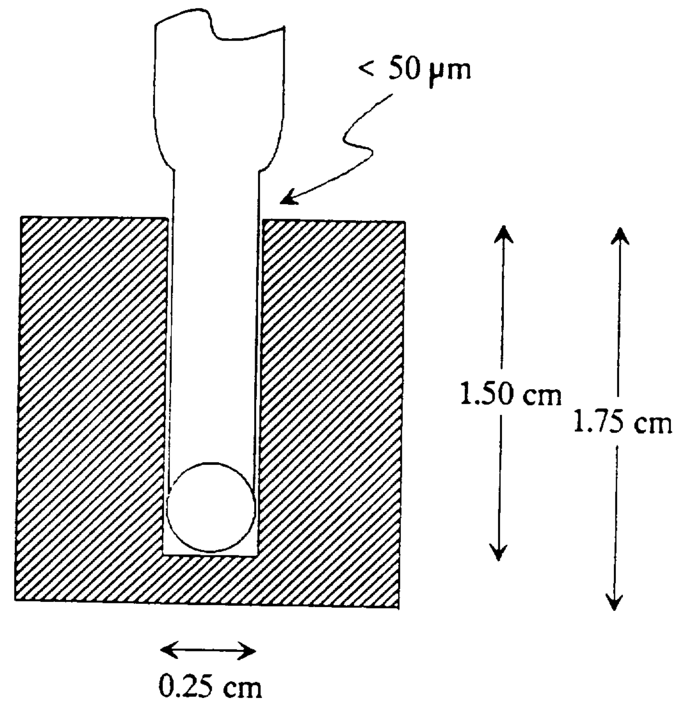
$$\left.\begin{array}{l}\bullet\ Al^{3+} \\ \bullet\ Li^{+} \\ \bullet\ Cu^{2+}\end{array}\right\}\ \text{hydrolysis}$$

- an external cathode

Approach

Simulated crevice technique

- in situ measurement
- avoid the size constraint associated with real crevices



Measure pH versus Time for:

Materials	Environments
99.99 Al	Aerated Bulk Solution
SHT Al-3Li	Isolated Crevice
SHT Al-3Cu	
SHT Al-3Cu-2Li	

Approach

Interpret steady state pH using Distribution Diagrams for monomeric hydrolysis products and knowledge of where electrochemical reduction reactions are occurring.

<u>Monomeric Hydrolysis</u>

$$xM^{z+} + yH_2O \leftrightarrow M_x(OH)_y^{(xz-y)+} + yH^+$$

* Rapid $10^5 < k < 10^{10}$ moles^{-1}sec^{-1}
* Reversible
* An equilibrium treatment is applicable

Reactions Considered

Aluminum	$-\log K_{xy}$
$Al^{3+} + H_2O \leftrightarrow AlOH^{2+} + H^+$	4.97
$Al^{3+} + 2H_2O \leftrightarrow Al(OH)_2^{+} + 2H^+$	9.3
$Al^{3+} + 3H_2O \leftrightarrow Al(OH)_3 + 3H^+$	15.0
$Al^{3+} + 4H_2O \leftrightarrow Al(OH)_4^{-} + 4H^+$	23.0
Lithium	
$Li^+ + H_2O \leftrightarrow LiOH + H^+$	13.86
Copper	
$Cu^{2+} + H_2O \leftrightarrow CuOH^+ + H^+$	8.0
$Cu^{2+} + 2H_2O \leftrightarrow Cu(OH)_2 + 2H^+$	17.3
$Cu^{2+} + 3H_2O \leftrightarrow Cu(OH)_3^{-} + 3H^+$	27.8
$Cu^{2+} + 4H_2O \leftrightarrow Cu(OH)_4^{2-} + 4H^+$	39.6
$Cu^{2+} + H_2O \leftrightarrow 1/2Cu_2(OH)_2^{2+} + H^+$	10.36
Electrochemical Reactions	
$M \rightarrow M^{n+} + ne^-$	internal
$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$	external
$2H^+ + 2e^- \rightarrow H_2$	internal
$H_2O + e^- \rightarrow H + OH^-$	internal

Construction of Distribution Diagrams

Formation Quotients (Baes and Mesmer, 1986.)

$$\log Q_{xy} = \log K_{xy} + \frac{aI^{1/2}}{(1 + I^{1/2})} + bI$$

$$I = \frac{\Sigma z_i^2[i]}{2}$$

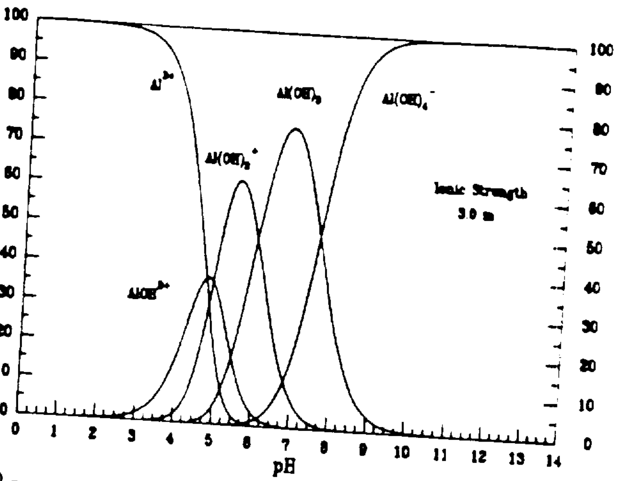
Mass Action Expressions

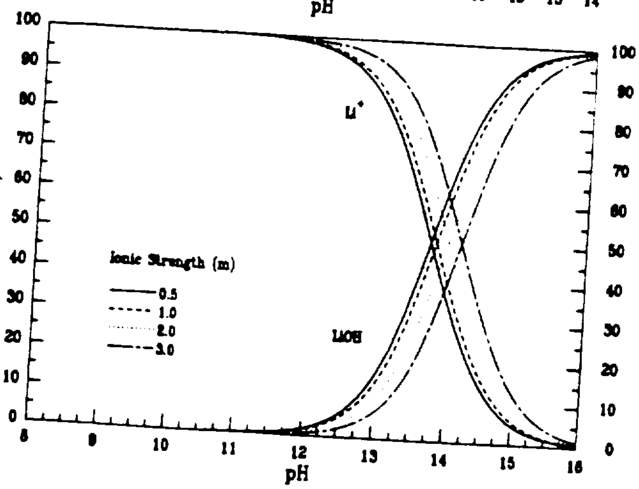
$$Q_{11} = \frac{[AlOH^{2+}][H^+]}{[Al^{3+}]}$$

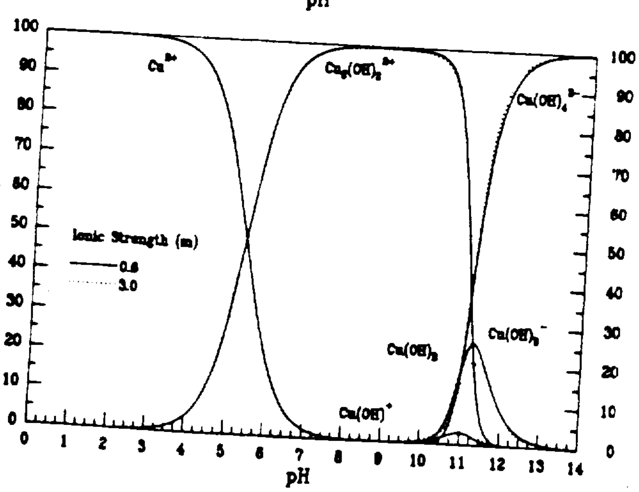
.
.
.

$$F_{AlOH^{2+}} = \frac{[AlOH^{2+}]}{\Sigma [species]}$$

Distribution Diagrams







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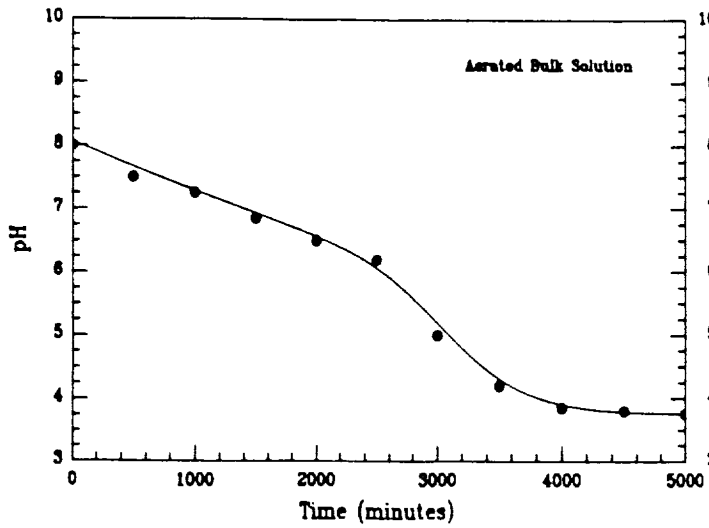
Results for Pure Aluminum



Electrochemical Reactions:

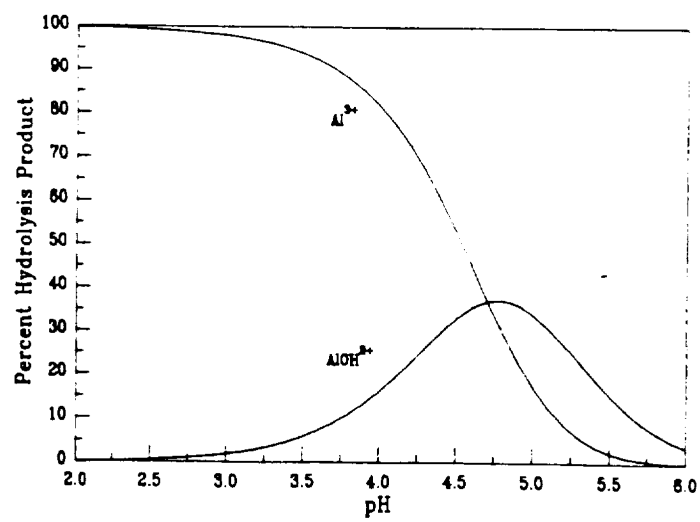
$Al \rightarrow Al^{3+} + 3e^-$ internal

$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$ external

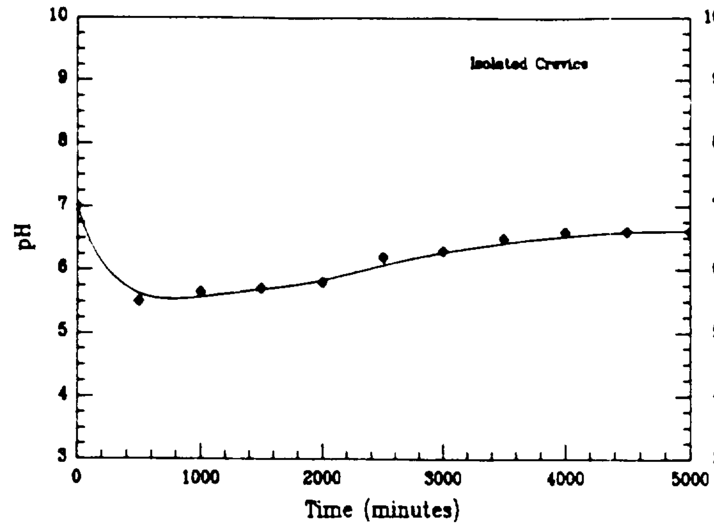
Hydrolysis Reaction:

$Al^{3+} + H_2O \leftrightarrow AlOH^{2+} + H^+$ internal

pH determined by $[Al^{3+}]/[AlOH^{2+}]$ in this range



Results for Aluminum



<u>Electrochemical Reactions:</u>

$Al \rightarrow Al^{3+} + 3e^-$ internal

$3H^+ + 3e^- \rightarrow 3/2H_2$ internal

dissolution of 1 Al consumes 3 H^+

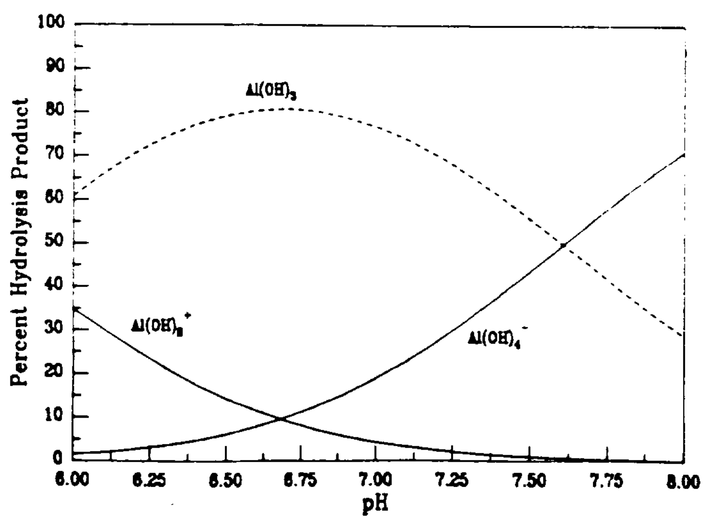
<u>Hydrolysis Reactions:</u>

$Al^{3+} + H_2O \rightarrow AlOH^{2+} + H^+$ net loss of 2 H^+

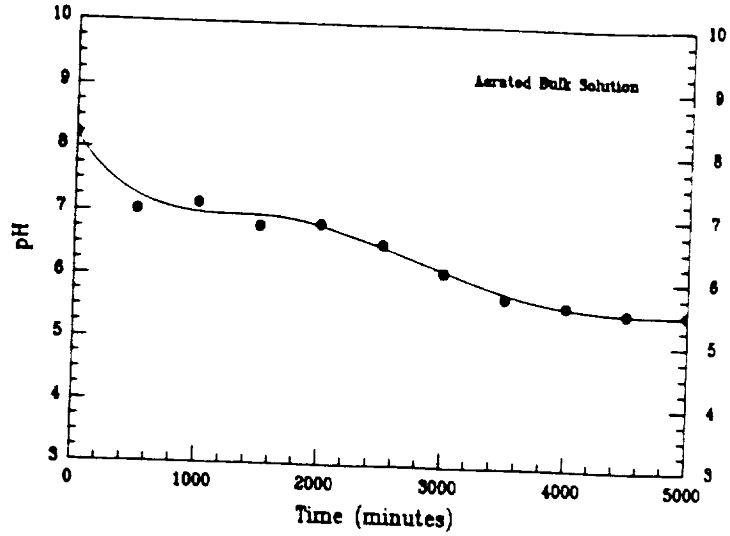
$Al^{3+} + 2H_2O \rightarrow Al(OH)_2{}^+ + 2H^+$ net loss of 1 H^+

$Al^{3+} + 3H_2O \rightarrow Al(OH)_3 + 3H^+$ no net loss of H^+

$Al^{3+} + 4H_2O \leftarrow Al(OH)_4{}^- + 4H^+$ net gain of 1 H^+



Results for SHT Al-3Li



Electrochemical Reactions:

$Al \rightarrow Al^{3+} + 3e^-$ internal

$Li \rightarrow Li^+ + e^-$ internal

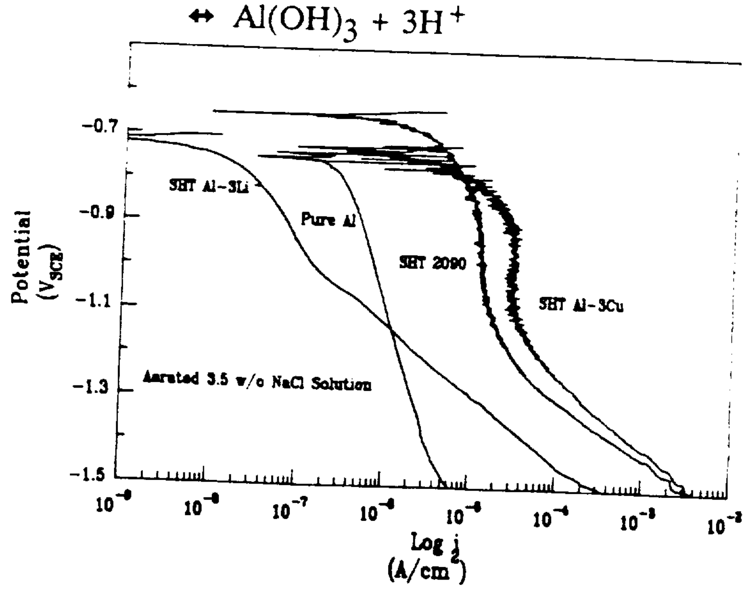
$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$ external

Hydrolysis Reactions:

$\leftrightarrow AlOH^{2+} + H^+$

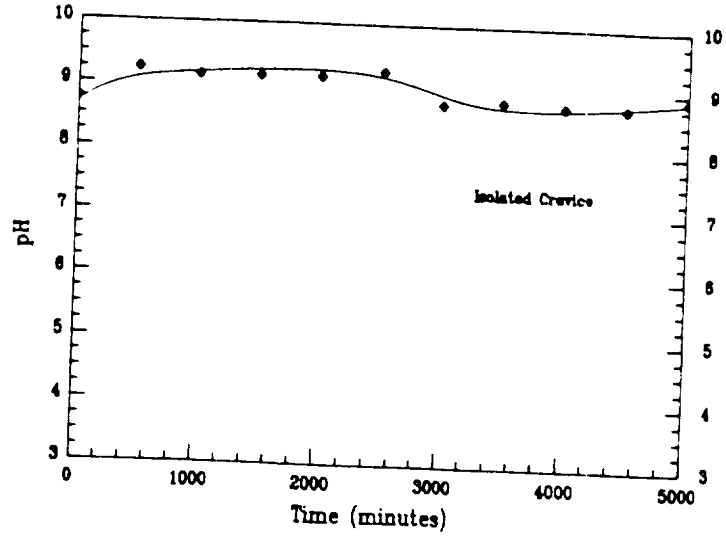
$\leftrightarrow Al(OH)_2{}^+ + 2H^+$

$\leftrightarrow Al(OH)_3 + 3H^+$



Reduction kinetics are slowed at the external cathode.

Results for SHT Al-3Li



Electrochemical Reactions:

$Li \rightarrow Li^+ + e^-$ internal

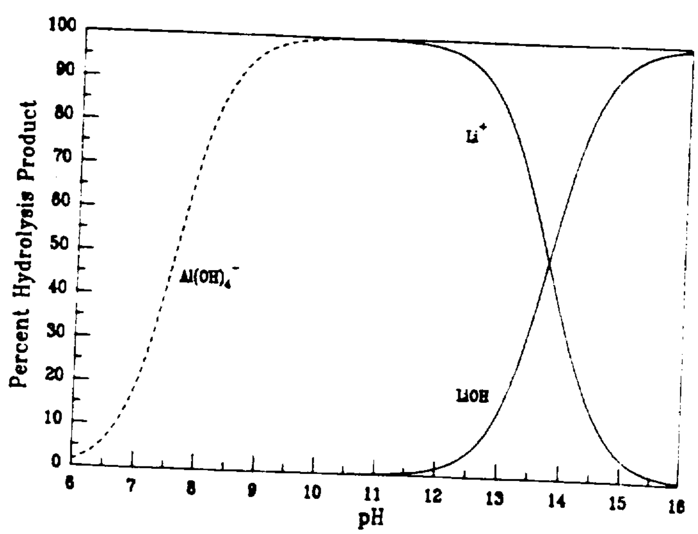
$H^+ + e^- \rightarrow 1/2H_2$ internal

$H_2O + e^- \rightarrow H + OH^-$ internal

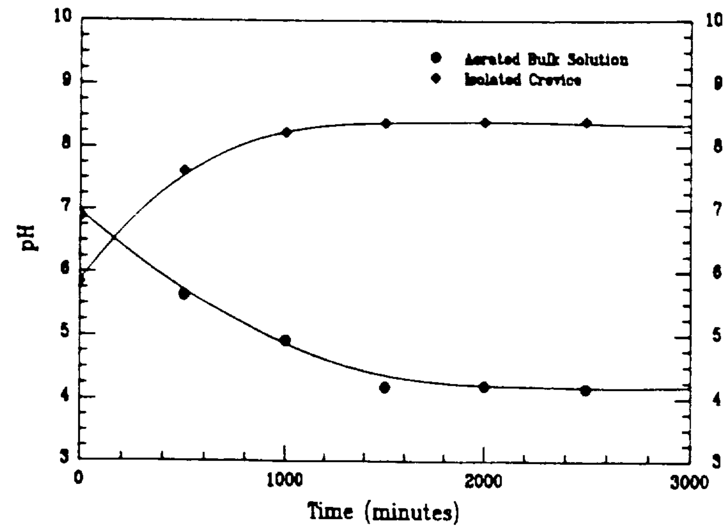
dissolution of 1 Li consumes 1 H^+

Hydrolysis Reactions:

$Li^+ + H_2O \leftrightarrow LiOH + H^+$ no net loss of H^+



Results for SHT Al-3Cu



Aerated Bulk Solution

Consistent with $Al^{3+} + H_2O \leftrightarrow AlOH^{2+} + H^+$ equilibrium.

Isolated Crevice

Electrochemical Reactions:

$Cu \rightarrow Cu^{2+} + 2e^-$ internal

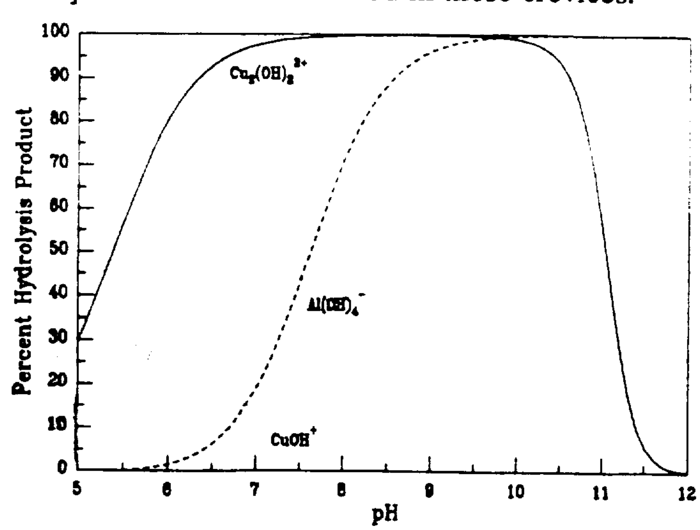
$2H^+ + 2e^- \rightarrow H_2$ internal

dissolution of 1 Cu atom form the alloy consumes 2 H^+.

Copper oxidation can not discharge H^+.

In RRDE experiments with Al_2Cu at potentials below E_R Cu/Cu^{2+}, copper deposits have been observed. (Mazurkiewicz and Piotrowski, 1983).

$[Cu^{2+}] > 10^{-9}$ M not detected in these crevices.



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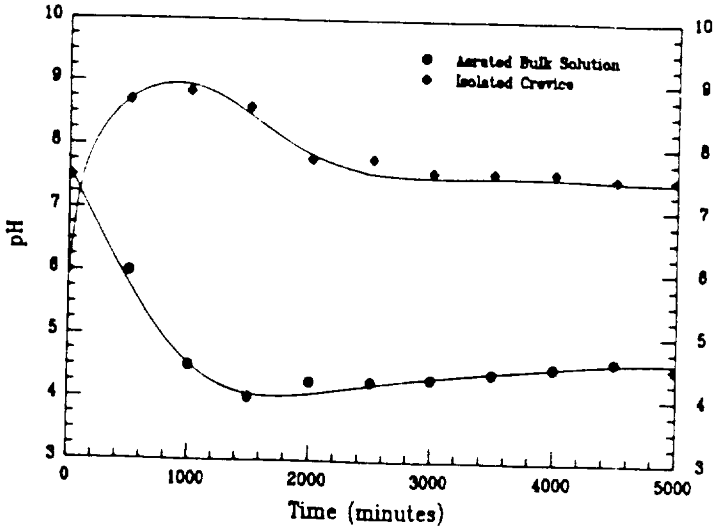
Results for SHT 2090



Aerated Bulk Solution

Consistent with $Al^{3+} + H_2O \leftrightarrow AlOH^{2+} + H^+$ equilibrium.

Isolated Crevice

$Li \rightarrow Li^+ + e^-$

$H^+ + e^- \rightarrow 1/2H_2$ assisted by elemental Cu on walls

$Li^+ + H_2O \leftrightarrow LiOH + H^+$

replaces H^+ and inhibits further pH increase.

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Summary

- In aerated bulk solutions, crevice pH is consistent with:

$$Al^{3+} + H_2O \leftrightarrow AlOH^{2+} + H^+$$

  dependent on reduction kinetics at the external cathode.

- $Al(OH)_2^+/Al(OH)_4^-$ system point defines the pH in pure Al, isolated crevices.

- $$\left.\begin{array}{l} Li \rightarrow Li^+ + e^- \\ H^+ + e^- \rightarrow 1/2H_2 \end{array}\right\} \text{gives an alkaline crevice}$$

  $Li^+ + H_2O \leftrightarrow LiOH + H^+$ replaces H^+

- Elemental Cu on walls of crevices may assist in generating alkaline crevice solutions.

N90-22657

Program 5 **The Effects of Zinc Addition on the Environmental Stability of Al-Li Alloys**

Raymond J. Kilmer and G.E. Stoner

Objectives

The objectives for this study are:

1) to document and correlate the microstructure of the ALCOA provided 8090 + Zn alloy with corrosion behavior and SCC phenomena;

2) to identify the intermetallics present in 8090 + Zn alloy most notably in the aging regimes displaying optimal mechanical properties;

3) to compare and contrast with baseline 8090 with regard to corrosion and SCC behavior in a number of environments.

The Role of Zn Additions to the Environmental Stability of Alloy 8090

R.J. Kilmer and G.E. Stoner

Department of Materials Science

It has been found that relatively small additions of Zn can improve the stress corrosion cracking (SCC) resistance of Al-Li alloys. However, the mechanism by which this is accomplished is unclear. This present project will investigate the role that Zn plays in altering the behavior of Alloy 8090. Early results suggest that Zn additions increase the volume fraction of δ' (Al_3Li) precipitation and differential scanning calorimetry (DSC) on these alloys confirms this. The four alloys studied each had initial compositions lying in the 8090 window and had varying amounts of Zn added to them.

Alloy 8090, like other Al-Li alloys, displays a δ' precipitate free zone (PFZ) upon artificial aging along the grain and subgrain boundaries. However Zn additions greatly decreased or eliminated a δ' PFZ after 100 hours at 160°C. This implies that the subgrain boundary precipitation kinetics are being altered and suppressed. Furthermore there appears to be a window of Zn concentration above which a δ' PFZ can reappear with the nucleation and growth of a currently unidentified precipitate on the boundaries.

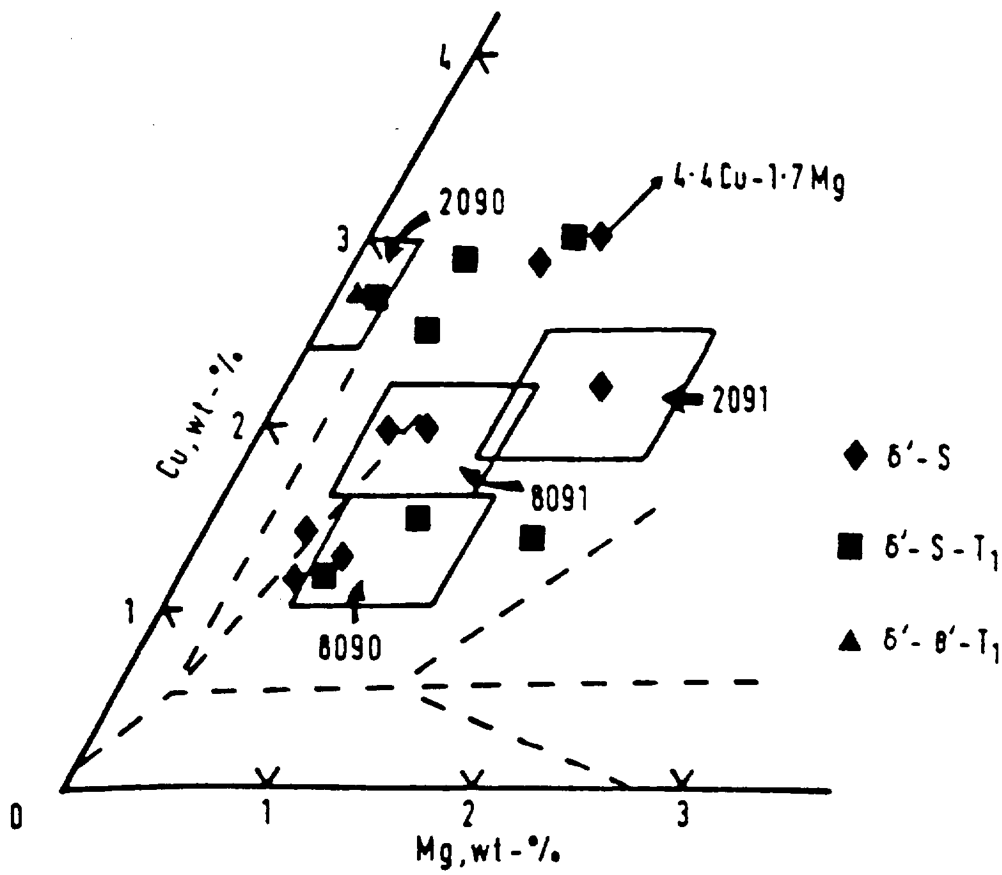
Polarization experiments were performed and the results presented. The experiments were performed in deaerated 3.5 w/o NaCl in both the as received (T3) condition and at peak aging of 100 hours at 160°C. The aging profile was determined via Vickers Hardness tests.

A proposed outline of the project will be presented with future research a main focus.

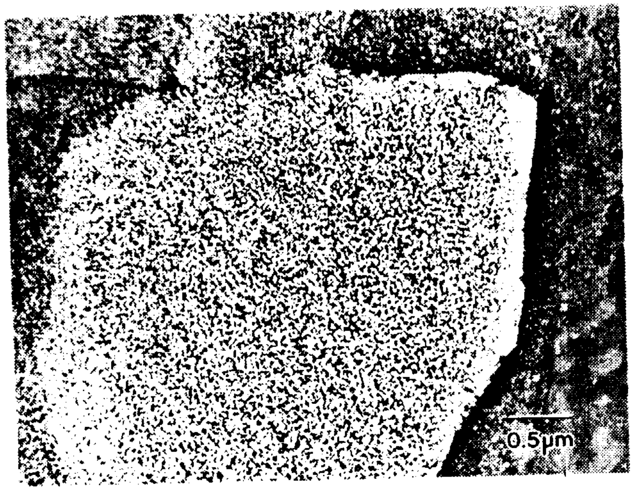
Sponsored by NASA, Langley Research Center, Hampton Virginia
Alcoa, Alcoa Technical Center, Alcoa Center, Pennsylvania

8090

Al-2.4Li-1.16Cu-0.67Mg-0.12Zr



Precipitate phases reported in quarternary Al-Cu-Mg alloys containing 2-3 wt-%Li in material aged at 190°C; where original source quotes composition range, centre of that range has been used as composition shown here; composition ranges of internationally designated Al-Li-Cu-Mg alloys and precipitate phase fields of ternary Al-Cu-Mg system at 190°C are also shown



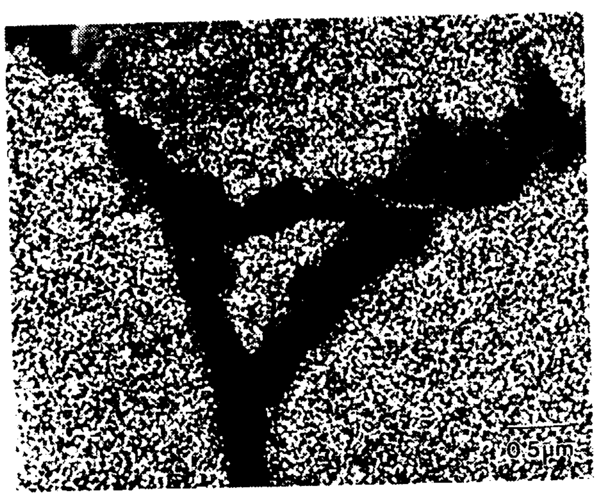
8 hrs

15 hrs

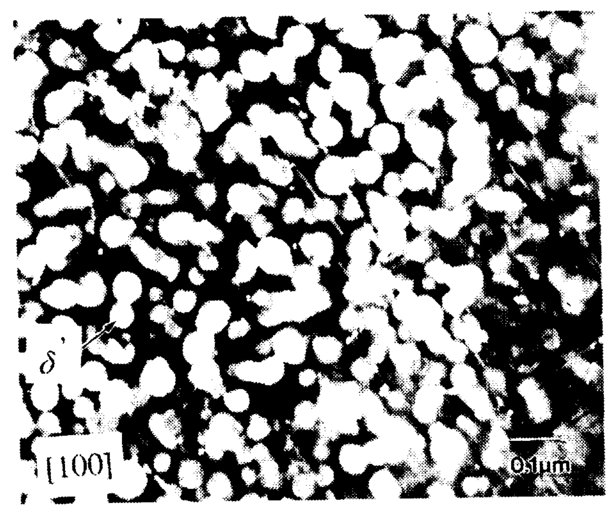
8090 Plate

Aging Temperature

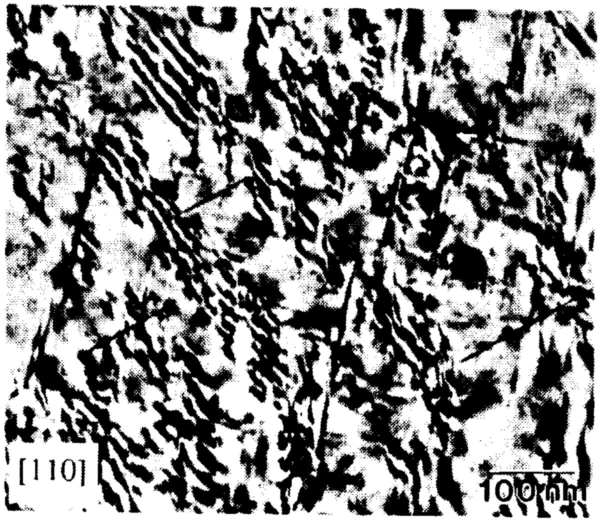
192 C

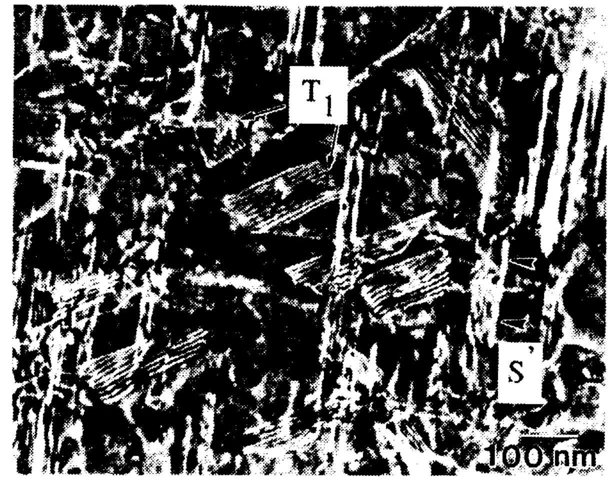


30 hrs



71 hrs





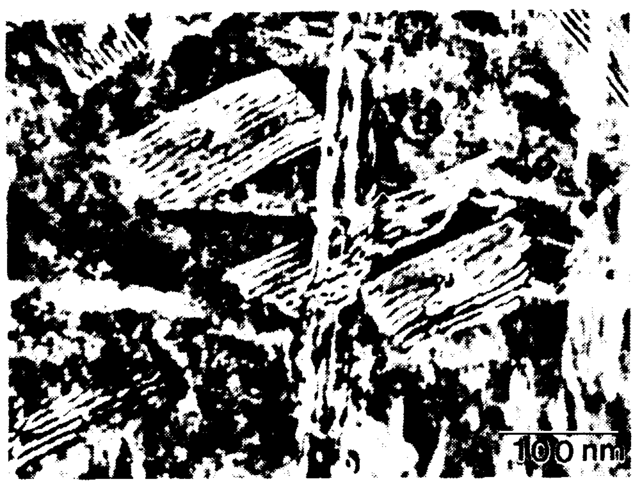
30 hrs

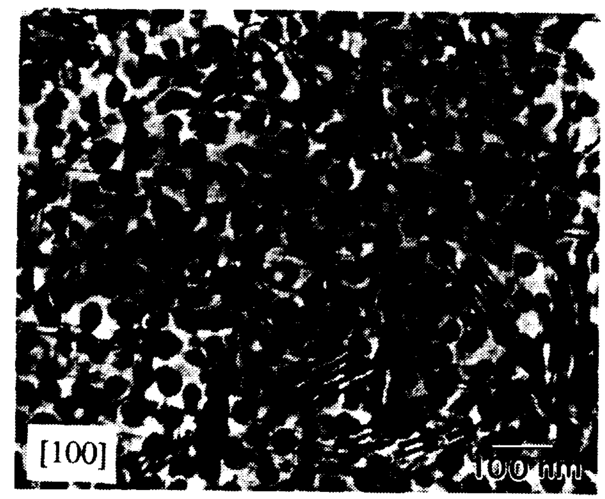
30 hrs

8090 Plate

Aging Temperature

192 C

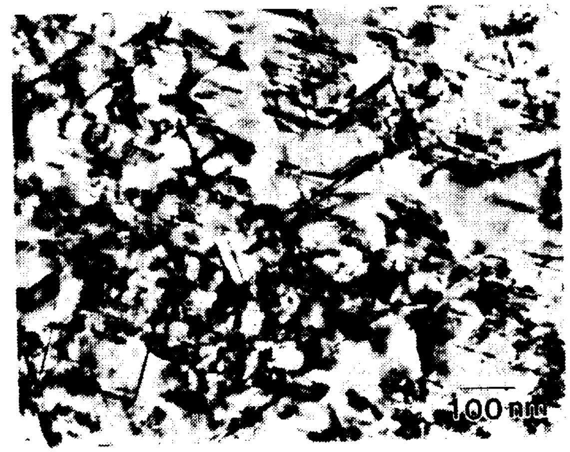




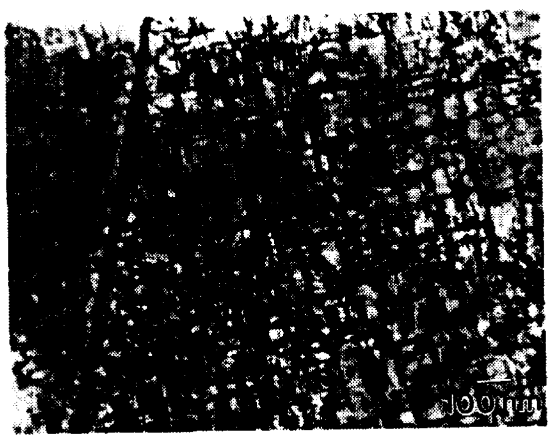
30 hrs

71 hrs

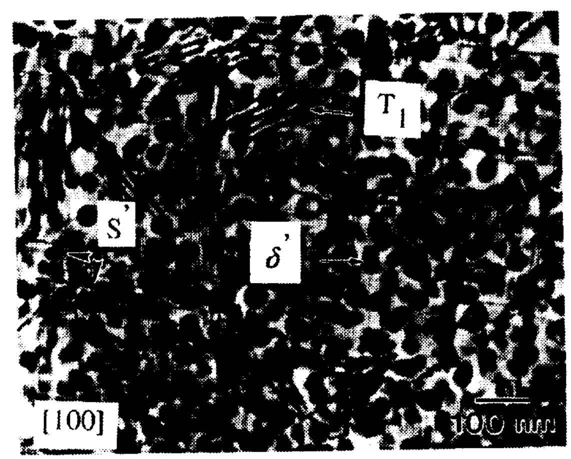
8 hrs



15 hrs



30 hrs

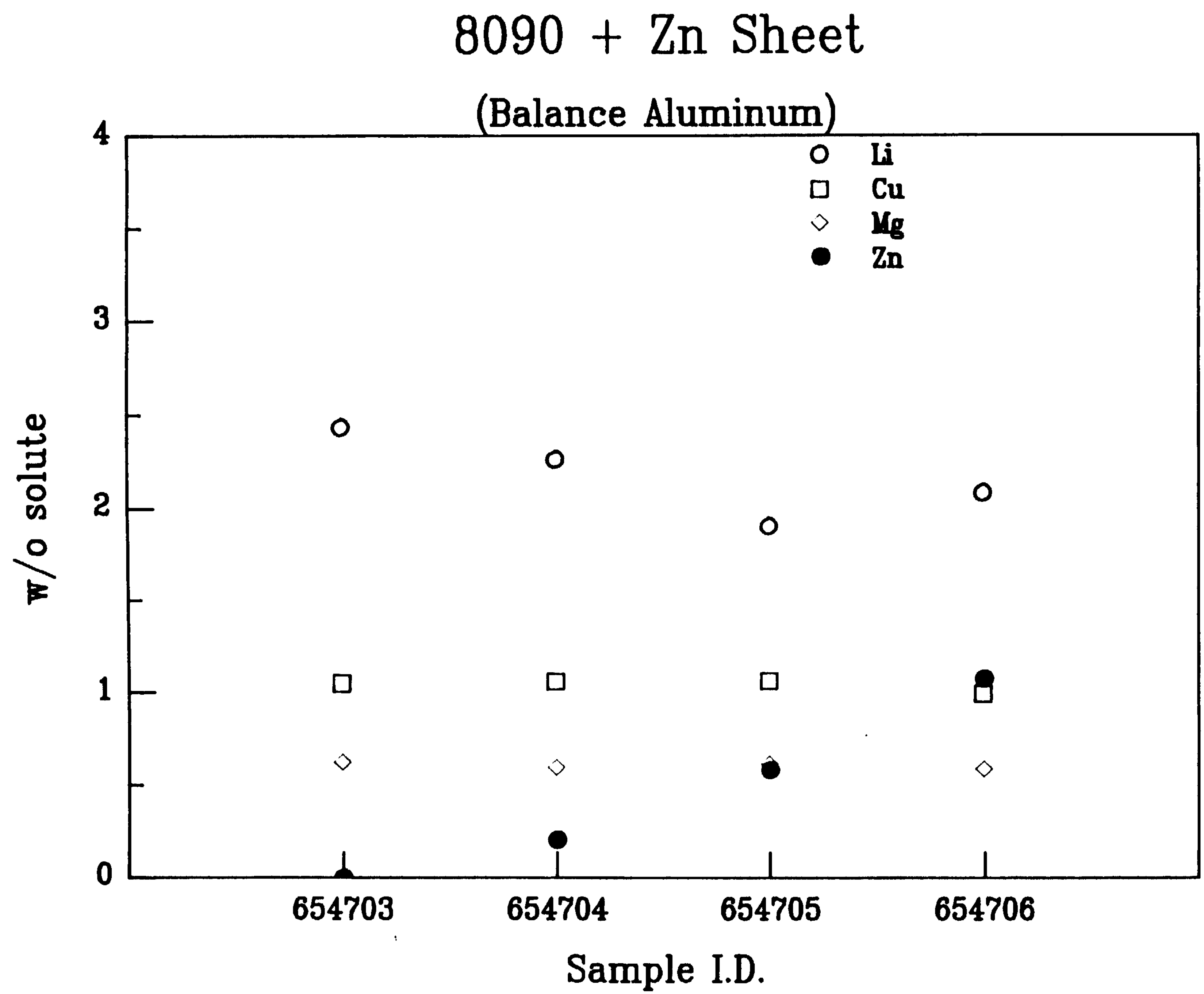


71 hrs

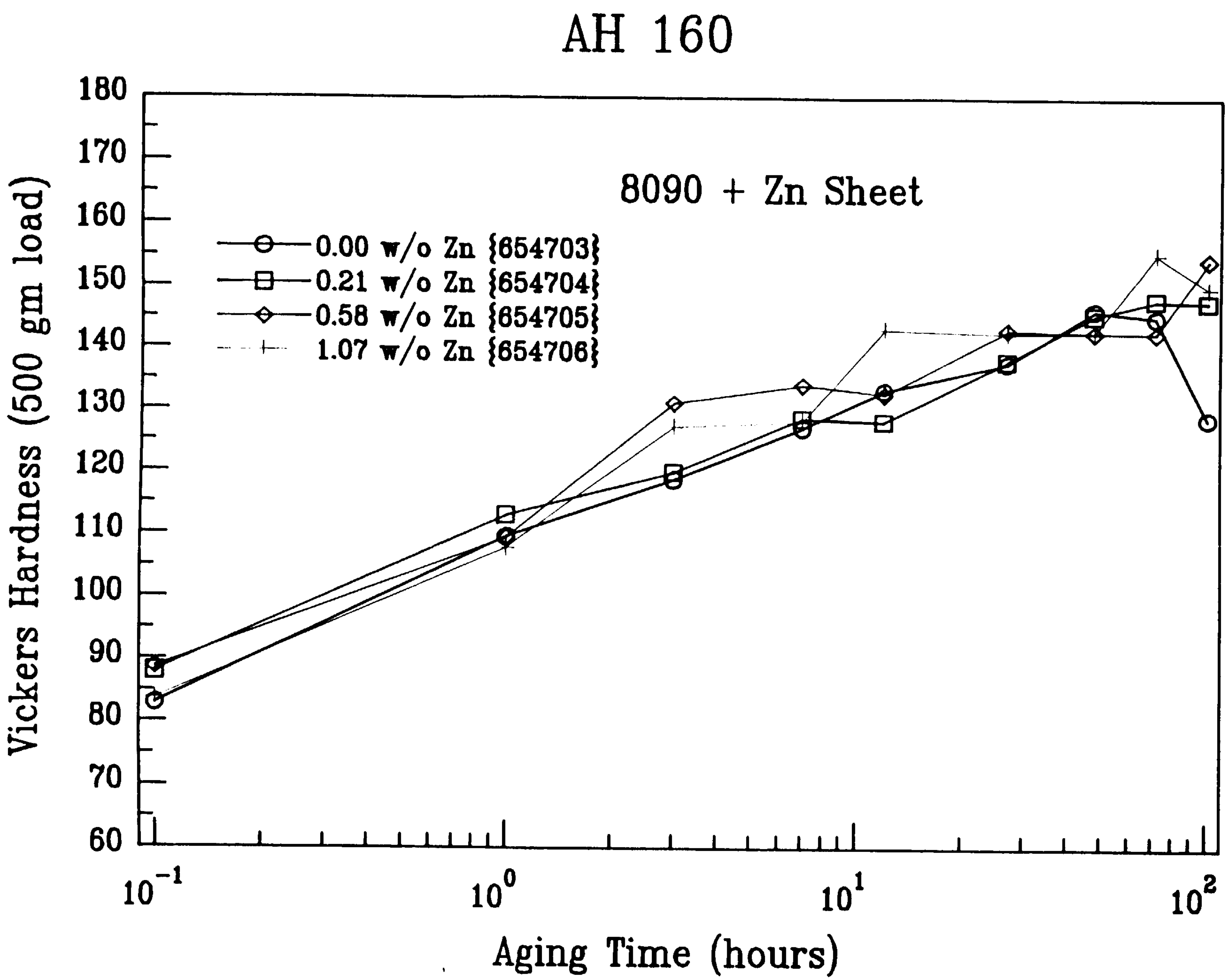
8090 + Zn Variants - Sheet

Atomic percent ratios

Sample I.D.	Target Alloy	Li/Zn	Cu/Zn	Mg/Zn
654703	8090 Baseline	-	-	-
654704	8090 + 0.21w/o Zn	101.8	5.2	7.7
654705	8090 + 0.58w/o Zn	31.0	1.9	2.9
654706	8090 + 1.07w/o Zn	18.4	1.0	1.5



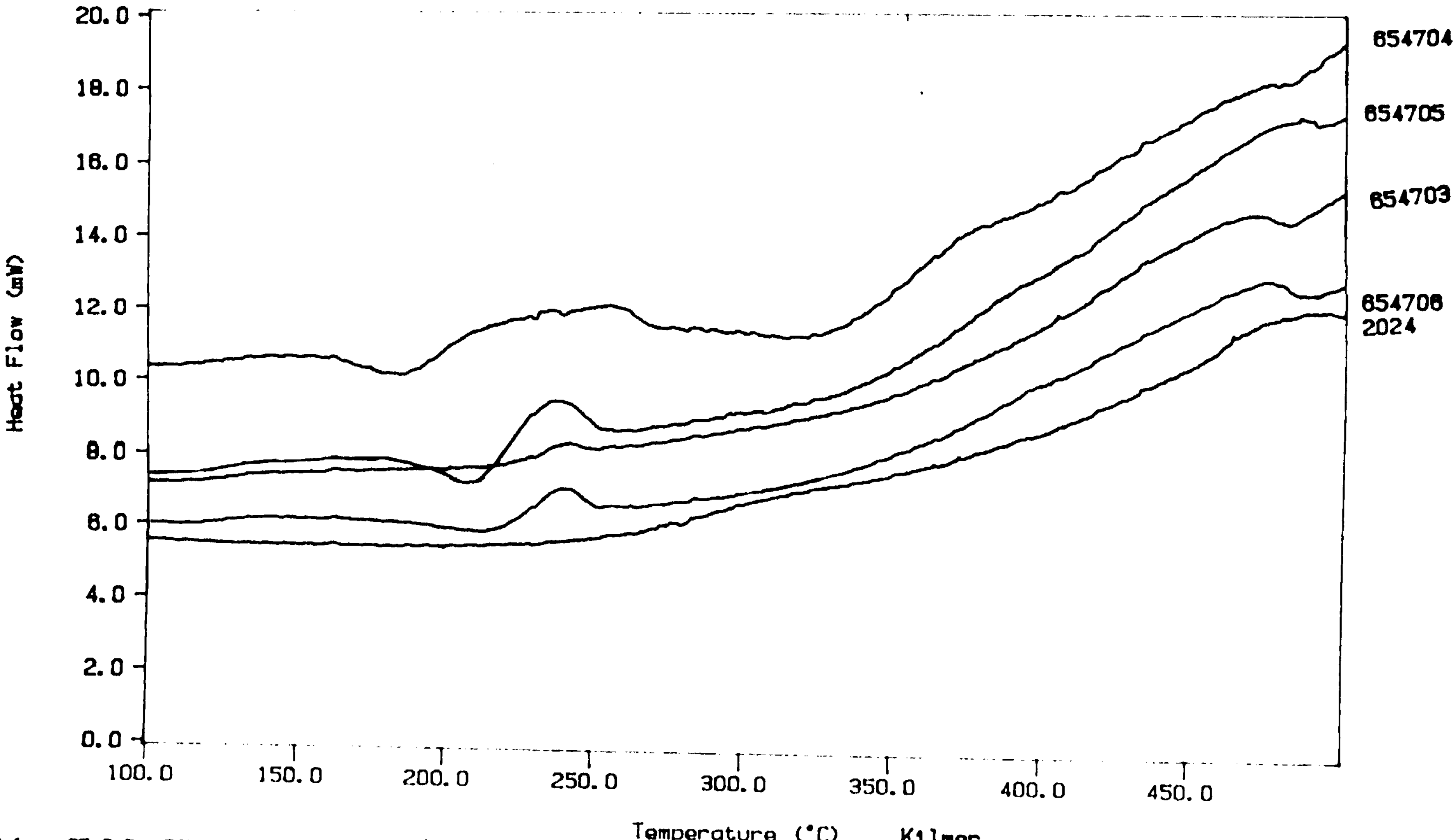
8090 + Zn Sheet
(Balance Aluminum)
Li
Cu
Mg
Zn
w/o solute
0
1
2
3
4
654703
654704
654705
654706
Sample I.D.



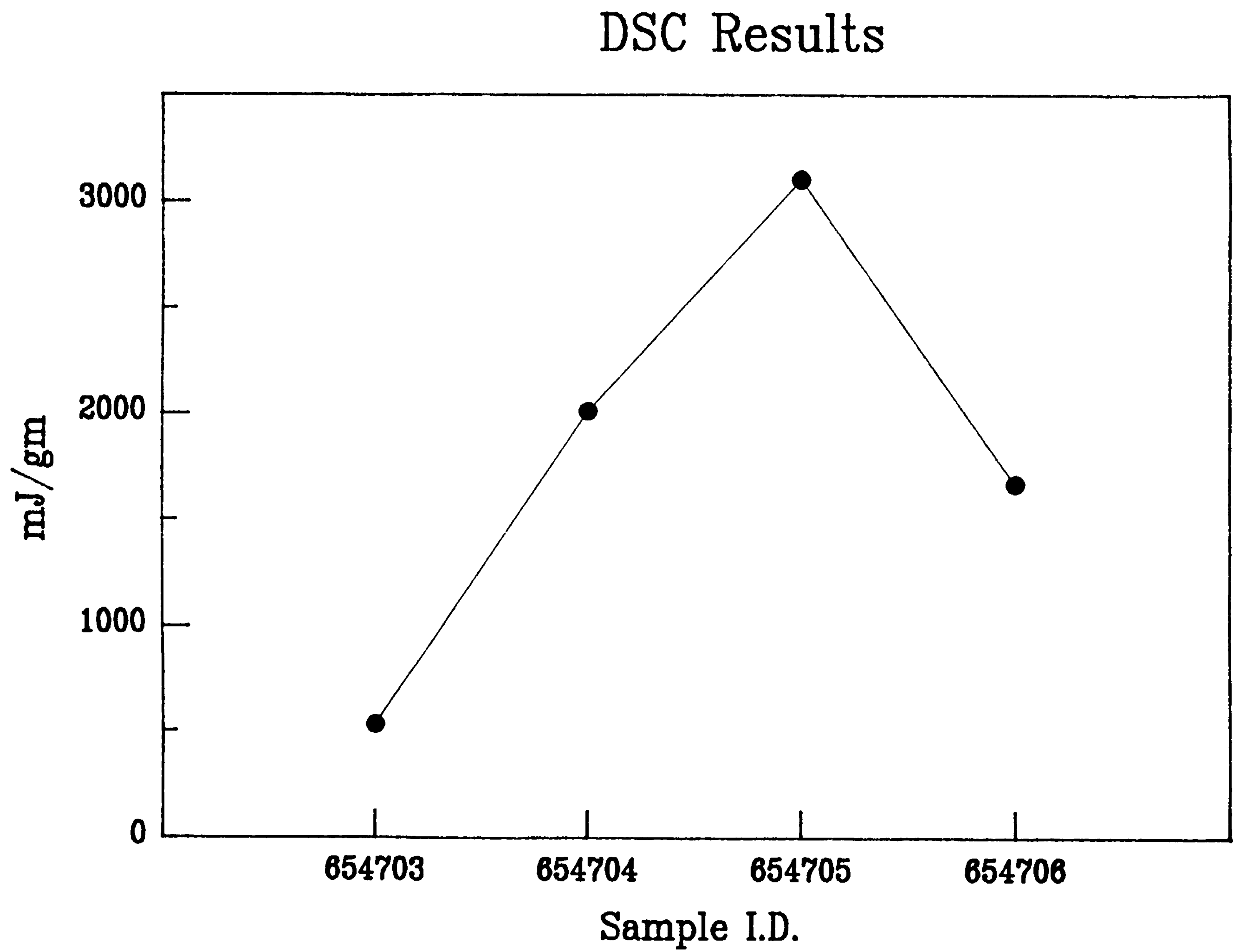
AH 160
8090 + Zn Sheet
0.00 w/o Zn {654703}
0.21 w/o Zn {654704}
0.58 w/o Zn {654705}
1.07 w/o Zn {654706}
Vickers Hardness (500 gm load)
180
170
160
150
140
130
120
110
100
90
80
70
60
10^{-1}
10^{0}
10^{1}
10^{2}
Aging Time (hours)

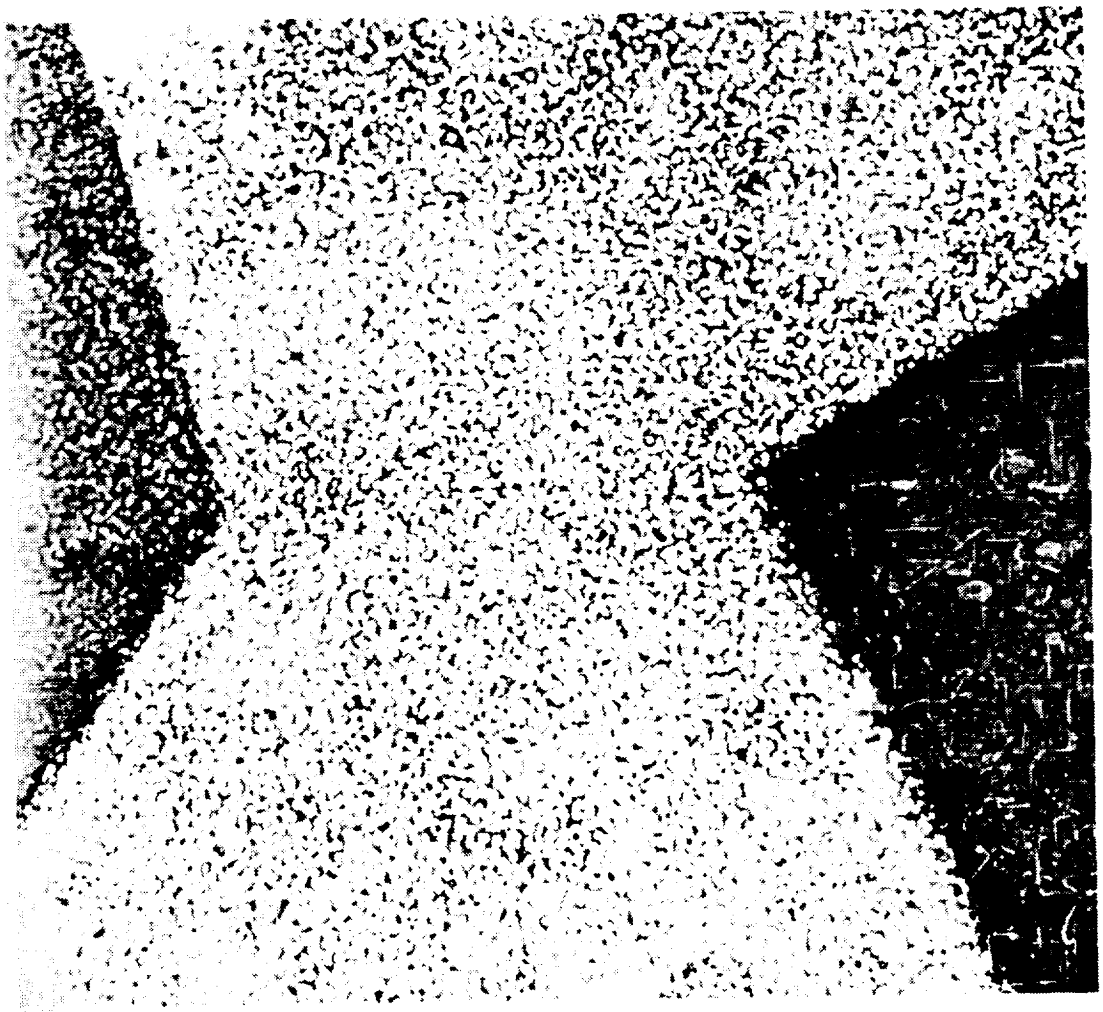
PERKIN-ELMER

7 Series Thermal Analysis System

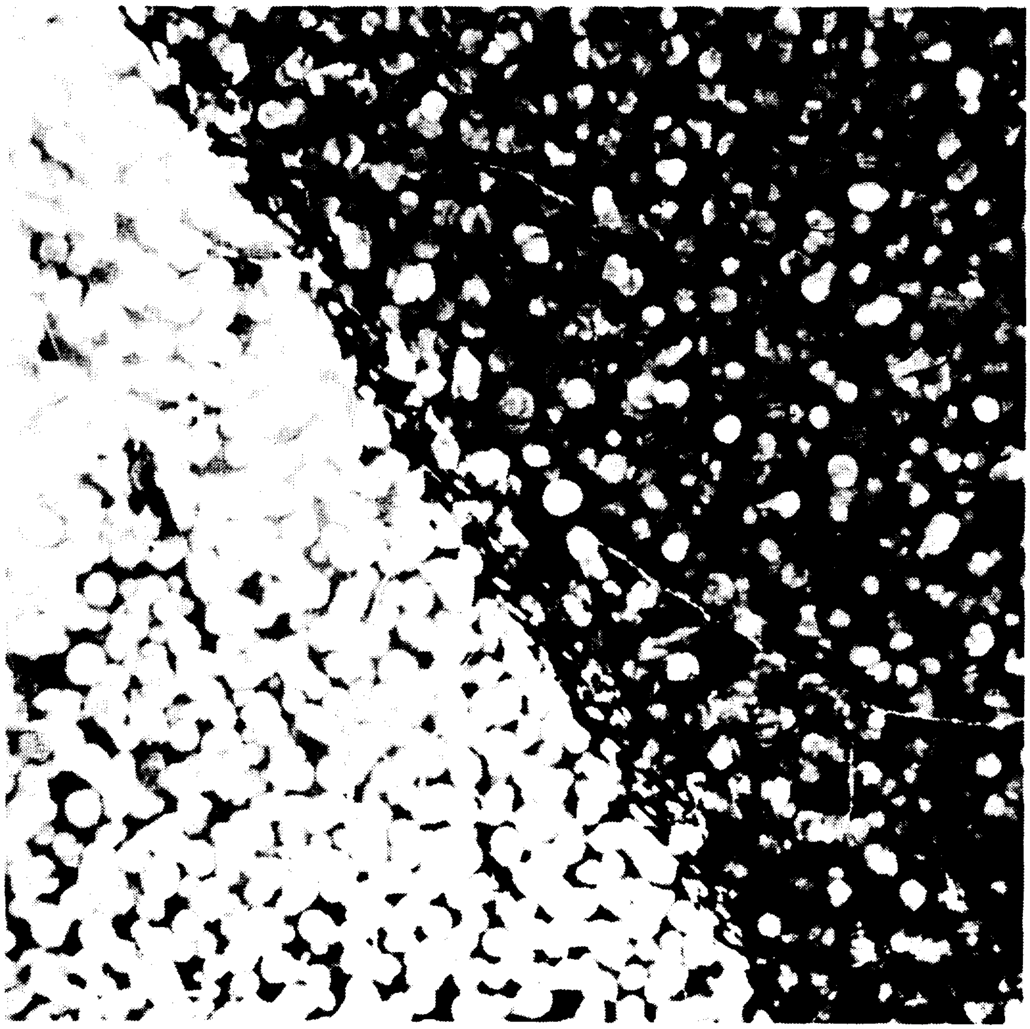


TEMP 1: 25.0 C TIME 1: 0.0 min RATE 1: 10.0 C/min
TEMP 2: 500.0 C

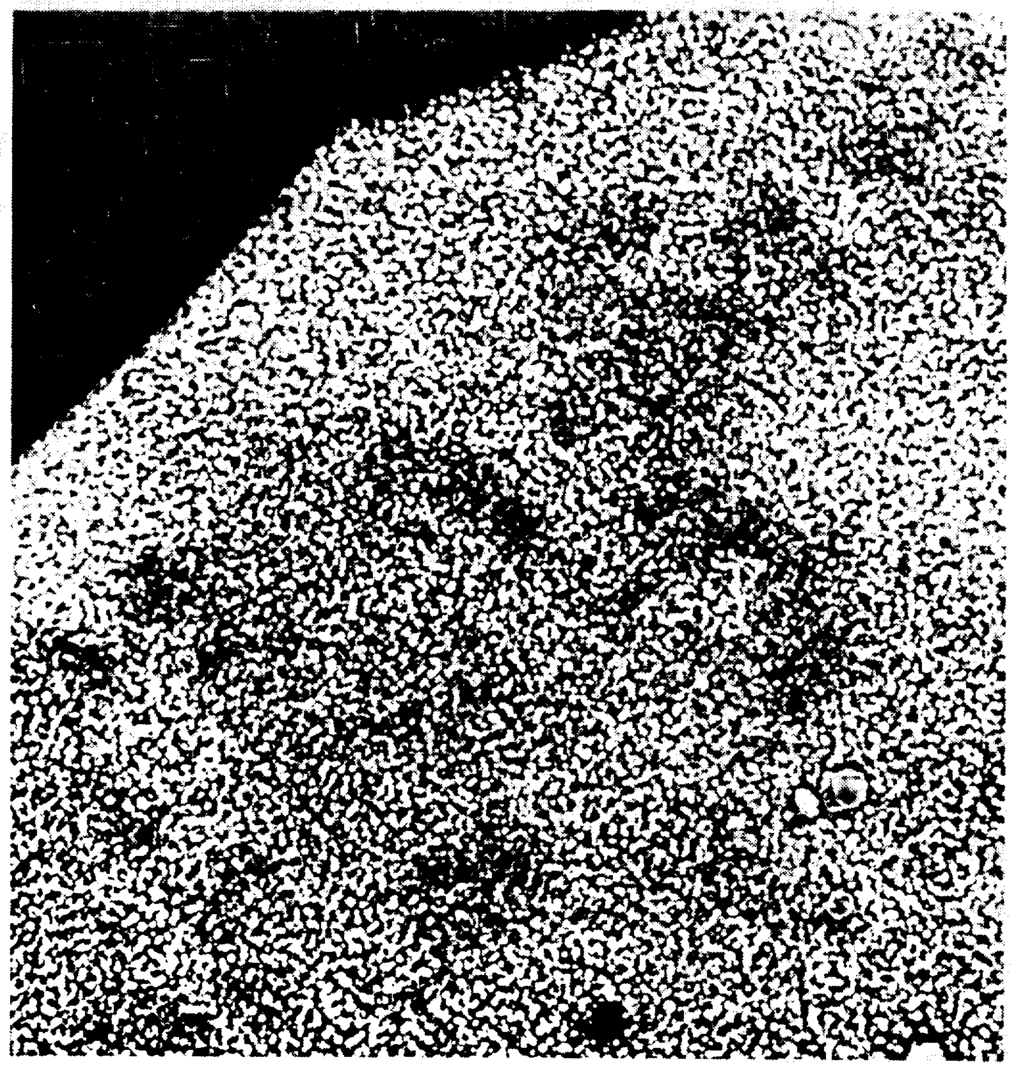

DSC Results
3000
2000
1000
0
mJ/gm
654703
654704
654705
654706
Sample I.D.



8090 + 0.2 w/o Zn (654704)

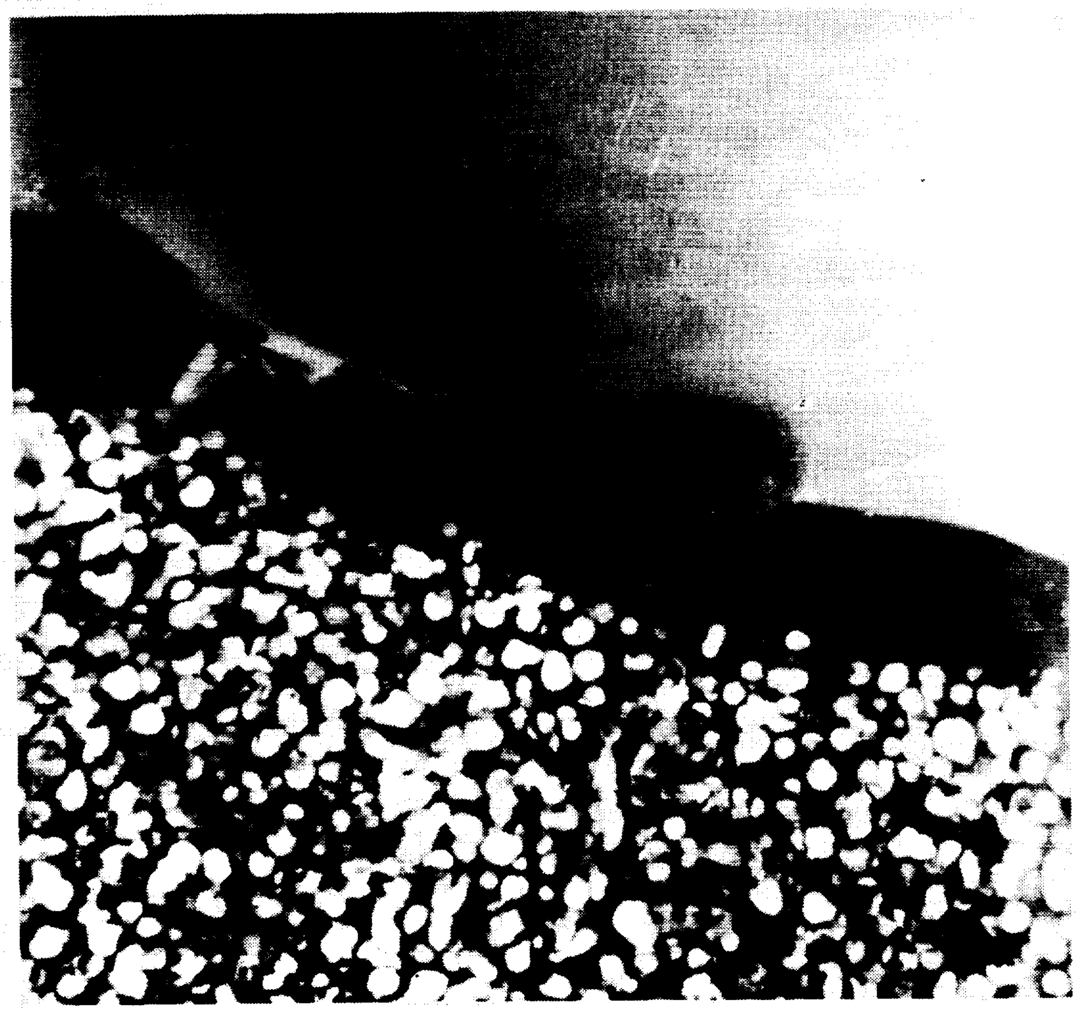


8090 + 0.2 w/o Zn (654704)

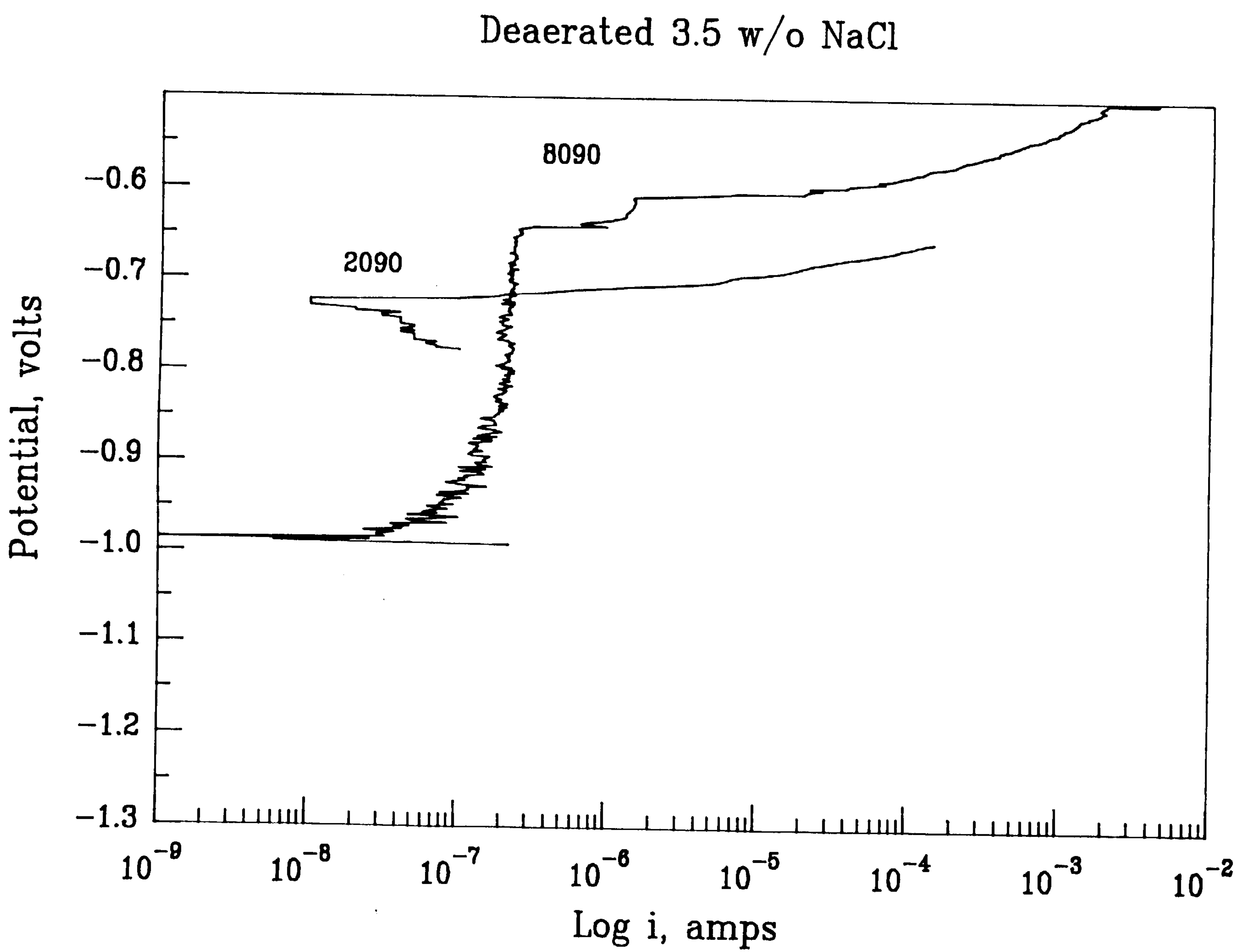


8090 + 0.5 w/o Zn (654705)

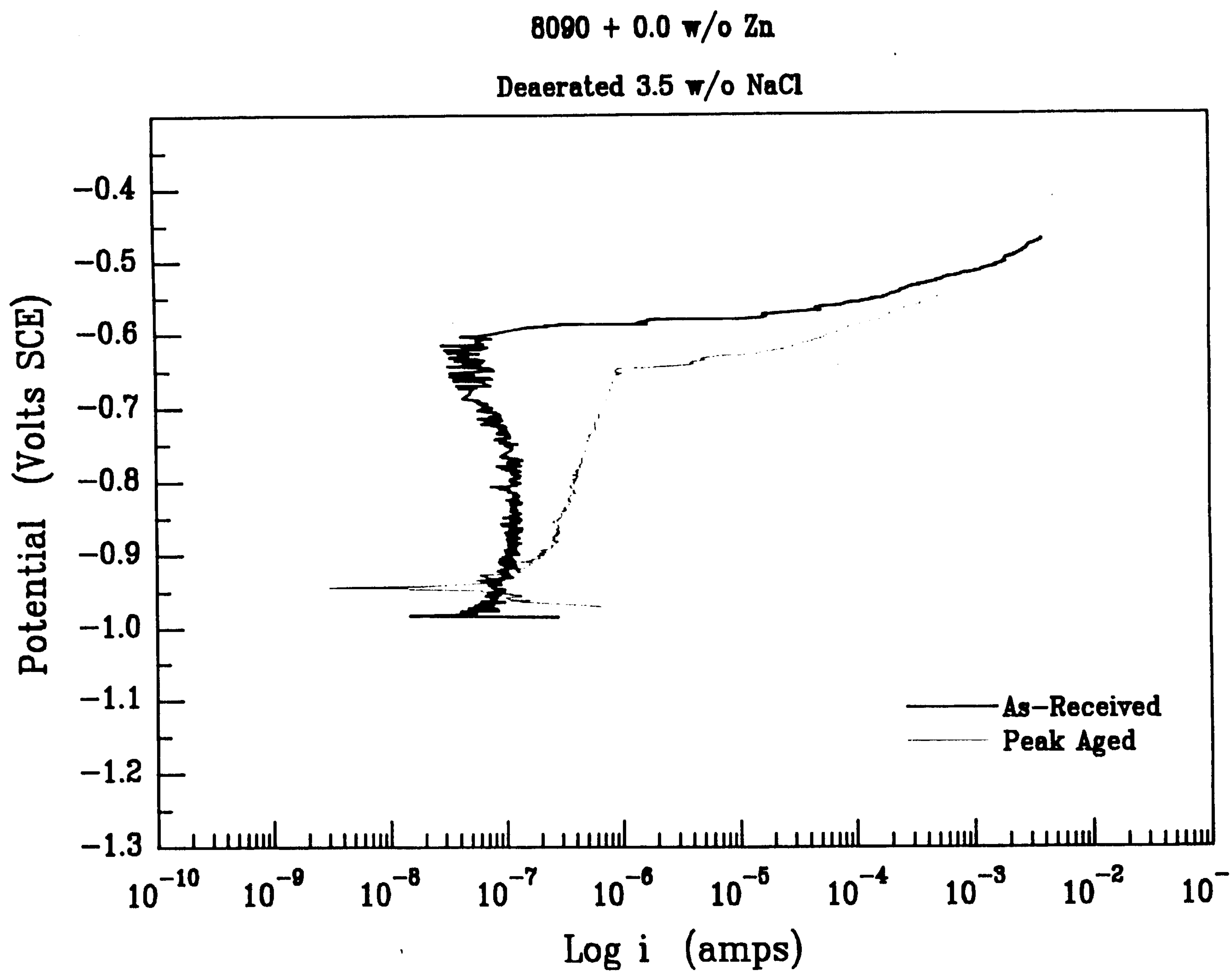
8090 + 1.0 w/o Zn (654706)

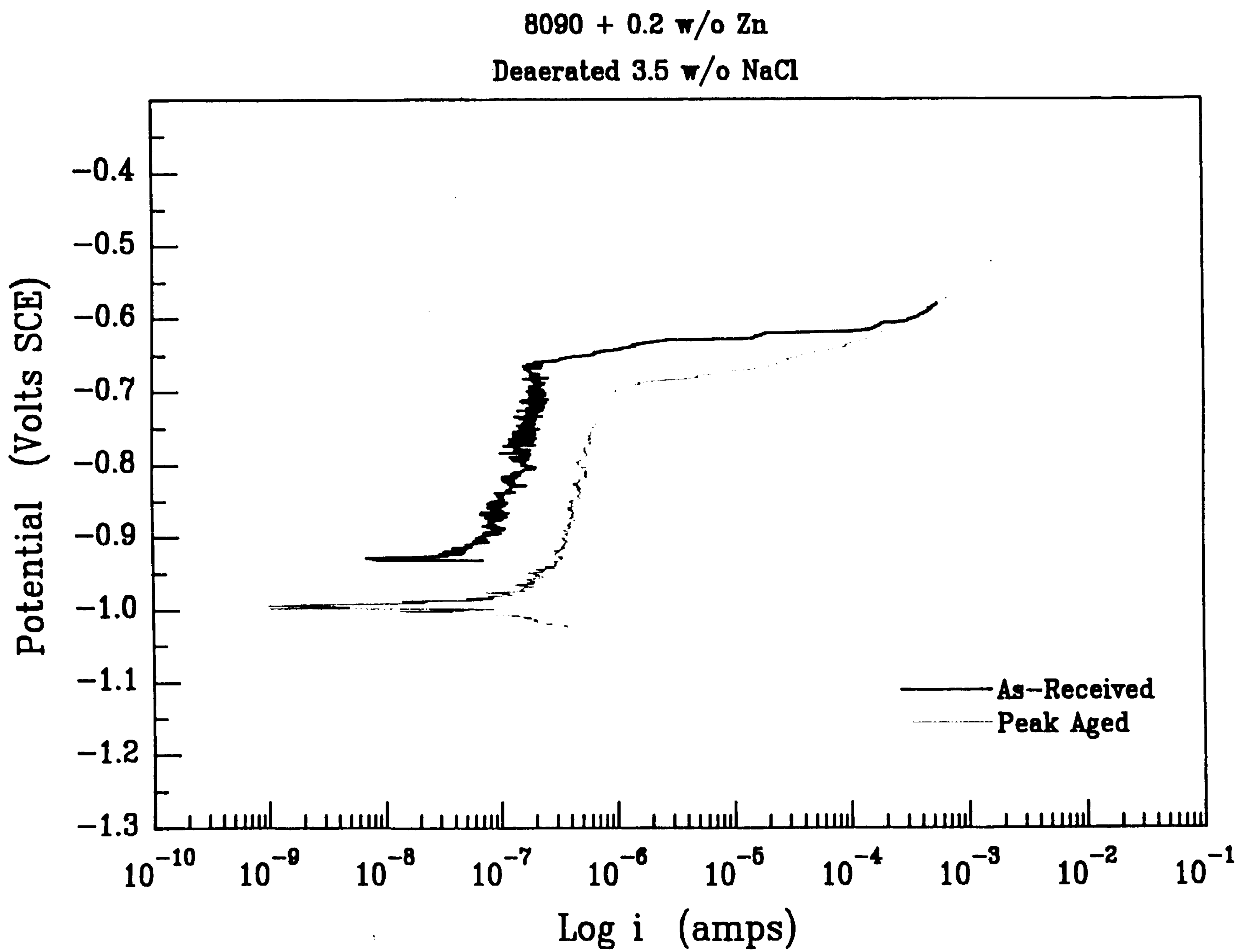


8090 + 1.0 w/o Zn (654706)

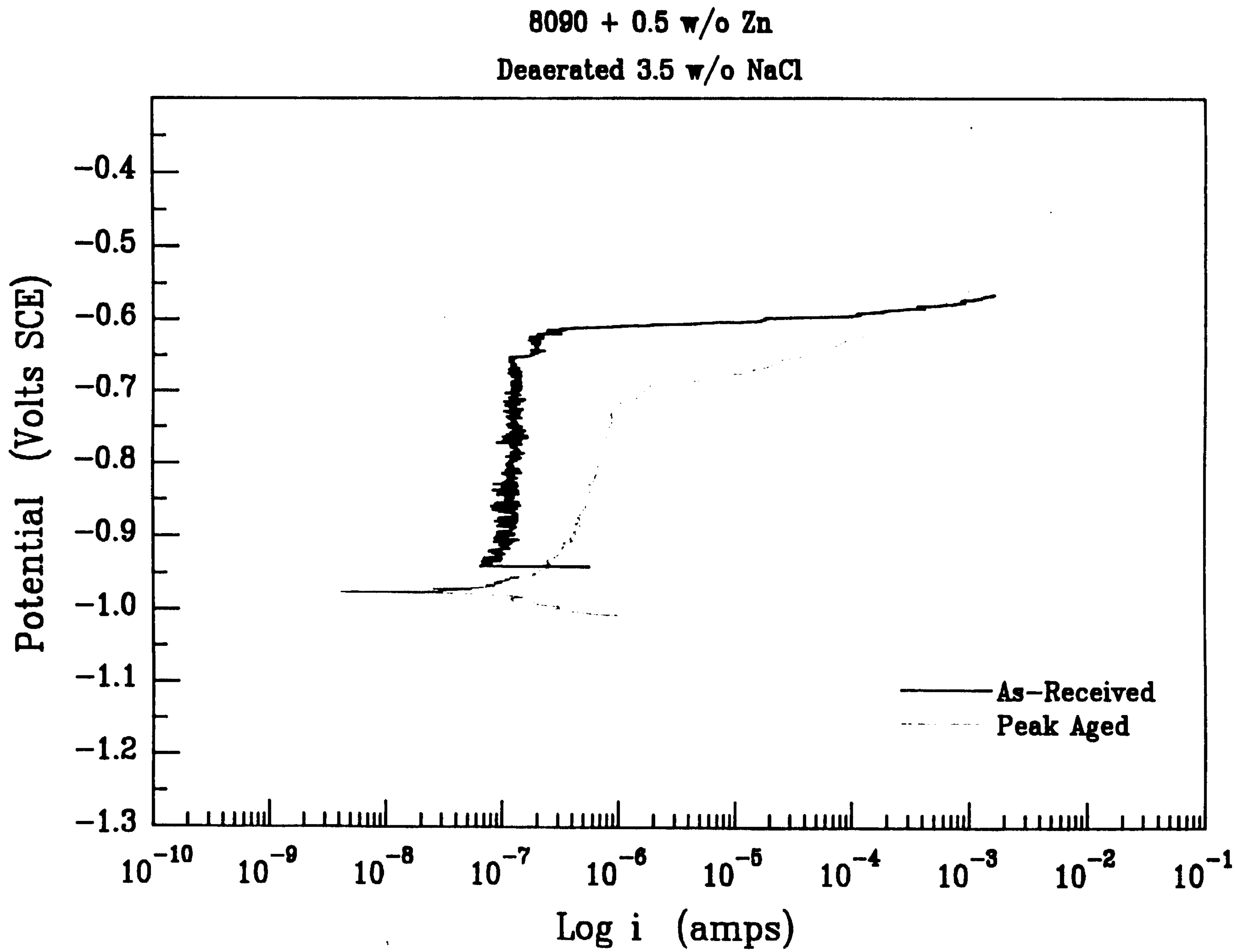


Deaerated 3.5 w/o NaCl
8090
2090
Potential, volts
-0.6
-0.7
-0.8
-0.9
-1.0
-1.1
-1.2
-1.3
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
Log i, amps

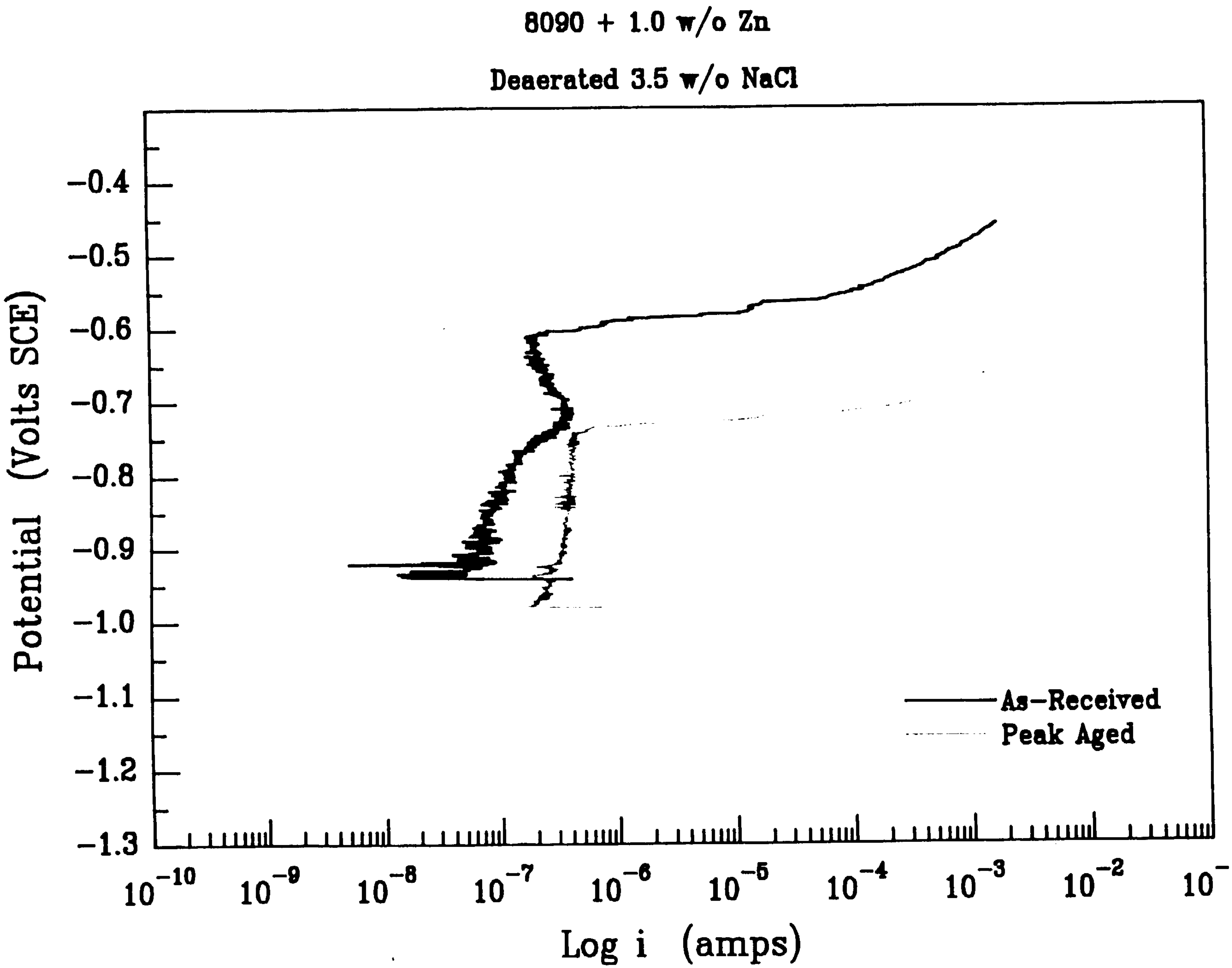

8090 + 0.0 w/o Zn
Deaerated 3.5 w/o NaCl
Potential (Volts SCE)
−0.4
−0.5
−0.6
−0.7
−0.8
−0.9
−1.0
−1.1
−1.2
−1.3
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Log i (amps)
As−Received
Peak Aged



8090 + 0.2 w/o Zn
Deaerated 3.5 w/o NaCl
Potential (Volts SCE)
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1.0
-1.1
-1.2
-1.3
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Log i (amps)
As-Received
Peak Aged



8090 + 0.5 w/o Zn
Deaerated 3.5 w/o NaCl
Potential (Volts SCE)
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1.0
-1.1
-1.2
-1.3
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Log i (amps)
As-Received
Peak Aged


8090 + 1.0 w/o Zn
Deaerated 3.5 w/o NaCl
Potential (Volts SCE)
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1.0
-1.1
-1.2
-1.3
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Log i (amps)
As-Received
Peak Aged

N90-22658

Program 6 **Deformation and Fracture of Aluminum-Lithium Alloys: The Effect of Dissolved Hydrogen**

F.C. Rivet and R.E. Swanson

Objective

The objective of this study is to characterize and understand the effects of hydrogen on the deformation and fracture behavior of 2090 and 2219, especially at low temperatures. Additionally, 8090 and Weldalite will be included in this program.

HYDROGEN EMBRITTLEMENT OF Al-Li ALLOYS

F. C. Rivet, Dr. R. E. Swanson

Department of Materials Engineering
Virginia Polytechnic Institute and State University

Abstract

The objective of this work is to study the effects of dissolved hydrogen on the mechanical properties of 2090 and 2219 alloys. The work done during this semi-annual period consists of the hydrogen charging study and some preliminary mechanical tests. Prior to SIMS analysis, several potentiostatic and galvanostatic experiments were performed for various times (going from 10 minutes to several hours) in the cathodic zone, and for the two aqueous solutions: 0.04N of HCl and 0.1N NaOH both combined with a small amount of As_2O_3. A study of the surface damage was conducted in parallel with the charging experiments. Those tests were performed to choose the best charging conditions without surface damage. Disk rupture tests and tensile tests are part of the study designed to investigate the effect of temperature, surface roughness, strain rate, and environment on the fracture behavior. In the present study, the importance of the roughness and environment have been shown using the disk rupture test as well as the importance of the strain rate under hydrogen environment. The tensile tests, without hydrogen effects, have not shown significant differences between low and room temperature.

Hydrogen Embrittlement of Al-Li Alloys

F.C. Rivet, M.S. Student
Dr. R.E. Swanson, Principal Investigator

Virginia Polytechnic Institute & State University
Dept of Materials Engineering
Blacksburg, Va 24061

Overview

- Objectives
- Approach
- Charging Experiments
  - Solutions tested
  - SIMS results
- Mechanical Tests
  - Disk Rupture
  - Tensile tests

Overview (Cont.)

- Aging experiments
  - PA for 2090T3 and W51
  - X-Ray Analysis
- Summary
- Need to Address
- Future work

Objectives

- Characterize effects of temperature, stress state, hydrogen on mechanical behavior.
- Correlate these effects with microstructure.

Approach

- Charpy Impact Test.
- Tensile Test
  control hydrostatic stress.
- Disk Rupture Test
  biaxial loading.
- Three Point Bend Test
  low strain rate.

Charging Experiments

- Methods to Charge Samples
- Electrochemical Solution
- Surface Analysis
- SIMS Results

Charging Experiments

Two principal methods can be used to charge samples:

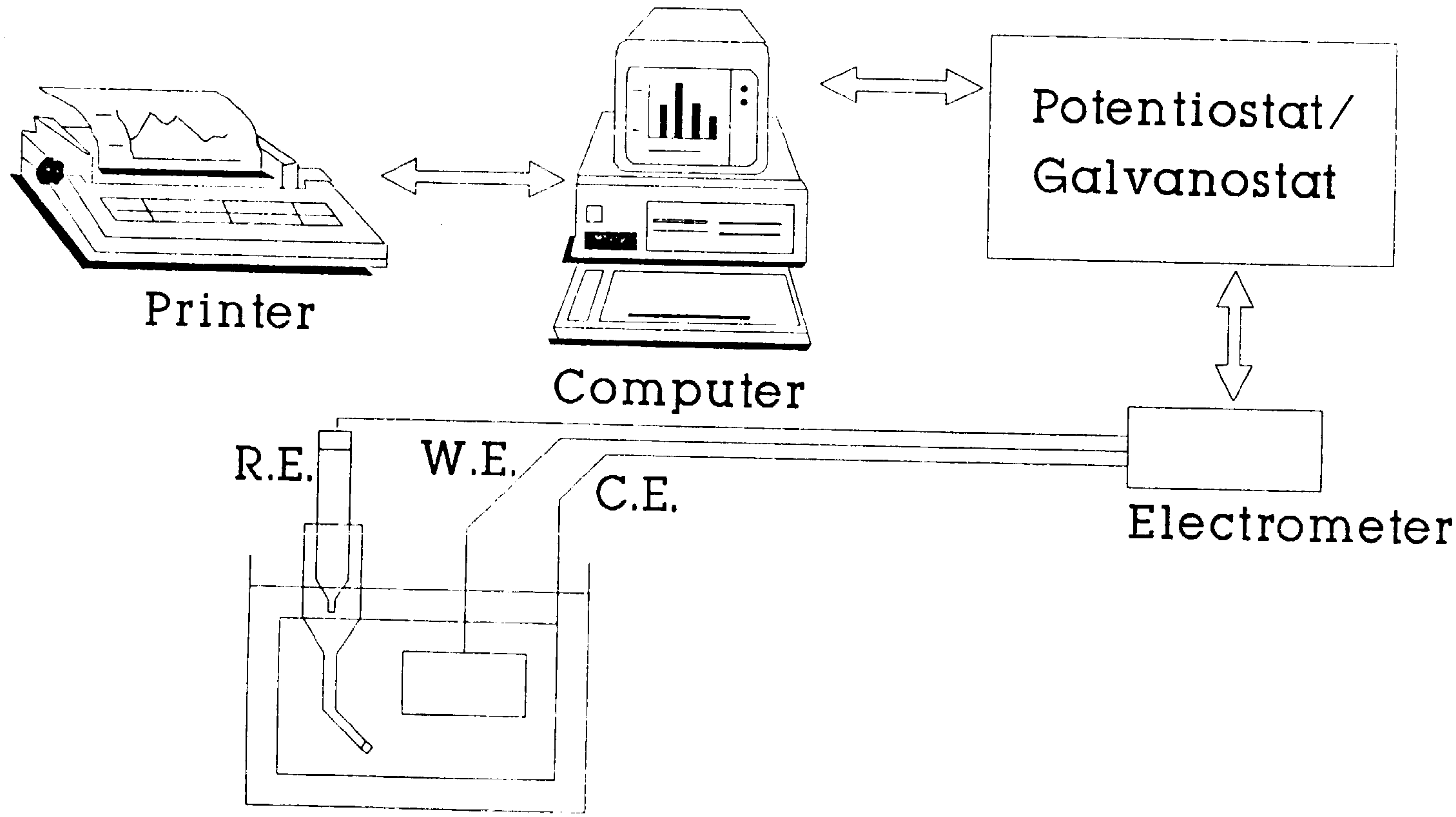
- Autoclave
- Electrochemical cell

Choice of the Aqueous Solution

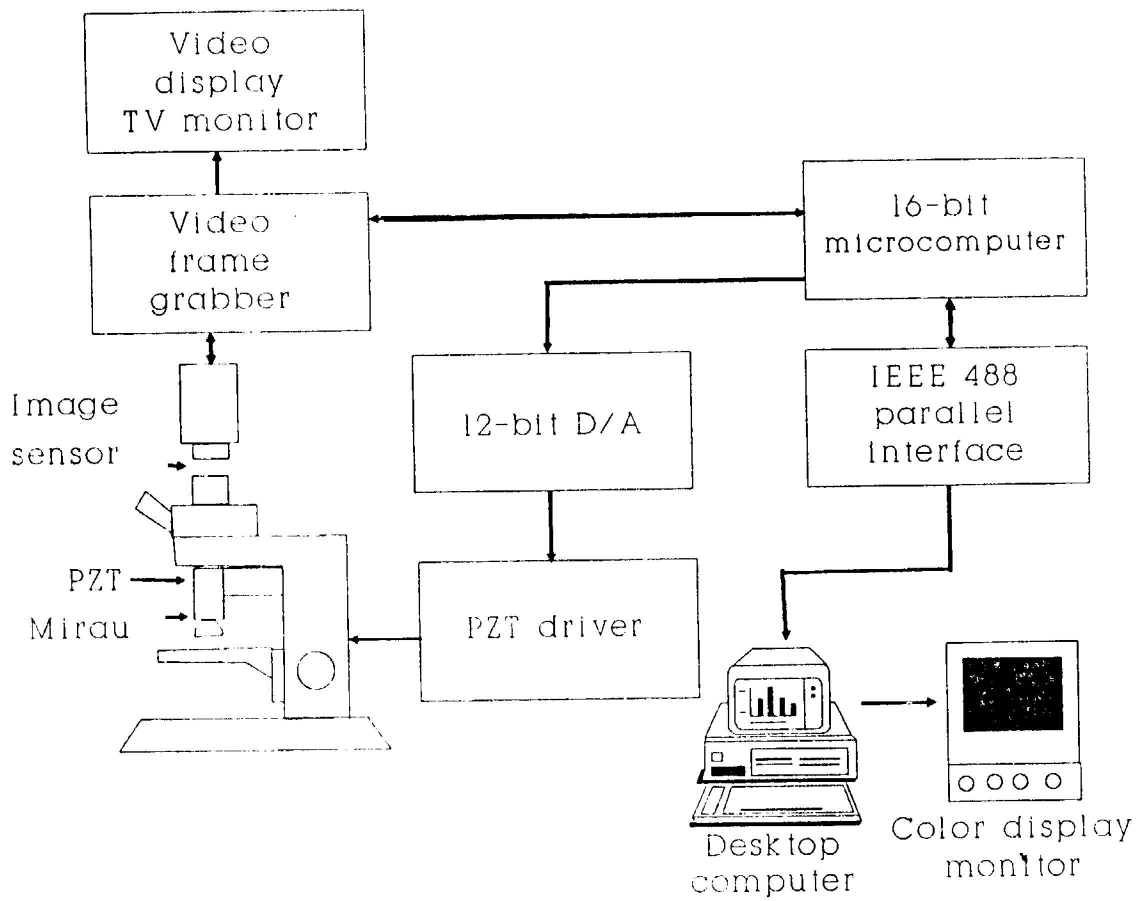
- Must contain H+
  => Low pH.

- Must not damage the sample
  => Choice of the charging voltage
  or current.

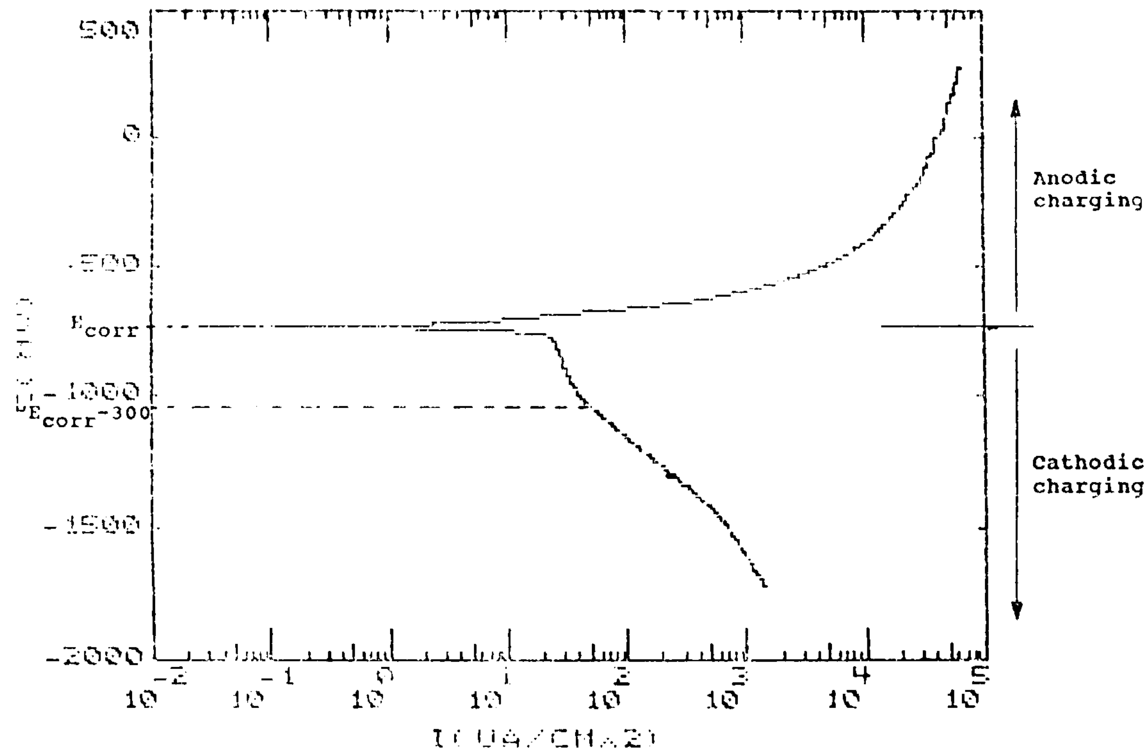
Instrumental Scheme



Optical Profilometer



Choice of the Voltage



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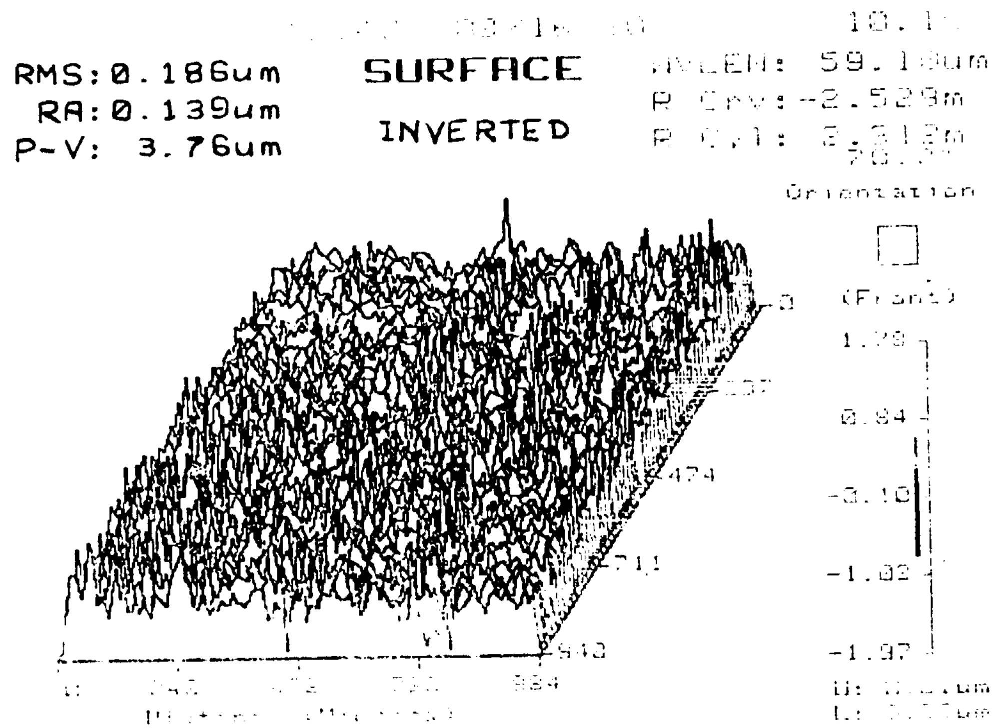
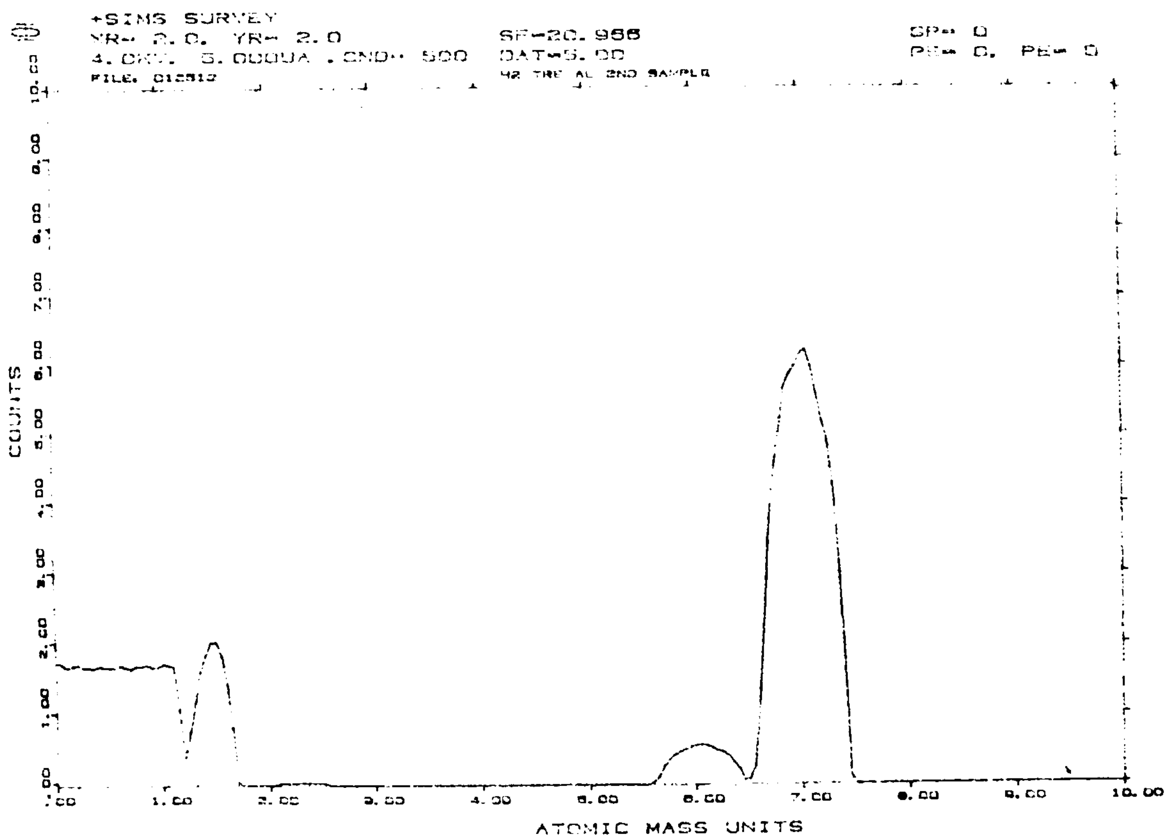
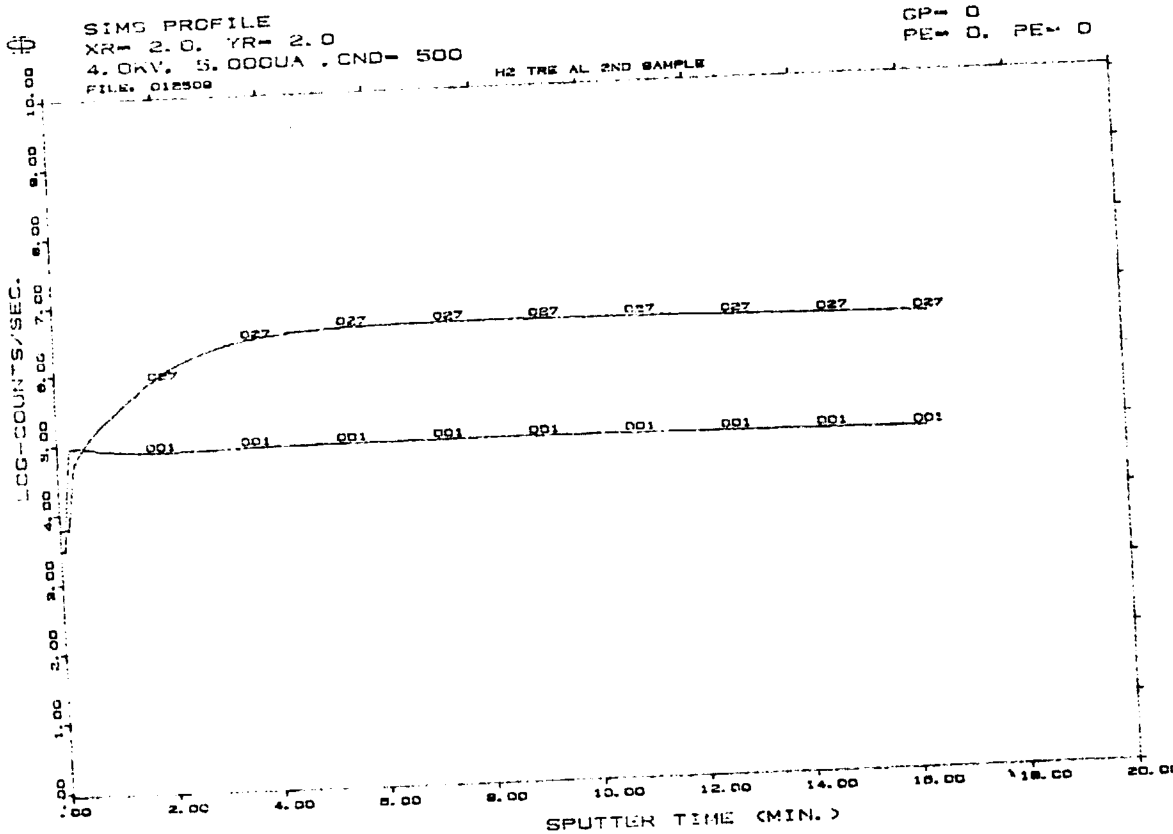
Optical Profilometer (Results)



SIMS Results



SIMS Results



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Interim Results

Hydrogen Charging Parameters

- 0.04 N HCL + As2O3 at -3V (1)
- 0.1 N NaOH + As2O3 at -3V (2)
- 0.04 N HCl + As2O3 at -500 μA (3)
- 0.04 N HCl + As2O3 at -5000 μA (4)

Interim Results

Hydrogen Charging Parameters

Solution	Time	Dif. of counts/sec	H content	Surface Roughness RMS (μm)
(1)	5 hrs	0.057		0.0795
(2)	.5 hrs	-------		0.185
(3)	20 hrs	0.059		0.0772
(4)	20 hrs	0.0185		0.0861
Uncharged	-----	-------		0.0752

Interim Results

Hydrogen Charging Parameters

The two selected charging solutions are:

- 0.04 N HCl+As2O3 at −3 V for 5 hrs
- 0.04 N HCl+As2O3 at −500 μA for 20hrs

Charging Experiments

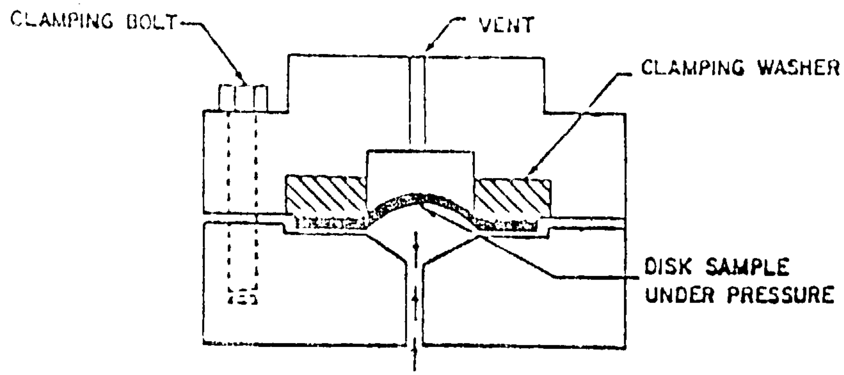
- SIMS technique has not yet been successful
- Evaluating other surface analytical techniques for hydrogen content and hydrogen profile

Disk Rupture Tests

- vary strain rate
- compare effect of nitrogen vs. effect of hydrogen
- vary surface finish

Disk Rupture tests

SCHEMATIC OF DISK PRESSURIZING ASSEMBLY



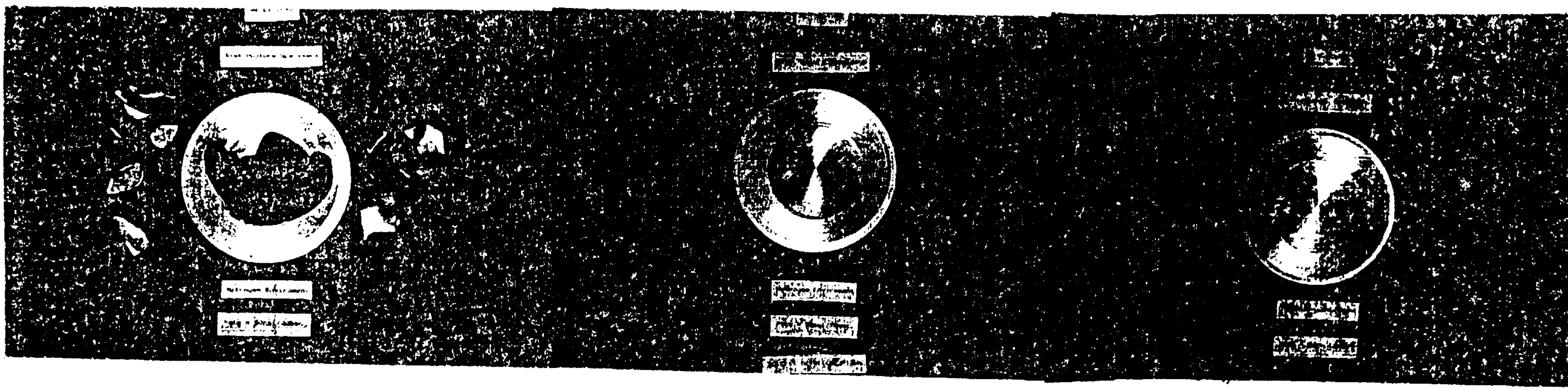
Interim Results

Disk Rupture Tests

Specimen	Hydrogen	Nitrogen
50psi/20sec	0.16in/.85ksi *	0.22in/1.6ksi
50psi/200sec	0.2in/1.15ksi *	0.19in/1.65ksi
50psi/300sec	0.14in/.7ksi	0.18in/1.45ksi
50psi/20sec(60 grit)	0.15in/.6ksi	= = = = = = = =
50psi/200sec(60 grit)	0.18in/.8ksi	= = = = = = = =
50psi/300sec(60 grit)	0.13in/.6ksi	= = = = = = = =

* Leaked instead of rupture

Typical Failures for the Disk Rupture Tests



Interim Results

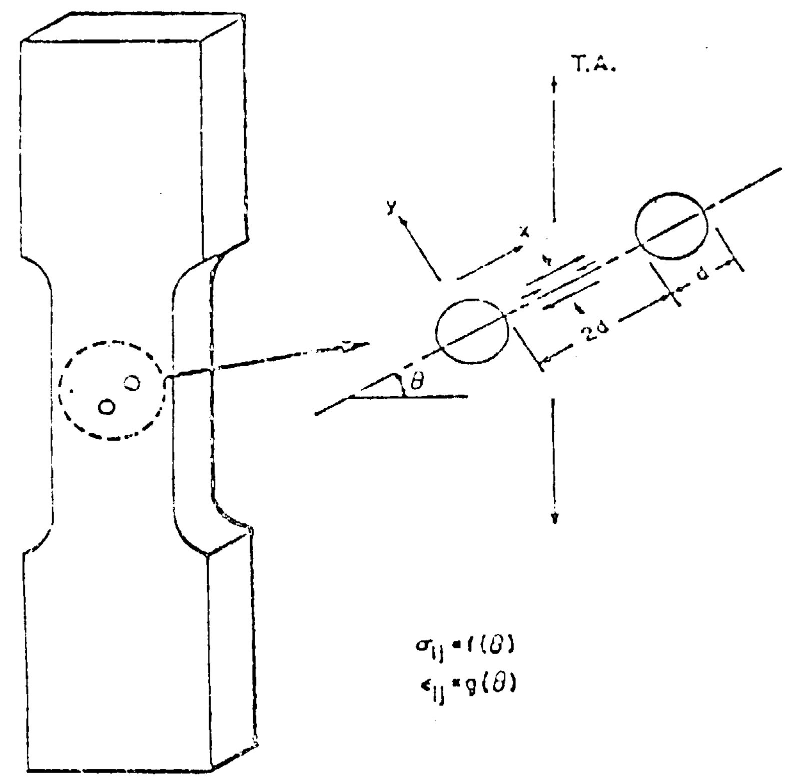
Disk Rupture Tests

- Minimized hydrogen embrittlement at intermediate strain rate.
- Rough surface results in burst type failure
- Rough surface decreased failure pressure
- The strain rate had no effect in nitrogen

Tensile Tests

- charged and uncharged
- vary σ_H
- vary temperature
- vary gas pressure

Tensile Tests



$\sigma_{ij} = f(\theta)$
$\epsilon_{ij} = g(\theta)$

Schematic of Two-Hole Flat Tensile Specimen

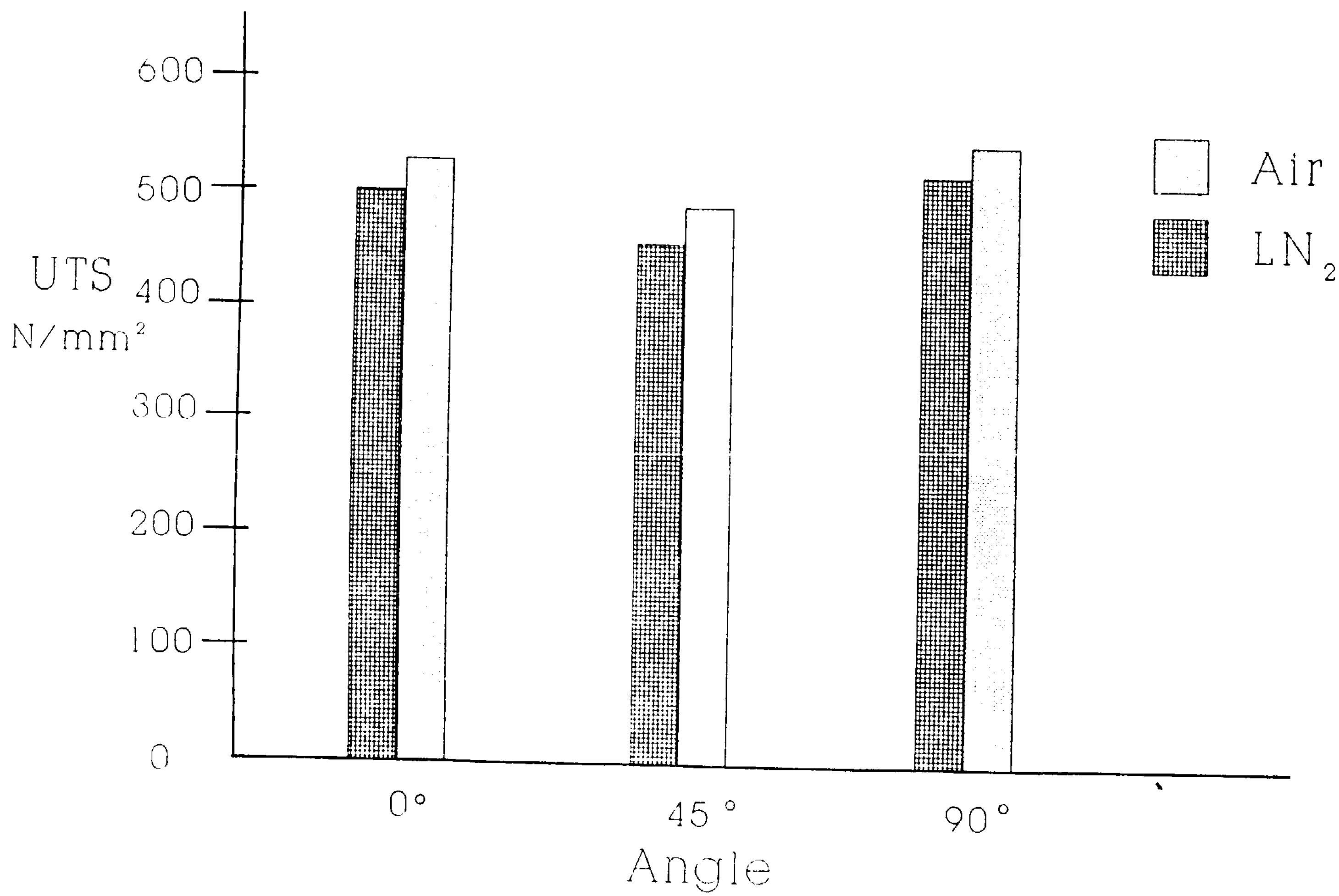
Interim Results

Tensile tests

Angle	Envir.	UTS, N/mm2	TD, mm	Ef, %
0 deg	Air	500	1.626	3.4
	LN_2	528	1.321	2.8
45 deg	Air	456	1.232	2.6
	LN_2	489	1.016	2.1
90 deg	Air	516	1.626	3.4
	LN_2	546	1.854	3.9

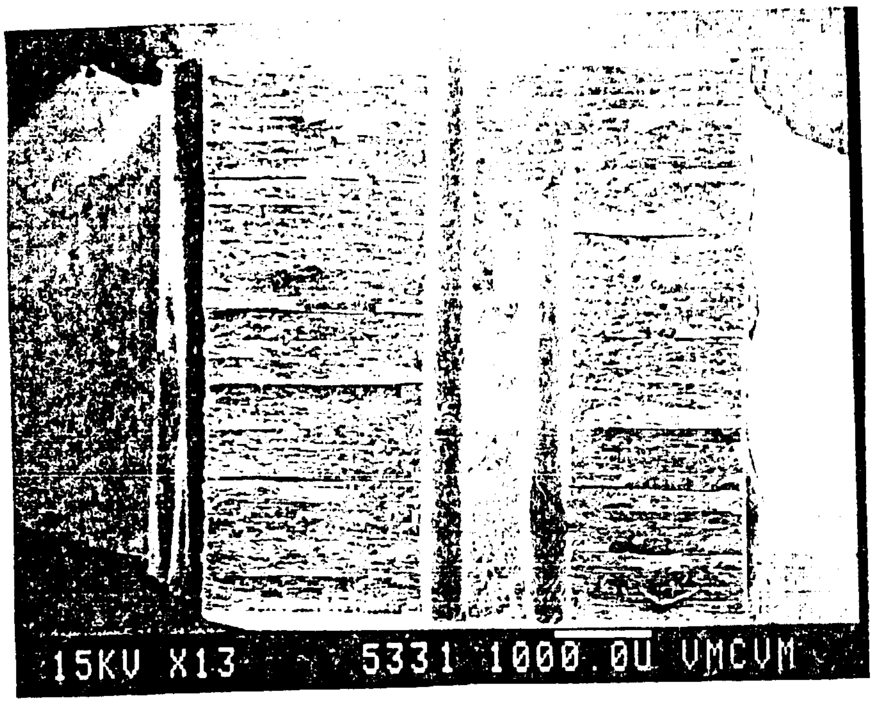
Interim Results

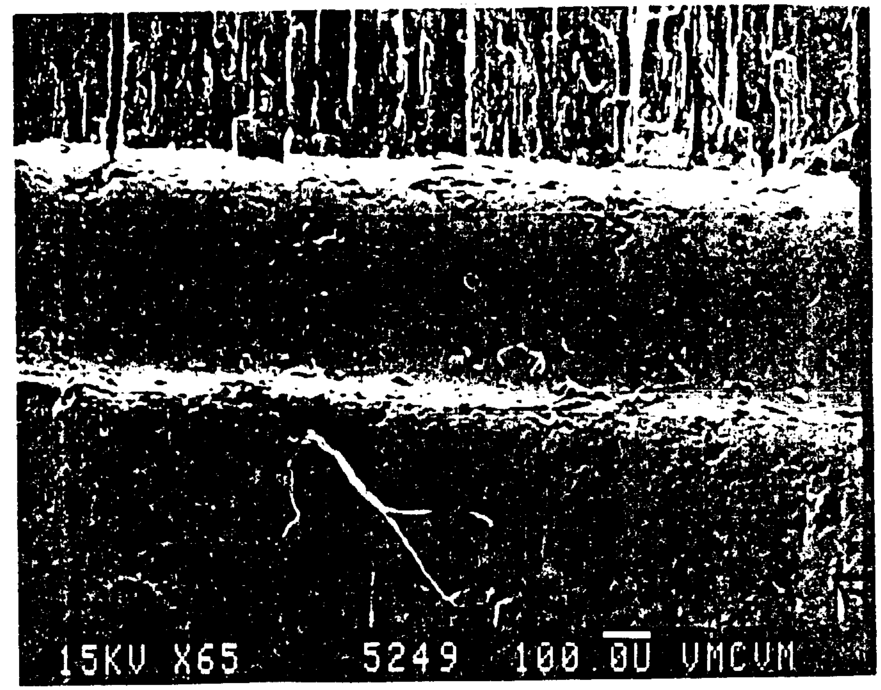
Tensile Tests



Fractography

Tensile Test Specimen at 45



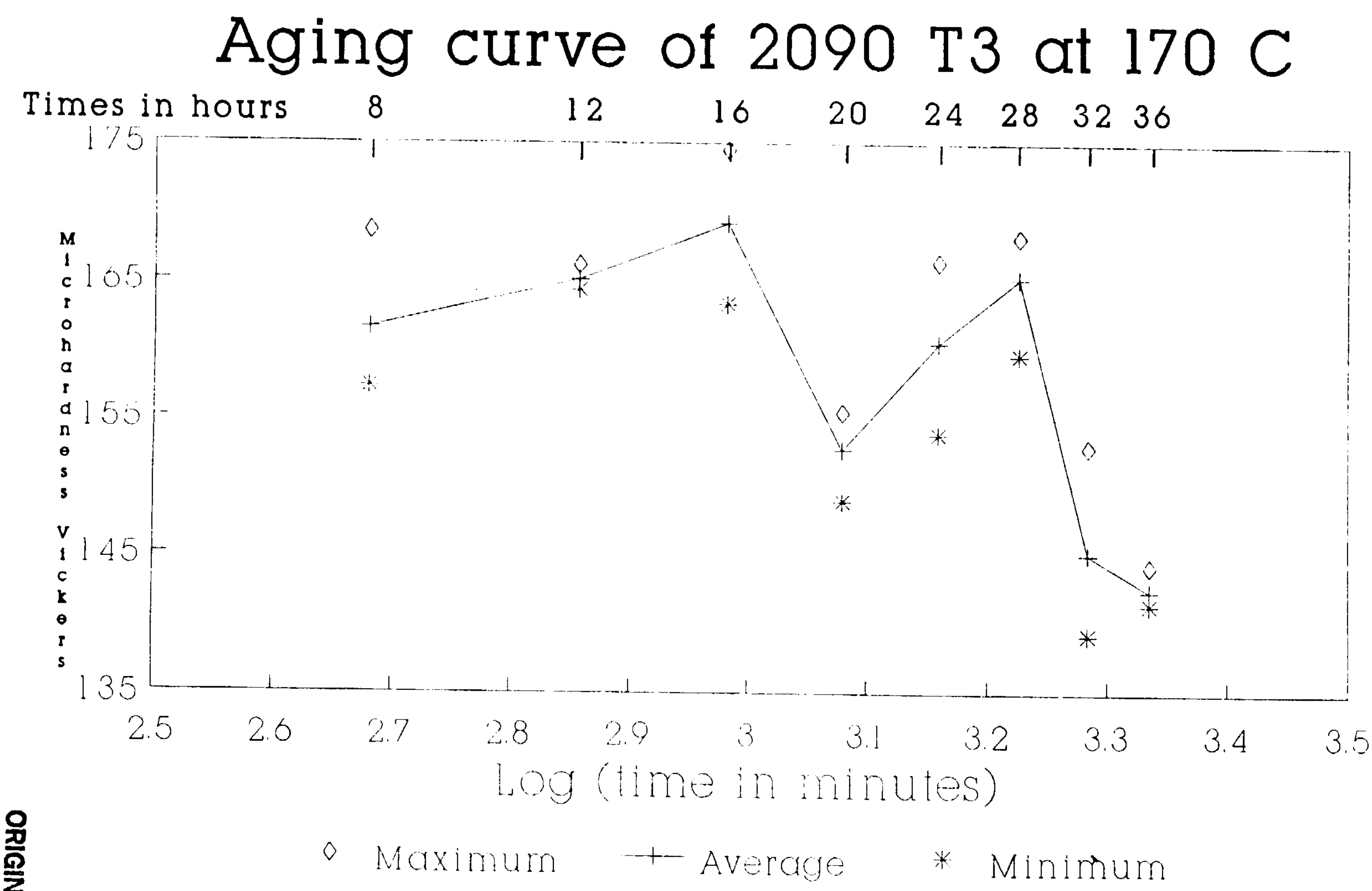


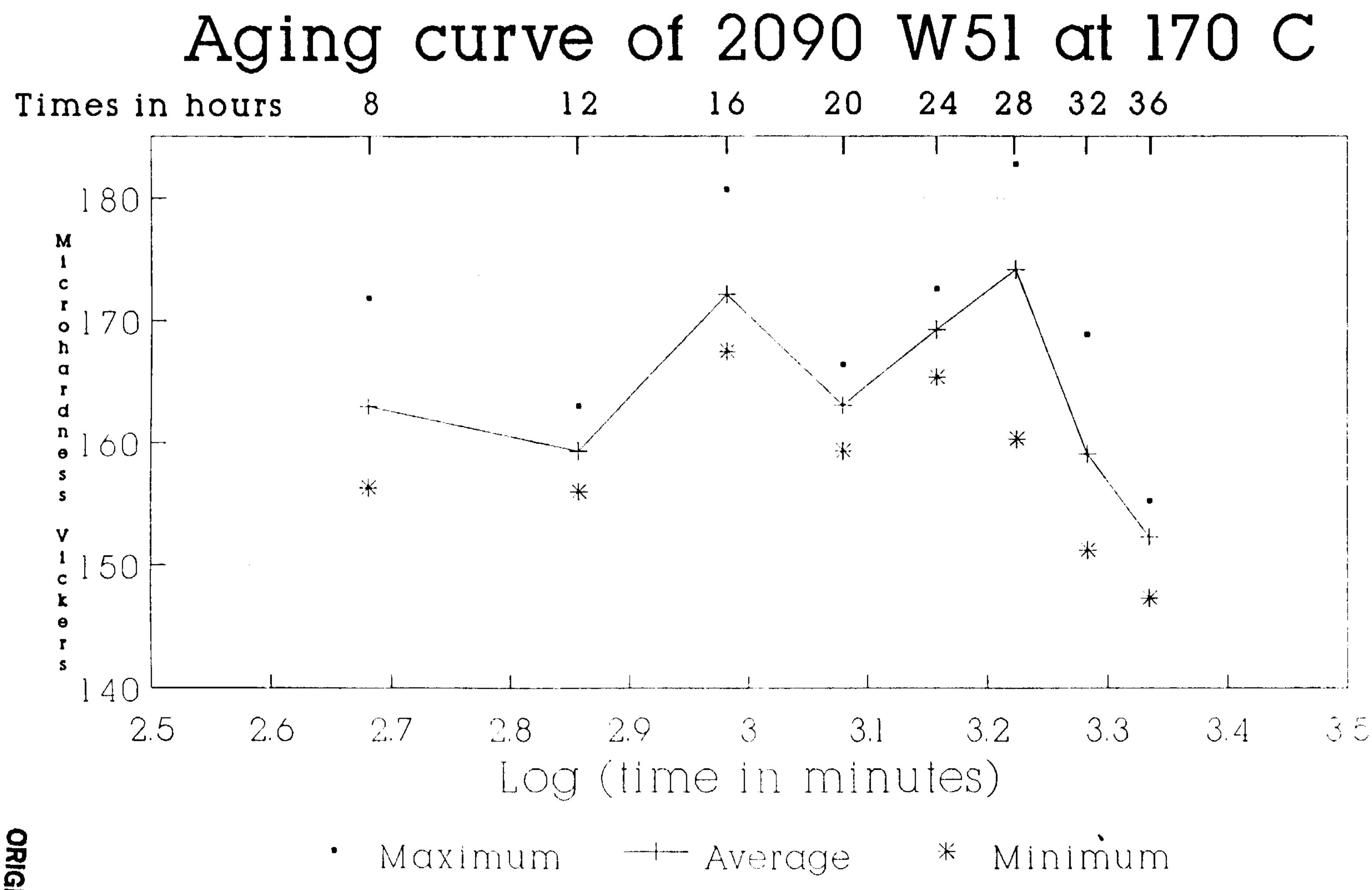
Interim Results
Tensile tests

- Greatest UTS for 90 , lowest for 45 .
- No difference between room temperature and low temperature.
- Fracture initiation close to the hole and rapid propagation.
- Ductile fracture only for 45 , and between the holes.

Aging Experiments

- Aging curves for 2090 T3 & W51
- X-Ray analysis


Aging curve of 2090 T3 at 170 C
Times in hours
8
12
16
20
24
28
32
36
Microhardness Vickers
175
165
155
145
135
2.5
2.6
2.7
2.8
2.9
3
3.1
3.2
3.3
3.4
3.5
Log (time in minutes)
Maximum
Average
Minimum

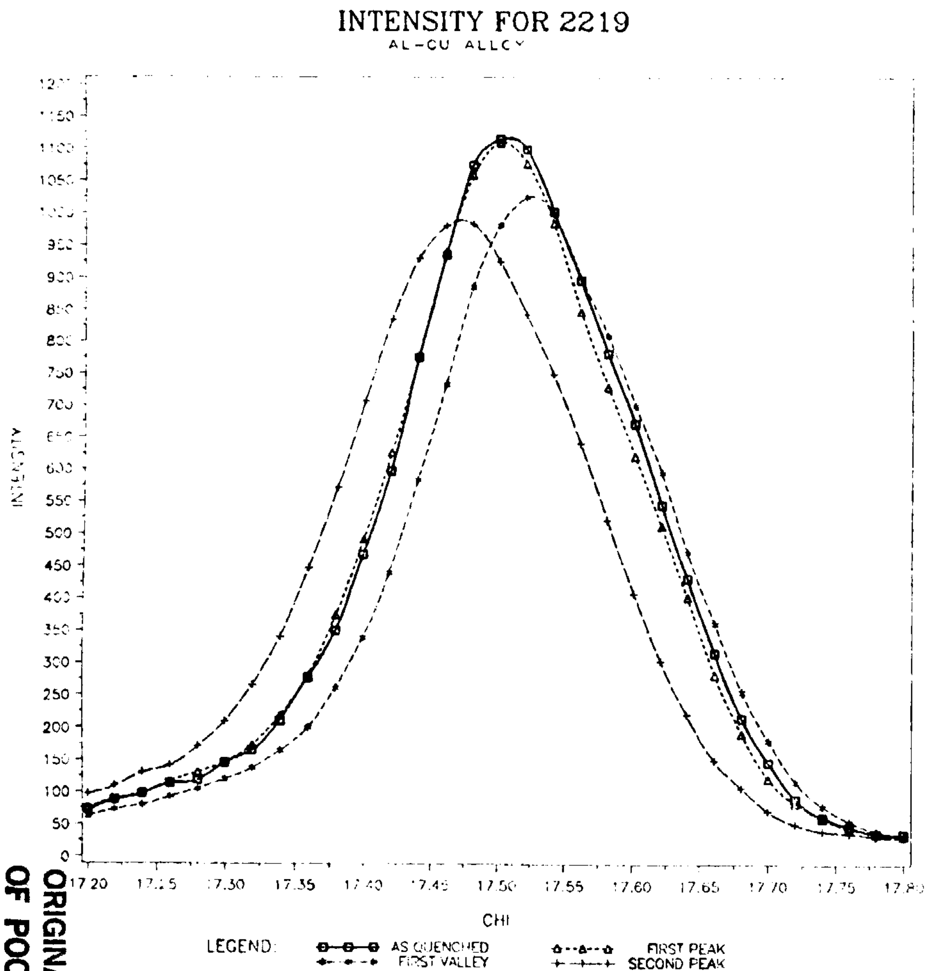


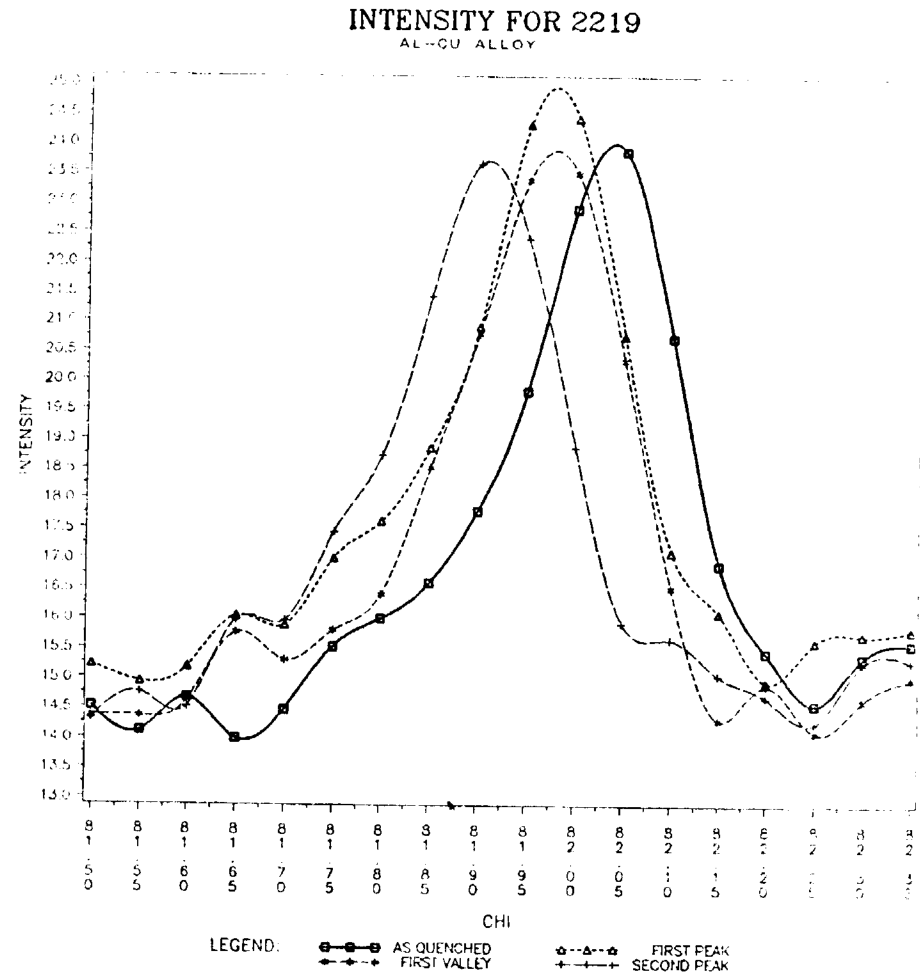
Aging curve of 2090 W51 at 170 C
Times in hours
8
12
16
20
24
28
32
36
Microhardness Vickers
180
170
160
150
140
2.5
2.6
2.7
2.8
2.9
3
3.1
3.2
3.3
3.4
3.5
Log (time in minutes)
Maximum
Average
Minimum

Aging Conditions for 2090 T3 & W51

- 16 hrs at 170 C for 2090 T3
- 16 hrs at 170 C for 2090 W51

X-Ray results





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X-Ray results

The shift corresponds to a variation of the lattice parameter of:

8.9*10-4 for the 1st peak
6.4*10-4 for the 1st valley
7.9*10-4 for the 2nd peak

Summary

- *Disk Rupture tests:*
  Rough surface =⟩ burst failure.
  Intermediate strain rate =⟩ less embrittlement.

- *Tensile tests:*
  45 =⟩ lower ductility.
  No apparent difference at low temperature.

Summary
(Cont.)

- *Charpy impact tests:*
  Nearly same impact initiation energy
  for all orientations.
  Higher propagation energy for L-S and T-S
  than for T- L and L-T orientations.
  Substantial tearring for T-S and L-S orientations.

- *Charging solutions:*
  Two give embrittlement without surface damage.

Hydrogen Embrittlement
Need to Address

- Orientation of samples for the mechanical tests
- Additional material needed:
    - 2219
    - 2090
    - 8090
    - Weldalite
- 2090 T83 or T84 ??

Inventory

- 2091 T3:
  - 1/2"x5.9"x13.5"
  - 1/4"x11.8"x31.5"
  - 1/10"x15.7"x39.4"
- 2090 W51: 1/2"x12"x14"
- 2219 T87: 1/4"x12"x36"

Hydrogen Embrittlement
Future work

- Confirmation of SIMS results and quantification of hydrogen content
- Mechanical tests on : 2090
  2091
  2219
- Fractography

N90-22659

Program 7 **Investigation of the Reaction Kinetics Between SiC Fibers and Selectively Alloyed Titanium Matrix Composites and Determination of Their Mechanical Properties**

Douglas B. Gundel and F.E. Wawner

Objective

The objective of this study is to investigate fiber-matrix interactions in selected titanium reinforced composites and to define reaction kinetics and influences on the mechanical properties of the composites.

Investigation of the Reaction Kinetics Between SCS-6 Fibers and Ti-1100 and Determination of Their Mechanical Properties

Douglas B. Gundel and F.E. Wawner
Department of Materials Science

Abstract

During high temperature exposure, an interfacial reaction occurs between SiC fiber reinforcement and titanium matrices which can be detrimental to the mechanical properties of the composite. The reaction kinetics between SCS-6 fibers and Ti-1100 were determined at 800 to 1000°C and found to be slower than those of other currently used titanium alloys (Ti-15-3, Ti-6-4). The experimentally determined reaction kinetics for Ti-1100 were extrapolated to 700°C and found to accurately predict reaction zone size after 1000 hours of exposure. Predictions of the time to consume the surface layer on the SCS-6 and SCS-9 fibers were made in an effort to estimate the time that the fiber will retain its strength in Ti-1100 during isothermal exposure at high temperatures. Using this approach, the strength of an SCS-6 fiber in Ti-1100 should be retained for over 20,000 hours at isothermal exposures less than 800°C. Strength predictions using the rule of mixtures for a unidirectional Ti-1100/SCS-6 composite are presented for short term exposures up to 700°C. Room temperature tests of an as-fabricated 20 volume percent fiber/Ti-1100 composite yielded a UTS of 226 ksi (1490 MPa) which is close to that predicted by the ROM.

INVESTIGATION OF THE REACTION KINETICS BETWEEN SCS-6 FIBERS AND Ti-1100 AND DETERMINATION OF THEIR MECHANICAL PROPERTIES

D.B. GUNDEL AND F.E. WAWNER

This research is supported by NASA, Langley Research Center, under Grant No. NAG-1-745, D. Dicus and W. Brewer contract monitors.

OBJECTIVE: TO INVESTIGATE FIBER-MATRIX INTERACTIONS OF SCS TYPE SiC FIBERS WITH Ti-1100 AND DETERMINE THE EFFECT ON MECHANICAL PROPERTIES OF THE COMPOSITE.

APPROACH:

FABRICATE COMPOSITES USING:

FIBERS - SCS-0 (140 μ), NO SURFACE LAYER
SCS-9 (75 μ), C-RICH SURFACE LAYER, 3.0 μ
SCS-6 (140 μ), C-RICH SURFACE LAYER, 4.5 μ
TiB_2 (1 μ) COATED SCS-6

MATRICES - Ti-1100 NEAR α
(Ti-6Al-2.8Sn-4.0Zr-.4Mo-.45Si-.07O_2-<.03Fe)

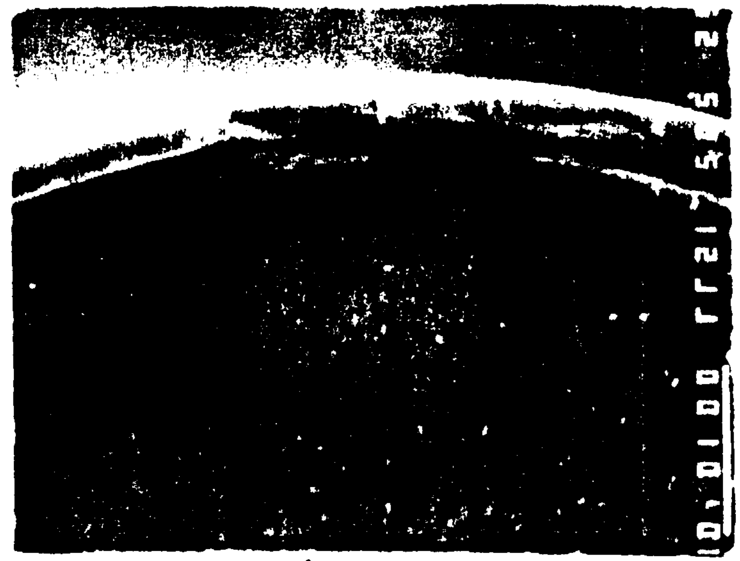
For Comparison

	UNALLOYED (UA) Ti	
	Ti-6Al-4V	$\alpha + \beta$
For Comparison	Ti-15V-3Al-3Cr-3Sn	β
	BETA 21S (Ti-15Mo-2.7Nb-3Al-.2Si)	β
	Ti-14(wt%)Al-21(wt%)Nb	$\alpha_2 + \beta$

FABRICATION - HAND LAYUP USING FOILS, 10-15 v/o FIBER, VACUUM HOT PRESSING

THERMAL EXPOSURE - VACUUM ENCAPSULATED AND HEATED 800 - 1100°C FOR 5 - 150 HOURS

SCS-6



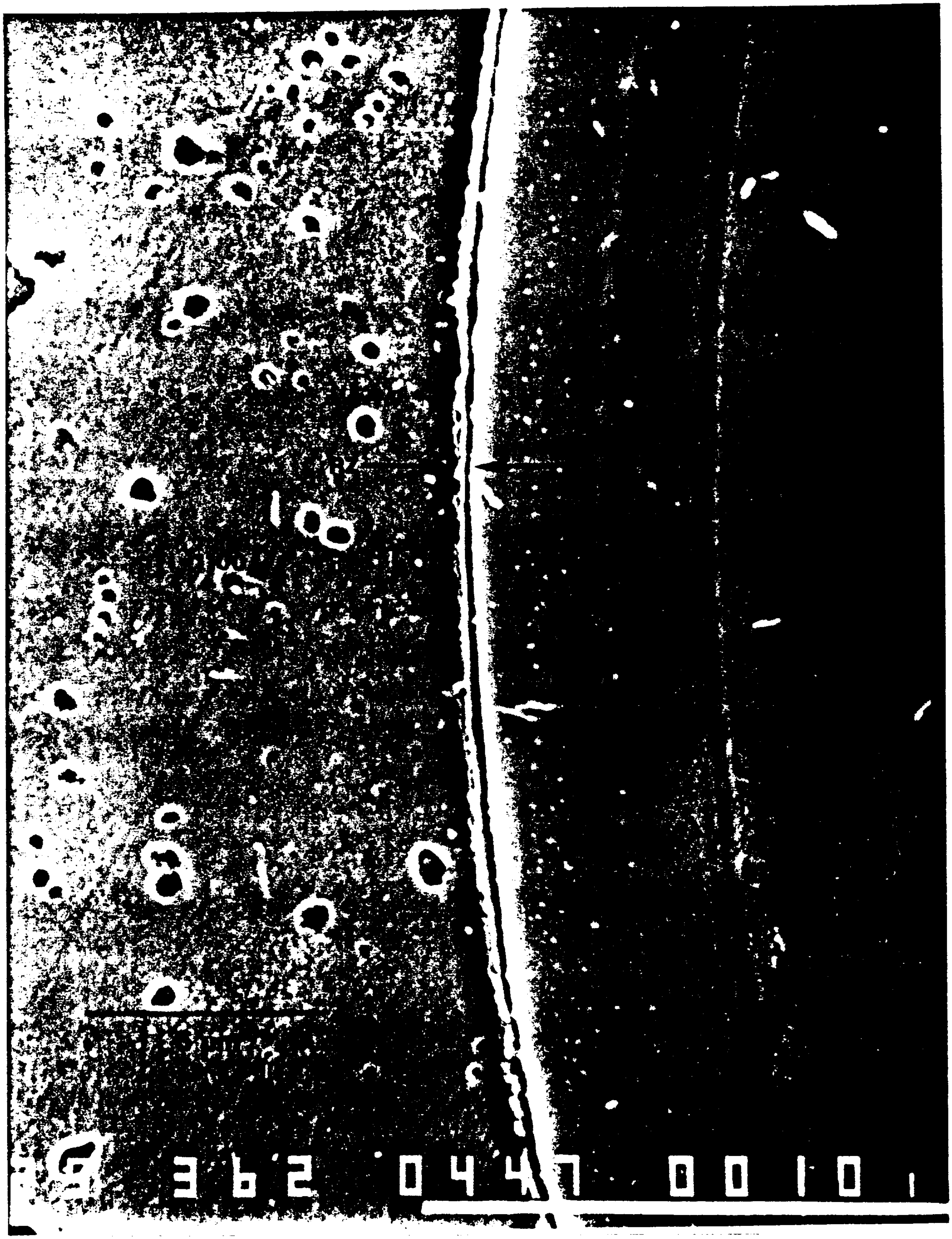
TiB_2/SCS-6

SCS-9

SCS-0

Matrix	UA Ti	Ti-15-3	Ti-6-4	Ti1100	Ti-14Al-21Nb
Fabrication Temperature(^{o}C)	850	875	950	975	1050
As-Fab. RZ Thickness (μm)	.43	.67	.66	.42	.58

Table 1. Fabrication parameters of the SCS-6 composites used in this study. All samples were fabricated using 15 ksi for 30 minutes.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REACTION KINETICS:

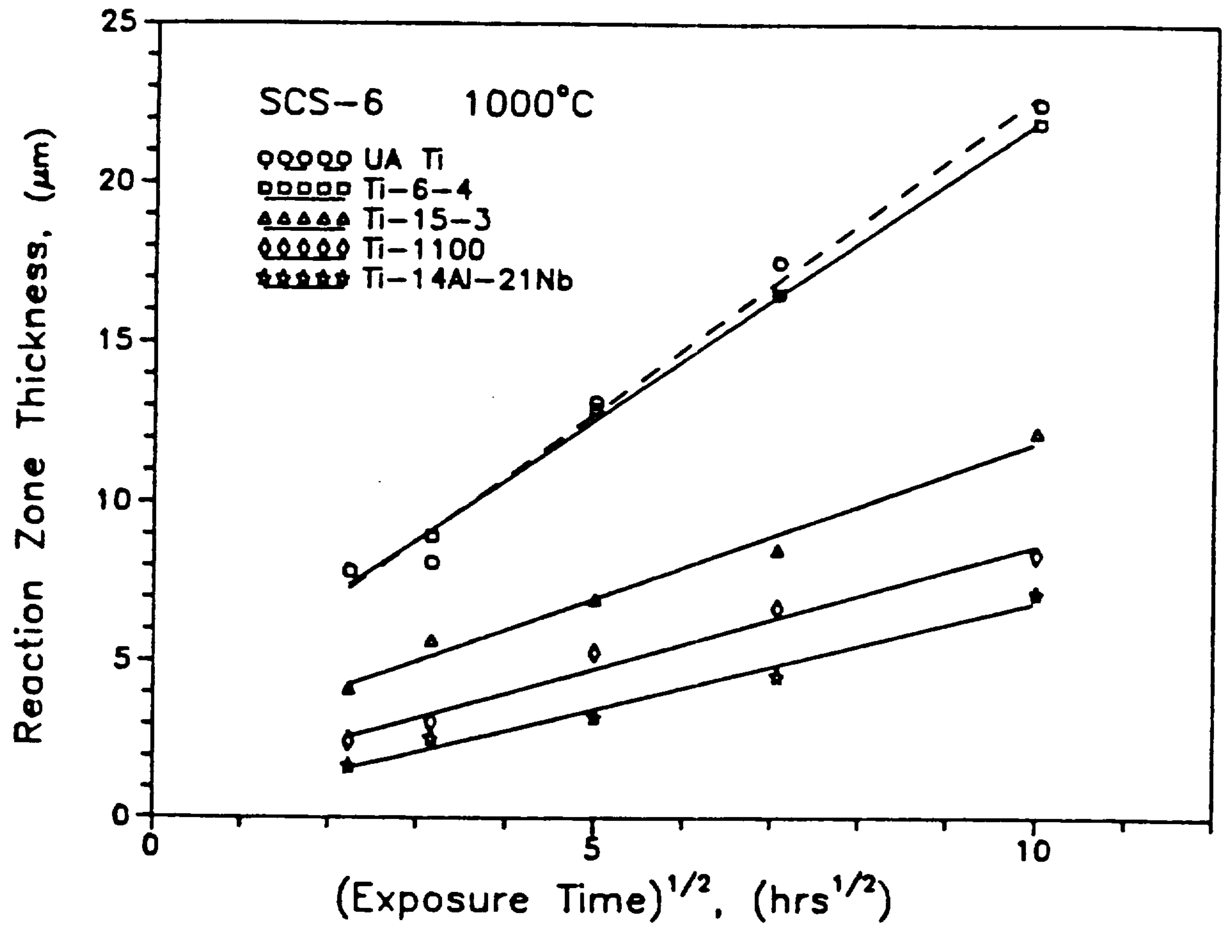
RATE OF REACTION ZONE (RZ) GROWTH HAS BEEN SHOWN TO FOLLOW A PARABOLIC LAW FOR THESE SYSTEMS:

$$Z = k(t)^{1/2} + b$$

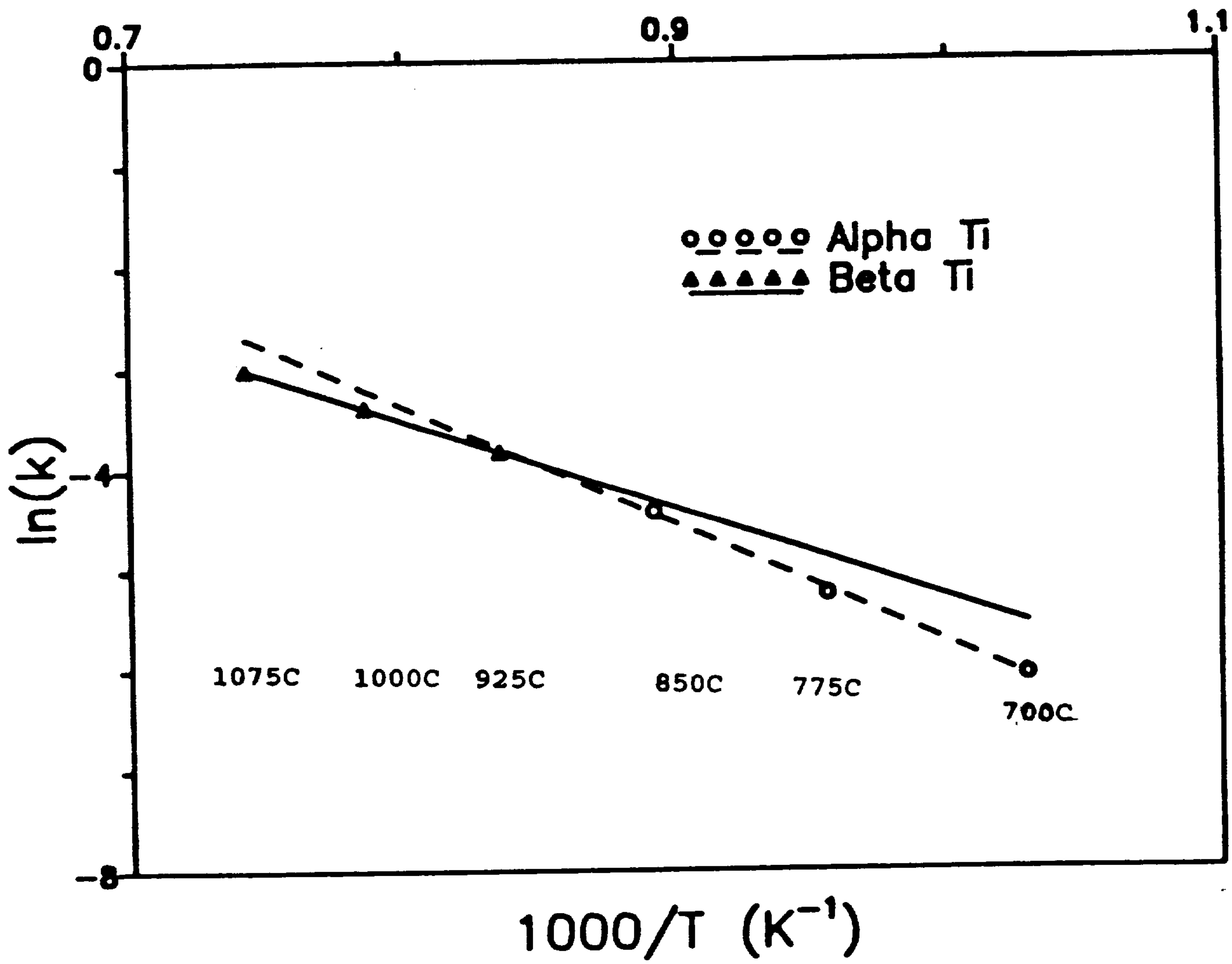
K FOLLOWS THE ARRHENIUS RELATION:

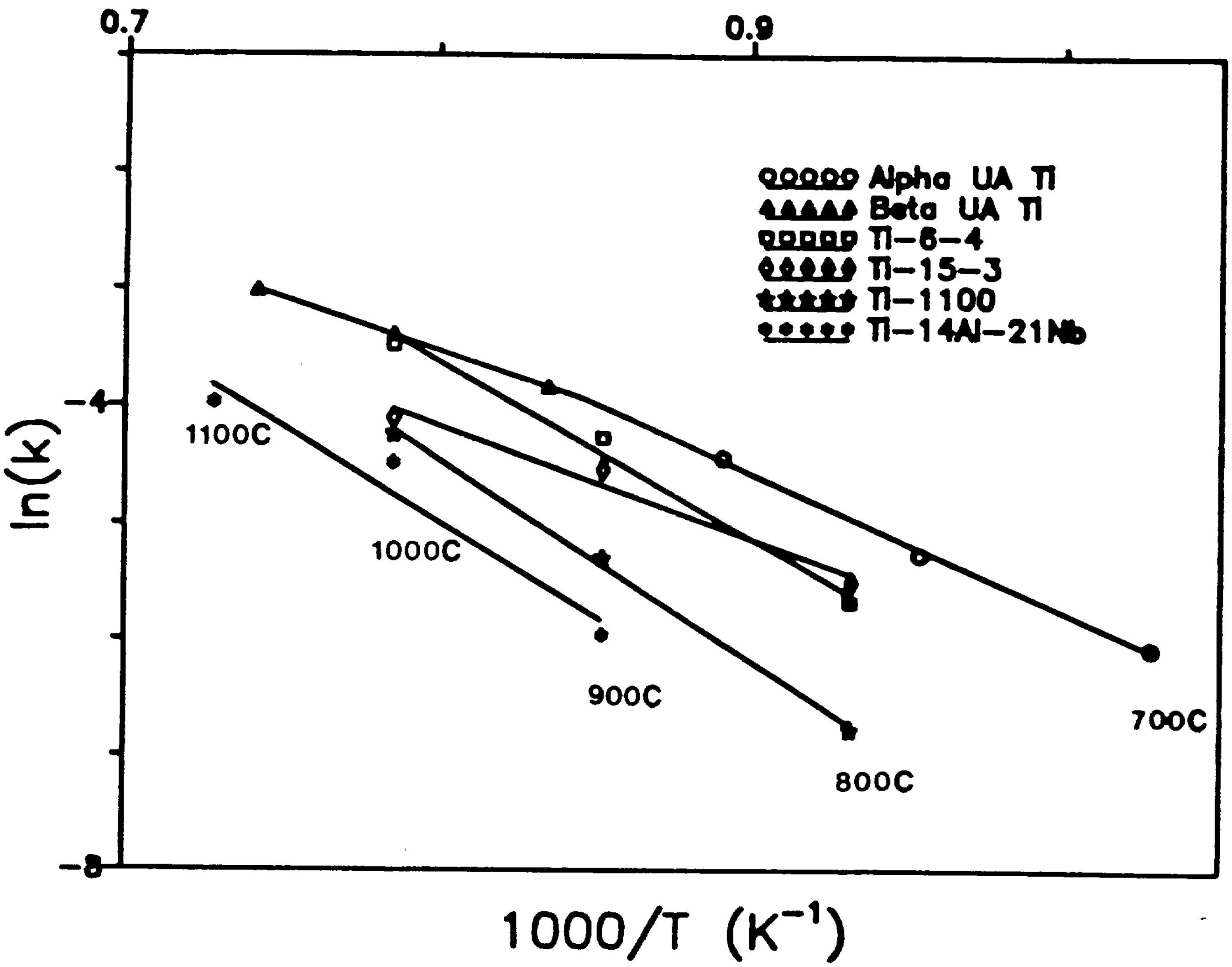
$$k = k_0 \exp(-Q/2RT)$$

RZ MEASURED AFTER THERMAL EXPOSURE BY IMAGE ANALYSIS OF SEM MICROGRAPHS



SCS-6 1000°C
UA Ti
Ti-6-4
Ti-15-3
Ti-1100
Ti-14Al-21Nb
Reaction Zone Thickness, (μm)
(Exposure Time)^1/2, (hrs^1/2)
0
5
10
15
20
25
0
5
10


0.7
0.9
1.1
0
-4
-8
Alpha Ti
Beta Ti
1075C
1000C
925C
850C
775C
700C
ln(k)
1000/T (K^{-1})

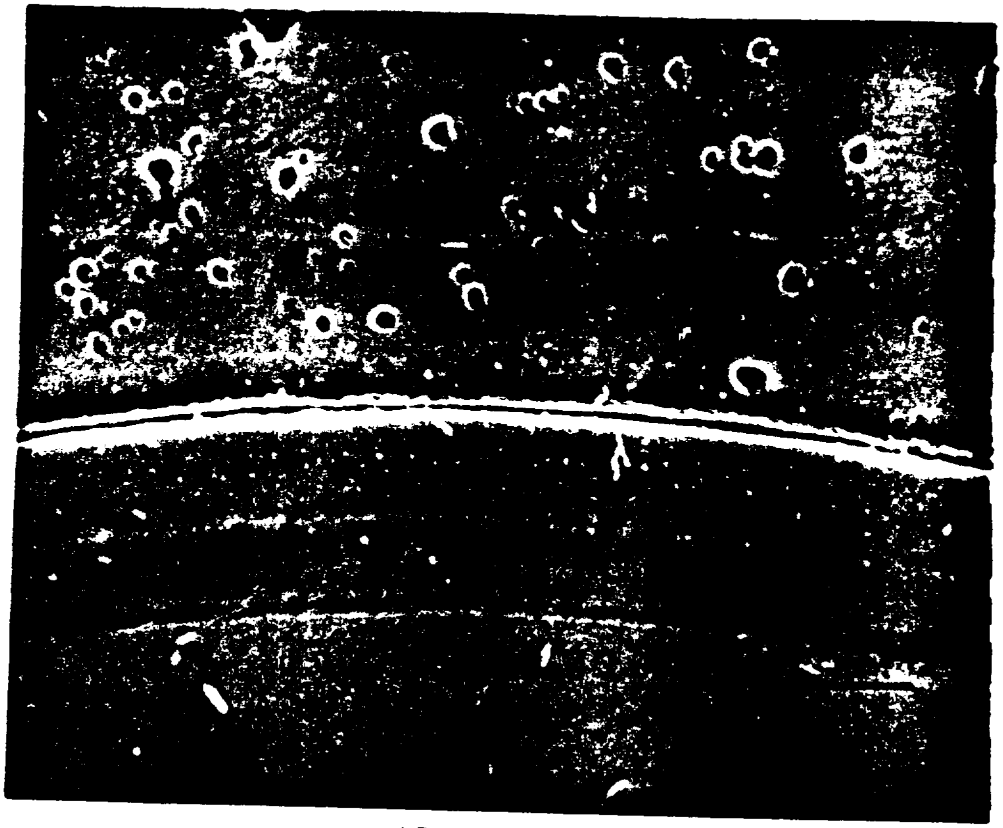


0.7
0.9
Alpha UA Ti
Beta UA Ti
Ti-6-4
Ti-15-3
Ti-1100
Ti-14Al-21Nb
-4
-8
ln(k)
1100C
1000C
900C
800C
700C
1000/T (K^{-1})

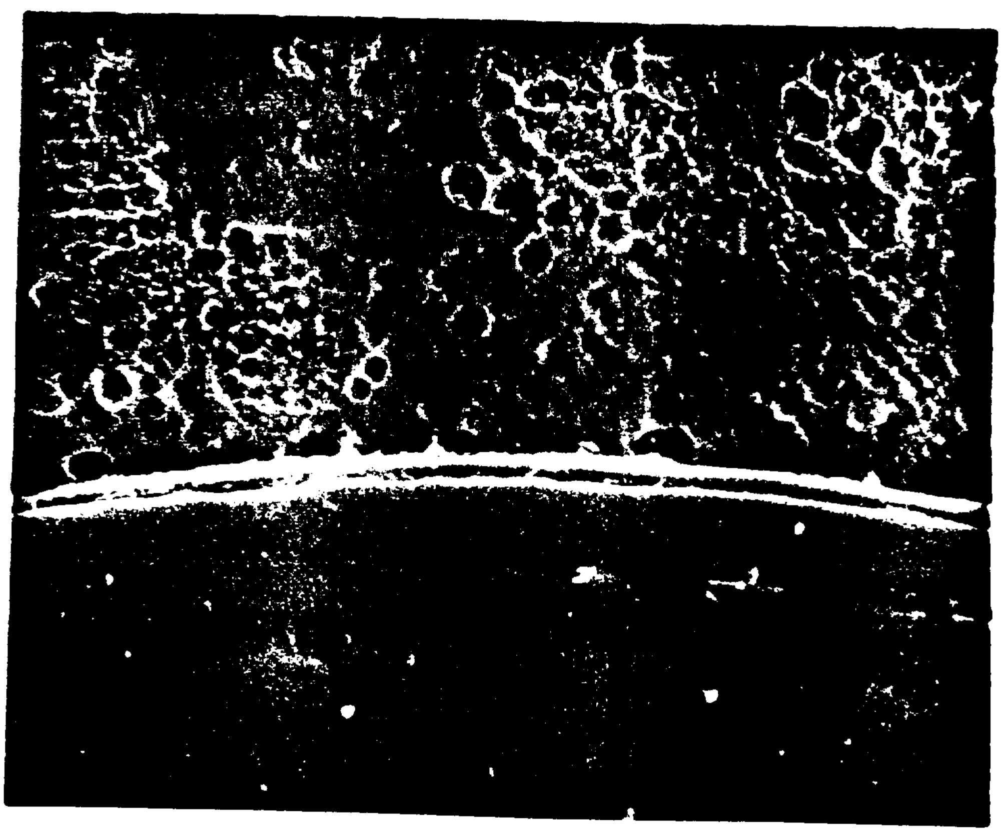
RZ SIZE (μ) AFTER EXPOSURE AT 700^{O}C FOR 1000 HOURS

	CALCULATED	MEASURED
UA Ti	4.7	5.2 ± .5
Ti-6-4	2.1	2.1 ± .3
Ti-1100	0.8	0.7 ± .1
Ti-14Al-21Nb	0.8	0.8 ± .1
Ti-15-3	3.8	1.5 ± .1

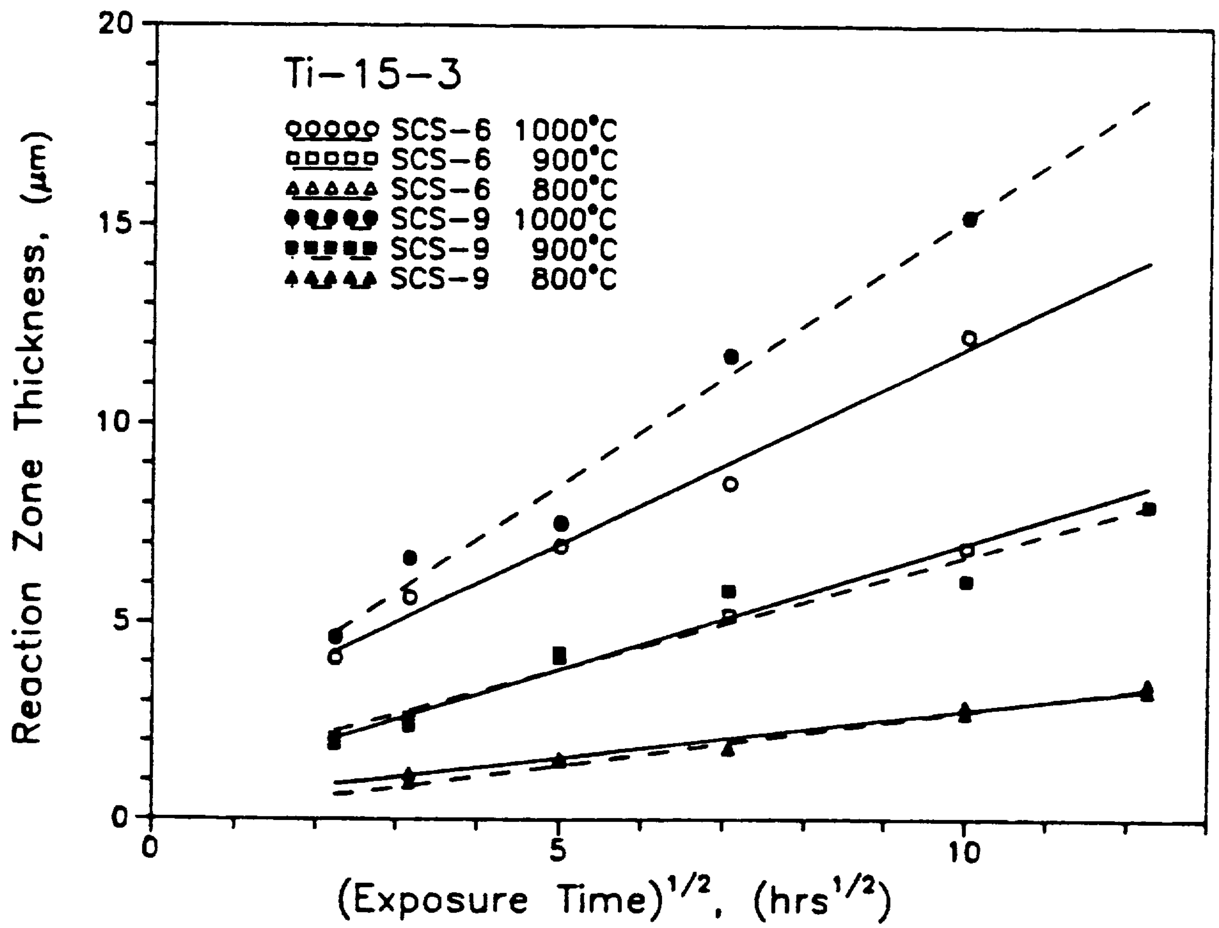
Ti-1100/SCS-6 INTERFACE



AS-FABRICATED



700^{0}C 1000 HOURS



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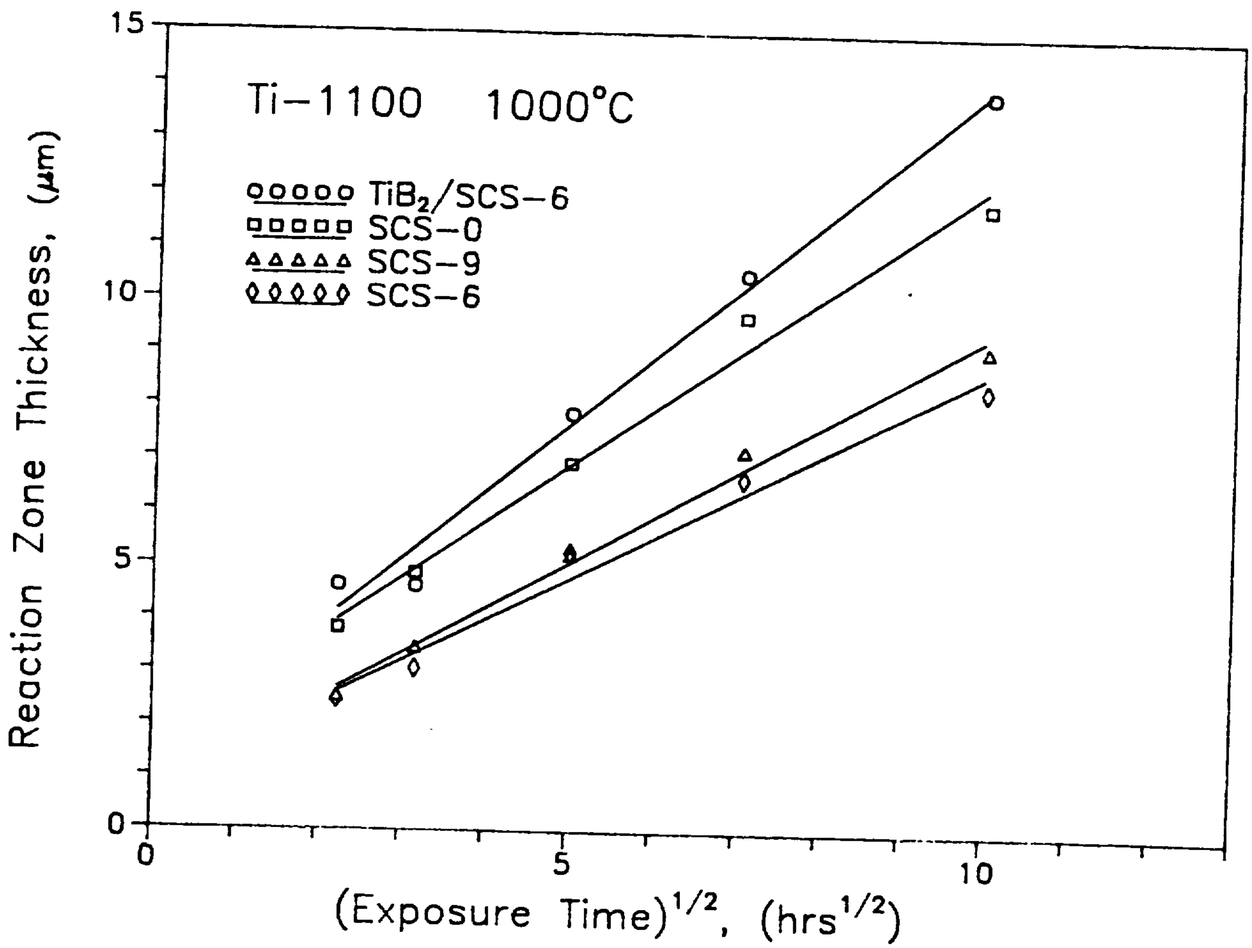
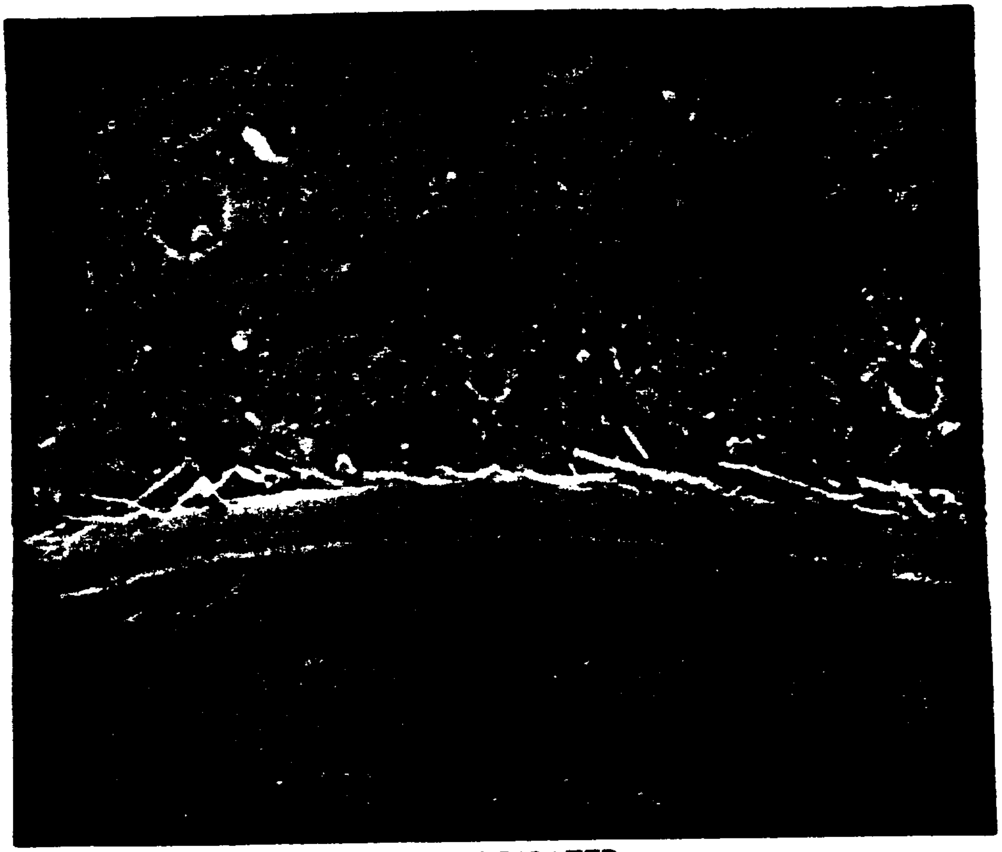
Ti 15 3 1000C 25H

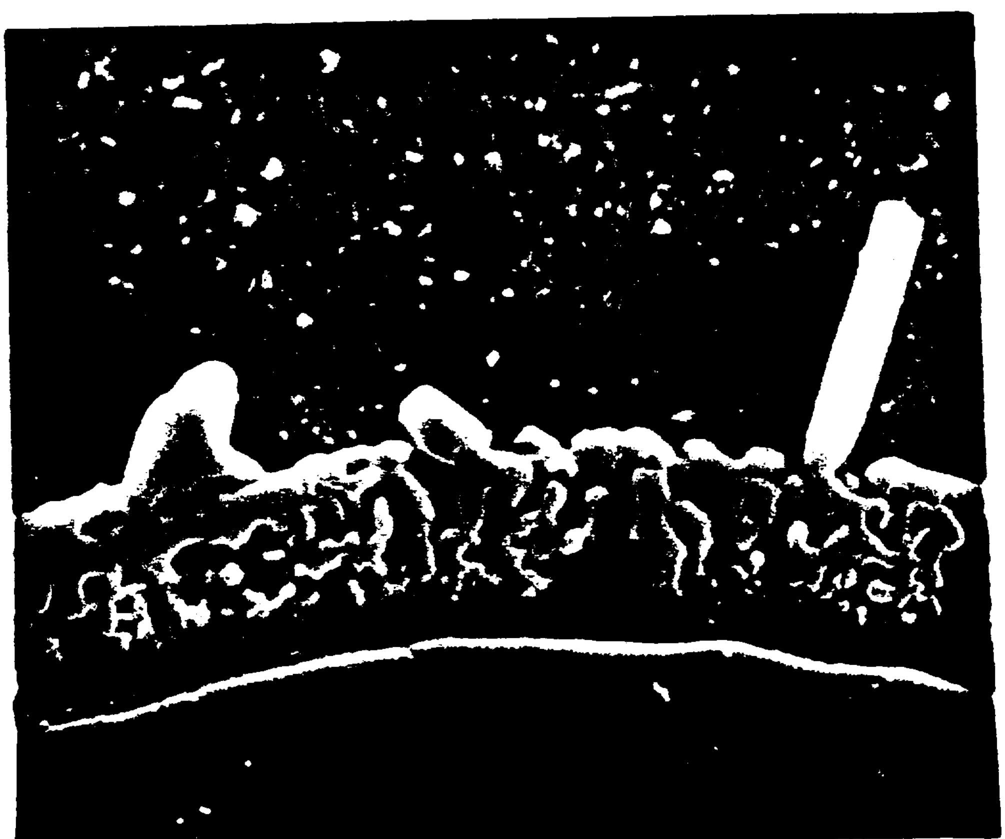


Ti−1100 1000°C
TiB2/SCS−6
SCS−0
SCS−9
SCS−6
Reaction Zone Thickness, (μm)
(Exposure Time)1/2, (hrs1/2)
0
5
10
15

TiB_2/SCS-6 IN Ti-1100



AS-FABRICATED



1000^{0}C 25 HOURS

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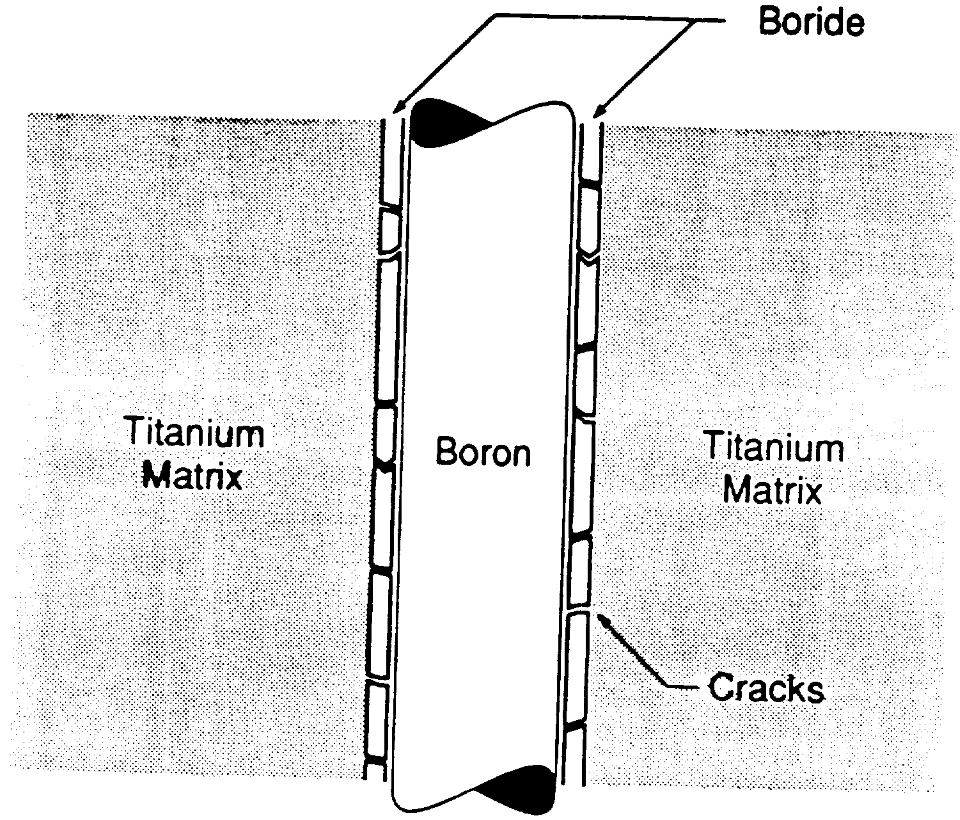
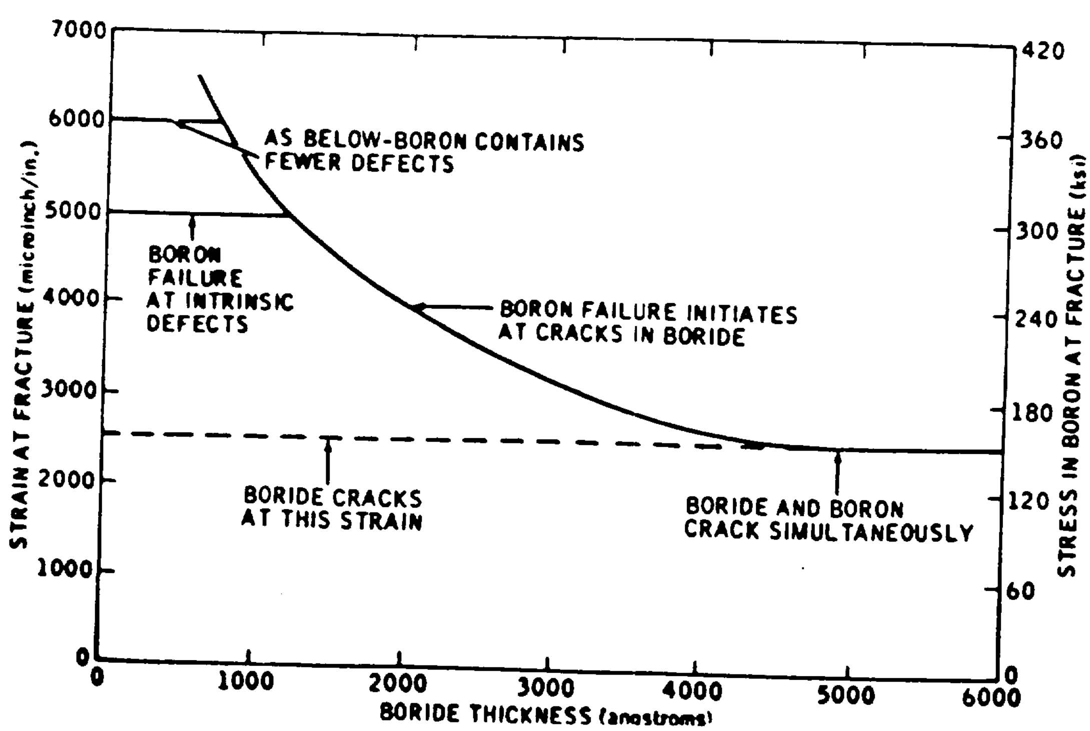
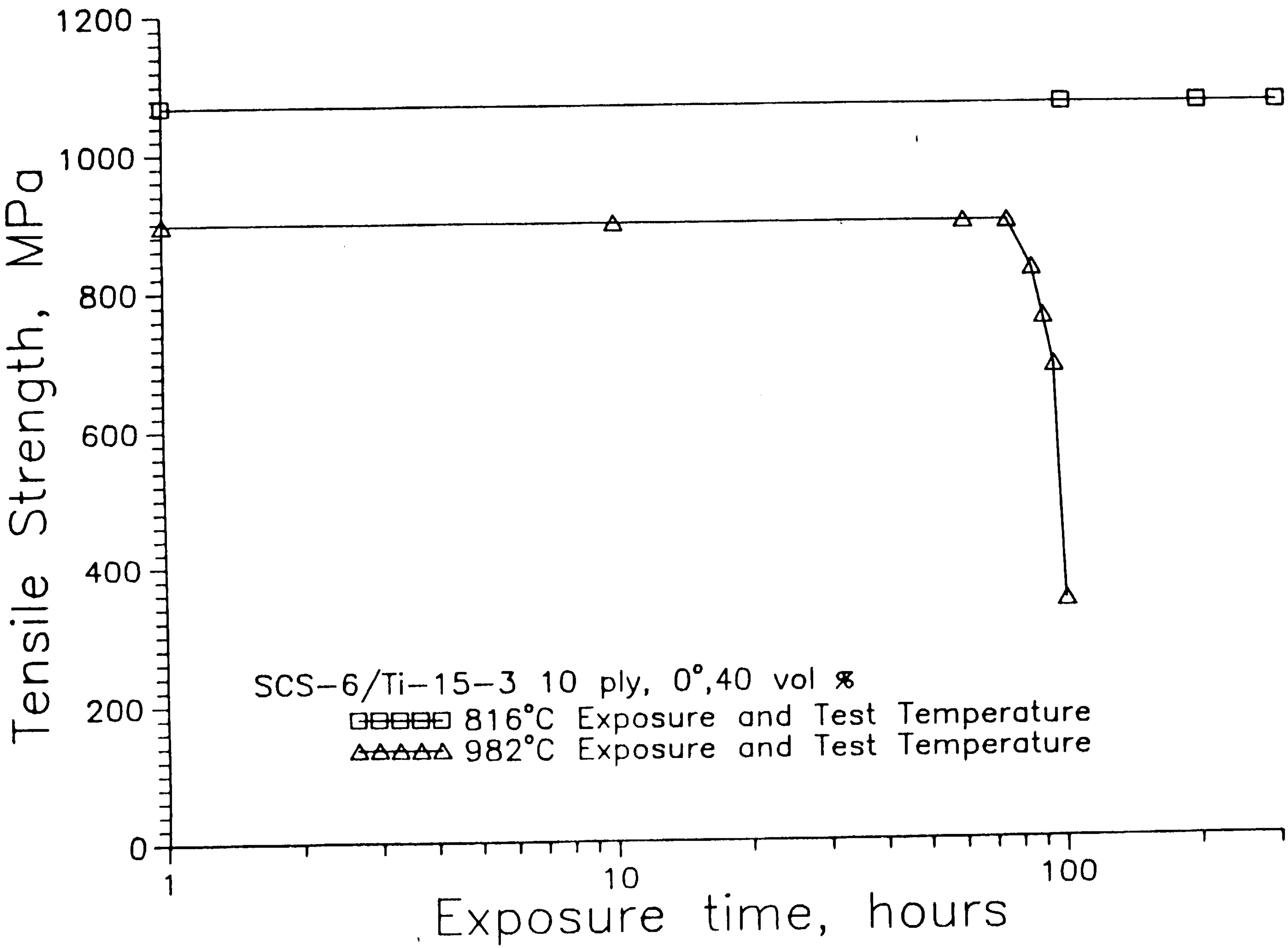

Boride
Titanium Matrix
Boron
Titanium Matrix
Cracks


7000
6000
5000
4000
3000
2000
1000
0
420
360
300
240
180
120
60
0
0
1000
2000
3000
4000
5000
6000
AS BELOW-BORON CONTAINS FEWER DEFECTS
BORON FAILURE AT INTRINSIC DEFECTS
BORON FAILURE INITIATES AT CRACKS IN BORIDE
BORIDE CRACKS AT THIS STRAIN
BORIDE AND BORON CRACK SIMULTANEOUSLY
STRAIN AT FRACTURE (microinch/in.)
STRESS IN BORON AT FRACTURE (ksi)
BORIDE THICKNESS (angstroms)



1200
1000
800
600
400
200
0
1
10
100
Tensile Strength, MPa
Exposure time, hours
SCS-6/Ti-15-3 10 ply, 0°,40 vol %
816°C Exposure and Test Temperature
982°C Exposure and Test Temperature

TIME TO CONSUME SURFACE LAYER (hours)

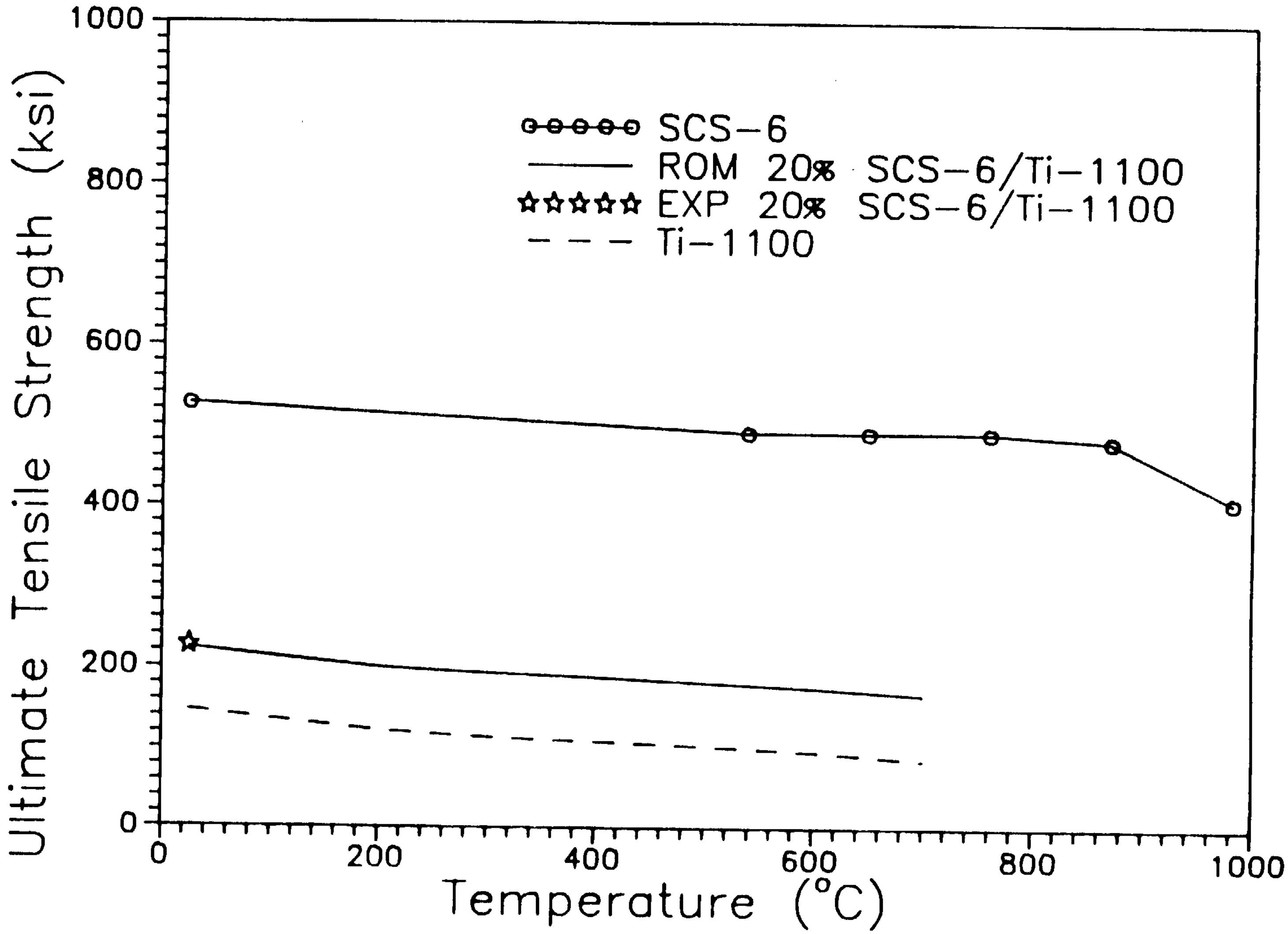
SCS-6

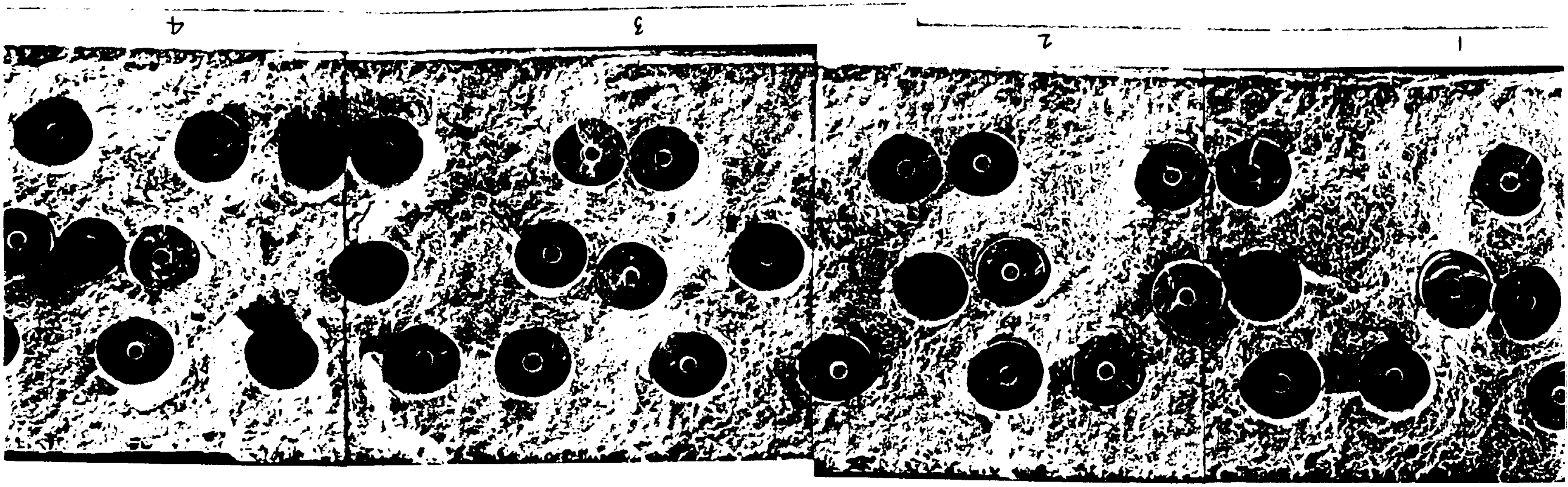
	UA Ti	Ti-6-4	Ti-15-3	Ti-1100	Ti-14Al-21Nb
700°C	7,100	51,000		750,000	1,000,000
800°C	590	2,900	2,000	28,000	58,000
900°C	87	280	420	1,800	4,500
1000°C	21	19	89	160	540
1100°C	<10				82

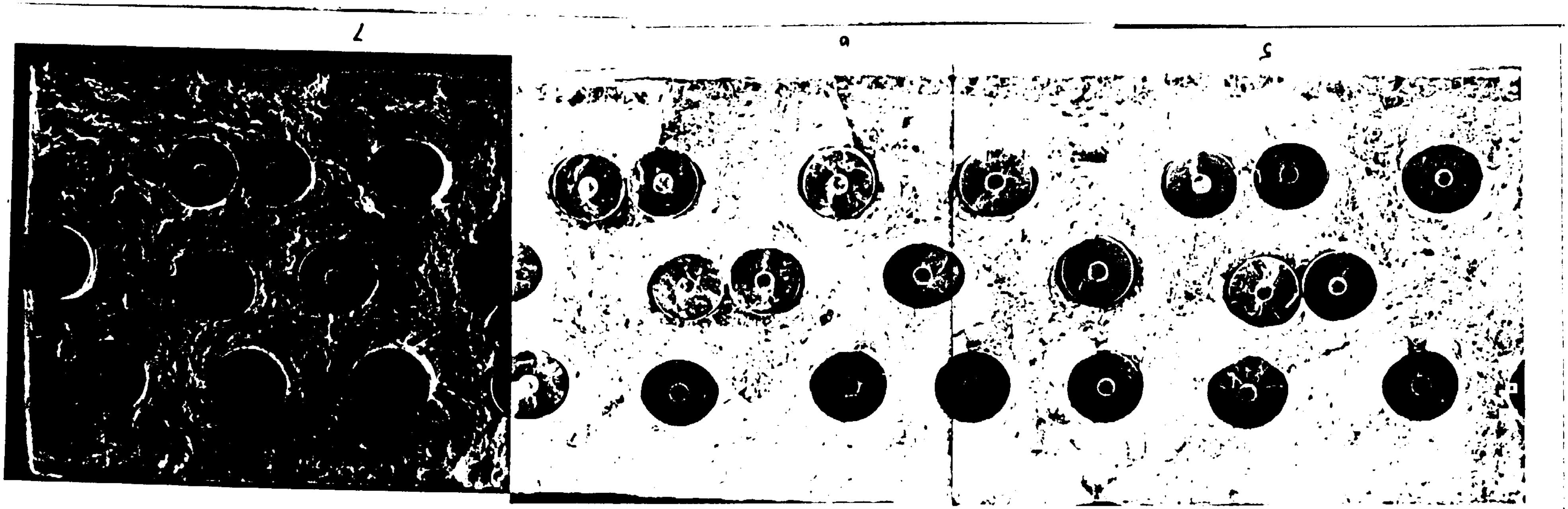
SCS-9

	UA Ti	Ti-6-4	Ti-15-3	Ti-1100	Ti-14Al-21Nb
700°C	1,600	12,000		170,000	290,000
800°C	91	640	430	6,200	13,000
900°C	14	58	97	390	1,000
1000°C	<10	<10	14	35	110

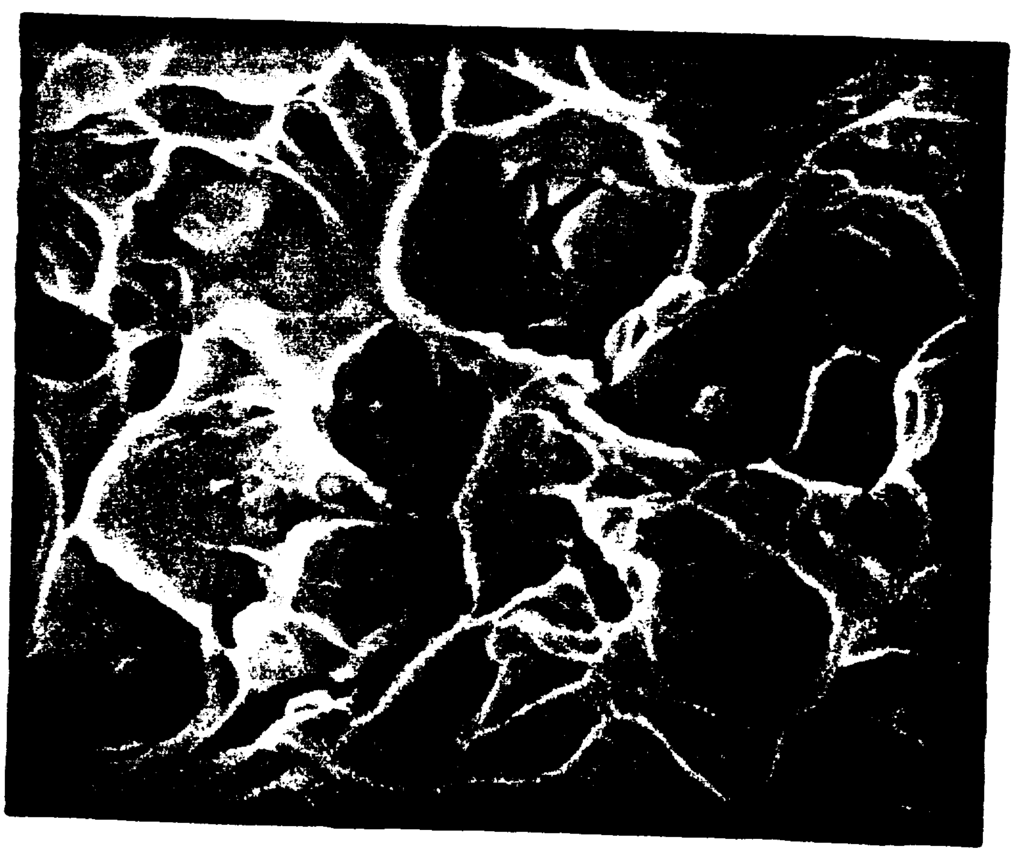
These values are the calculated exposure times for the RZ to reach 12μ for the SCS-6 fiber, and 6μ for the SCS-9 fiber.


SCS-6
ROM 20% SCS-6/Ti-1100
EXP 20% SCS-6/Ti-1100
Ti-1100
Ultimate Tensile Strength (ksi)
1000
800
600
400
200
0
0
200
400
600
800
1000
Temperature (°C)





FRACTURE SURFACE OF Ti-1100/SCS-6



CONCLUSIONS

- THE SCS SURFACE LAYER ON THE SCS-6 AND SCS-9 FIBER REACT AT THE SAME RATE WITH A GIVEN TITANIUM MATRIX.

- ALLOY ADDITIONS TO TITANIUM SLOWED THE RATE OF REACTION IN ALL OF THE CASES STUDIED.

- BELOW 1000°C TI-1100 REACTS MORE SLOWLY WITH THE SCS COATING THAN UA TI, TI-15-3, AND TI-6-4 -- AND SLIGHTLY FASTER THAN TI-14AL-21NB.

- THE KINETIC PARAMETERS DETERMINED IN THIS STUDY CAN BE EXTRAPOLATED TO 700°C FOR TI-6-4, TI-1100, AND TI-14AL-21NB, BUT NOT FOR TI-15-3.

- REACTION ZONE GROWTH IN THE TI-14AL-21NB SYSTEM WAS ACCOMPANIED BY THE GROWTH OF A BETA-DEPLETED ZONE IN THE MATRIX AROUND THE FIBER.

FUTURE RESEARCH

- TENSILE TEST SAMPLES OF Ti-1100/SCS-6 AT ELEVATED TEMPERATURES.

- EXPOSE SAMPLES TO HIGH TEMPERATURES FOR VARYING LENGTHS OF TIME TO DETERMINE HOW LONG STRENGTH IS MAINTAINED.

- THERMALLY CYCLE Ti-1100/SCS-6 COMPOSITE SAMPLES.

N90-22660

Program 8 **Quantitative Characterization of Spatial Distribution of Particles in Materials: Application to Materials Processing**

J.B. Parse and J.A. Wert

Project Objective

The objective of this project is to develop methods for quantitative analysis of the spatial distribution of second phases in structural materials. Coupling of these methods with models and/or experimental data for deformation and fracture will reveal the effects of non-random phase distribution on material performance.

A Method for Analyzing the Uniformity of Distribution of Second Phase Particles

J. B. Parse and J. A. Wert
Department of Materials Science

Abstract

Most engineering materials contain second phase particles or fibers which serve to reinforce the matrix phase. The effect of reinforcements on material properties is usually analyzed in terms of the average volume fraction and spacing of reinforcements, quantities which are global microstructural characteristics. However, material properties can also depend on local microstructural characteristics; for example, on how uniformly the reinforcing phase is distributed in the material. Previous studies have shown that the ductility and fracture properties of particulate composite materials depend on the distribution of particulate in the matrix. Similarly, electrical conductivity in metal-filled polymers depends on the uniformity of distribution of metal fibers. Only a few attempts have been made to analyze the distribution of particles in engineering materials. The objective of this research project is to develop a method for analyzing clustering of second phase particles in a matrix. The analysis method will then be applied to a materials processing problem to discover how processing parameters can be selected to maximize redistribution of the reinforcing phase during processing.

Several mathematical analysis methods could be adapted to the problem of characterizing the distribution of particles in materials. A tessellation-based method has been selected for the present investigation. In the first phase of the investigation, a software package has been written to automate the analysis. Typical results will be shown during the presentation. The analysis technique allows us to find the degree to which particles are clustered together, the size and spacing of particle clusters, and the particle density in clusters. The analysis methods have been applied to computer-generated distributions and to a few real particle-containing materials.

Methods for analyzing a nonuniform particle distribution in a material can be applied to two broad classes of materials science problems: understanding how processing methods affect the particle distribution and understanding how the resulting particle distribution affects properties. Previous investigators have analyzed how a nonuniform particle distribution affects fracture of a MMC. We have chosen to apply the analysis method described above to a materials processing problem: how to select extrusion conditions to maximize the redistribution of reinforcing particles that are initially nonuniformly distributed. The experiments will be conducted using a model material, but the results will be applicable to extruded MMCs, powder-metallurgy materials and filled polymer composites. In addition, interaction with a student in the Department of Applied Mathematics has led to adaptation of our tessellation-based method to analyze star distributions in spiral galaxies, illustrating the diverse types of problems to which the analysis method can be applied.

A METHOD FOR ANALYZING THE UNIFORMITY OF DISTRIBUTION OF SECOND PHASE PARTICLES

J.B. PARSE and J.A. WERT

Dept. Materials Science
University of Virginia

Sponsored by
NASA-UVa Light Aerospace Alloy and Structures
Technology Program

OUTLINE

- INTRODUCTION
- METHOD OF ANALYSIS
- DIRECTION OF RESEARCH
- SUMMARY

OBJECTIVE

TO DEVELOP A METHOD FOR ANALYZING THE UNIFORMITY OF DISTRIBUTION OF SECOND PHASE PARTICLES

INTRODUCTION

- Most engineering materials are composed of two or more phases

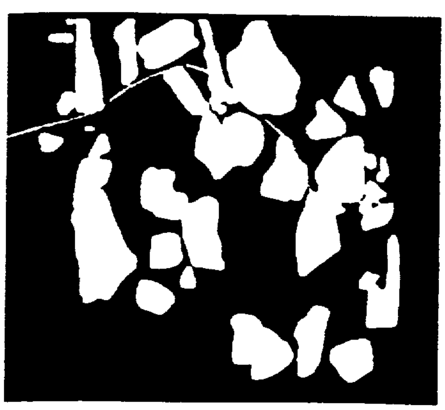
- Many properties of interest to the researcher, manufacturer, or designer depend on the distribution of the second phase:

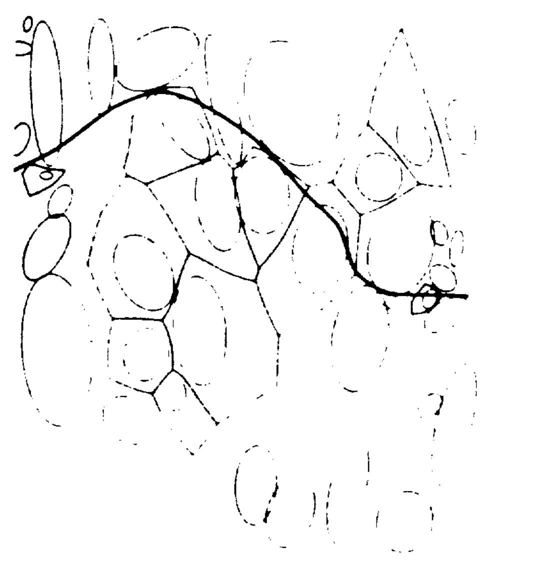
  Fracture Characteristics
  Strength
  Stiffness
  Electrical/Thermal Conductivity

EXAMPLE 1

- Fracture characteristics of particulate reinforced metal matrix composites (MMC's).

- Crack path typically follows regions of high local reinforcement volume fraction; leads to lower energy absorption.



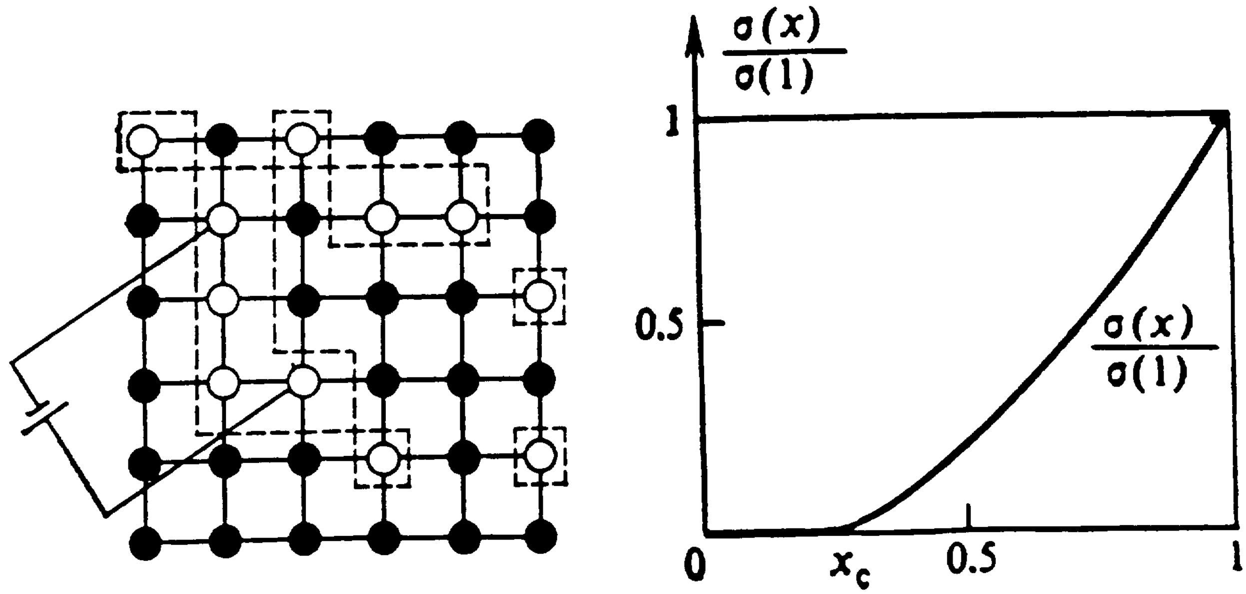


Liu, Lewandowski and Hunt (1989)

EXAMPLE 2

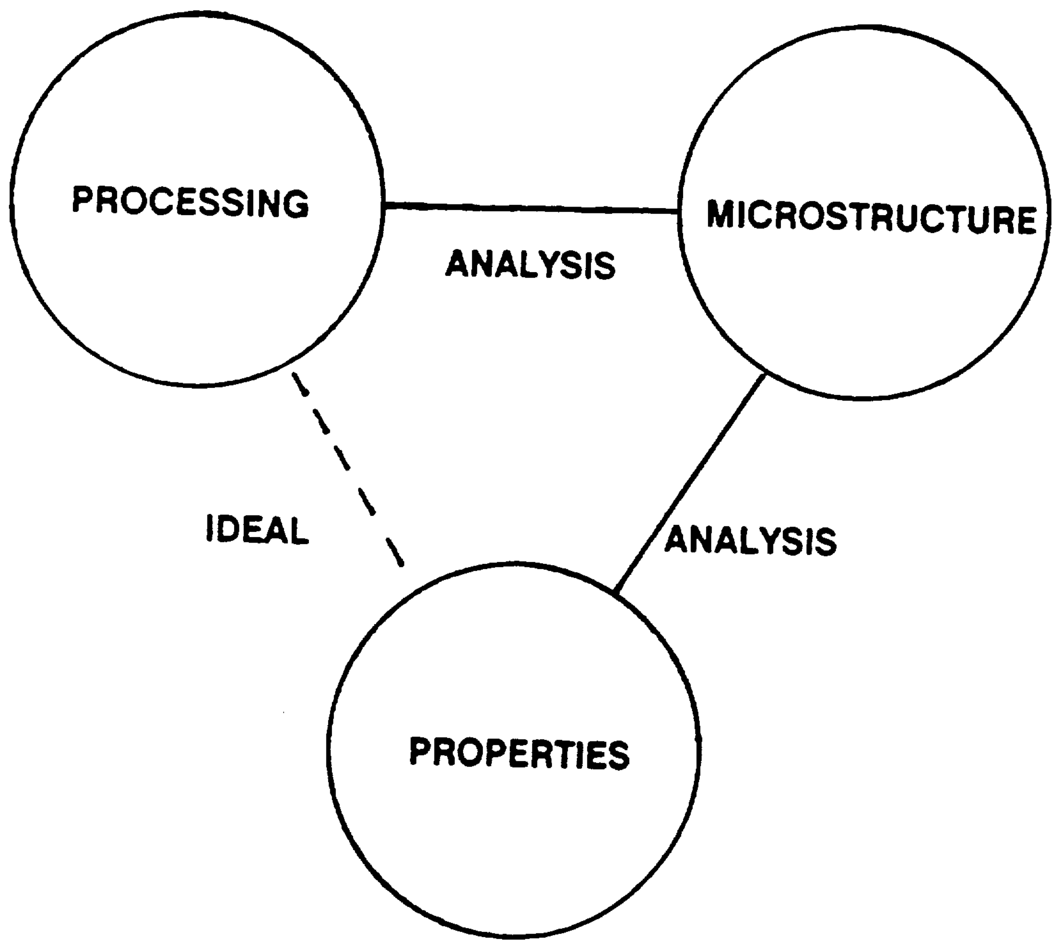
- Electrical conduction in metal filled polymers

- Electrical conduction depends on distribution and volume fraction of second phase.



Efros (1986)

OPPORTUNITIES FOR APPLICATION OF ANALYSIS TECHNIQUES



PREVIOUS APPLICATIONS TO MATERIALS SCIENCE

Fracture of Two Phase Materials

Embury / McMaster University

- Considered effect of spatial distribution of second phase particles on damage accumulation and fracture initiation in several materials

- Used Dirichlet tessellation technique to quantify spatial distribution and clustering of particles

Liu / ALCOA Laboratories

- Studied crack growth in SiC particulate reinforced 7XXX series Al alloys (PM process)

- Found that crack path tended to follow clustered regions

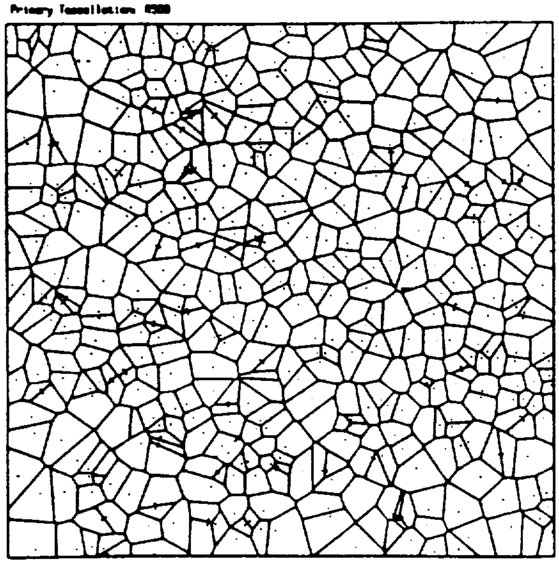
- Clusters were preferred sites for damage initiation and for damage accumulation ahead of the propagating crack

POTENTIAL ANALYSIS METHODS

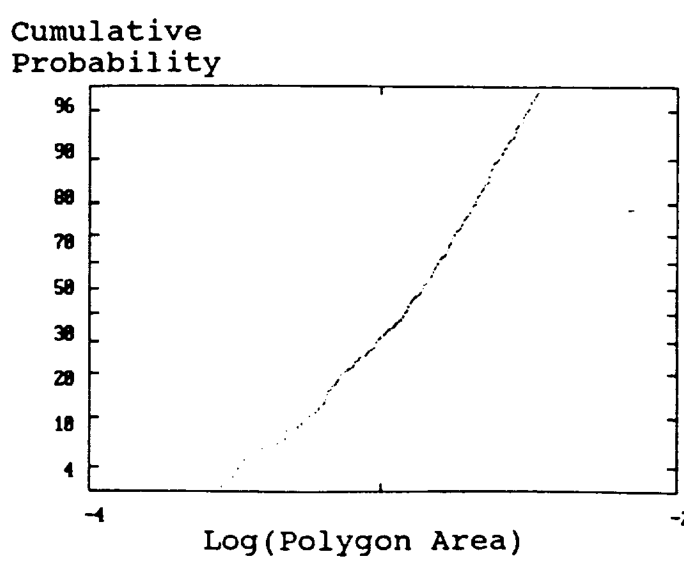
- Tessellation Methods
- Cluster Analysis Methods
- Fractal Dimension Analysis
- Percolation Theory

Basic idea of tessellation analsysis:

Construct tessellation



Analyze characteristics



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METHOD OF ANALYSIS

(IN PLACE)

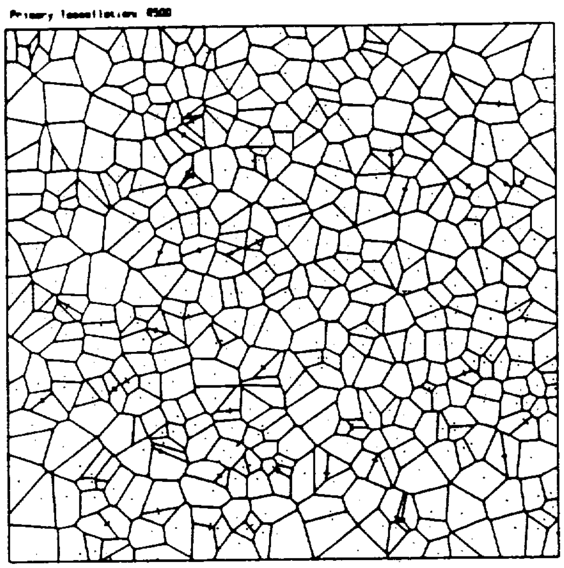
TESSELLATION-BASED ANALYSIS:

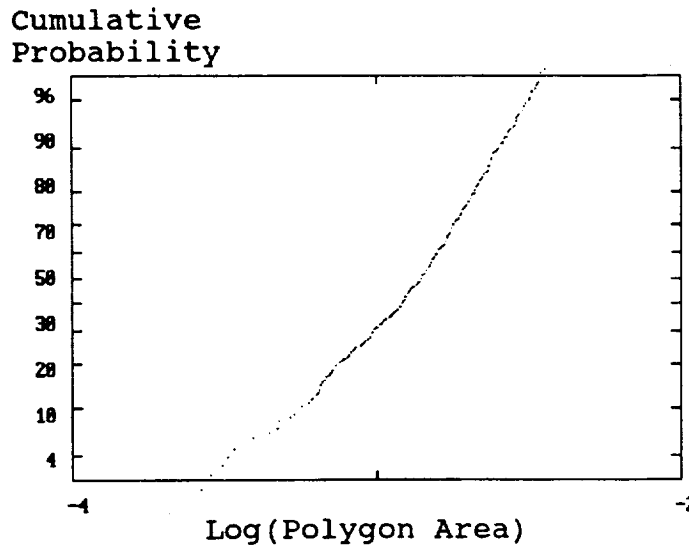
- Properties of individual particles are evaluated
- Yields statistical distribution of parameters for second phase particle distribution
- Currently runs on PC

PARTICLE CLUSTERING ANALYSIS:

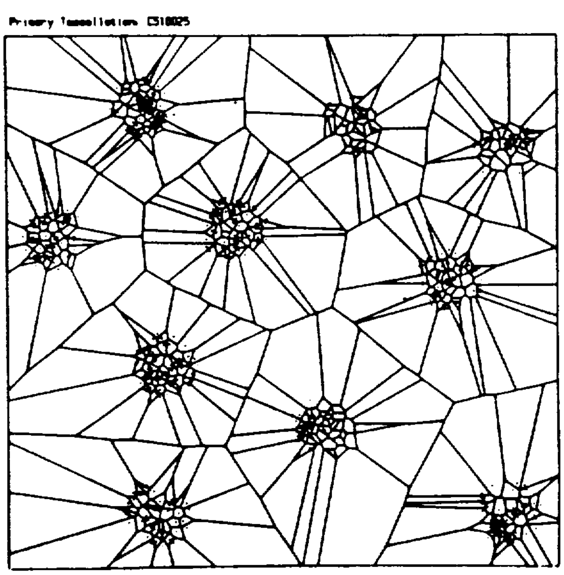
- Builds on output of Tessellation Analysis
- Requires working definition of a "cluster"
- Yields properties of groups of particles

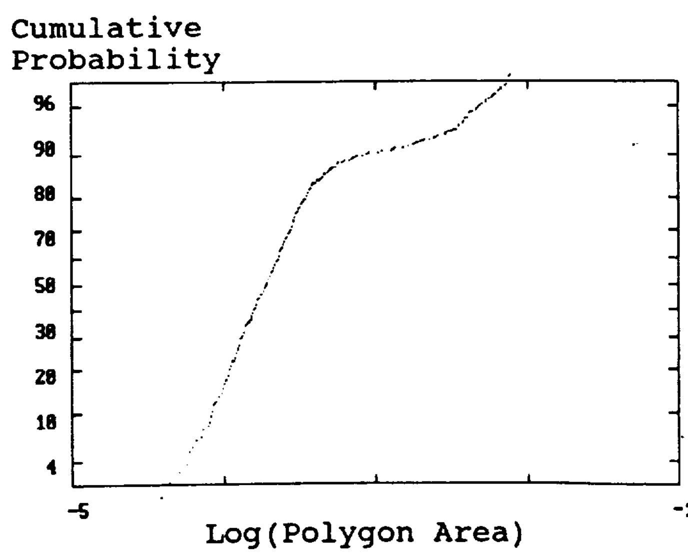
TESSELLATION-BASED ANALYSIS





------------------------RANDOM ARRAY------------------------





------------------------CLUSTERED ARRAY------------------------

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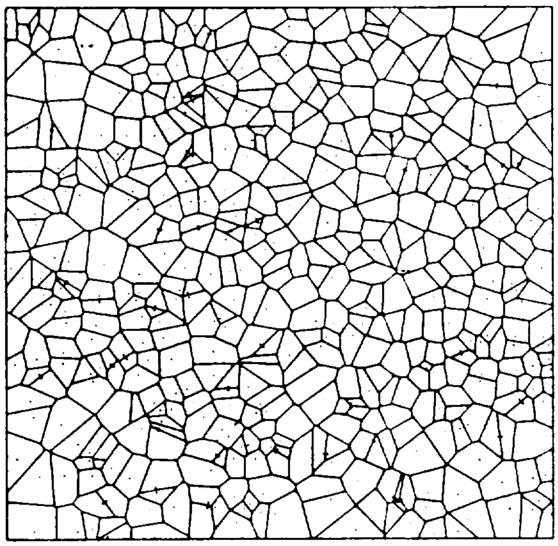
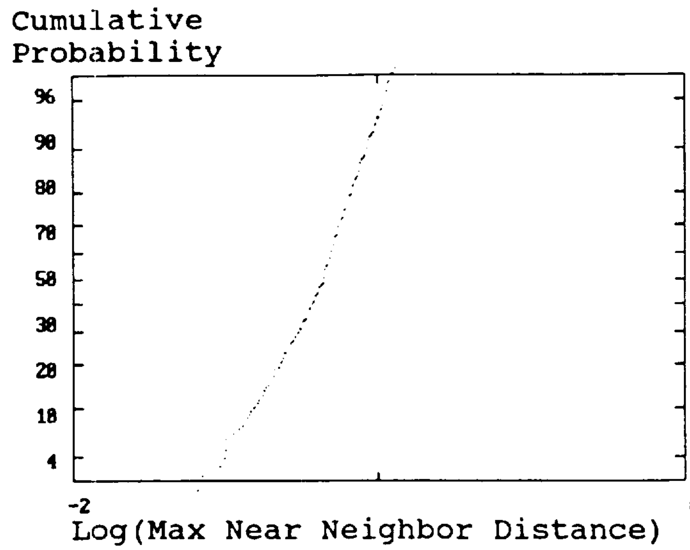
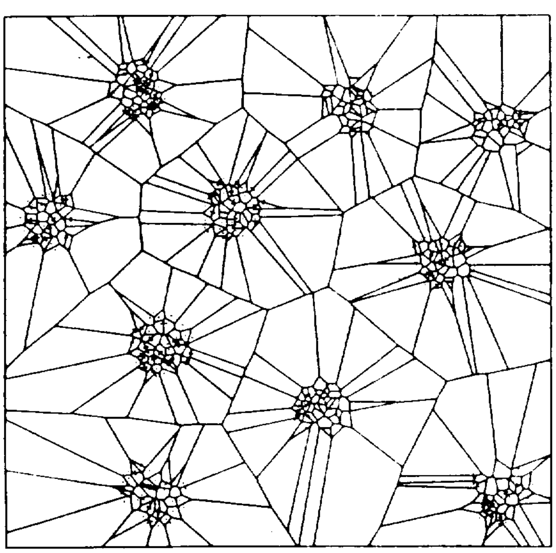
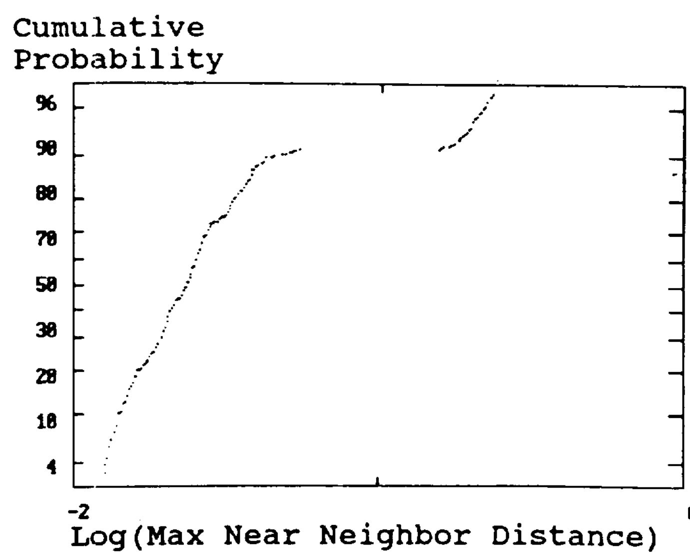
PARTICLE CLUSTERING ANALYSIS





------------------------RANDOM ARRAY------------------------





------------------------CLUSTERED ARRAY------------------------

DIRECTION OF RESEARCH:

NEAR TERM GOALS:

Apply analysis techniques to processing of advanced materials:

- Examine the effect of extrusion ratio and die angle on second phase particle distribution in MMC's
- Select a model material for extrusion experiments: hard particles in Pb (fcc) matrix
- Correlate processing parameters with second phase particle distribution

LONG TERM GOALS:

Apply analysis techniques to micromechanical modeling:

- Collaborate with researchers using numerical techniques to model behavior of multi-phase materials
- Incorporate more accurate descriptions of second phase particle distributions into models to allow more realistic representation of real materials

SUMMARY

ANALYTICAL PROCEDURES IN PLACE

- Tessellation analysis gives distribution of properties for individual particles
- Clustering analysis characterizes clustering of particles
- System runs on a desktop PC.

APPLICATION OF ANALYSIS PROCEDURES TO PROCESSING OF REAL MATERIALS

- Analysis of effect of extrusion parameters on the distribution of particles is beginning

N90-22661

Program 9 **Inelastic Response of Metal Matrix Composites Under Biaxial Loading**

F. Mirzadeh, M.-J. Pindera and C.T. Herakovich

Objectives

The long-term objective of this investigation is aimed at attaining a complete understanding of the inelastic response of metal matrix composites subjected to arbitrary, biaxial load histories. The core of the research program is a series of biaxial tests conducted on different types of advanced metal matrix composite systems using the combined axial/torsional hydraulic load frame in the Composite Mechanics Laboratory at the University. Tests involve primarily tubular specimens and include tension, compression, torsion and combinations of the above load histories in order to critically assess the inelastic response of advanced metal matrix composites in a wide temperature range.

Yielding of SCS-6/Ti-15-3 MMC Under Biaxial Loading

Carl T. Herakovich
Marek-Jerzy Pindera
Farshad Mirzadeh

Department of Civil Engineering

Abstract

Elements of the analytical/experimental program to characterize the response of silicon carbide titanium (SCS-6/Ti-15-3) composite tubes under biaxial loading are outlined. The present investigation is part of a long-term program to investigate the inelastic response of metal matrix composites in a wide temperature range under arbitrary, biaxial loading. The analytical program comprises prediction of initial yielding and subsequent inelastic response of unidirectional and angel-ply silicon carbide titanium tubes using a combined micromechanics approach and laminate analysis. The micromechanics approach is based on the method of cells model and has the capability of generating the effective thermomechanical response of metal matrix composites in the linear and inelastic region in the presence of temperature and time-dependent properties of the individual constituents and imperfect bonding. The preliminary results discussed herein illustrate the effect of residual stresses and imperfect bonding on the initial yield surfaces and inelastic response of [0] and $[\pm 45]_s$ SCS-6/Ti-15-3 laminates loaded by different combinations of stresses. The generated analytical predictions will be compared with the experimental results.

The experimental program comprises generation of initial yield surfaces, subsequent stress-strain curves and determination of failure loads of the SCS-6/Ti-15-3 tubes under selected loading conditions. The results of the analytical investigation will be employed to define the actual loading paths for the experimental program. A brief overview of the experimental methodology is given herein. This includes the test capabilities of the Composite Mechanics Laboratory at the University of Virginia, the SCS-6/Ti-15-3 composite tubes secured from McDonnell Douglas Corporation, a text fixture specifically developed for combined axial-torsional loading, and the MTS combined axial-torsion loader that will be employed in the actual testing.

YIELDING OF SCS-6/TI-15-3 MMC UNDER BIAXIAL LOADING

by

Carl T. Herakovich
Marek-Jerzy Pindera
Farshad Mirzadeh

Civil Engineering Department
University of Virginia

Supported by : Mechanics of Materials Branch

Technical monitor : W. Steven Johnson

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OBJECTIVES

Long-term

- Inelastic response of metal matrix composites in a wide temperature range under arbitrary, biaxial loading

Short-term

- Characterization of the response of SCS-6/Ti-15-3 tubes under biaxial loading

  — [0] tubes

  — $[\pm 45]_S$ tubes

  — initial yielding

  — inelastic response

  — failure

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METHODOLOGY

- Analytical/experimental approach

Analysis

- Micromechanical modeling of lamina response
  - Method of cells (Jacob Aboudi, Tel-Aviv University)
- Macromechanical modeling of laminate response
  - Method of cells + tube analysis
  - Method of cells + laminate analysis
- Initial yield surfaces
- Stress-strain response

METHODOLOGY

Experiment

- Biaxial loading of SCS-6/Ti-15-3 tubes
  - room and elevated temperatures
  - different loading paths

ANALYTICAL INVESTIGATION

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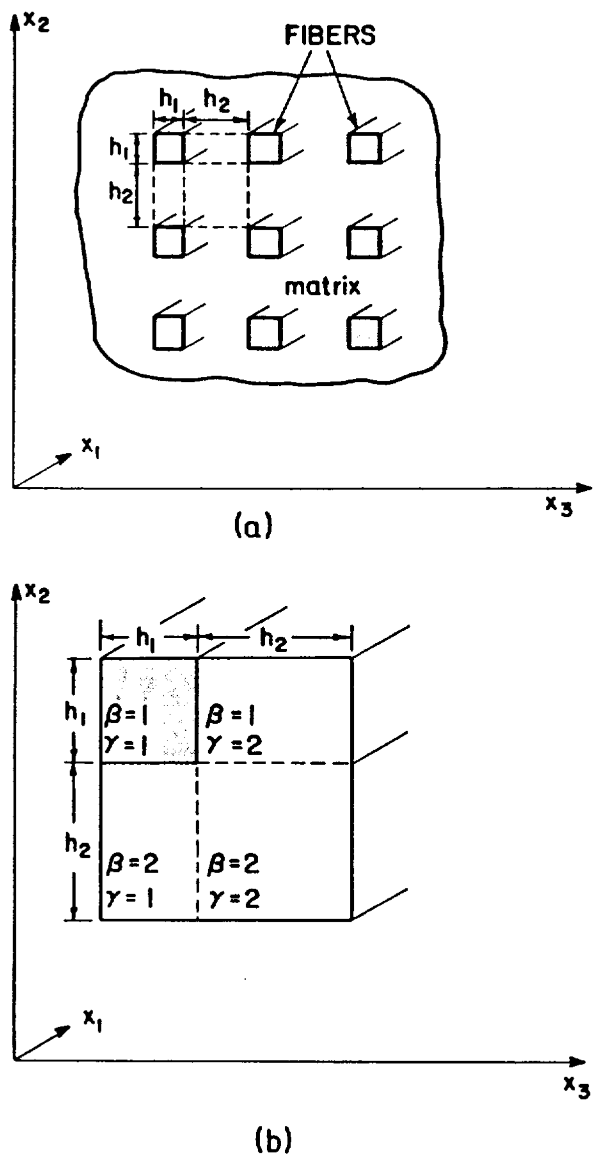
METHOD OF CELLS



Doubly periodic array of cells

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METHOD OF CELLS

- Repeating unit cell array

- Square geometry
  - square fiber
  - three matrix subcells

- Linear displacement field in each subcell

- Averaging process
  - microstructure $\rightarrow$ continuum

- Closed form expressions

METHOD OF CELLS

Capabilities

- elastic moduli
- initial yield surfaces
- elastoplastic response
- viscoelastic response
- thermal loading
- temperature-dependent properties
- imperfect bonding : R_n and R_t parameters
  - R_n : normal interfacial compliance
  - R_t : tangential interfacial compliance

CONSTITUENT RESPONSE

- Linear elastic fibers

- Initial yielding : Von Mises matrix

$$f(\hat{S}_{ij}^{(\beta\gamma)}) = \frac{1}{2}\,\hat{S}_{ij}^{(\beta\gamma)}\,\hat{S}_{ij}^{(\beta\gamma)} - \frac{1}{3}\,Y^2 = 0$$

- Inelastic response : Bodner-Partom matrix

$$\dot{L}_{ij}^{(\beta\gamma)} = \Lambda_{(\beta\gamma)}\,\hat{S}_{ij}^{(\beta\gamma)} \quad , \quad \beta + \gamma \neq 2$$

$$\Lambda_{(\beta\gamma)} = D_0 \exp\{-\hat{n}\,[Z^2_{(\beta\gamma)}/(3J_2^{(\beta\gamma)})]^n\}/[J_2^{(\beta\gamma)}]^{1/2}$$

$$Z_{(\beta\gamma)} = Z_1 + (Z_0 - Z_1)\exp[-m\,W_p^{(\beta\gamma)}/Z_0]$$

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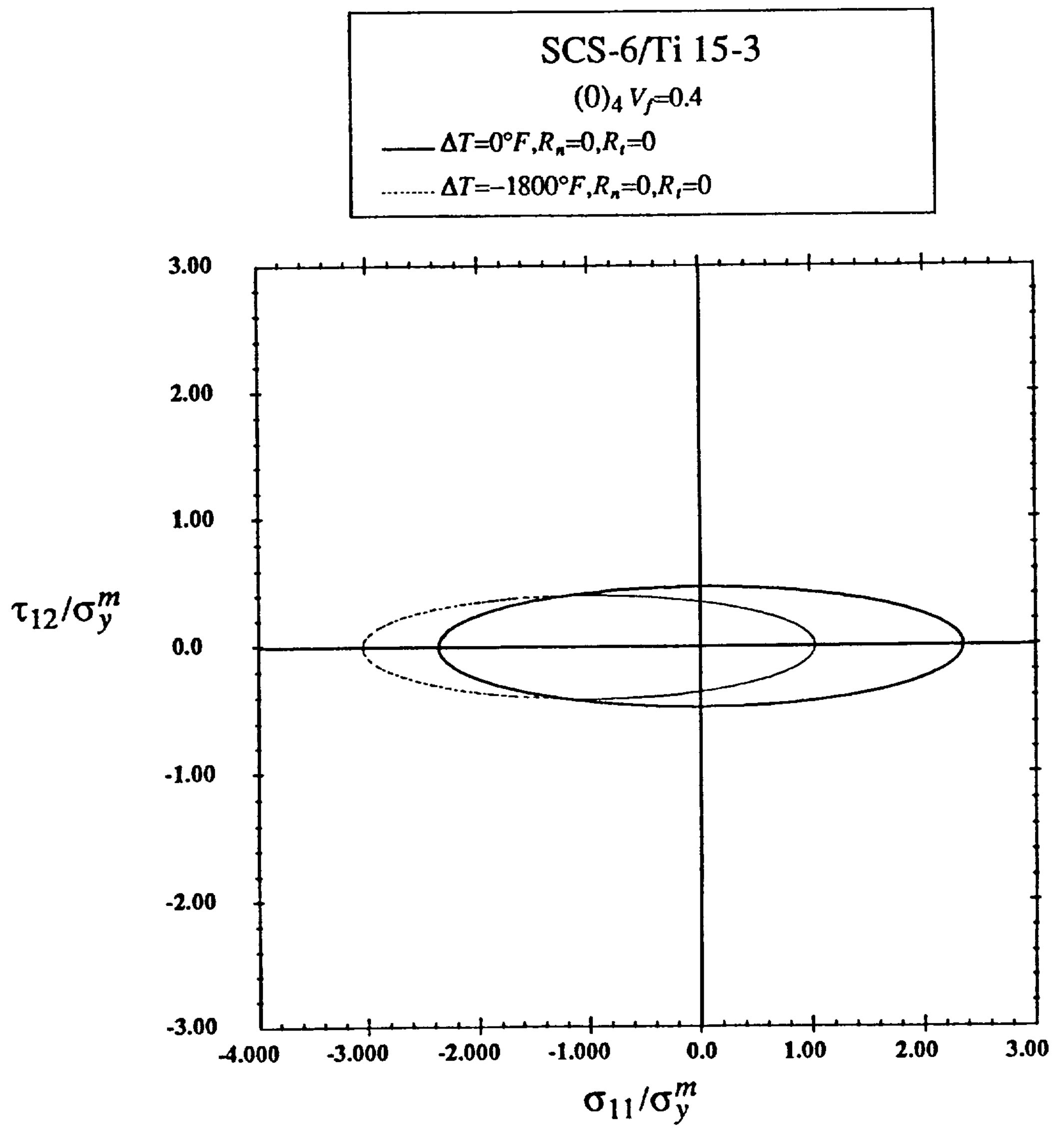
INITIAL YIELD SURFACE



Unidirectional lamina

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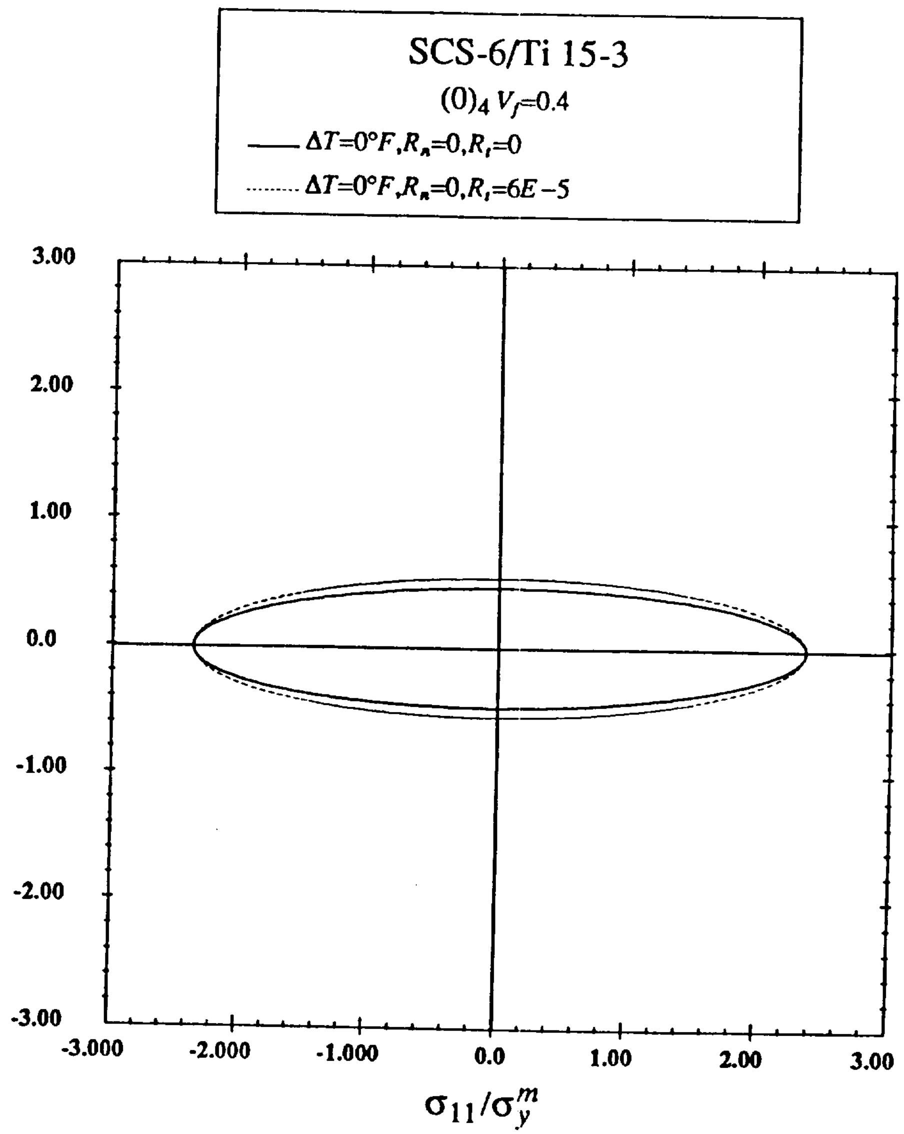
INITIAL YIELD SURFACE



Unidirectional lamina

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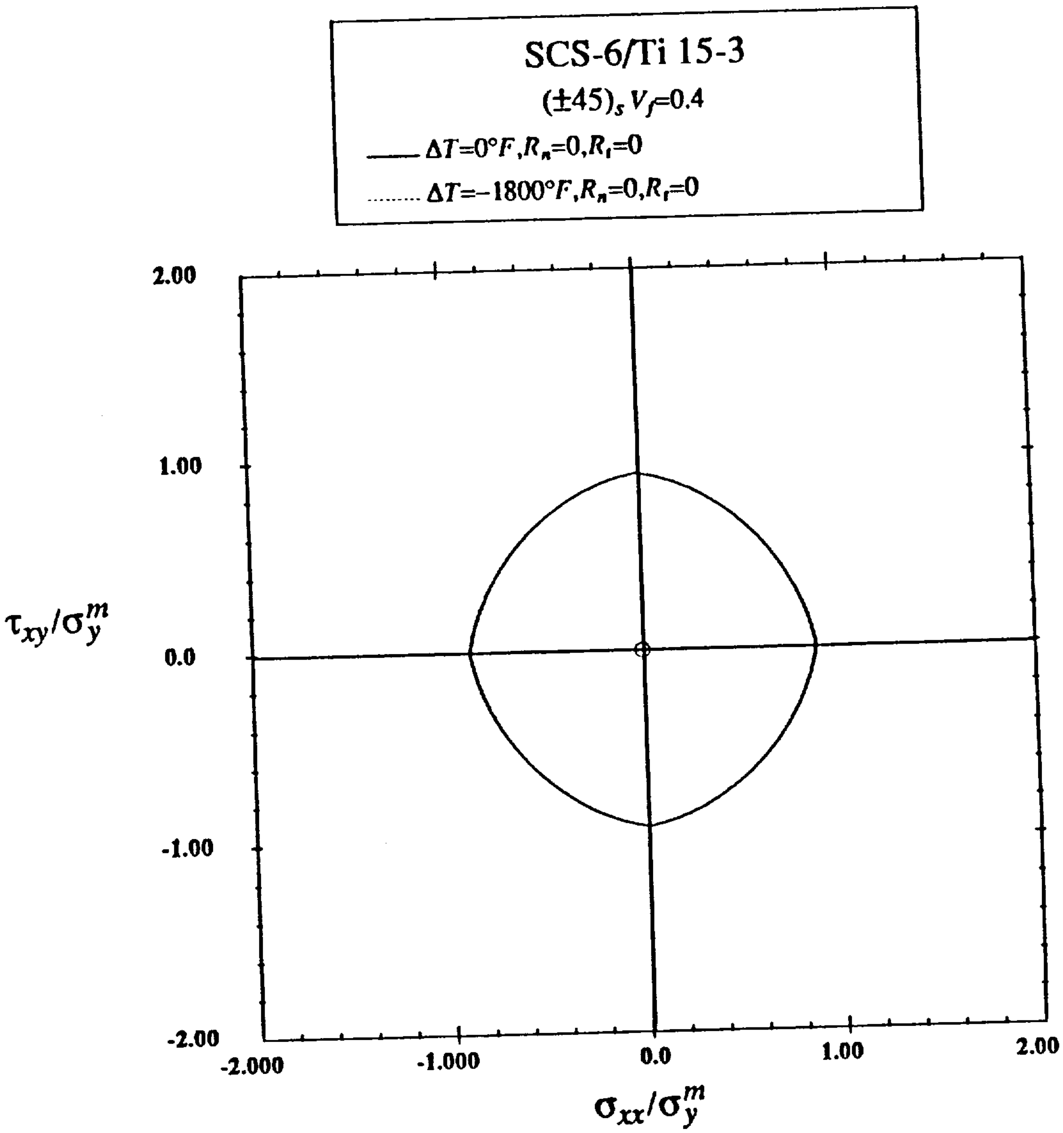
INITIAL YIELD SURFACE



$[\pm 45]_s$ angle-ply laminate

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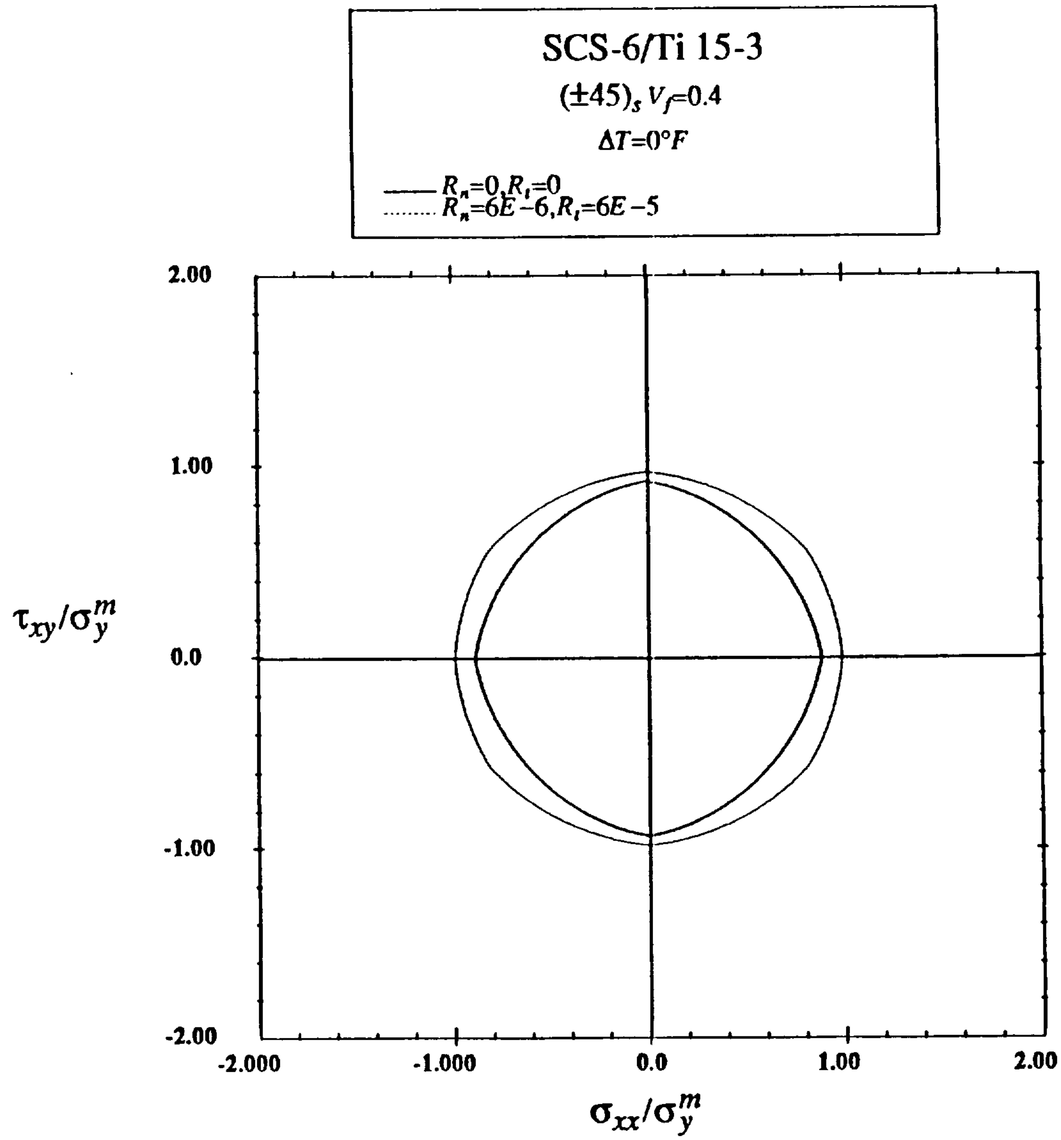
INITIAL YIELD SURFACE



$[\pm 45]_S$ angle-ply laminate

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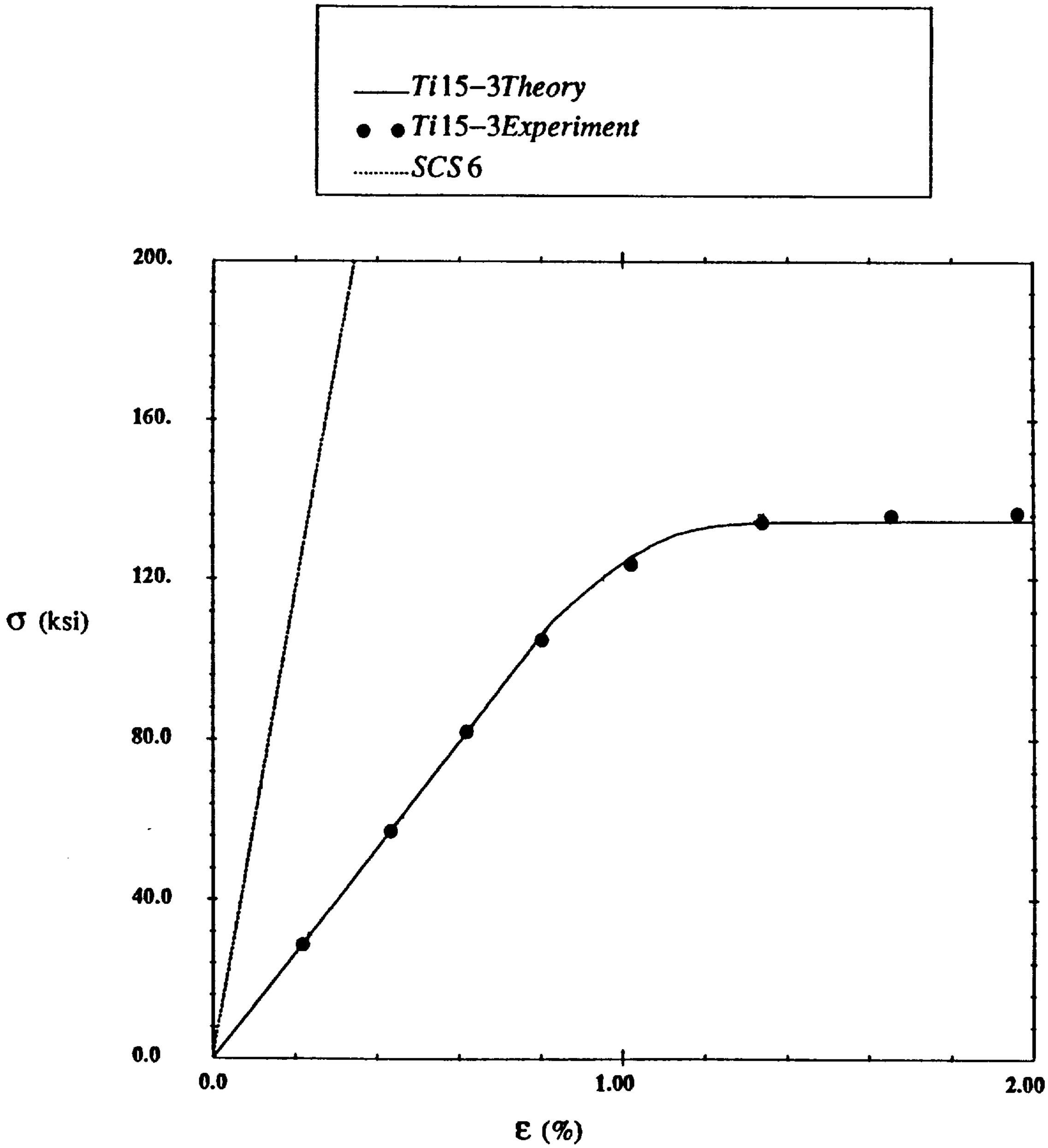
INELASTIC RESPONSE



Constituent response

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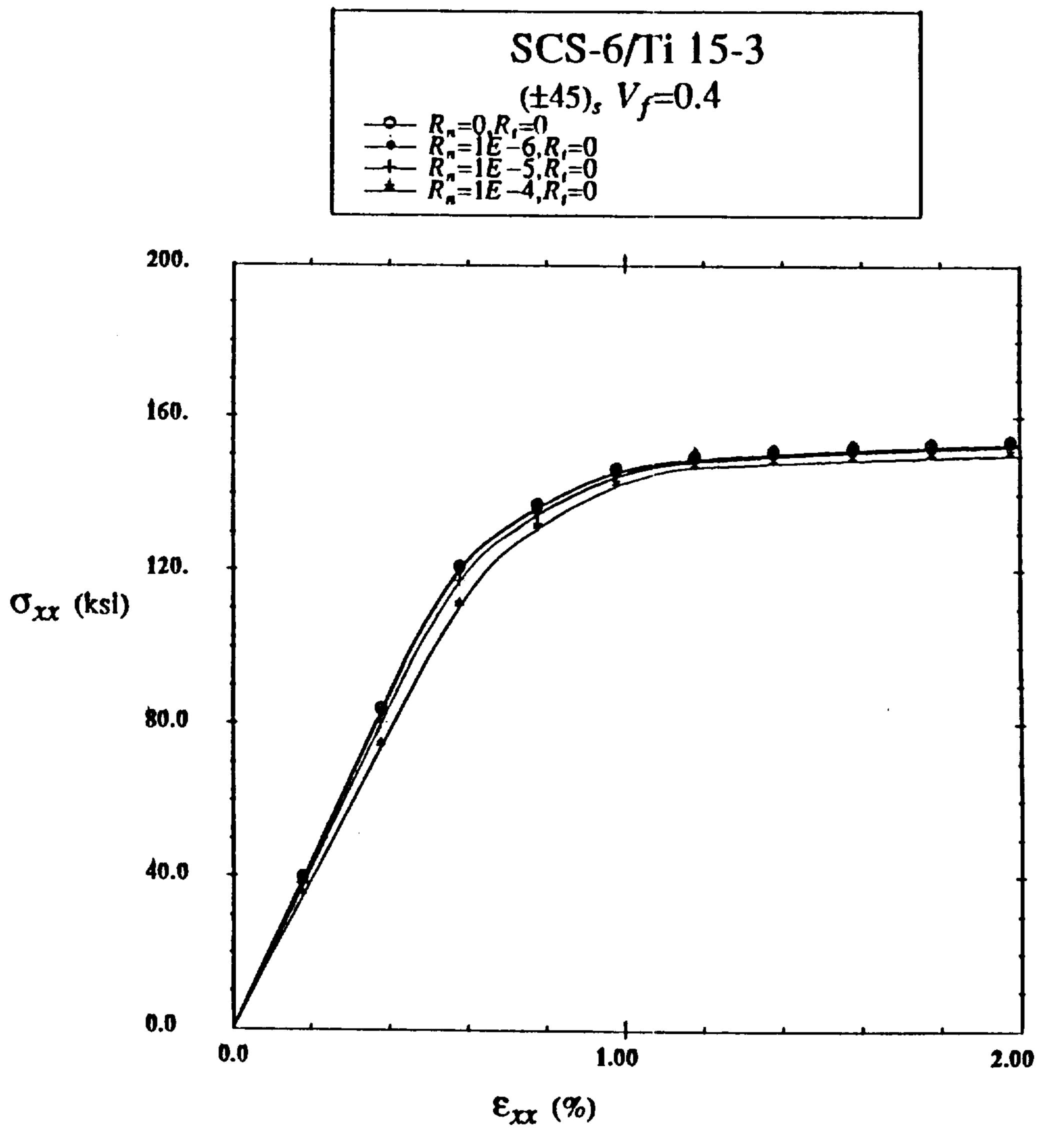
INELASTIC RESPONSE



$[\pm 45]_S$ angle-ply laminate response

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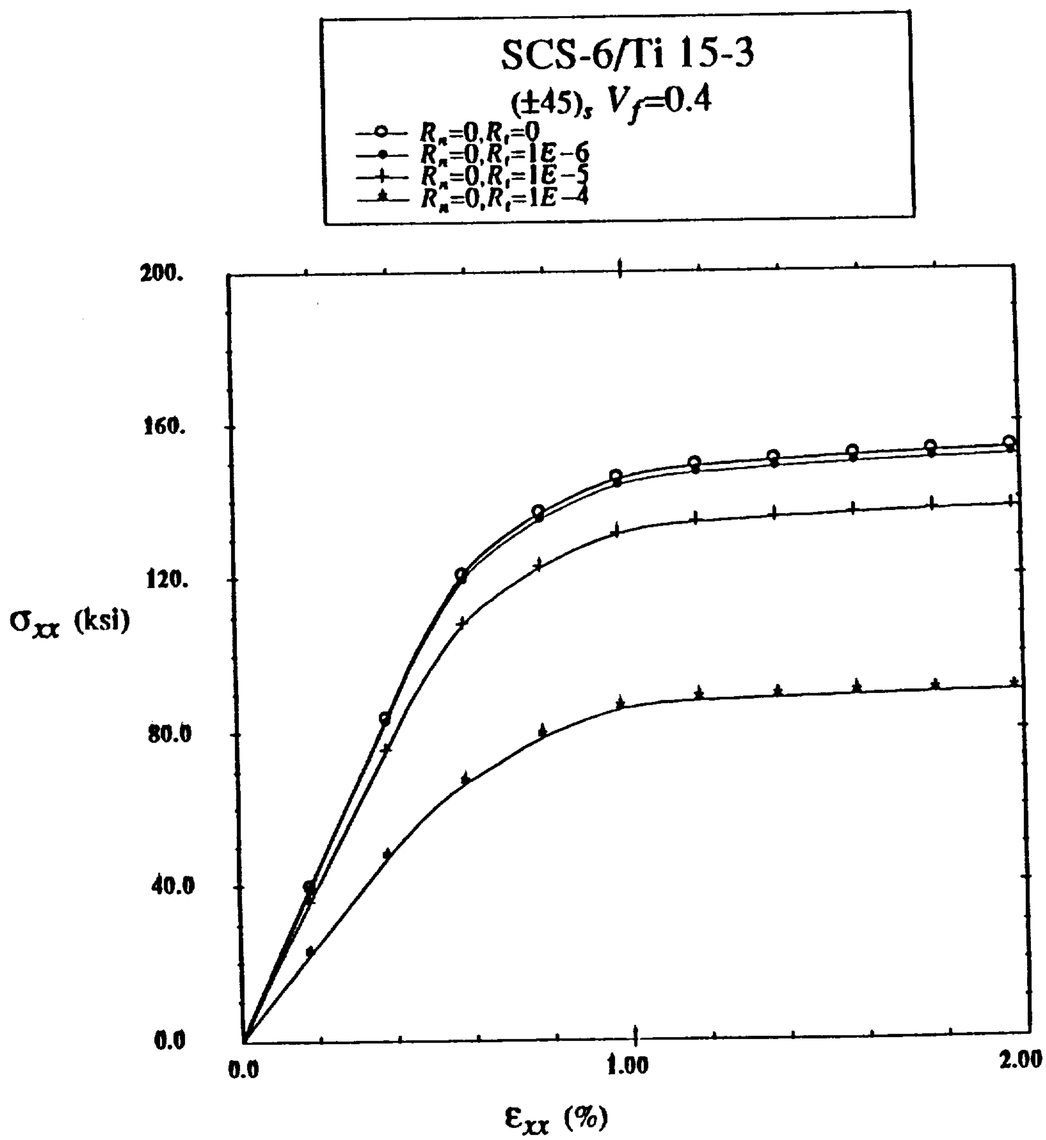
INELASTIC RESPONSE



$[\pm 45]_S$ angle-ply laminate response

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ANALYTICAL RESULTS - SUMMARY

- Initial yielding

  — Residual stresses : translation and decrease in the size of initial yield surfaces, more pronounced effect on initial yielding of $[\pm 45]_S$ laminates than [0] laminae

  — Imperfect bonding : increase in the size of initial yield surfaces, more pronounced effect on $[\pm 45]_S$ laminates than [0] laminae

- Inelastic response

  — Imperfect bonding : reduction in the initial elastic moduli and subsequent inelastic response, loading direction dependent

EXPERIMENTAL INVESTIGATION

Material:

SCS6/Ti15-3

Ti15-3 ≡ Ti - 15V - 3Cr - 3AL - 3Sn

Geometry:

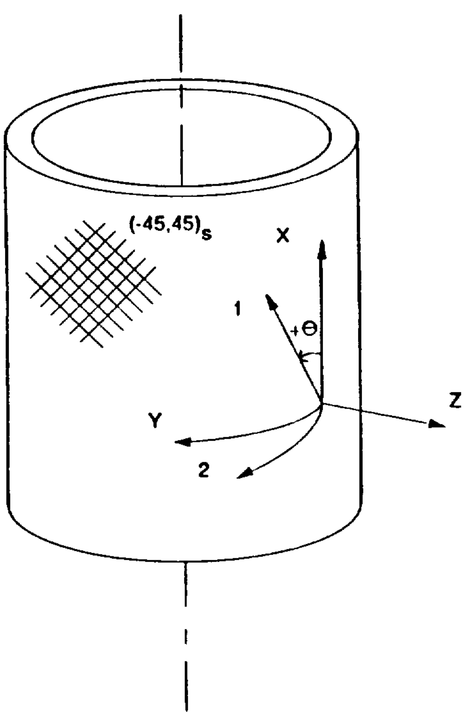
A: Six Tubes D=4", L=12", t=0.032"

B: Four Tubes D=1.5", L=7", t=0.032"

Stacking Sequence:

A: $[\pm 45]_s$

B: $[0]_4$



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Loading:

1 - Axial (Tension, Compression)

2 - Torsional (Positive, Negative)

3 - Internal Pressure

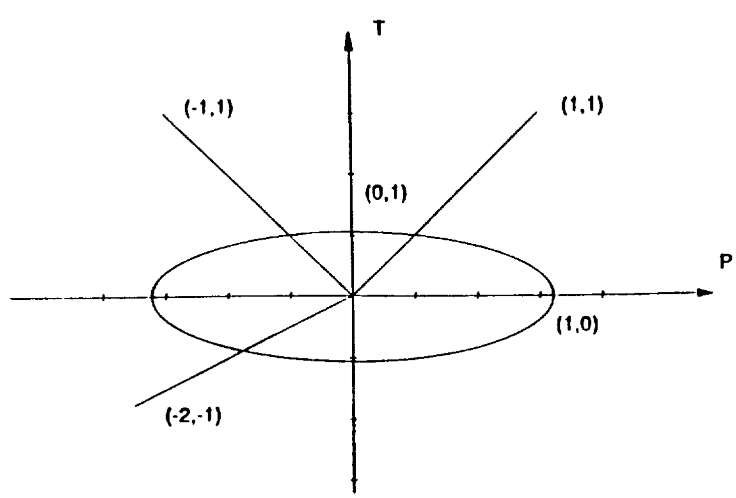
4 - Combinations of 1, 2, and 3

Environment:

A & B: Room temperature

A: Elevated temperature
≤ 425°C (800°F)

B: Elevated temperature
≤ 1700°C (3100°F)



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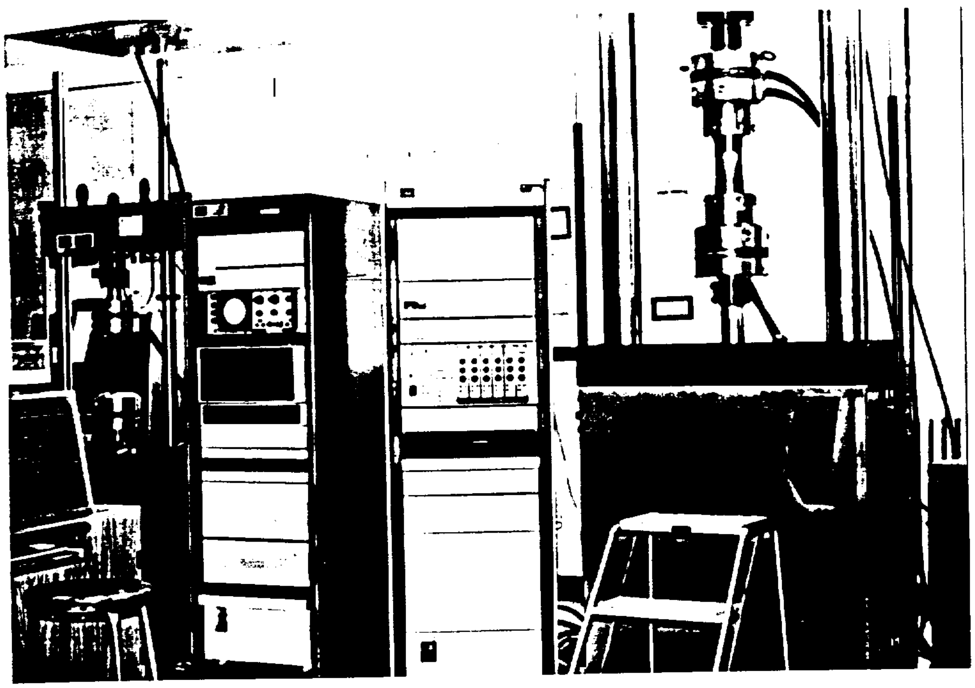
COMPOSITE MECHANICS LAB

AT UVA



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COMPOSITE MECHANICS LAB AT UVA

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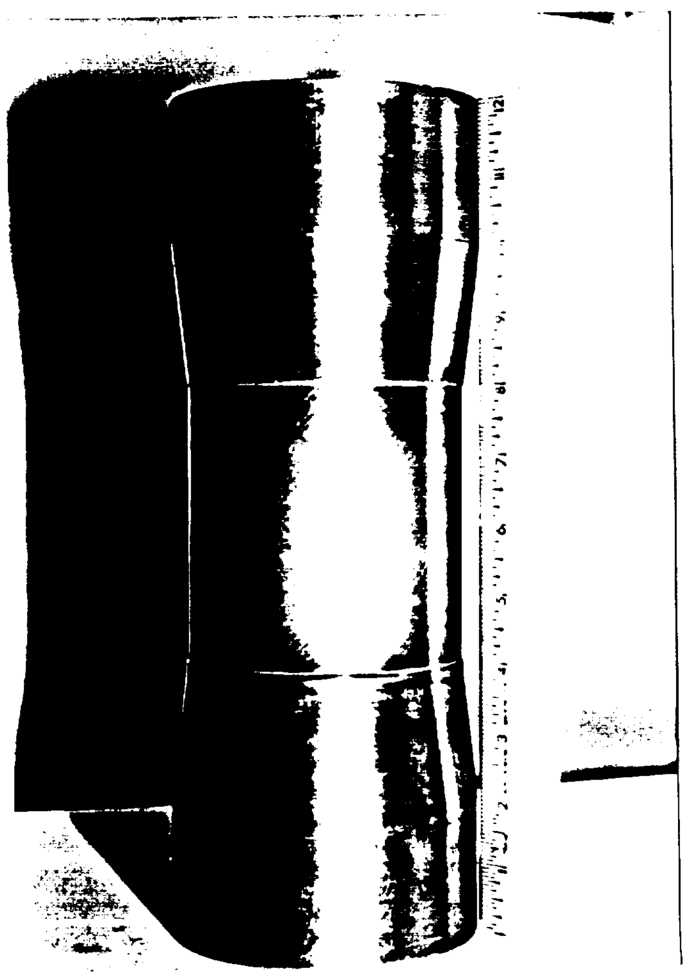
SCS6/Ti15-3 TUBE



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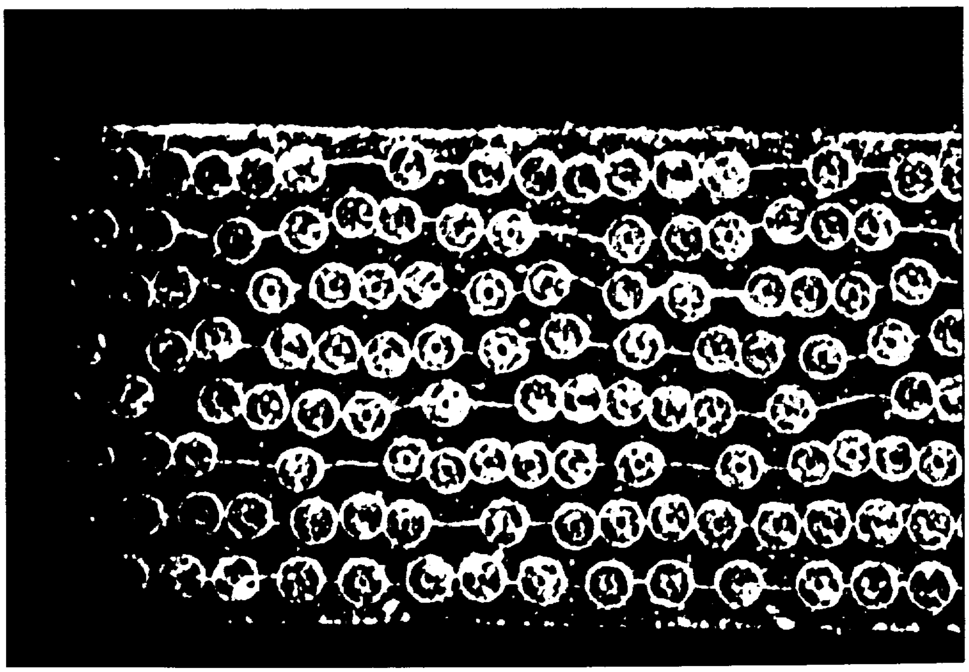
SCS6/Ti15-3 PHOTOMICROGRAPH



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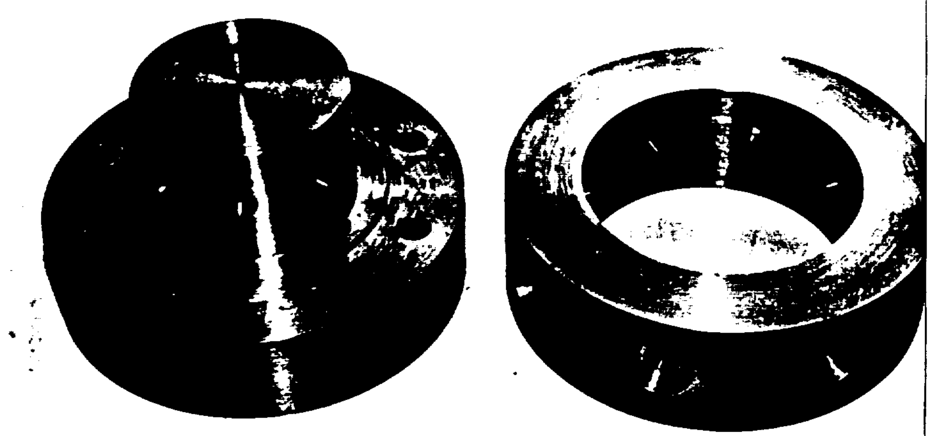
TUBE FIXTURE



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TUBE FIXTURE

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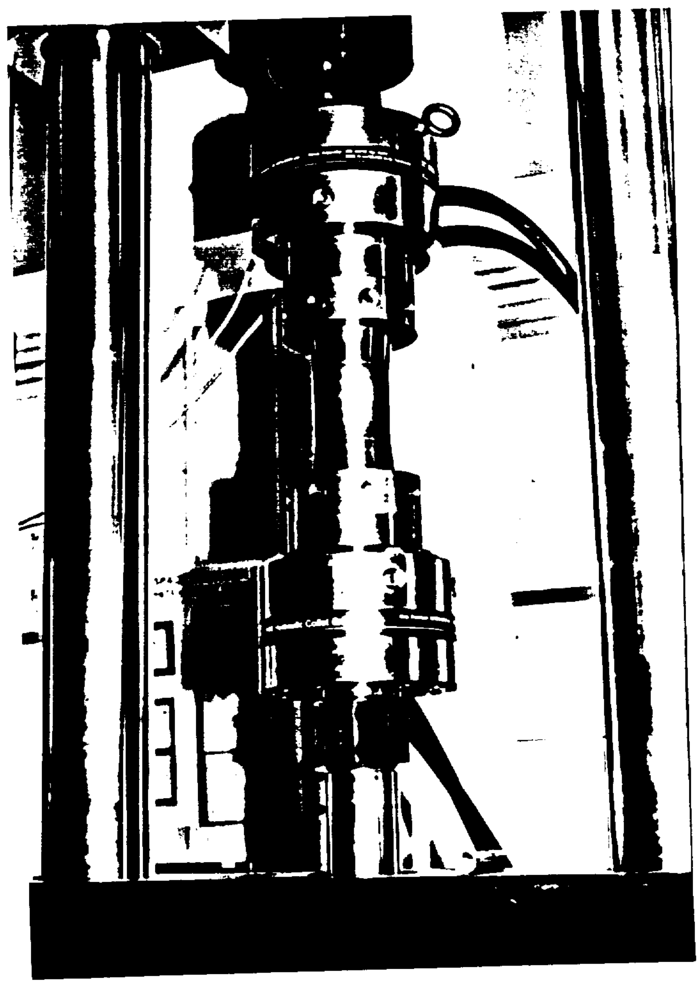
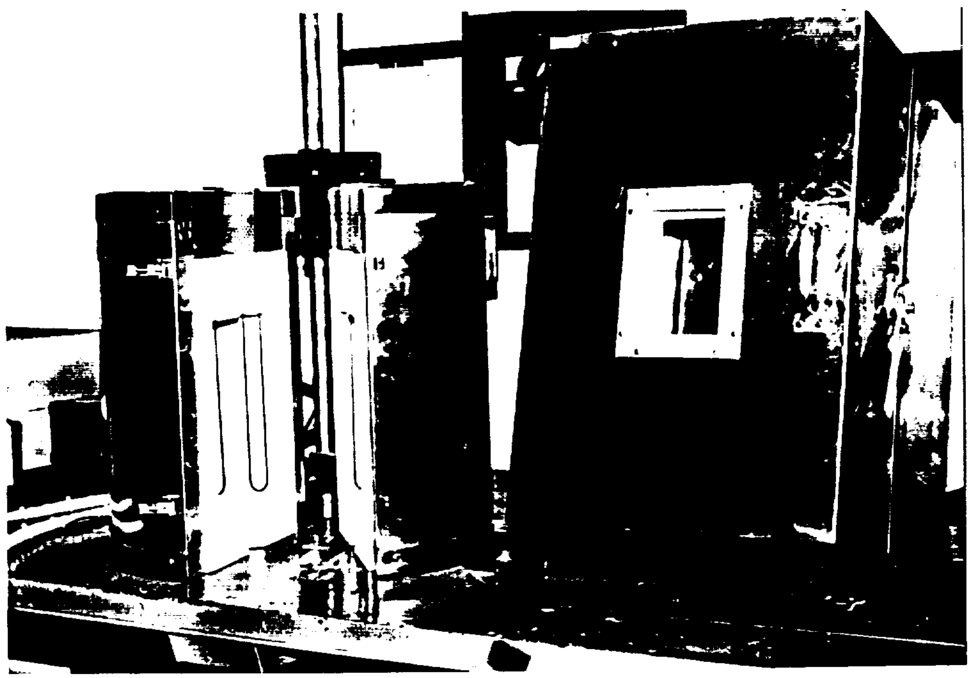
SCS6/Ti15-3 TUBE IN MTS AXIAL-TORSION LOAD FRAME



UVA APPLIED MECHANICS

ATS OVENS



PRESENT AND FUTURE WORK

- Analytical
  - — Further exercise micromechanics model at the lamina and laminate level
  - — Extend existing composite tube model to metal matrix composites
- Experimental
  - — Generate initial yield surfaces at room and elevated temperatures
  - — Generate stress-strain curves under biaxial loading
  - — Determine failure loads for selected loading paths
- Correlate theory and experiment

N90-22662

Program 10 **Design of Cryogenic Tanks for Launch Vehicles**

Charles Copper, W.D. Pilkey and J.K. Haviland

Objectives

The primary objective of this study is to find ways to reduce the life-cycle costs of cryogenic tanks for launch vehicles, such as the Advanced Launch Vehicle (ALS). A major saving can be achieved if the tanks are recoverable, however this introduces severe heating and aerodynamic loads, leading to thermo-structural design problems.

The secondary objective, which has been the focus of the present study, is to investigate the considerable reductions in manufacturing costs which are possible with sophisticated skin and stringer designs and with the use of new materials and fabrication techniques.

Design of Cryogenic Tanks for Launch Vehicles

W. D. Pilkey, J. K. Haviland, C. Copper
Department of Mechanical and Aerospace Engineering

Abstract

During the period since January 1990, work has been concentrated on the problem of the buckling of the structure of an ALS tank during the boost phase. The primary problem has been to analyze a proposed hat stringer made by superplastic forming, and to compare it with an integrally stiffened stringer design. A secondary objective has been to determine whether structural rings having the identical section to the stringers will provide adequate support against overall buckling. All of the analytical work has been carried out with the TESTBED program on the CONVEX computer at Langley, using the University of Virginia's PATRAN programs to create models.

Analyses of skin/stringer combinations have shown that the proposed stringer design is an adequate substitute for the integrally stiffened stringer. Using a highly refined mesh to represent the corrugations in the vertical webs of the hat stringers, effective values have been obtained for cross-sectional area, moment of inertia, centroid height, and torsional constant. Not only can these values be used for comparison with experimental values, but they can also be used for beams to replace the stringers and frames in analytical models of complete sections of tank. The same highly refined model was used to represent a section of skin reinforced by a stringer and a ring segment in the configuration of a cross. It was intended that this would provide a baseline buckling analysis representing a basic mode, however, the analysis proved to be beyond the scope of the CONVEX computer. One quarter of this model was analyzed, however, to provide information on buckling between the spot welds.

Models of large sections of the tank structure have been made, using beam elements to model the stringers and frames. In order to represent the stiffening effects of pressure, stresses and deflections under pressure should first be obtained, and then the buckling analysis should be made on the structure so deflected. So far, uncharacteristic deflections under pressure have been obtained from the TESTBED program using two types of structural elements. Similar results have been obtained using the ANSYS program on a mainframe computer, although two finite element programs on microcomputers have yielded realistic results. Pending a solution to this problem, a buckling analysis is to be made on the undeflected tank structure to determine whether the proposed rings are stiff enough to ensure conventional buckling of the stringers between the rings as opposed to overall buckling of rings and stringers.

The present work emphasizes the feasibility of the proposed stringer design, as opposed to providing a final design. To summarize, the stringers appear to be adequate, but the rings, as presently conceived, may be inadequate.

DESIGN OF CRYOGENIC TANKS FOR LAUNCH VEHICLES

NASA MONITORS: RUMMLER, DAVIS

UVA INVESTIGATORS: PILKEY, HAVILAND, COPPER

PRESENTATION BY CHARLES COPPER

PROBLEM: INVESTIGATE SPF VS INTEGRAL STRINGERS

ALS TANK

MODELLING OF SUBSTRUCTURES

FLAT PANELS

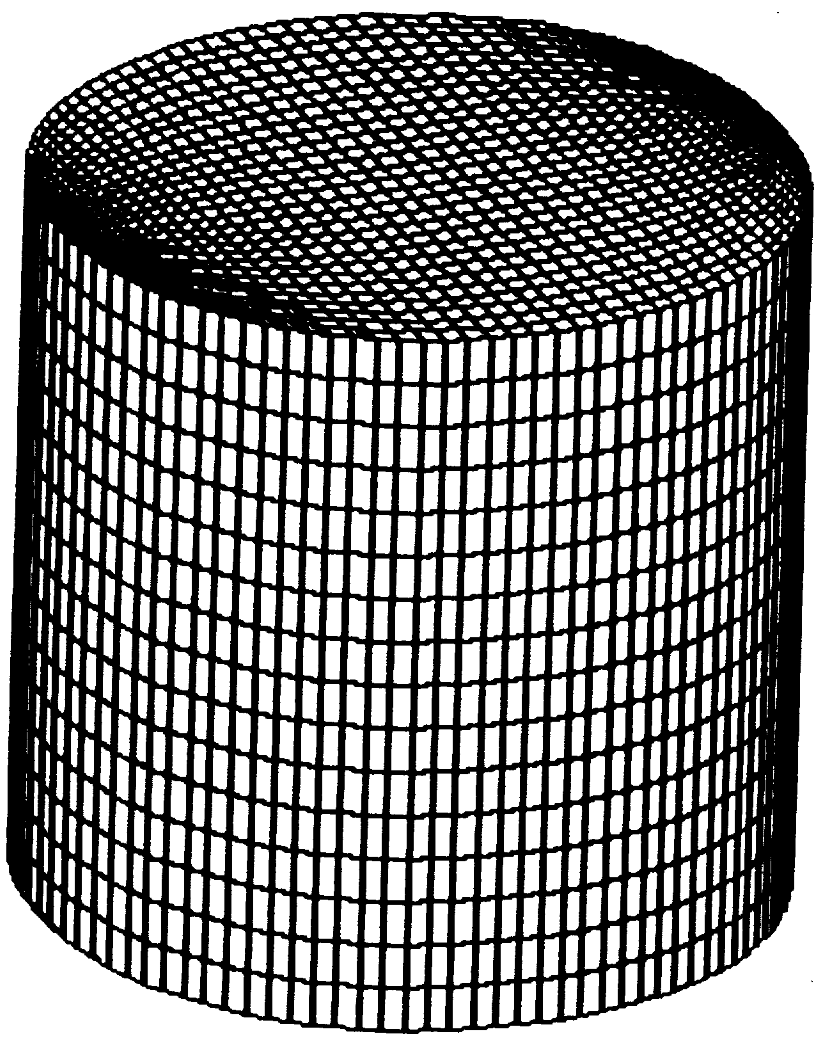
BEAM PROPERTIES OF SPF HAT STRINGER

INTERNAL BUCKLING OF SPF HAT STRINGER

PARTIAL MODELLING OF TANK

CONCLUSIONS

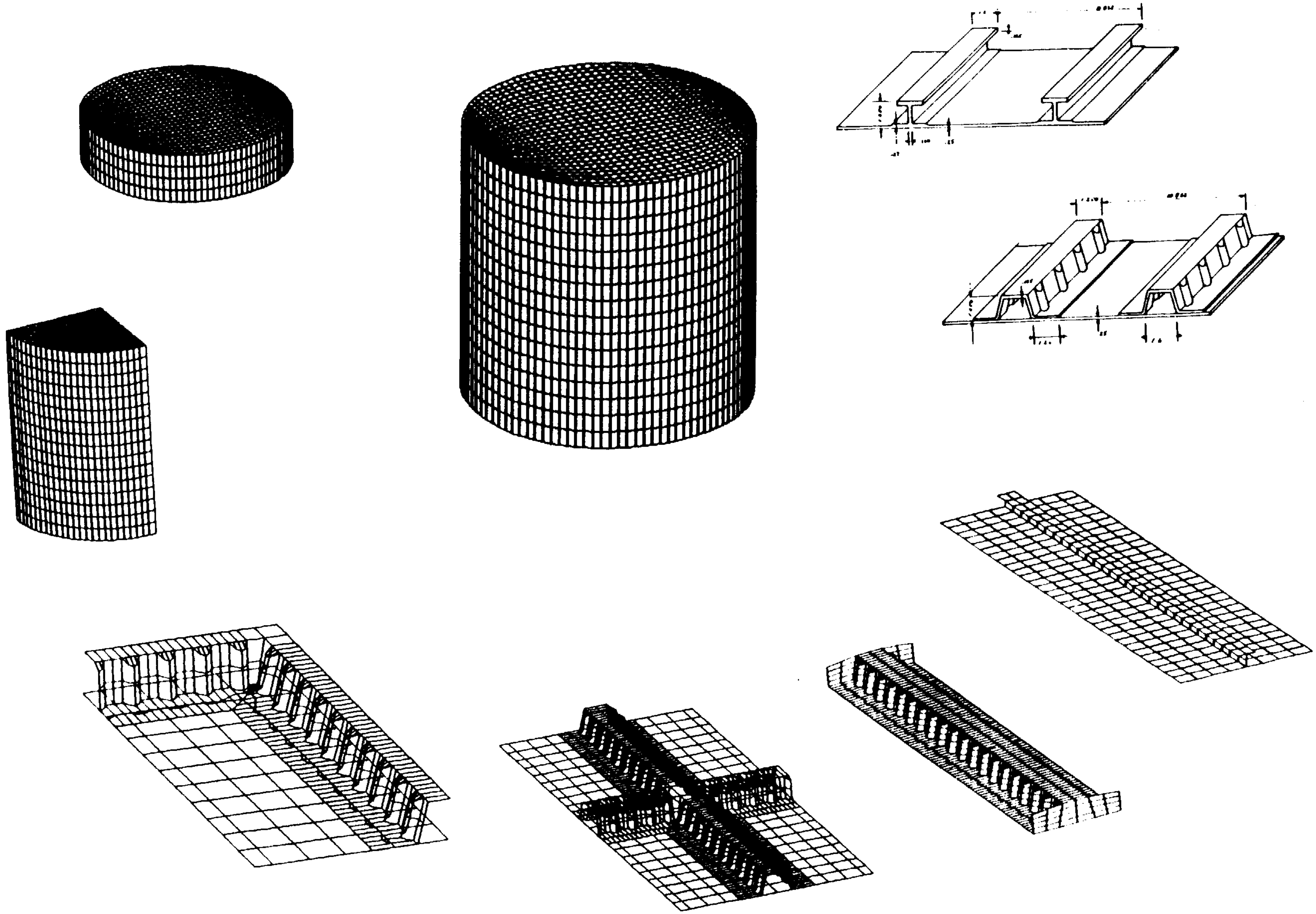
COMPLETE FUEL TANK



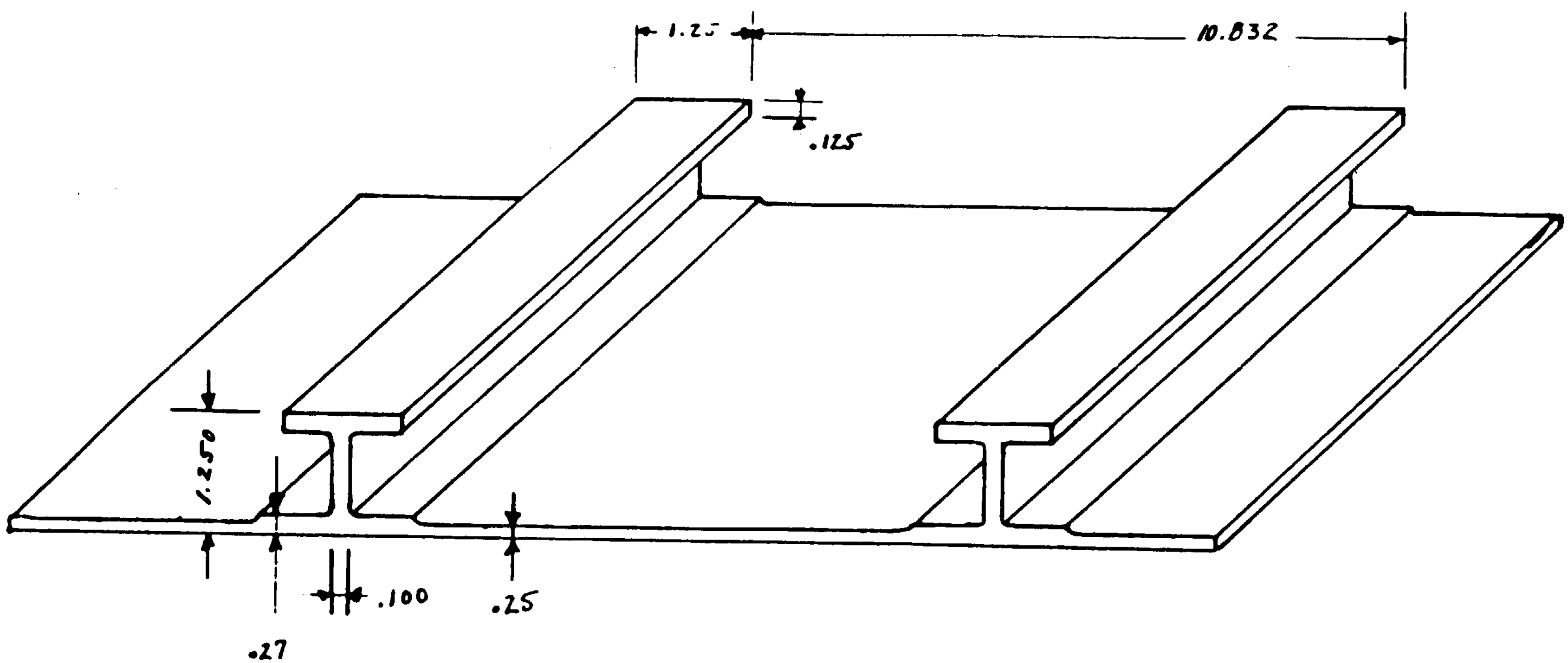
DESIGN INFORMATION

TANK DIAMETER		= 30 ft.
TANK HEIGHT		= 30 to 33 ft.
RING SPACING		= 20 to 30 ins.
STRINGER SPACING		= 10 to 15 ins.
WALL THICKNESS	TOP	= 0.25 ins.
	BOTTOM	= 0.60 ins.
DESIGN COMPRESSIVE LOAD		= 4,000 kips. (TOTAL)
INTERNAL PRESSURE HEAD		= 28 psi.
DESIGN LOAD IN WALLS		= 1,150 kips.
ULTIMATE LOAD IN WALLS		= 1,725 kips.

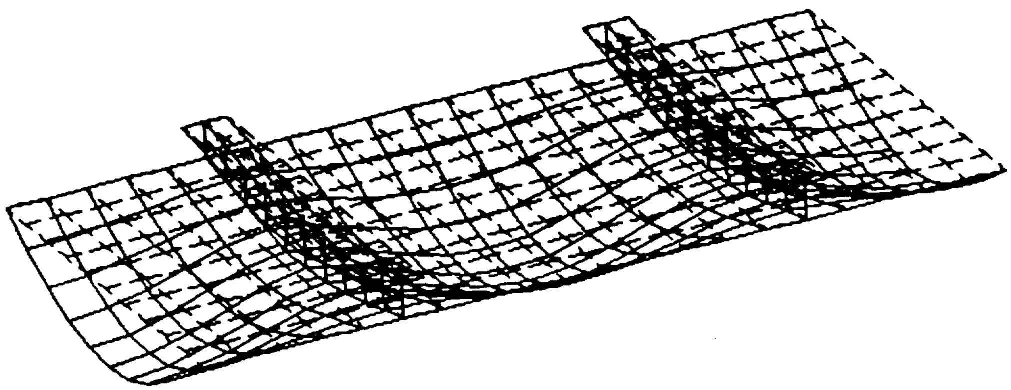
MODELLING OF SUBSTRUCTURES



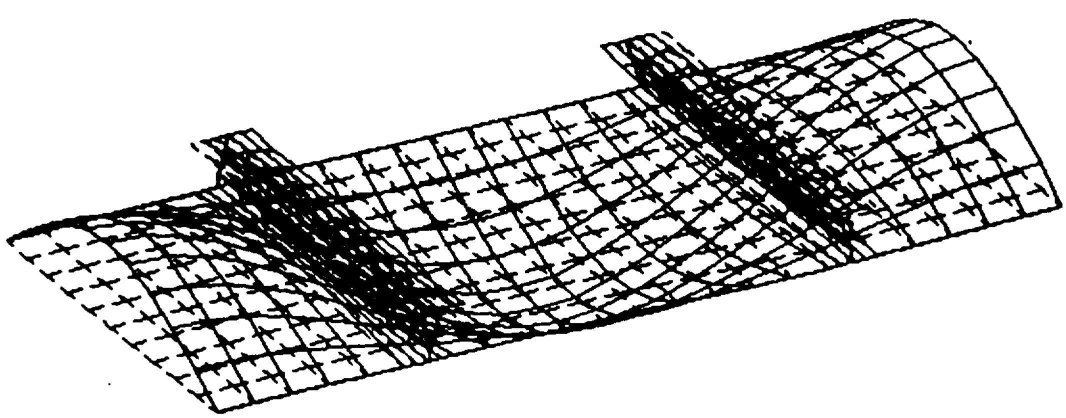
MACHINED–OUT I–BEAMS



MACHINED-OUT I-BEAMS: TWO MODES

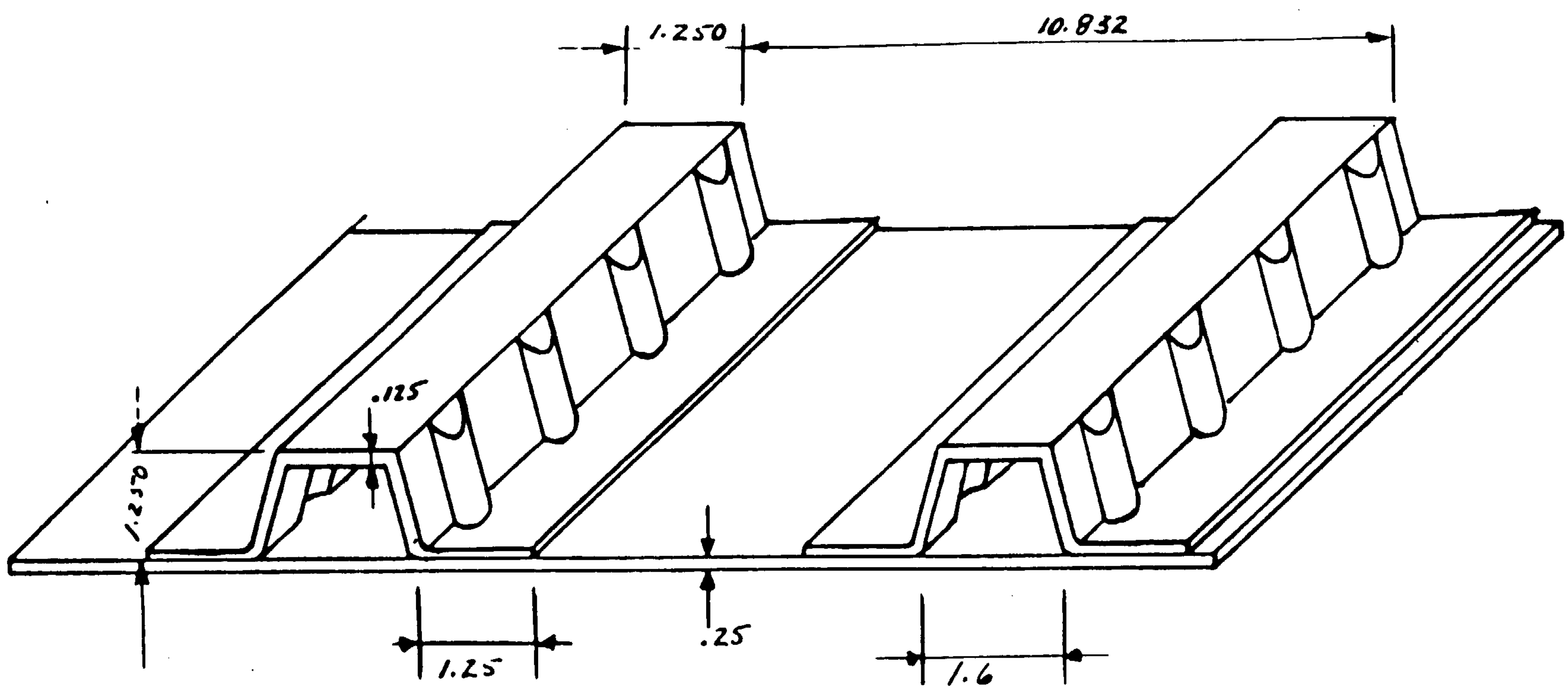


STRESS 73,600 psi; LOAD 20,800 kips

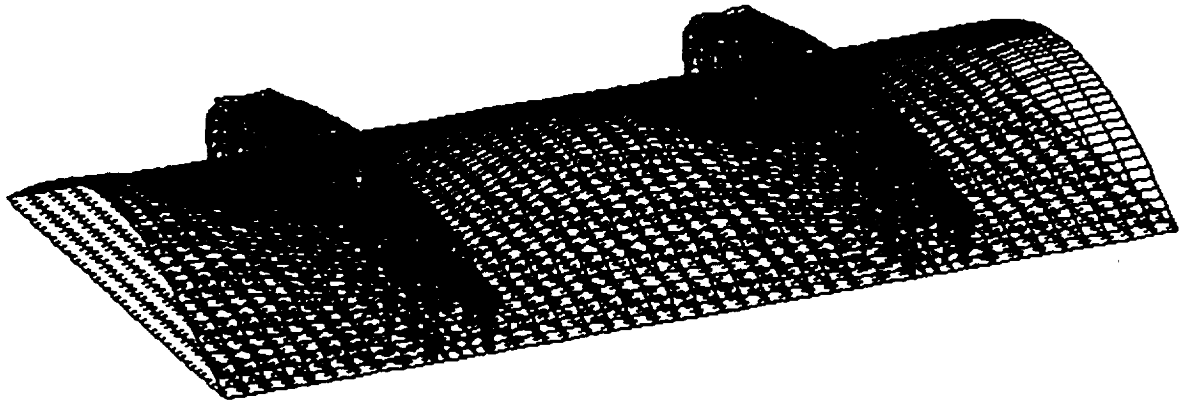


STRESS 19,000 psi; LOAD 5,400 kips

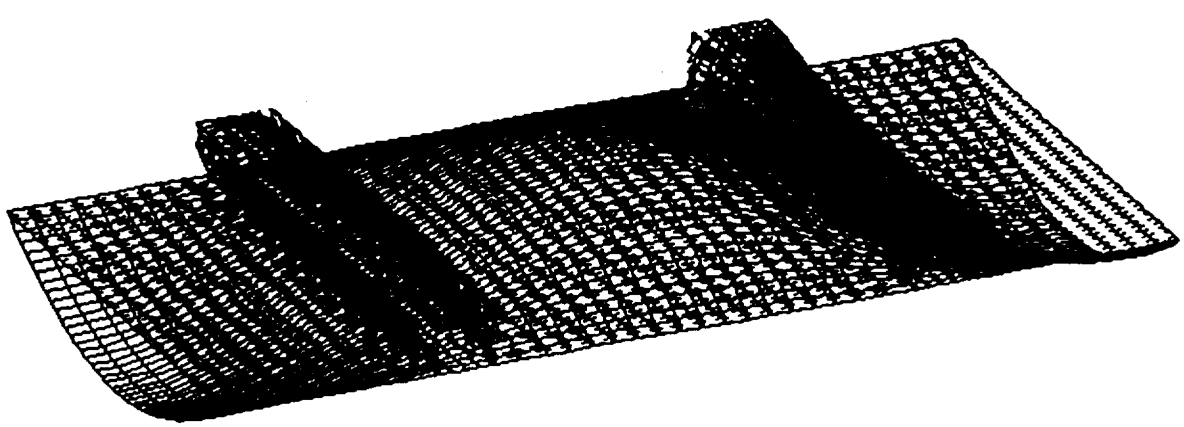
SPF HAT STRINGER



SPF HAT STRINGER: TWO MODES

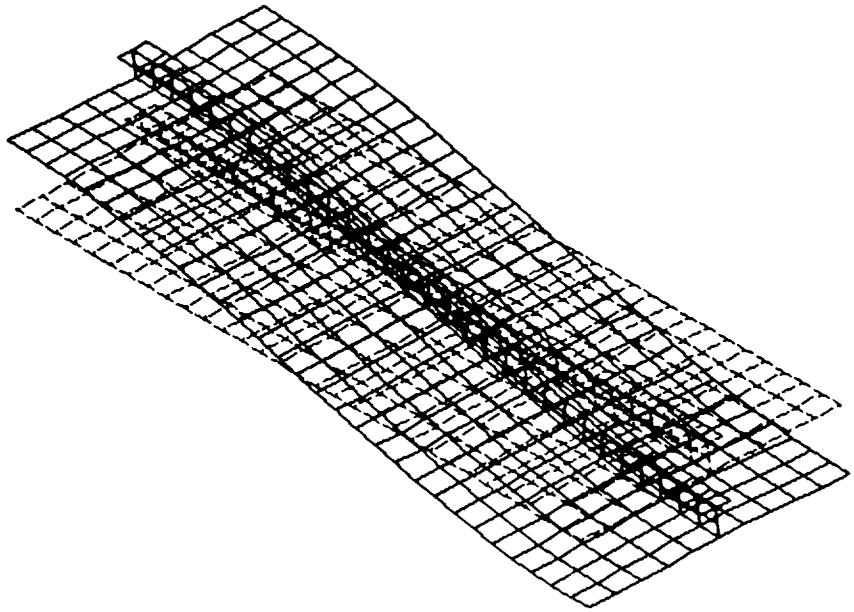


STRESS 26,400 psi: LOAD 7,500 kips

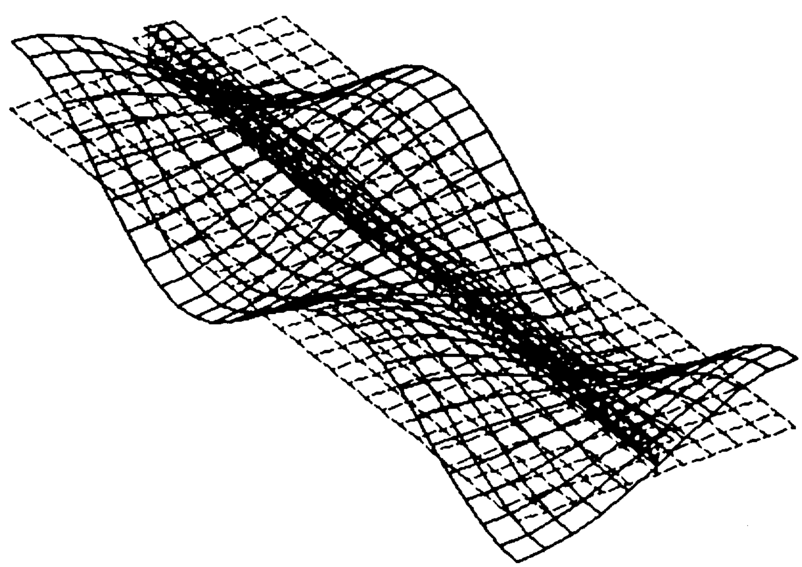


STRESS 24,500 psi; LOAD 6,900 kips

30" I-BEAM STRINGER & SKIN: TWO MODES

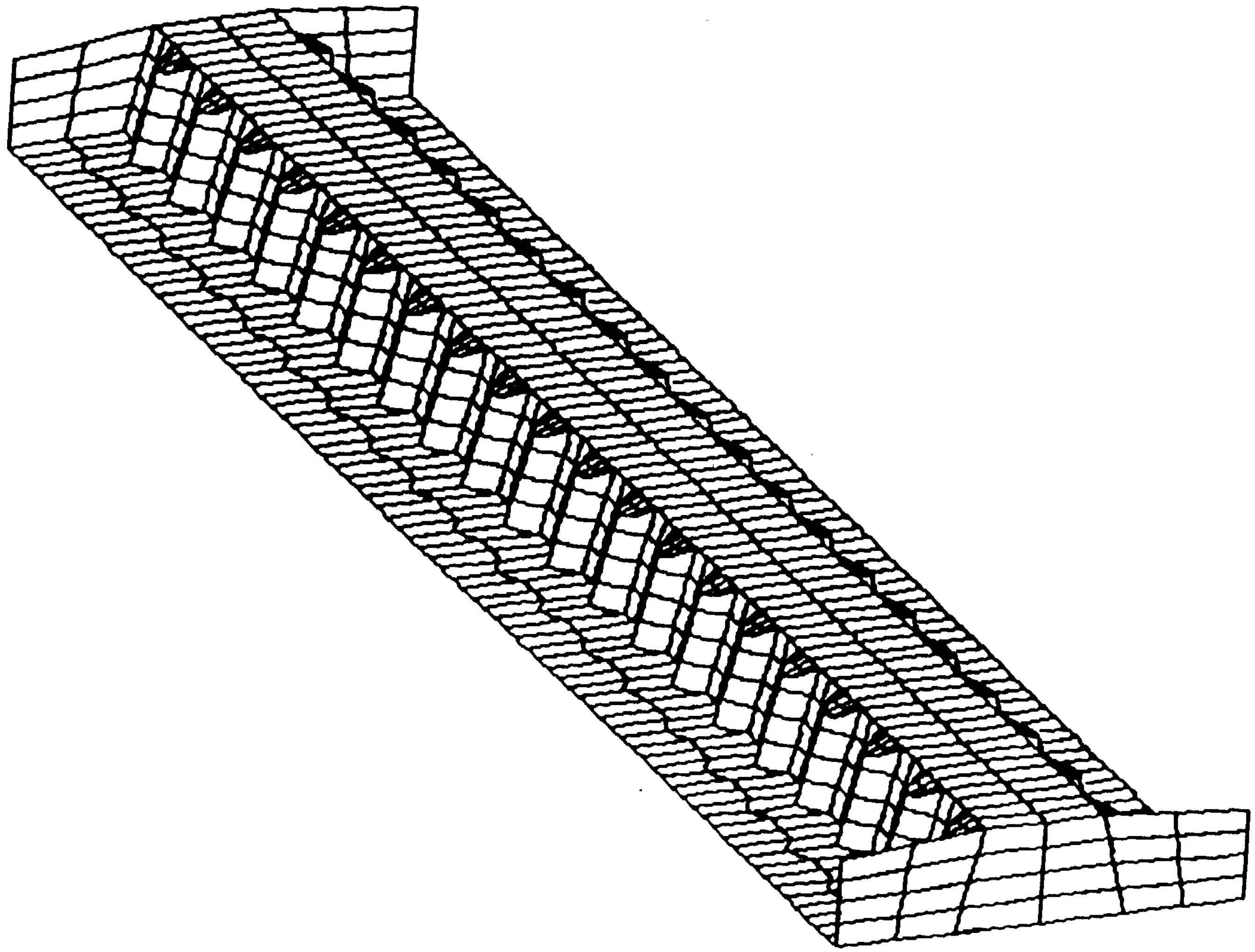


STRESS = 9,900 psi: LOAD = 2,800 kips



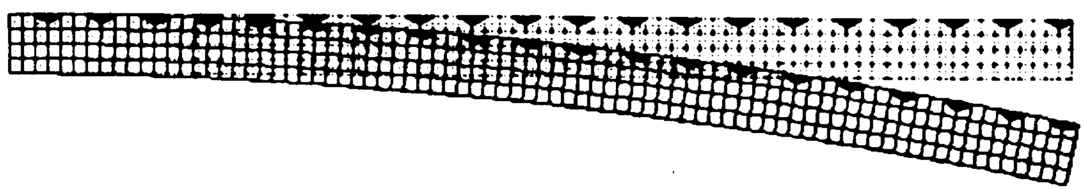
STRESS = 19,000 psi: LOAD = 5,400 kips

DETAIL MODEL OF SPF HAT STRINGER

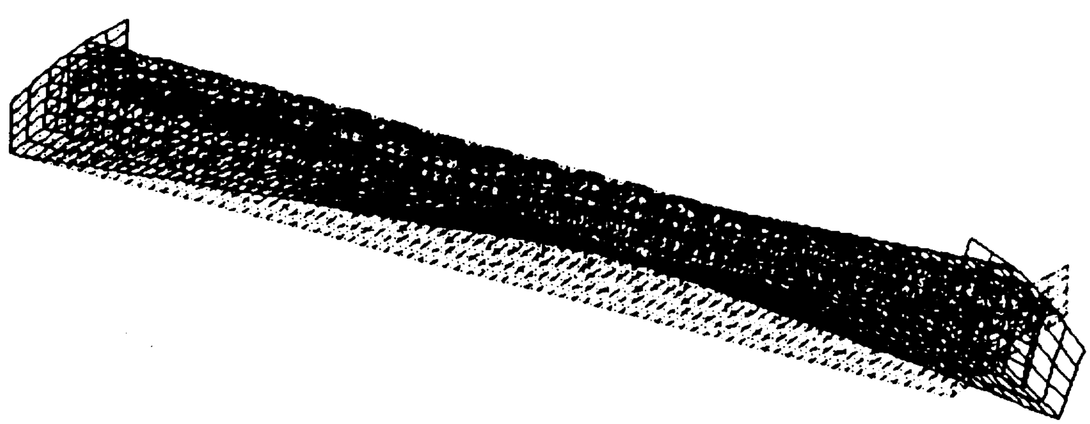


LOADED SPF HAT STRINGERS

COMPRESSION, $A_{eff} = 0.368$ in^2

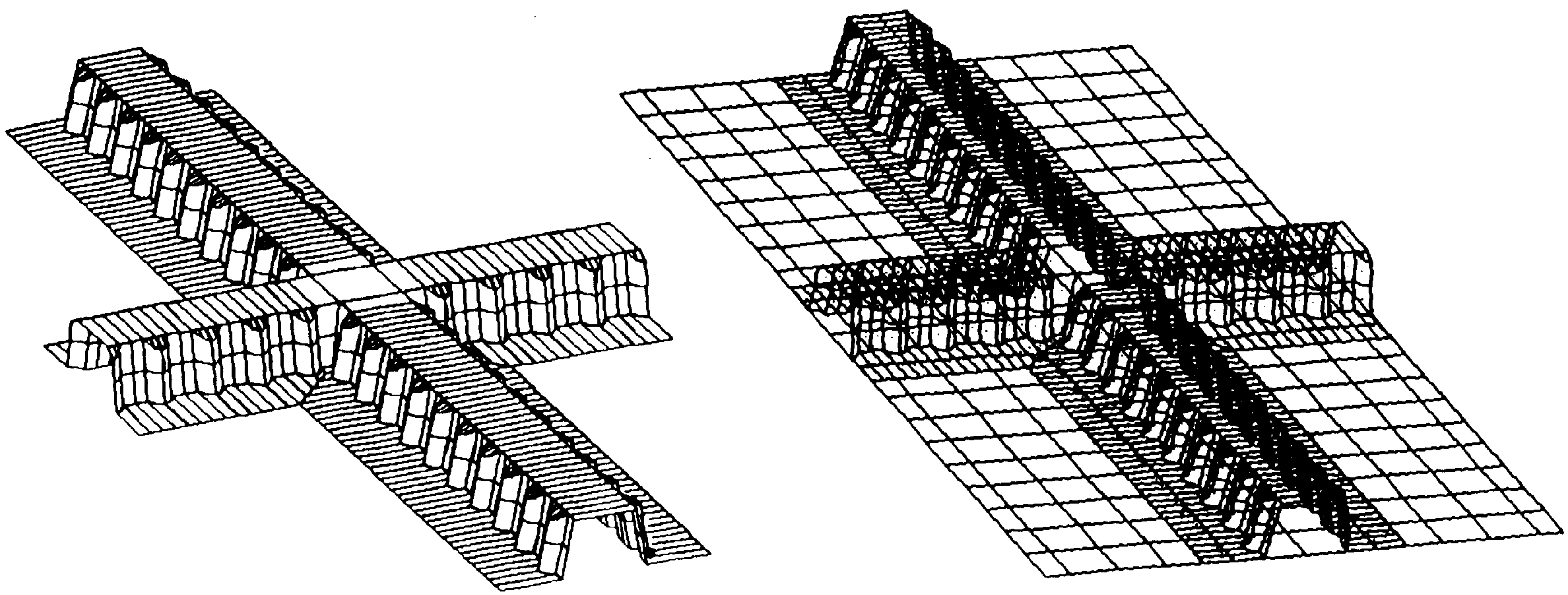


BENDING, $I_{eff} = 0.129$ in^4

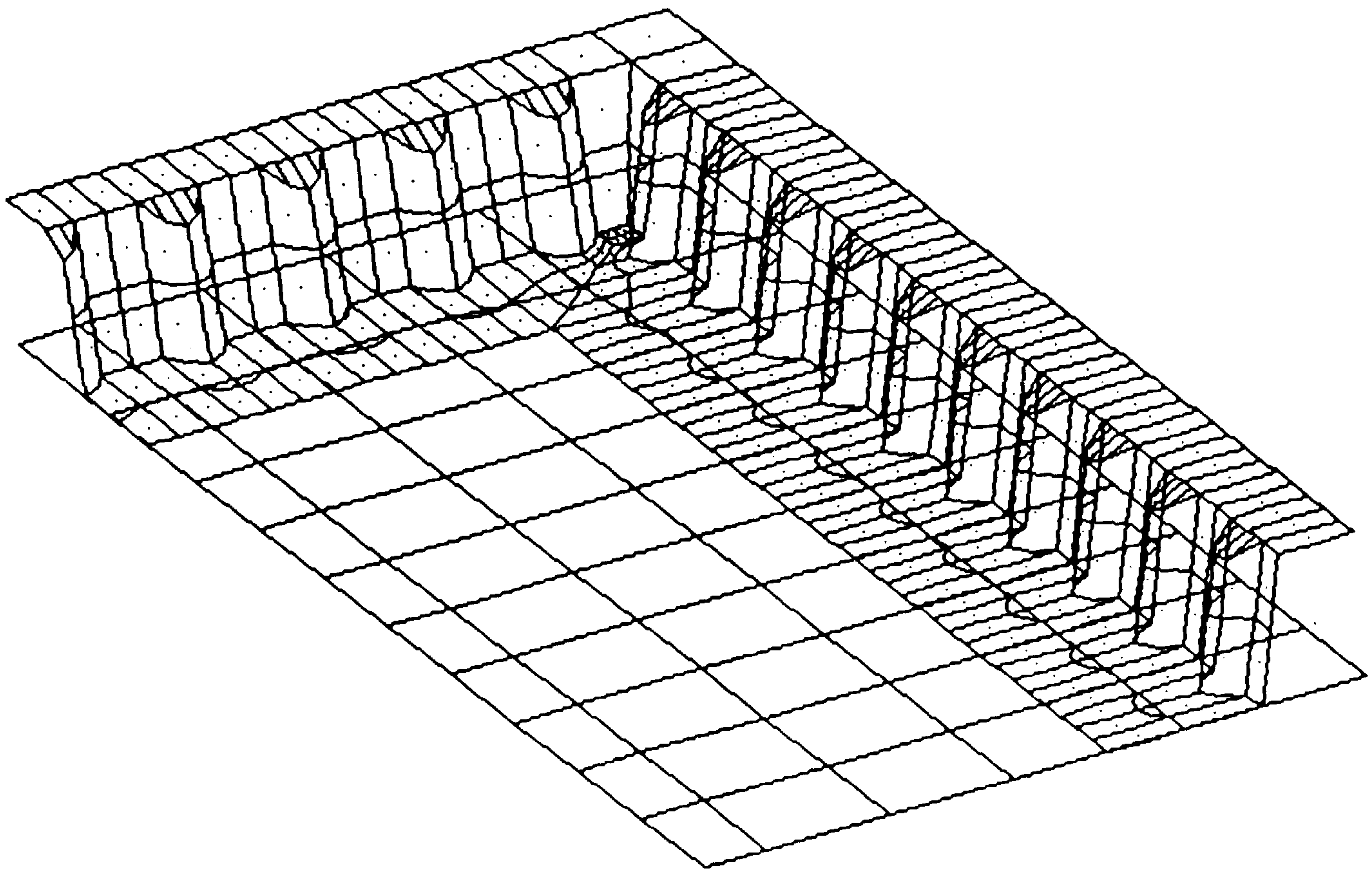


TORSION, $J_{eff} = 0.249$ in^4

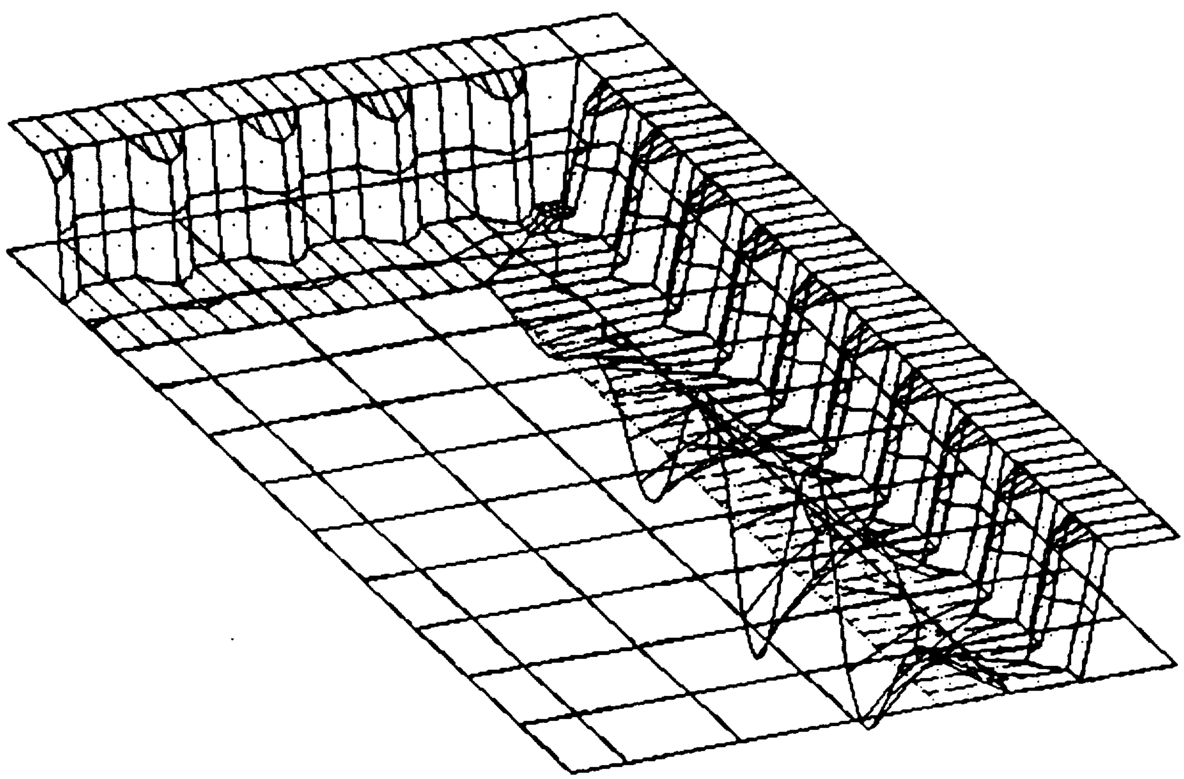
SPF STRINGER/FRAME PANEL



QUARTER SPF STRINGER/FRAME PANEL

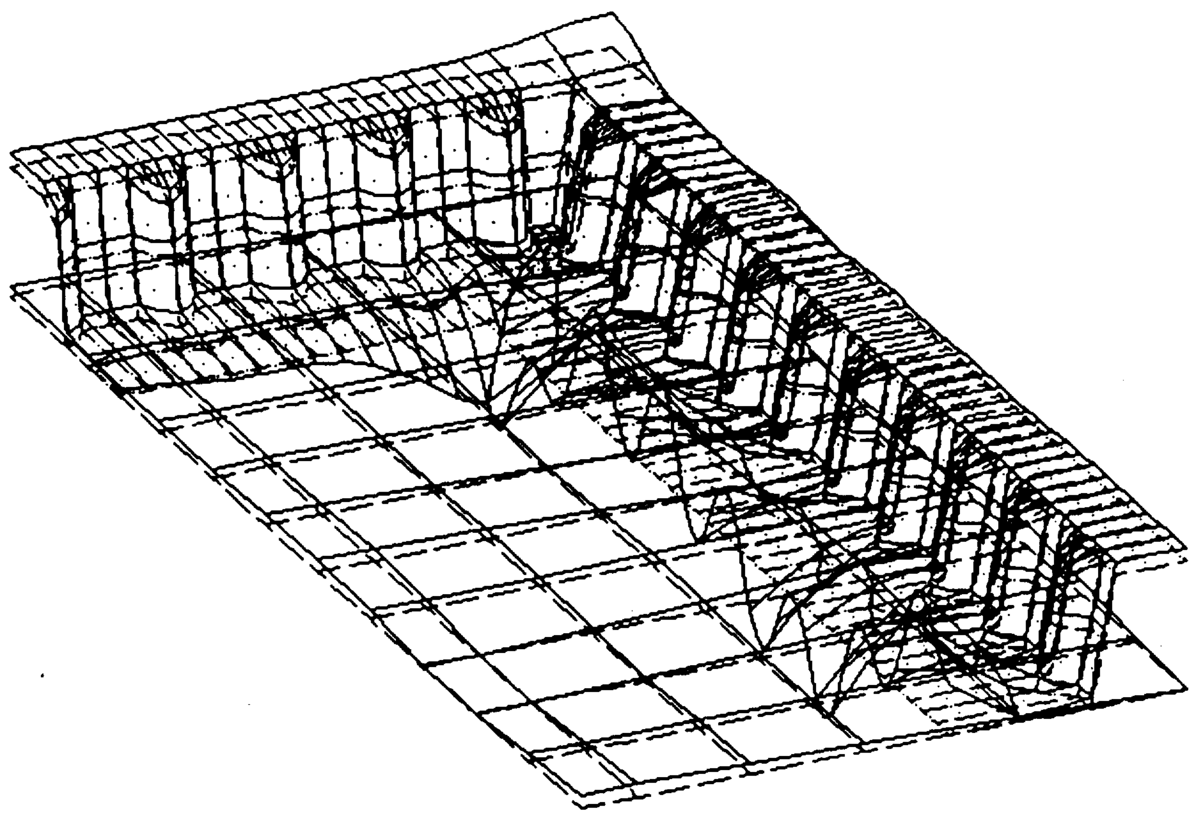


QUARTER SPF STRINGER/FRAME PANEL



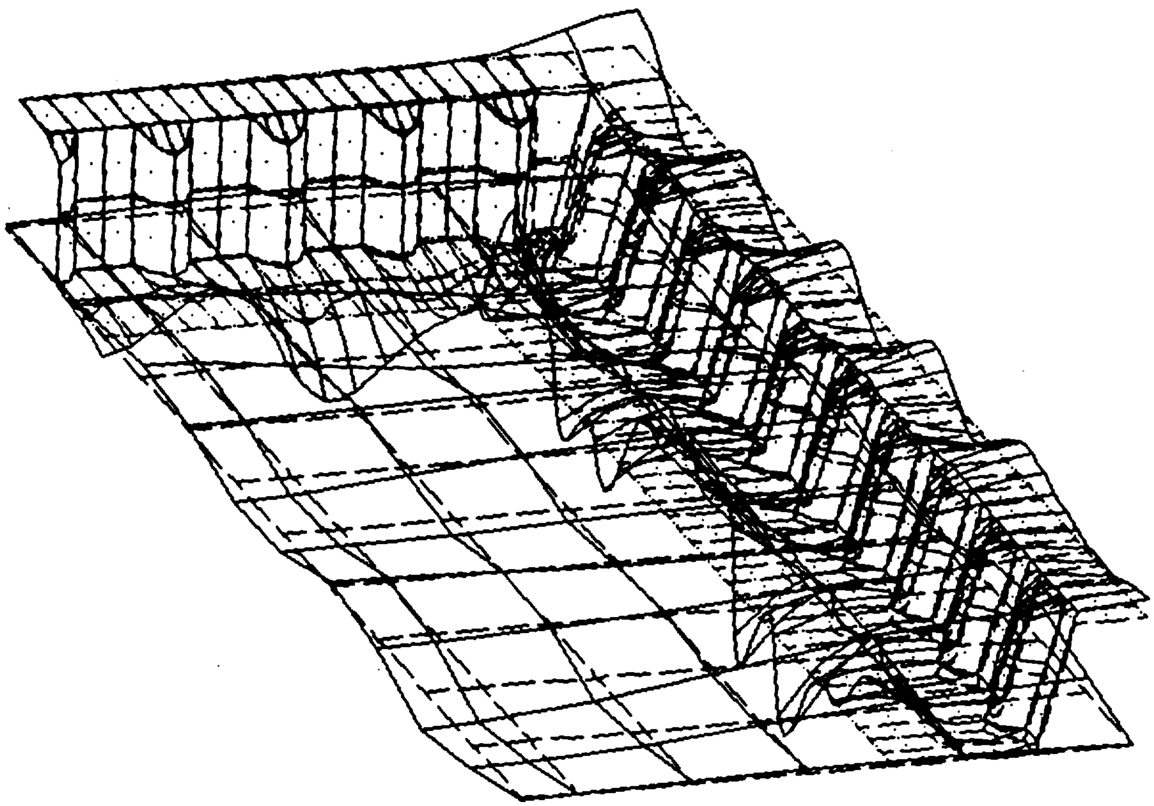
STRESS = 113,000 psi: LOAD = 32,000 kips

QUARTER SPF STRINGER/FRAME PANEL



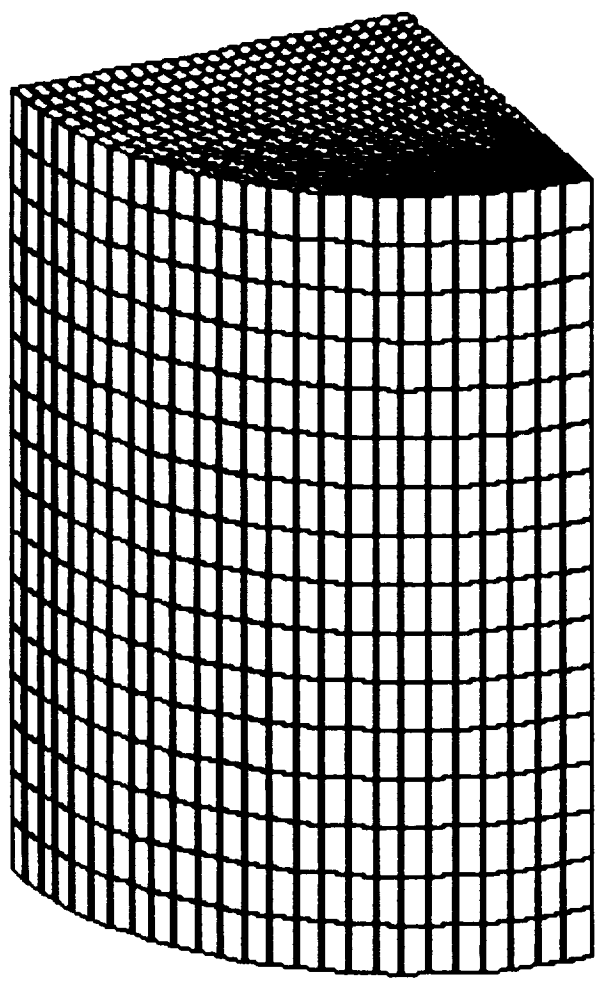
STRESS = 206,000 psi: LOAD = 58,000 kips

QUARTER SPF STRINGER/FRAME PANEL

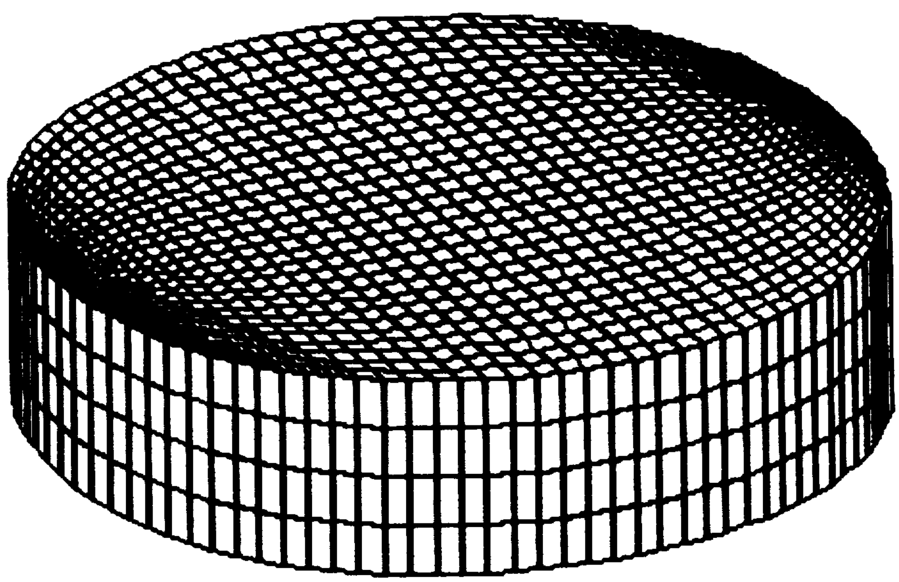


STRESS = 331,000 psi: LOAD = 94,000 kips

QUARTER WEDGE OF TANK



UPPER QUARTER OF TANK



N90-22663

Program 11 Experimental and Computational Study of the Viscoplastic Response of High Temperature Structures

E. A. Thornton, M. F. Coyle and J. D. Kolenski

Objectives

The basic objectives of the research program are to: (1) investigate thermoviscoplastic (TVP) response of thin panels subject to intense local heating, and (2) evaluate finite element thermal-structural analyses with TVP constitutive models by comparison with experimental data.

Experimental and Computational Studies of Thermoviscoplastic Panels

Earl A. Thornton
Marshall Coyle
J.D. Kolenski

Department of Mechanical and Aerospace Engineering

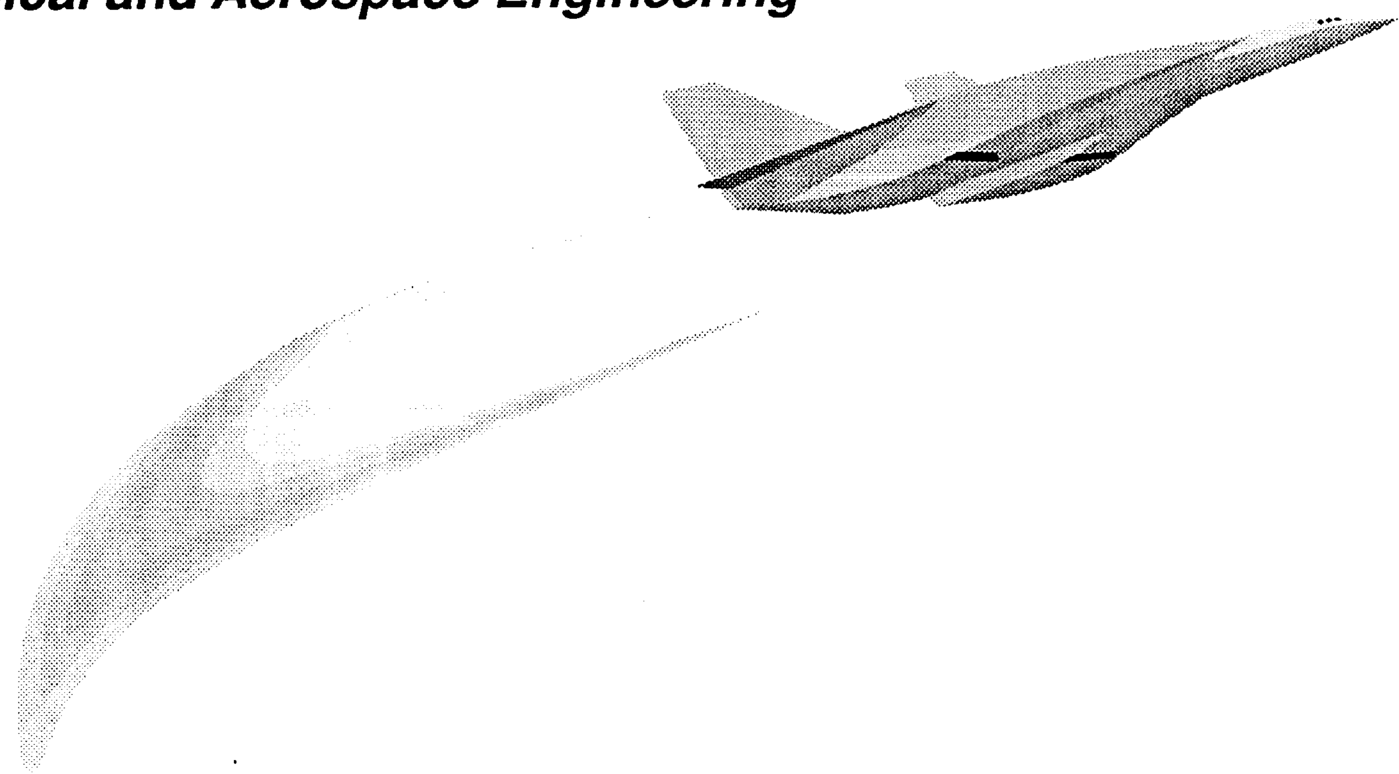
Abstract

The presentation will describe the first nine months of experimental and computational studies of the thermal-structural behavior of thin panels subjected to localized heating. Initial experimental studies have focused on developing an experimental set-up with well-defined thermal-structural boundary conditions. Preliminary tests with a "Heldenfels" panel have demonstrated out of plane bending (thermal buckling) due to panel initial imperfections. Initial computational studies have focused on: (1) validation of a thermoviscoplastic code to predict thermal stresses in the unbuckled panel, and (2) investigating in-plane stresses for test panels under transient thermal loading. Plans for future research are described in the presentation.

EXPERIMENTAL AND COMPUTATIONAL STUDIES OF THERMOVISCOPLASTIC PANELS

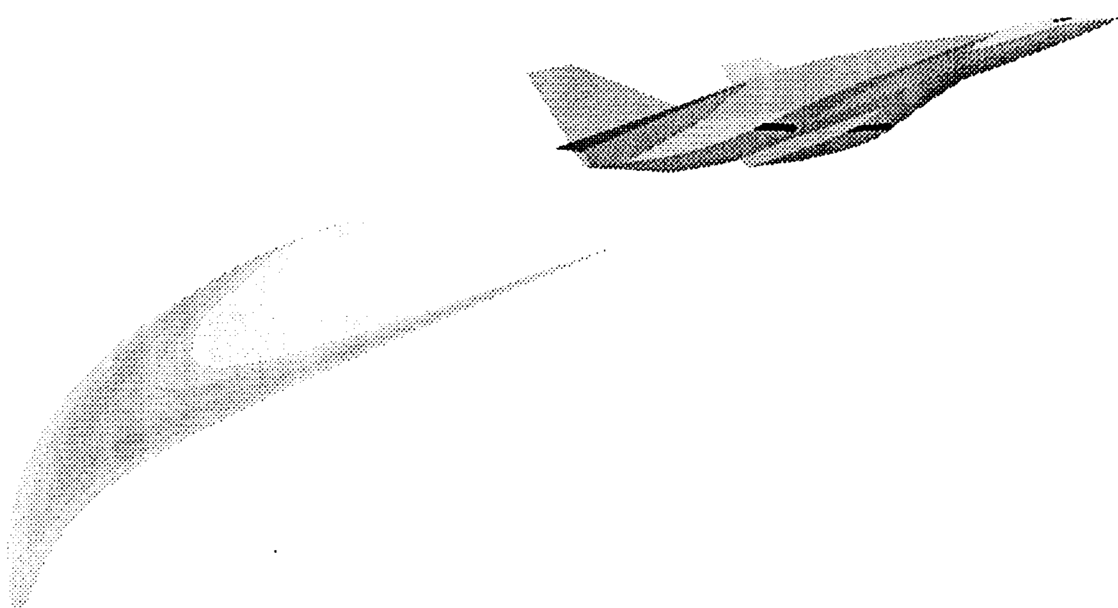
Earl A. Thornton
Marshall Coyle
J. D. Kolenski

Mechanical and Aerospace Engineering

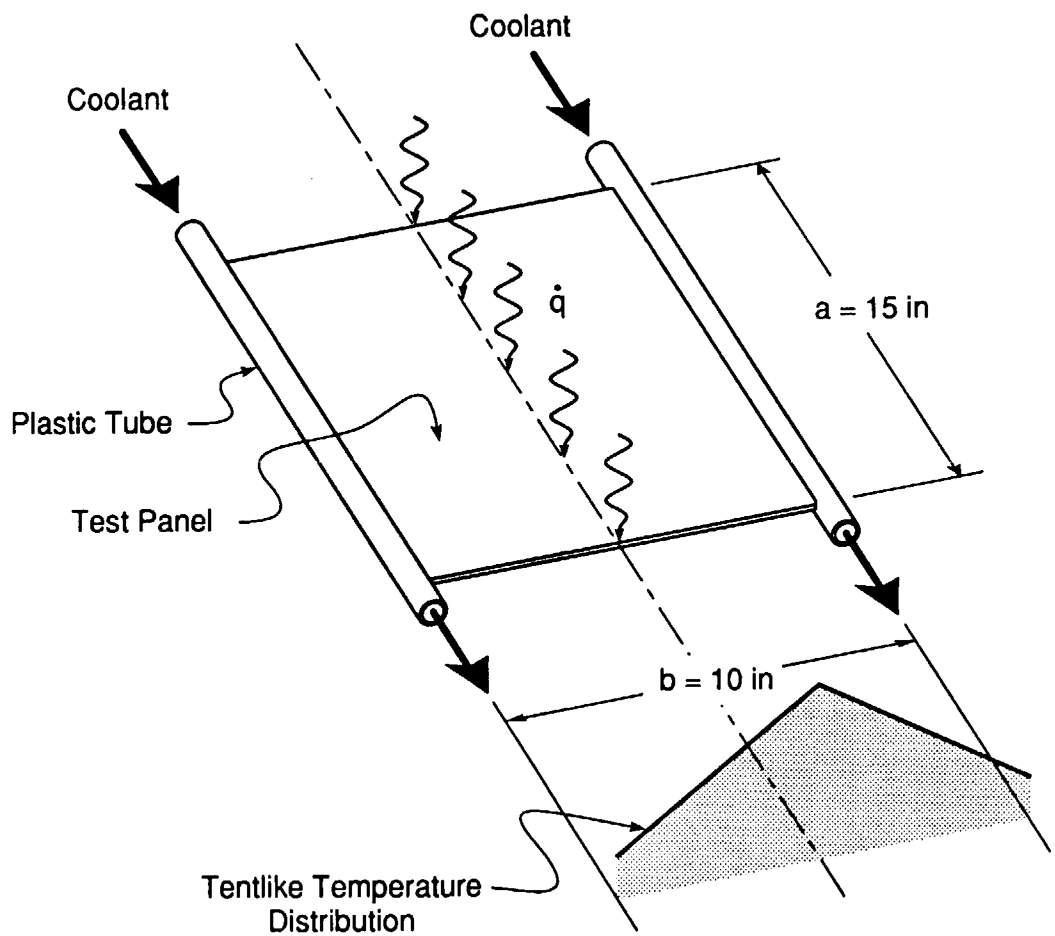


RESEARCH OBJECTIVES

- Investigate Thermoviscoplastic (TVP) response of thin panels subject to intense local heating.
- Evaluate finite element Thermal-Structural analyses with unified TVP constitutive models by comparison with experimental data.



HELDENFELS PROBLEM



EXPERIMENTAL PROGRAM

PHASE 1 - UNSUPPORTED "HELDENFELS" PANEL (304 SS)

OBJECTIVES:

- Evaluate Nichrome Wire Heating Technique
- Check out Coolant System
- Observe Qualitative Behavior of Panel

PHASE 2 - ENCLOSED SUPPORTED PANEL

OBJECTIVES:

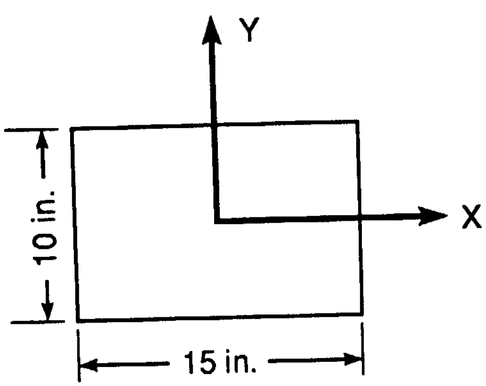
- Investigate Alternative Insulation Schemes
- Obtain Thermal Data
- Investigate Support System Design
- Install Data Acquisition System

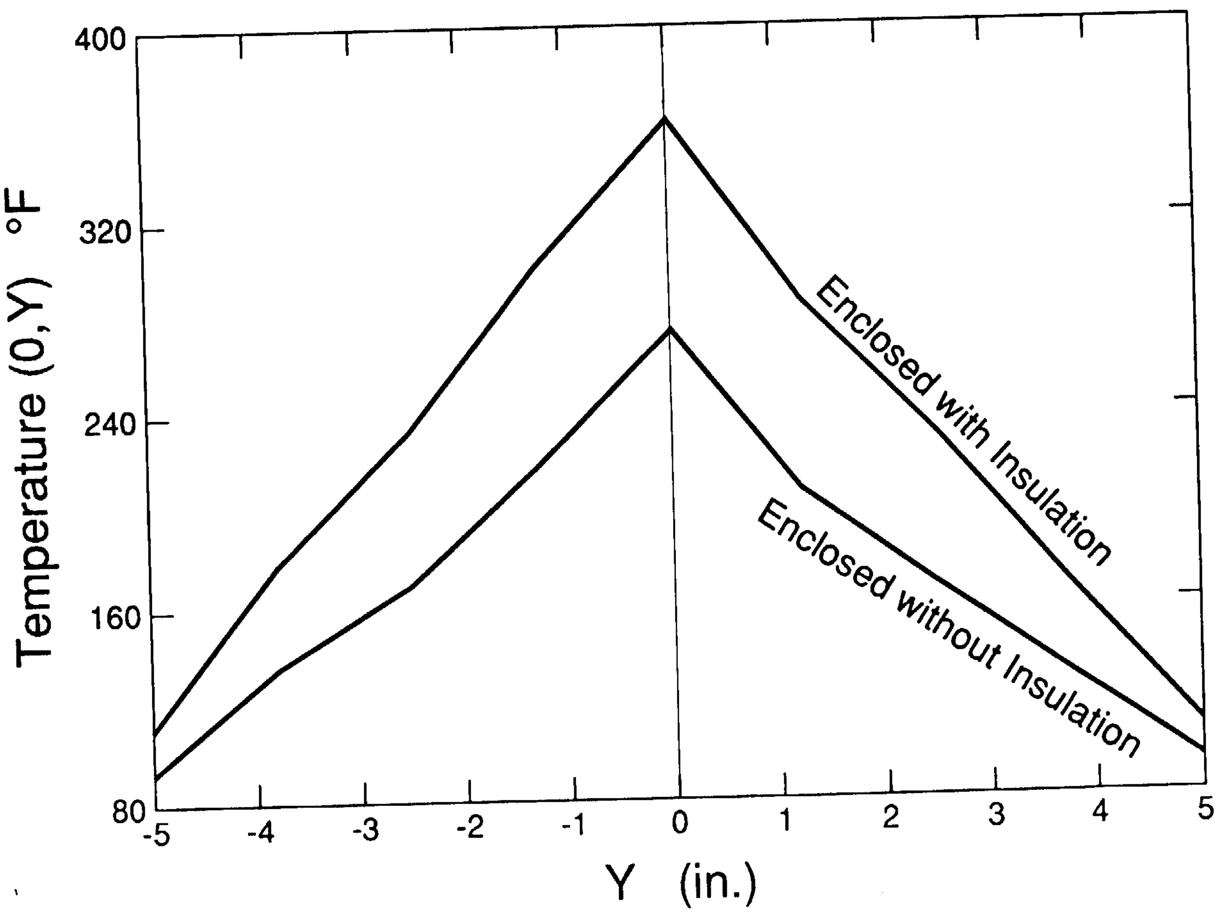
Color Slides Will Show The Experiments

INITIAL EXPERIMENTAL RESULTS

- WIRE HEATING
  - -Produces up to 20W/in.
  - -Limited to Panel Temperatures of 500° F by RTV
- CLOSED-LOOP CHILL WATER COOLING SYSTEM DESIRABLE
- PANEL DEMONSTRATES SIGNIFICANT BENDING
  - -Thickness Delta Temperature Less than 3° F
  - -Thermal Buckling due to Panel Initial Deflections
- HEAVY INSULATION REQUIRED FOR LINEAR TEMPERATURES
- TO TEST BARE PANEL, NEED TO MINIMIZE FREE CONVECTION

EXPERIMENTAL TEMPERATURES FOR TEST PANEL

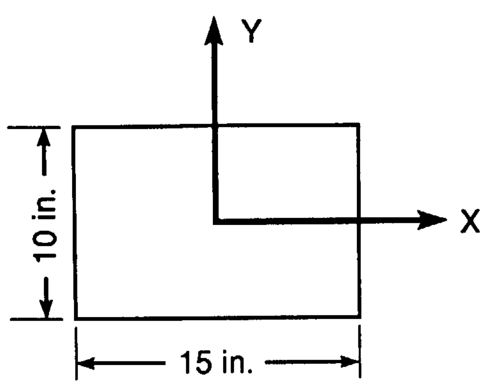


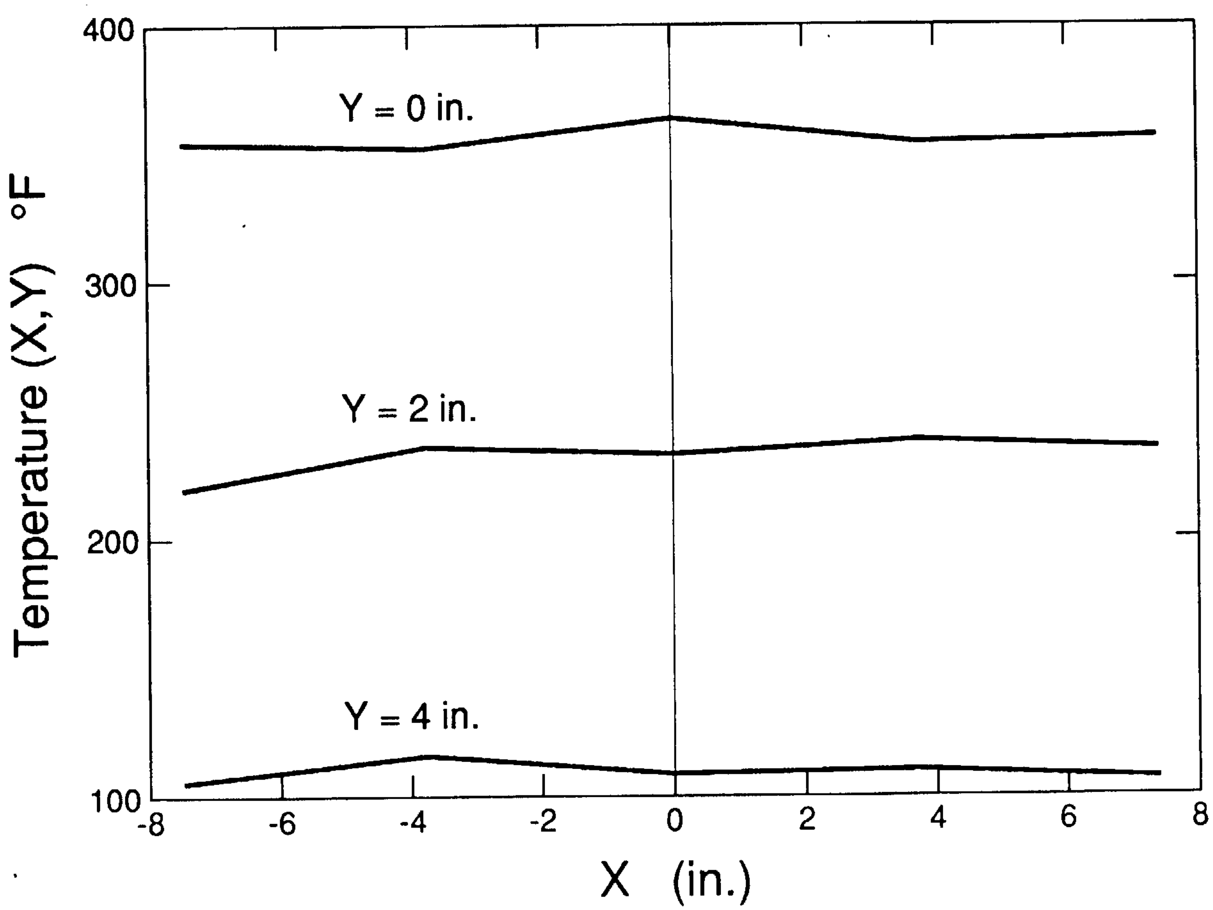


FUTURE RESEARCH PLANS

- MEASURE INITIAL DEFORMATIONS OF HASTELLOY-X
- INSTALL AND EVALUATE CHILL-WATER COOLANT SYSTEM
- INSTRUMENT HASTELLOY-X TEST PANEL
- BEGIN TESTS OF HASTELLOY-X PANEL

EXPERIMENTAL TEMPERATURES FOR INSULATED TEST PANEL



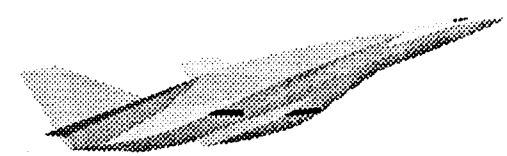


C-5

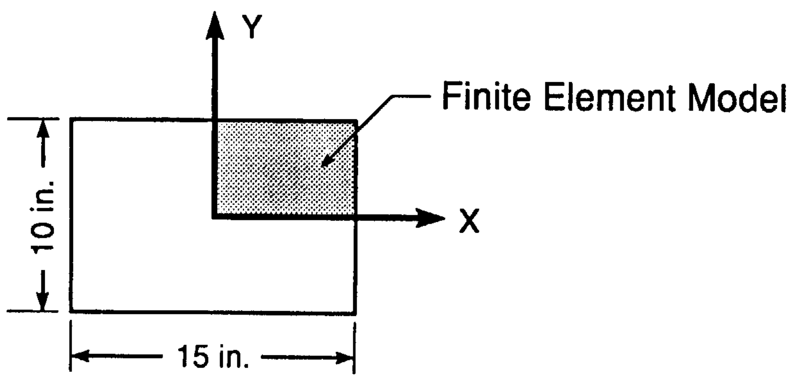
NP

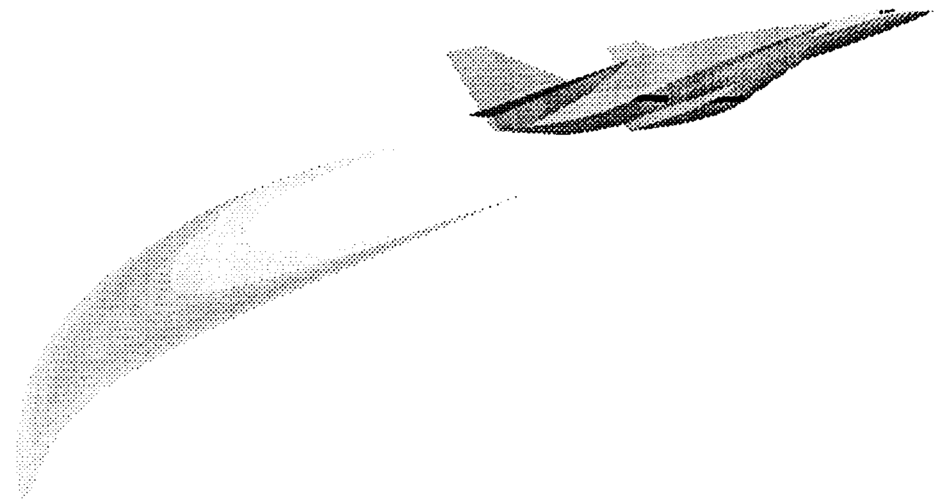
FINITE ELEMENT THERMOVISCOPLASTIC ANALYSIS

- ASSUMES QUASI-STATIC THERMAL STRESS BEHAVIOR
  - -Neglects Thermal-Mechanical Coupling in Energy Equation
  - -Neglects Inertia Forces in Equations of Motion
- ASSUMES PLANE STRESS
- USES BODNER-PARTOM CONSTITUTIVE MODEL
- IMPLEMENTS EQUATIONS IN RATE FORM AND USES TIME-MARCHING ALGORITHM (REFERENCE 3)
- USE QUADRILATERAL ELEMENTS



FINITE ELEMENT ELASTIC VALIDATION ANALYSIS

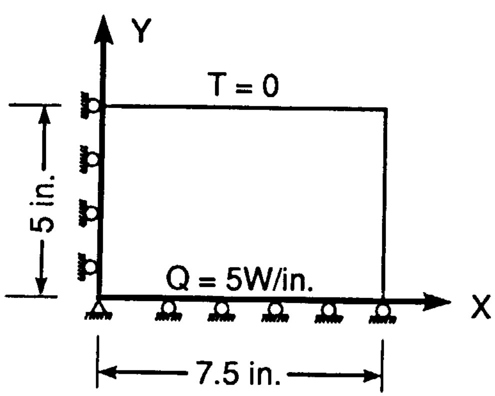




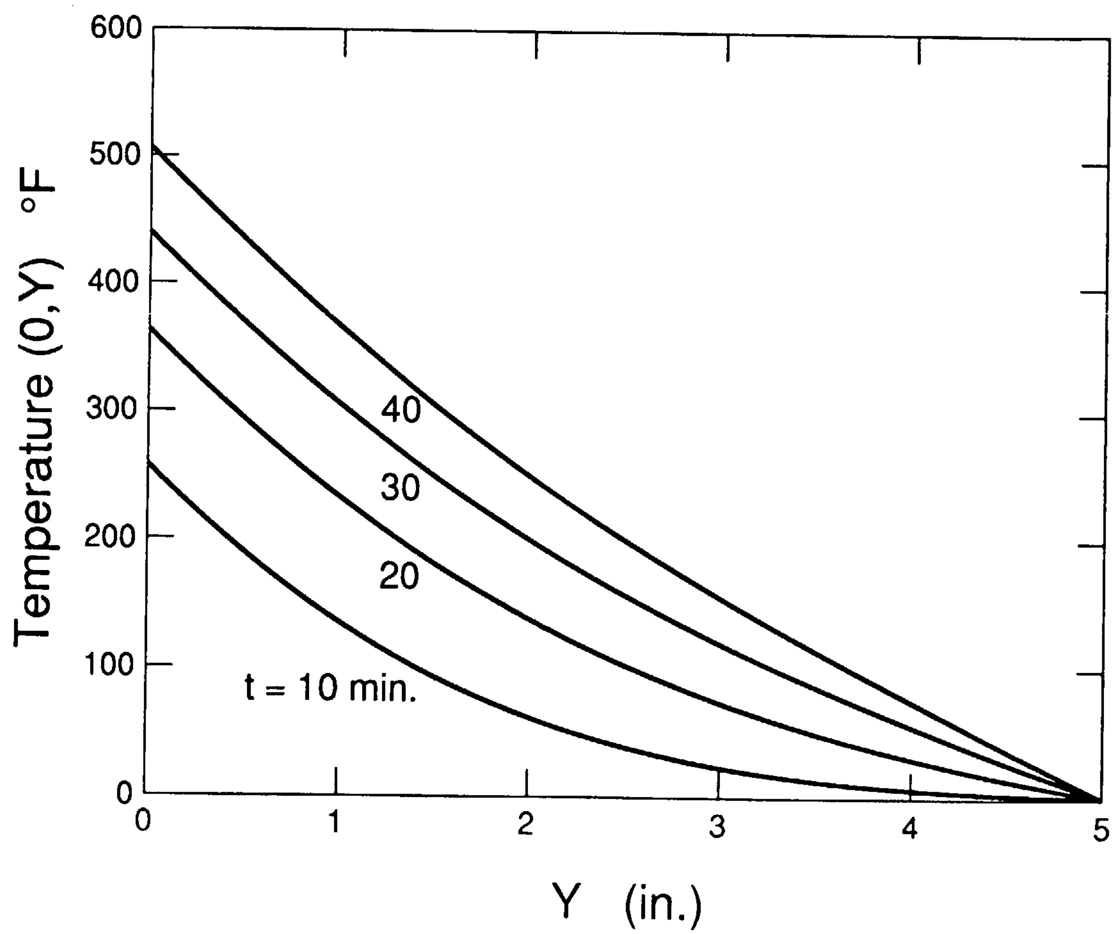
- USES 1D ANALYTICAL SOLUTION FOR T (Y,t)
- ASSUMES 1/4 SYMMETRY
- UNIFORM MESH - 176 nodes and 150 elements
- USES B1900 + Hf SUPERALLOY MATERIAL
- COMPARED RESULTS WITH COMMERCIAL *ANSYS* CODE

ELASTIC VALIDATION ANALYSIS

Boundary Conditions

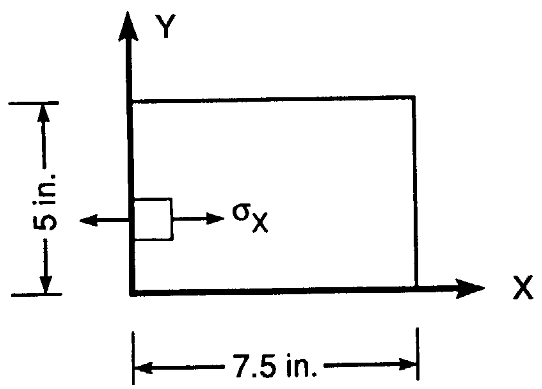


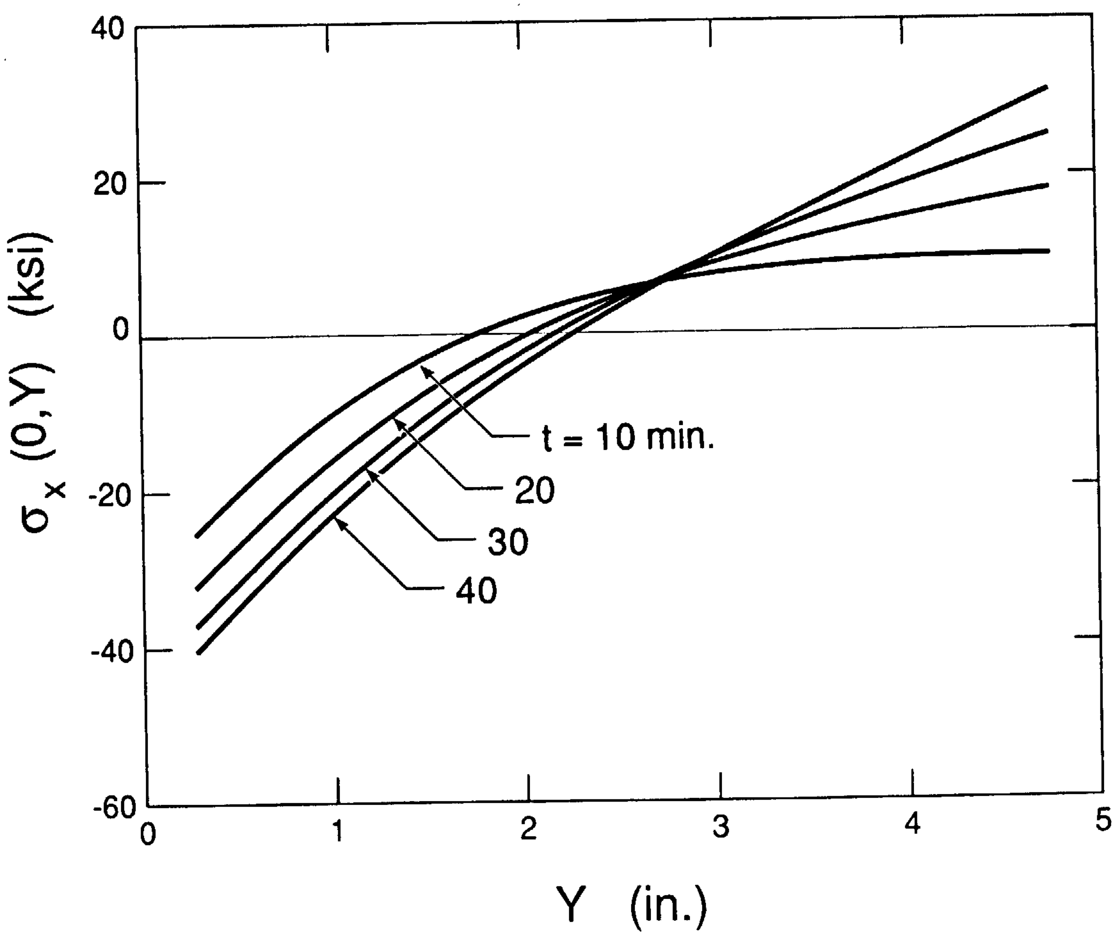
Analytical Solution



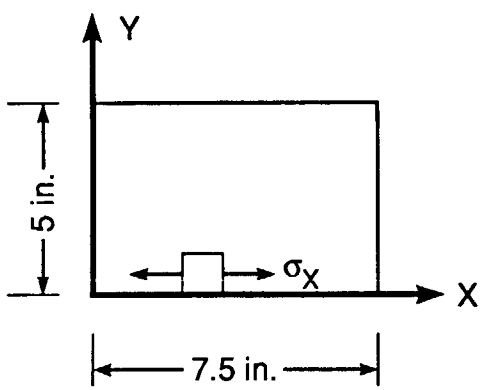
ELASTIC VALIDATION ANALYSIS

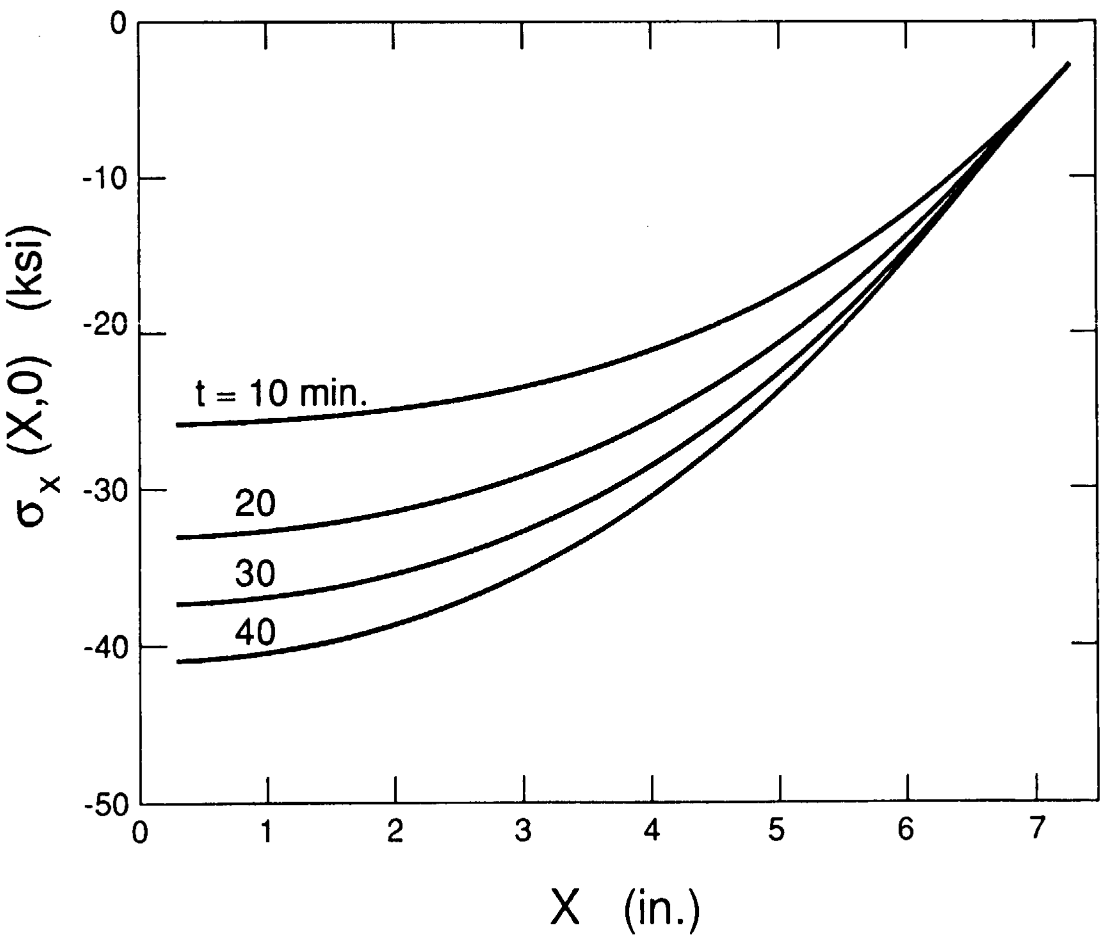
- Predicted Stresses Identical to ***ANSYS*** Results



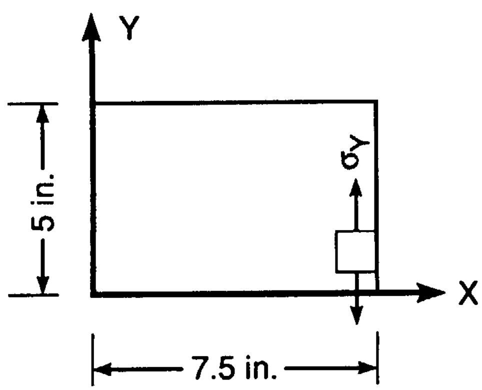


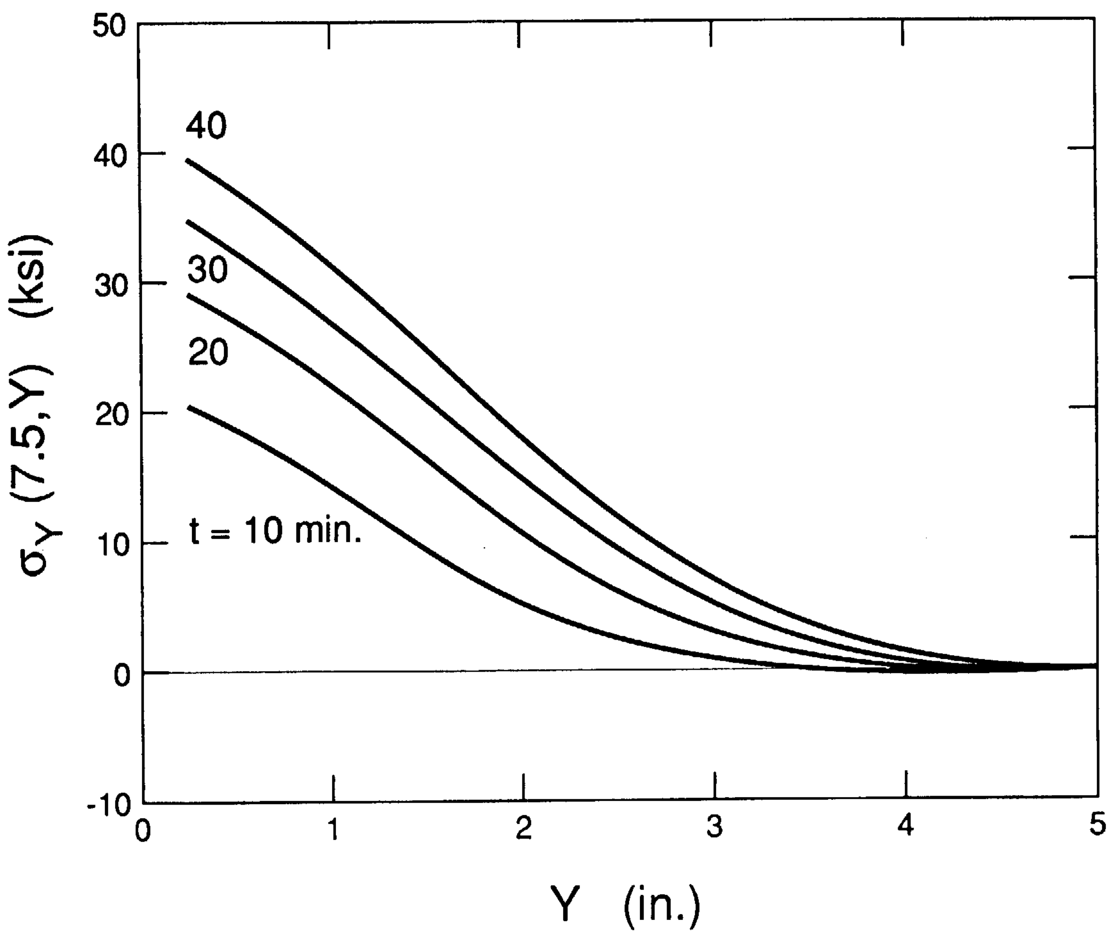
ELASTIC VALIDATION ANALYSIS



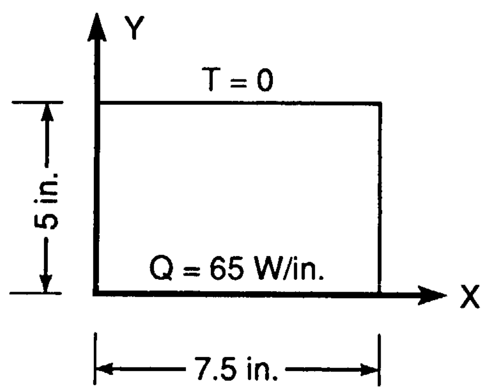


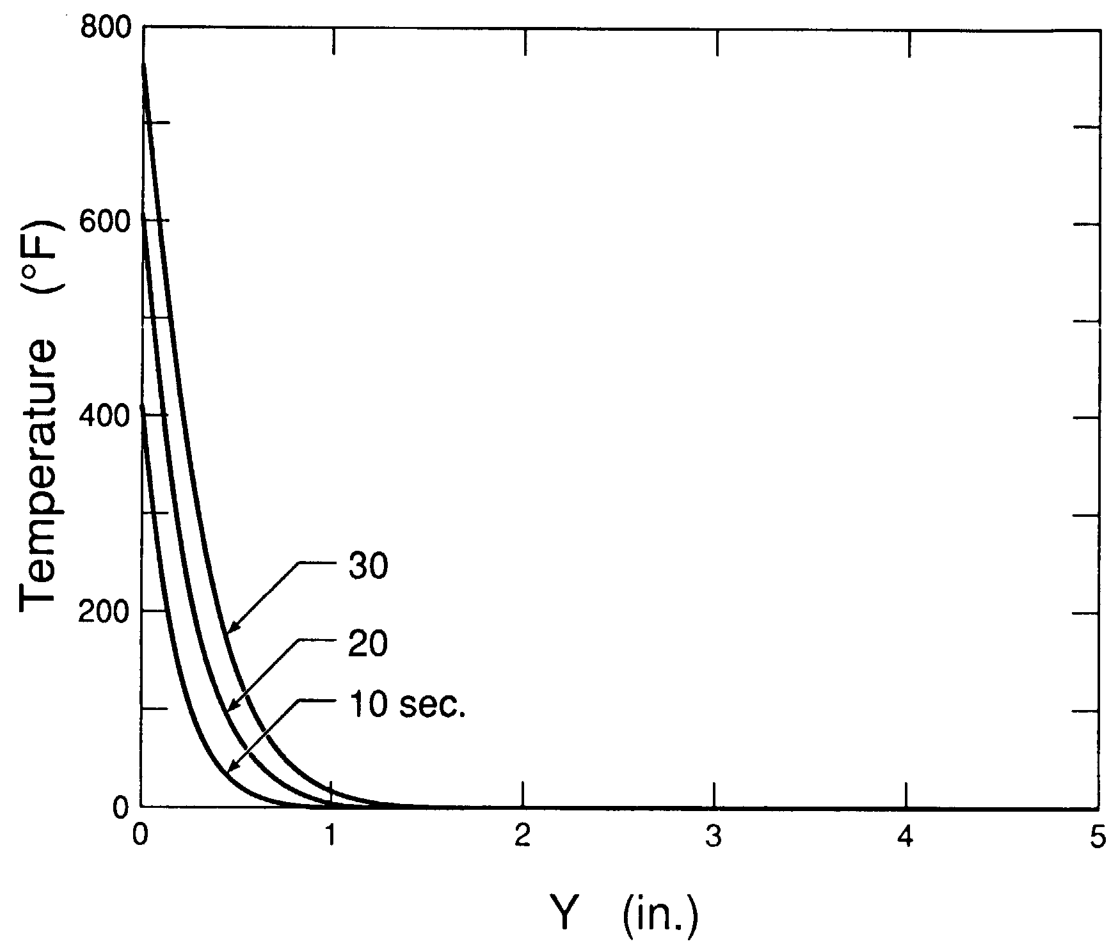
ELASTIC VALIDATION ANALYSIS





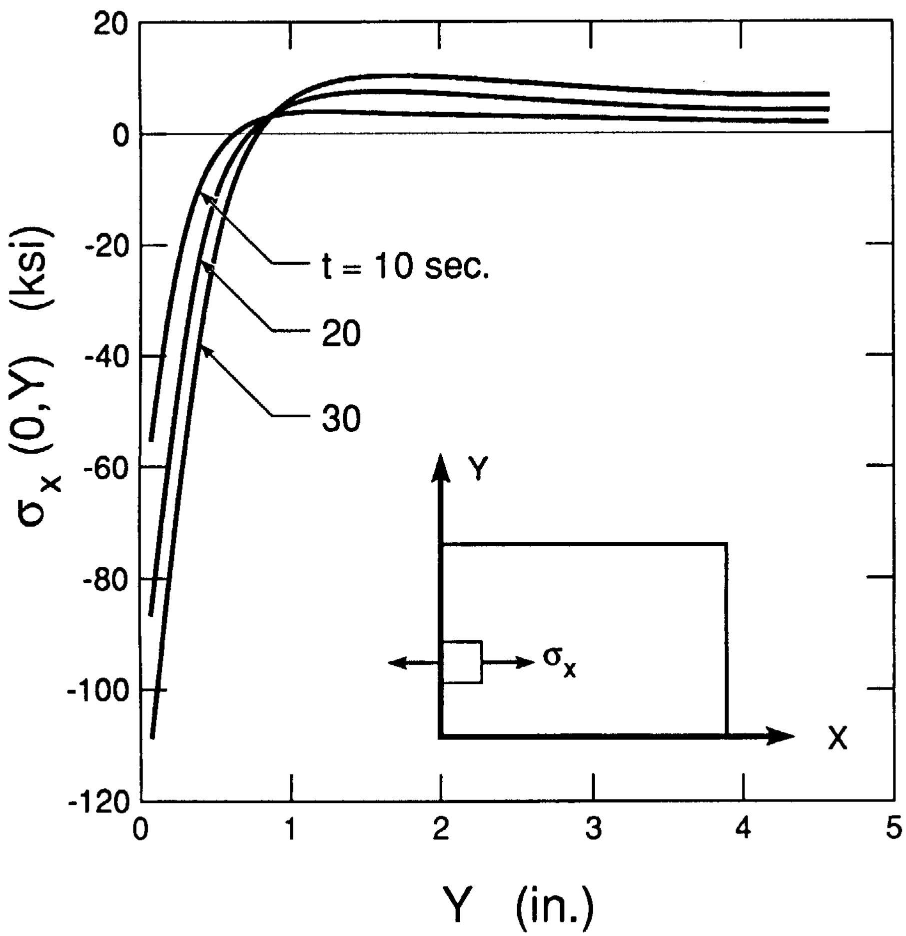
ELASTIC VS. VISCOPLASTIC RESPONSE FOR HIGH HEATING



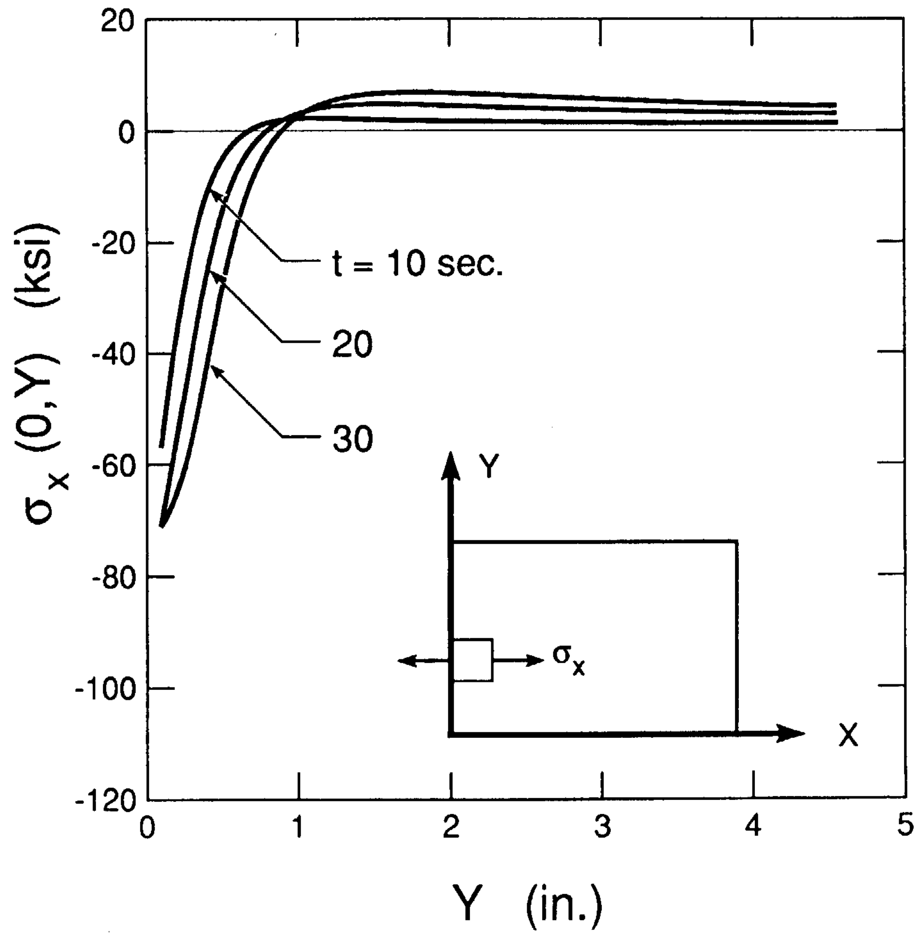


ELASTIC VS. VISCOPLASTIC RESPONSE

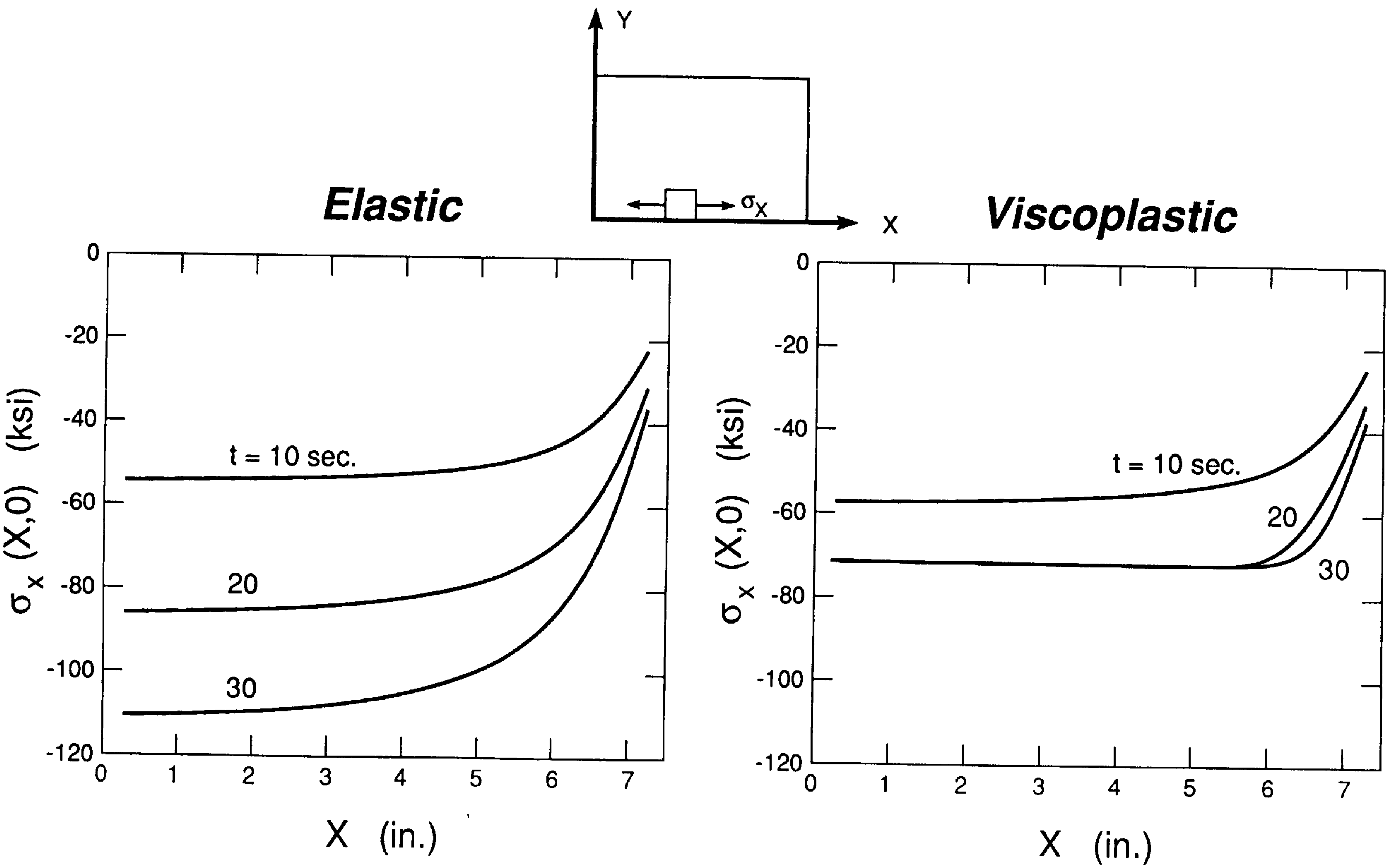
Elastic



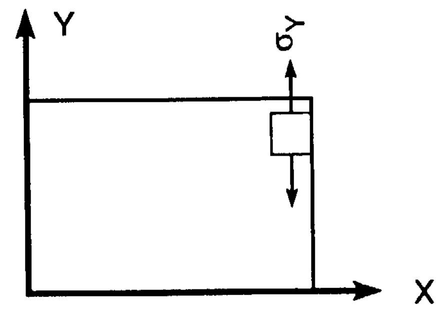
Viscoplastic



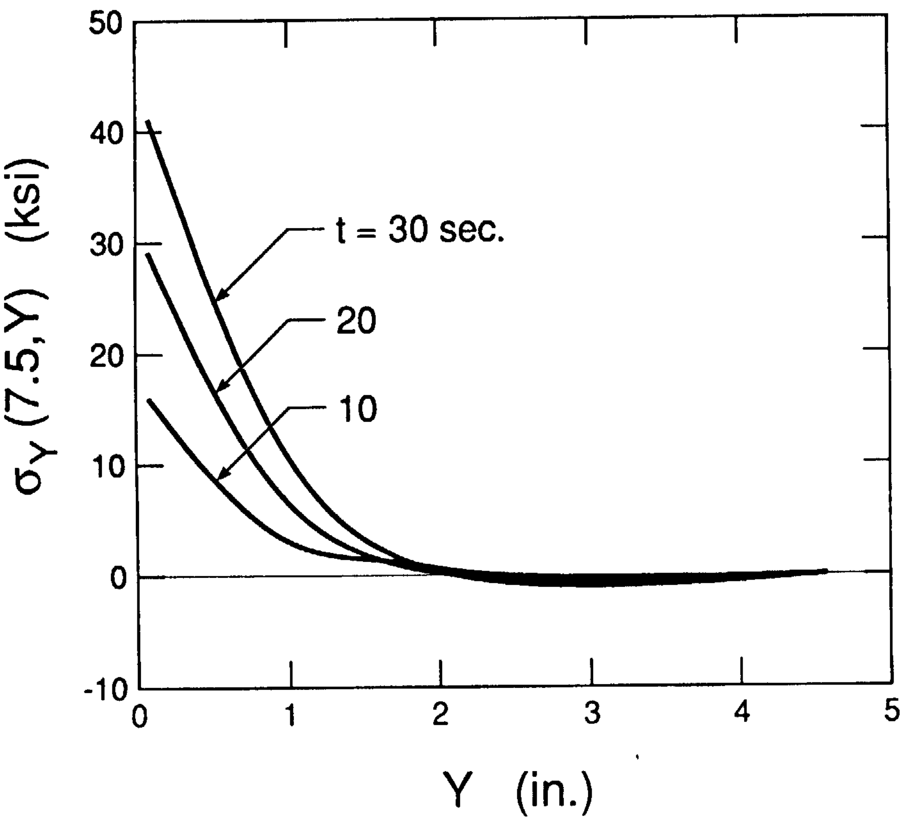
ELASTIC VS. VISCOPLASTIC RESPONSE



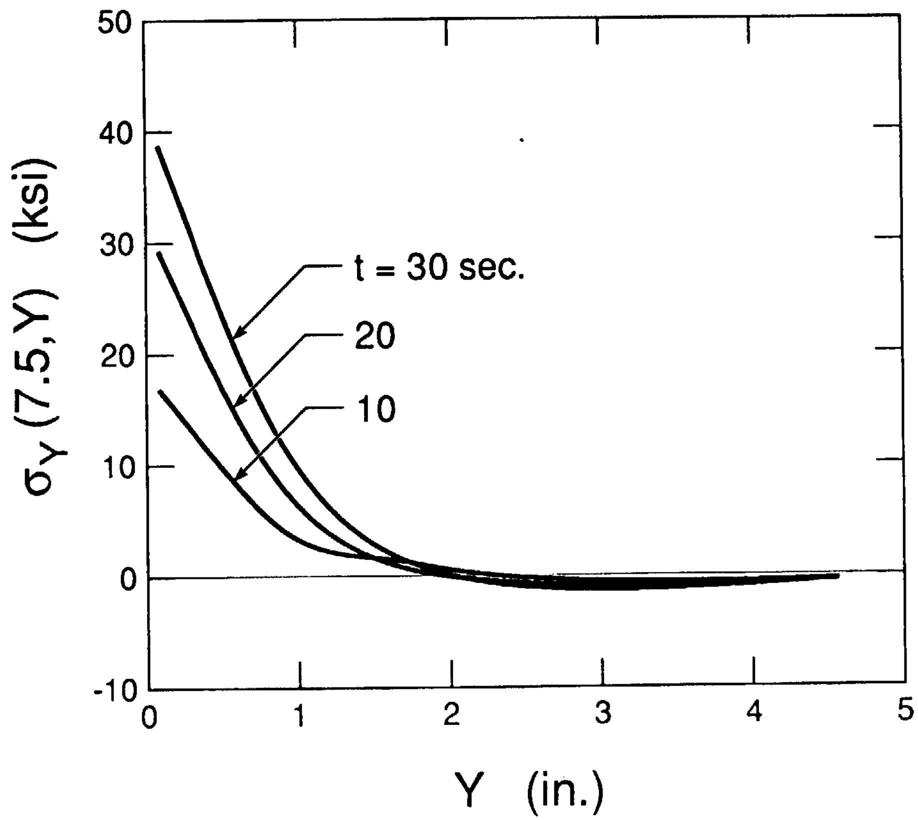
ELASTIC VS. VISCOPLASTIC RESPONSE



Elastic



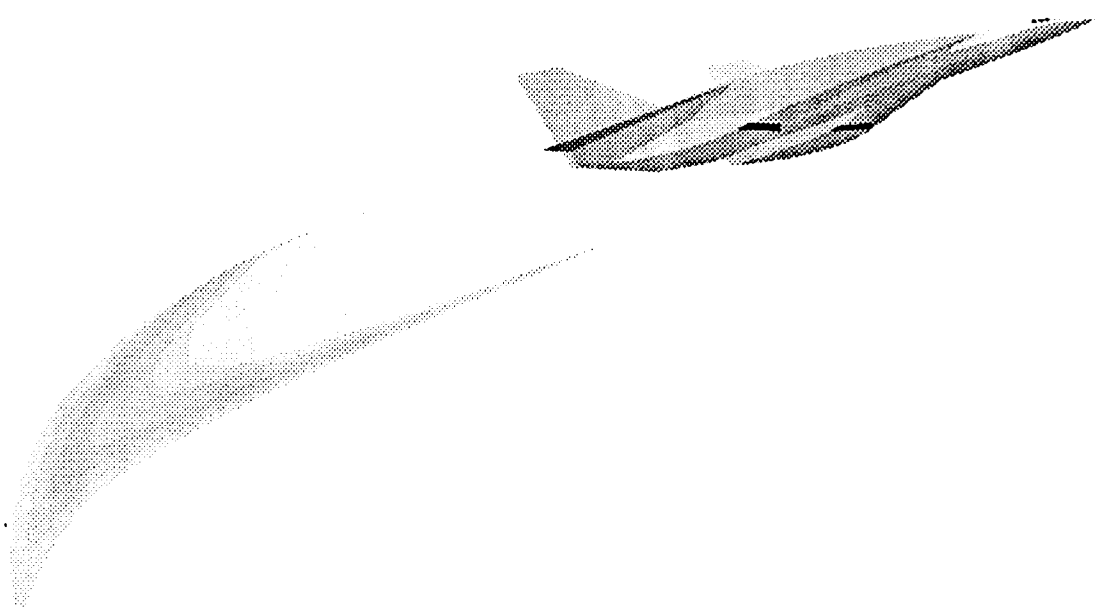
Viscoplastic



FUTURE RESEARCH

COMPUTATIONAL:

- INVESTIGATE QUASI-STATIC ASSUMPTION FOR TVP
- BEGIN DEVELOPMENT OF LARGE DEFLECTION, TVP, PLATE BENDING ANALYSIS



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1. Heldenfels, Richard R. and Roberts, William M.: "Experimental and Theoretical Determination of Thermal Stresses in a Flat Plate," NACA TN 2769, 1952.

2. Gossard, Myron L., Seide, Paul and Roberts, William M.: "Thermal Buckling of Plates," NACA TN 2771, 1952.

3. Thornton, Earl A., Oden, J. Tinsley, Tworzydlo, W. Woytek and Youn, Sung-Kie: "Thermo-Viscoplastic Analysis of Hypersonic Structures Subjected to Severe Aerodynamic Heating," AIAA 89-1226, 1989. To appear in the Journal of Aircraft.

APPENDIX I: GRANT PUBLICATIONS

1. R.P. Gangloff, "Hydrogen Effects on Fatigue Crack Propagation in Metals", in Proceedings Conference on Advanced Earth-To-Orbit Propulsion Technology, R.J. Richmond and S.T. Wu, eds., NASA, Marshall Space Flight Center, Huntsville, Alabama, in press (1990).[1]

2. R.P. Gangloff, R.S. Piascik, D.L. Dicus and J.C. Newman, "Fatigue Crack Propagation in Aerospace Aluminum Alloys", Proceedings 17th ICAS Congress, Royal Aeronautical Society, London, UK, in press (1990).

3. R.G. Buchheit, J.P. Moran and G.E. Stoner, "The Role of Hydrolysis in the Crevice Corrosion of Aluminum-Lithium-Copper Alloys", Corrosion '90, Paper No. 93, NACE, Houston, TX (1990).

4. C.T. Herakovich, J. Aboudi and J.L. Beuth, Jr., "A Micromechanical Composite Yield Model Accounting for Residual Stresses", Proceedings, IUTAM Symposium on Inelastic Behavior of Composite Materials, RPI, Troy, NY, May (1990).

5. J. Aboudi and M.-J. Pindera, "Matrix Mean-Field and Local-Field Approaches in the Analysis of Metal Matrix Composites", Proceedings, IUTAM Symposium on Inelastic Behavior of Composite Materials, RPI, Troy, NY, May (1990).

[1] This research was predominantly supported by R.G. Forman of the L.B. Johnson Space Flight Center, Houston, Texas.

APPENDIX II: GRANT PRESENTATIONS

1. R.P. Gangloff, "Environmental Fatigue Crack Propagation in Al-Li-Cu Alloys", Department of Materials Science, University of California, Berkeley, CA, April, 1990.

2. R.S. Piascik and R.P. Gangloff, "Environmental Fatigue Crack Propagation in Al-Li-Cu Alloys", Corrosion/90, NACE, Las Vegas, NV, April, 1990.

3. R.P. Gangloff, "Hydrogen Effects on Fatigue Crack Propagation in Metals", Conference on Advanced Earth-To-Orbit Propulsion Technology, Huntsville, AL, May, 1990.

4. R.S. Piascik, "Mechanisms of Corrosion Fatigue Crack Propagation: Al-Li-Cu System", Advanced Aerospace Materials and Processes Conference, Long Beach, CA, May, 1990.

5. D.B. Gundel and F.E. Wawner, " Investigation of the Reaction Kinetics Between SiC Fibers and Selectively Alloyed Titanium Matrices", 14th Annual Conference on composite Materials and Advanced Structures, Cocoa Beach, FL, January, 1990.

6. F.E. Wawner and D.B. Gundel, "Investigation of Reaction Kinetics and Interfacial Phase Formation in Ti_3Al + Nb Composites", Titanium Aluminide Composite Workshop, Orlando, FL, May, 1990.

7. D.B. Gundel and F.E. Wawner, "Investigation of the REaction Kinetics Between SiC Fibers and Selectively Alloyed Titanium Matrix Composites", Advanced Aerospace Materials and Processes Conference, Long Beach, CA, May, 1990.

8. R.G. Buchheit, J.P. Moran and G.E. Stoner, "The Role of Hydrolysis in the Crevice Corrosion of Aluminum-Lithium-Copper Alloys", Corrosion/90, NACE, Las Vegas, NV, April, 1990.

9. J.P. Moran, R.G. Buchheit and G.E. Stoner, "The Effects of Bulk and Local Solution Chemistries on the SCC Behavior of Alloy 2090 (Al-Li-Cu)", Research Symposium, Corrosion/90, NACE, Las Vegas, NV, April, 1990.

<u>APPENDIX III: ABSTRACTS OF GRANT PUBLICATIONS</u>

HYDROGEN ENVIRONMENT ENHANCED FATIGUE CRACK PROPAGATION IN METALS[1]

RICHARD P. GANGLOFF[2]

Abstract

Fracture mechanics-based methods for damage tolerant fatigue life prediction do not adequately describe the deleterious effect of the surrounding environment. Such analyses are complicated by the time dependence of crack growth rates (da/dN), by a multitude of important variables and by compromises of ΔK similitude. Gases and electrolytes which produce hydrogen by reactions with crack surfaces enhance da/dN in aerospace iron, aluminum and nickel-based alloys. Environment causes time-dependent cracking above the sustained load threshold (K_{ISCC}) and cycle-time-dependent cracking below K_{ISCC} where cyclic deformation is uniquely damaging. Crack growth in superalloys in elevated temperature oxidizing air is phenomenologically similar to low temperature hydrogen environment fatigue. The magnitude of the hydrogen environment effect on da/dN depends on environment activity (gas pressure, temperature and electrode potential); ΔK, waveform and mean level; loading frequency and hold time; and alloy composition, microstructure and σ_{ys}. Models for da/dN-ΔK are developed based on linear superposition, empirical curve fitting, and chemical damage mechanisms. With additional cited research, hydrogen effects can be incorporated into existing fatigue life prediction codes such as NASA FLAGRO.

Introduction

The fracture mechanics approach to damage tolerant control of fatigue crack propagation employs laboratory data on crack growth rate (da/dN) versus stress intensity range ($\Delta K = K_{max} - K_{min}$) for quantitative predictions of component life through the similitude concept suggested by Paris and coworkers[1]. Over the past 15 years, the method has been advanced to account for near-threshold fatigue cracking[2], small crack effects[3], crack closure[4], spectrum loading[5] and the behavior of anisotropic advanced materials[6]. This method has been successfully incorporated into computerized life prediction codes for aerospace components[7-10]; however such work has focused on fatigue in moist air.

Environment, particularly when capable of producing atomic hydrogen through reactions with a metal, deleteriously affects rates of fatigue crack propagation in most structural alloys[11-18]. The application of fracture mechanics to environmental fatigue crack propagation has progressed over the past 25 years[19]. Notable advances include: (a) the demonstration of ΔK similitude[20], (b) developments of experimental methods[21], (c) characterizations of da/dN-ΔK[11], (d) identification of crack closure and small crack-environment interactions[2,3], (e) scientific studies of mechanisms[19] and (f) life prediction methods for energy systems[22,23]. Hydrogen environment effects have not, however, been systematically incorporated into life prediction methods for aerospace components.

Two factors hinder quantitative life prediction to control environmental fatigue crack propagation

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[1]This work is conducted in collaboration with R.G. Forman of the L.B. Johnson Space Flight Center under contract LESC-SOW-N-2584.

[2]Professor, Department of Materials Science, School of Engineering and Applied Science, Thornton Hall, University of Virginia, Charlottesville, VA, 22903.

In: Proceedings Conference on Advanced Earth-To-Orbit Propulsion Technology, R.J. Richmond and S.T. Wu, eds., NASA, Marshall Space Flight Center, Huntsville, Alabama, in press (1990).

FATIGUE CRACK PROPAGATION IN AEROSPACE ALUMINUM ALLOYS

R.P. Gangloff[1], R.S. Piascik[2], D.L. Dicus[3] and J.C. Newman, Jr.[4]

Abstract

This paper reviews fracture mechanics based, damage tolerant characterizations and predictions of fatigue crack growth in aerospace aluminum alloys. The results of laboratory experimentation and modeling are summarized in the areas of: (a) fatigue crack closure, (b) the wide range crack growth rate response of conventional aluminum alloys, (c) the fatigue behavior of advanced monolithic aluminum alloys and metal matrix composites, (d) the short crack problem, (e) environmental fatigue and (f) variable amplitude loading. Remaining uncertainties and necessary research are identified. This work provides a foundation for the development of fatigue resistant alloys and composites, next generation life prediction codes for new structural designs and extreme environments, and to counter the problem of aging components.

I. Introduction

The fracture mechanics approach to fatigue crack propagation quantitatively couples laboratory studies on alloy performance and fatigue mechanisms with damage tolerant life prediction methods through the concept of growth rate similitude. This method, illustrated in Figure 1, is traceable to the seminal results of Paris and coworkers for the case of moist air environments[1] and is outlined in current textbooks[2]. Subcritical fatigue crack propagation is measured in precracked laboratory specimens according to standardized methods[3]. Crack length (a) versus load cycles (N) data are analyzed to yield a material property; averaged fatigue crack growth rate (da/dN) as a function of the applied stress intensity range, ΔK. ΔK is the difference between maximum (K_{max}) and minimum (K_{min}) stress intensity values during a load cycle. Paris experimentally demonstrated the principle of similitude; that is, equal fatigue crack growth rates are produced for equal applied stress intensity ranges, independent of load, crack size and component or specimen geometry[1]. Wei and coworkers extended this concept to describe corrosion fatigue crack propagation in aggressive gas and liquid environments[4].

The similitude principle enables an integration of laboratory da/dN-ΔK data to predict component fatigue

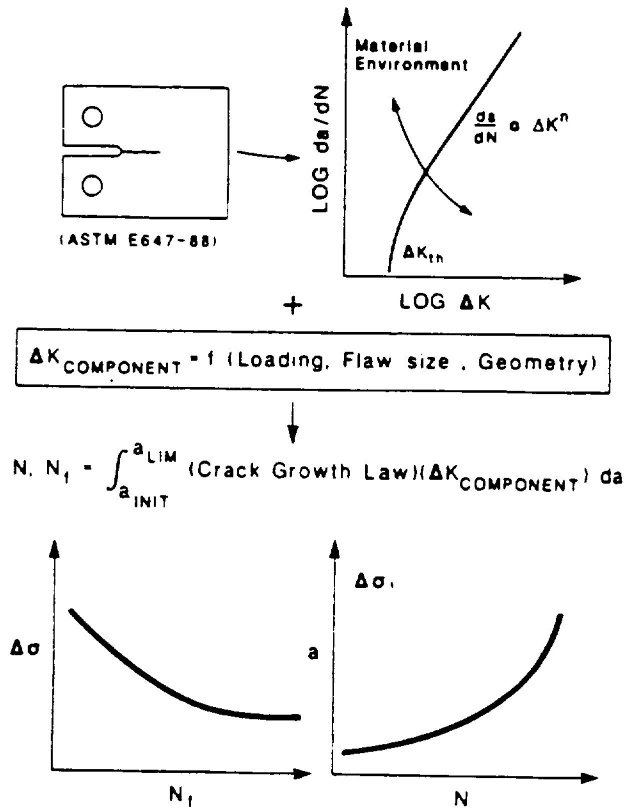

Figure 1. *Fracture mechanics approach to fatigue crack growth: material characterization and component life prediction.*

behavior, in terms of either applied stress range ($\Delta\sigma$) versus total life (N_f) or crack length (a) versus load cycles (N), for any initial defect size and component configuration. These calculations require component loading and stress analyses, initial crack size and shape, and a component stress intensity solution. This method has been developed for complex structural applications in the energy, petrochemical and

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3 Metallic Materials Branch, Materials Division, NASA Langley Research Center, Hampton, VA, 23665.

4 Mechanics of Materials Branch, Materials Division, NASA Langley Research Center, Hampton, VA, 23665.

IN: *Proceedings 17th ICAS Congress, Royal Aeronautical Society, London, UK, in press (1990).*

THE ROLE OF HYDROLYSIS IN THE CREVICE CORROSION OF ALUMINUM-LITHIUM-COPPER ALLOYS

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Department of Materials Science
University of Virginia
CHarlottesville, VA 22901

ABSTRACT

The hydrolytic behavior of cations plays an important role in the crevice corrosion of aluminum and its alloys. Hydrolysis equilibrium reactions can either consume or produce H^+ thereby altering pH. An external cathode electrolytically coupled to a crevice can also influence the pH developed in a crevice. In this study, simulated crevice experiments were performed with pure aluminum, solution heat treated (SHT) Al-3Li and SHT Al-3Cu to determine the effects of Al^{3+}, Li^+ and Cu^{2+} hydrolysis on steady state pH. Simulated crevice experiments were carried out with aerated bulk solutions, deaerated bulk solutions and with no bulk solution to determine the effect of a remote cathode on the steady state pH response. The pH response was interpreted in terms of distribution diagrams constructed from formation quotients and mass action equations for the appropriate hydrolysis products. Finally, the results of the above experiments were used to assess the roles of hydrolysis and the external cathode in determining the steady state pH measured in the ternary alloy Al-3Cu-2Li (AA 2090). In all experiments crevice acidification occurred when the bulk solution was aerated. When the bulk solution was deaerated or when no bulk solution was present a mildly alkaline crevice pH developed. Analysis of distribution diagrams shows that Al^{3+} hydrolysis can generate an acidic to neutral crevice solution. Lithium hydrolysis does not occur until a pH of 11 and is not an important process at the pH values observed here. However,lithium dissolution can assist in generating mild alkalinity. Evidence also suggests that some Cu^{2+} hydrolysis occurs contributing to the alkaline pH observed for isolated crevice in SHT Al-3Cu and SHT 2090.

A Micromechanical Composite Yield Model Accounting for Residual Stresses

C. T. Herakovich, J. Aboudi[1] and J. L. Beuth, Jr.
Civil Engineering Department
University of Virginia
Charlottesville, VA 22903

Abstract

An analytical micromechanical model is used to predict yielding in continuous-fiber unidirectional metal-matrix composite materials. The von Mises criterion is used to predict yielding of the composite matrix based on (1) the average stresses in the matrix, and (2) the largest of the average stresses in each of the modelled matrix subcells. Two-dimensional yield surfaces are generated under thermomechanical loading conditions for two metal matrix composites, boron/aluminum and silicon carbide/titanium. Results indicate that, depending on the material, temperature excursions typically experienced in processing may cause matrix yielding at zero far-field applied stress. The analysis shows that thermal stresses distort and shift the yield surface based upon subcell stresses. Thus the importance of micromechanics is demonstrated.

1. Introduction

The ability to use metal matrix composites at high temperatures is one of their important advantages over resin matrix composites. Since the metal matrix is an elastoplastic material, it appears that the prediction of the overall yield surface of the composite is a fundamental step toward the study of its behavior. Yielding of the composite is caused by the yielding of its metal matrix. The prediction of the initial yield surfaces of metal matrix composite in the absence of thermal effects was presented by Pindera and Aboudi (1988). It was shown that yield surfaces generated on the basis of the average matrix behavior generally underestimate initial yielding as compared with predictions based on local matrix stresses and that the results obtained on the basis of local matrix stresses correlate very well with finite element predictions of Dvorak et al (1973). The approach presented by Pindera and Aboudi (1988) is based on the micromechanical model of periodic array of fibers which was recently reviewed by Aboudi (1989). This micromechanical approach is analytical and requires minimal computational effort, while offering the ability to model generalized

[1]Visiting from Tel Aviv University, Tel Aviv, Israel

Presented at the IUTAM Symposium, Troy, NY, May, 1990 and published in the proceedings of the IUTAM Symposium on Inelastic Behavior of Composite Materials.

Matrix Mean-Field and Local-Field Approaches in the Analysis of Metal Matrix Composites

Jacob Aboudi[1]

Marek-Jerzy Pindera[2]

Abstract

A micromechanical investigation of the inelastic response of metal matrix composites analyzed by two different methodologies is presented. The first method is based on the mean stress field in the entire ductile matrix phase, while the second one is based on the local stress field. The present study is a continuation of a previous investigation in which a micromechanics model based on a periodic array of fibers was employed to generate yield surfaces of metal matrix composites using local and mean matrix stresses. In this paper, we extend the aforementioned analysis to the prediction of the inelastic stress-strain response of metal matrix composites subjected to different loading histories. Results for the overall elastoplastic response of the investigated metal matrix composites indicate that the mean-field approach may lead to significant deviations of the effective composite behavior as compared either to finite element results or measured data. The predictions of the effective composite response generated by the two approaches are compared with experimental and numerical data on unidirectional boron/aluminum and graphite/aluminum.

Introduction

In a previous investigation, Pindera and Aboudi (1988) discussed the use of average matrix stress in determining initial yield surfaces of metal matrix composites. Specifically, the micromechanics model proposed by Aboudi (1986) was employed to generate initial yield surfaces of unidirectional and multidirectional (cross-ply) boron/aluminum laminates under a variety of loading conditions using two different approaches. In the first approach, overall yielding of

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