



LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Laminated Metal Composites (LMC) for Aerospace Application Final Report CRADA No. TC-169-91

D. Lesuer, R. Bush, C. Musson, D. Alexander, B.
Norris, A. Lee

March 14, 2018

Disclaimer

This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor Lawrence Livermore National Security, LLC, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Laminated Metal Composites (LMC) for Aerospace Applications

Final Report

CRADA No. TC-169-91

Date: December 18, 1996

TACT: AMPE

Revision: 1

A. Parties

The project is a relationship between the Lawrence Livermore National Laboratory (LLNL), Aluminum Company of America (ALCOA), United Technologies, Pratt & Whitney, Rohr, Inc. and Sutek Corporation.

University of California
Lawrence Livermore National Laboratory'
P.O. Box 808, L-795
Livermore, CA 94551

ALCOA
100 Technical Drive
Alcoa Center, PA 15069-0001

United Technologies, Pratt & Whitney
P.O. Box 109600
West Palm Beach, FL 33410-9600

Rohr, Inc.
P.O. Box 878
Chula Vista, CA 91912-0878

Sutek Corporation
14 Brent Drive
Hudson, MA 01749

B. Project Scope

Lawrence Livermore National Laboratory, Aluminum Company of America (ALCOA), Rohr, Incorporated, Sutek Corporation, and United Technologies, Pratt & Whitney entered into an agreement to identify and develop moderate-cost, high-performance Laminated Metal Composites (LMC) for aerospace applications. This project developed and implemented technology that will improve the fabricability of metal composites, thus reducing their manufacturing costs. LMC was used because of its superior properties in strength, toughness, and damping behavior. The new high-performance, moderate-cost materials are expected to result in economic strength for participating industries, as well as fuel savings, weight economy, and increased safety margins for the aerospace industry. This collaboration developed a unique material in a class of composites that is expected to have a large market growth in the next five to ten years.

C. Technical

Milestones and Deliverables	Completion Date:	
	Scheduled	Actual
1. Demonstrated ballistic performance superior to current technology.	05/94	05/94
2. Achieved mechanical property targets for medium & high strength aluminum metal matrix laminate	06/94	06/94
3. Demonstrate property targets for medium strength laminates.	06/94	06/94
4. Demonstrate property targets for high strength laminates.	01/95	02/95
5. Establish structure-property correlation for medium & high strength laminates.	03/95	02/95
6. Establish scaling laws for ballistics tests.	06/94	06/94
7. Evaluate laminates for ballistics performance.	07/94	08/94
8. Complete metallographic analysis of 30 and 50 caliber tests	12/94	12/94
9. Complete additional testing of Al to determine the existence of a transition zone	05/95	06/95
10. Complete thick target testing - Ti data	05/95	04/95
11. Complete thick target testing - Al data	02/95	03/95
12. Identify key property variables for Ti & steel that influence ballistic performance	04/95	04/95
13. Developed model containing Johnson-Cook failure criteria	02/95	02/95
14. Use model capability developed in 11/determine mechanisms responsible for performance trends in 10	07/95	
15. Characterization of Ti in the transition region	03/95	04/95
16. Milestone on Ti-Be/Al testing depends on delivery of material from Los Alamos dependent (testing one month after receiving material).		
17. Complete plan for 1/4 scale testing	06/95	06/95
18. Complete 1/4 scale tests on Ti targets	02/96	
19. Complete 1/4 scale tests on Ti laminates targets	06/96	

D. Partner Contribution

Participants' contributions validated by a) supply of material, b) supply of test data, c) completion of milestones and d) supply of a videotape showing test results.

E. Documents/Reference ListReports

Quarterly reports for: 3/31/94, 6/30/94, 9/30/94, 12/31/94, 3/31/95, 6/30/95

Documents

See attached Bibliography, Attachment IV

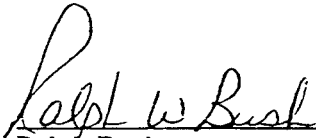
Inventions

No subject inventions were created under this CRADA.

F. Acknowledgment

Participant's signature of the final report indicates the following:

- 1) The Participant has reviewed the final report and concurs with the statements made therein.
- 2) The Participant agrees that any modifications or changes from the initial proposal were discussed and agreed to during the term of the project.
- 3) The Participant certifies that all reports either completed or in process are listed and all subject inventions and the associated intellectual property protection measures attributable to the project have been disclosed or are included on a list attached to this report.
- 4) The Participant certifies that if real property was exchanged during the agreement, all has either been returned to the initial custodian or transferred permanently.
- 5) The Participant certifies that proprietary information has been returned or destroyed by LLNL.


Ralph Bush
ALCOA

7/15/97
Date

F. Acknowledgment

Participant's signature of the final report indicates the following:

- 1) The Participant has reviewed the final report and concurs with the statements made therein.
- 2) The Participant agrees that any modifications or changes from the initial proposal were discussed and agreed to during the term of the project.
- 3) The Participant certifies that all reports either completed or in process are listed and all subject inventions and the associated intellectual property protection measures attributable to the project have been disclosed or are included on a list attached to this report.
- 4) The Participant certifies that if real property was exchanged during the agreement, all has either been returned to the initial custodian or transferred permanently.
- 5) The Participant certifies that proprietary information has been returned or destroyed by LLNL.

Arthur Lee
Sutek Corporation

Date

Laminated Metal Composites for Aerospace Applications

**Final Abstract
Attachment I
CRADA No. TC-0169-91**

Lawrence Livermore National Laboratory, Aluminum Company of America (ALCOA), Rohr, Incorporated, Sutek Corporation, United Technologies Pratt & Whitney entered into an agreement to identify and develop moderate-cost, high-performance Laminated Metal Composites (LMC) for aerospace applications. This project developed and implemented technology that will improve the fabricability of metal composites, thus reducing their manufacturing costs. LMC will be used because of its superior properties in strength, toughness, and damping behavior. The new high-performance, moderate-cost materials are expected to result in economic strength for participating industries as well as fuel savings, weight economy, and increased safety margins for the aerospace industry. This project will develop a unique material in a class of composites that is expected to have a large market growth in the next five to ten years.

Laminated Metal Composites (LMC) for Aerospace Applications

Project Accomplishments Summary (Attachment II) CRADA No. TC-169-91

Date: December 18, 1996

Revision: 1

A. Parties

The project is a relationship between the Lawrence Livermore National Laboratory (LLNL), Aluminum Company of America (ALCOA), United Technologies, Pratt & Whitney, Rohr, Inc. and Sutek Corporation.

University of California
Lawrence Livermore National Laboratory
P.O. Box 808, L-795
Livermore, CA 94551

ALCOA
100 Technical Drive
Alcoa Center, PA 15069-0001

United Technologies, Pratt & Whitney
P.O. Box 109600
West Palm Beach, FL 33410-9600

Rohr, Inc.
P.O. Box 878
Chula Vista, CA 91912-0878

Sutek Corporation
14 Brent Drive
Hudson, MA 01749

B. Background

Aluminum Company of America (ALCOA) has headquarters at ALCOA Center, Pennsylvania; Rohr, Inc. at Chula Vista, California; Sutek Corporation at Hudson, Massachusetts.; and United Technologies, Pratt & Whitney at West Palm Beach, Florida. The industries are major U.S. materials and component processing companies with strong interests in the aerospace industry. The purpose of this CRADA was to develop moderate-cost, high-performance Laminated Metal Composites (LMC) suitable for aerospace sheet applications.

C. Description

Lawrence Livermore National Laboratory, Aluminum Company of America (ALCOA), Rohr, Industries, Sutek Corporation, and United Technologies, Pratt & Whitney entered into an agreement to identify and develop moderate-cost, high-performance LMC for aerospace applications. This project developed and implemented technology that will improve the fabricability of metal composites, thus reducing their manufacturing costs. LMC was used because of its superior properties in strength, toughness, and damping behavior. The new high-performance, moderate-cost materials are expected to result in economic strength for participating industries as well as fuel savings, weigh economy, and increased safety margins for the aerospace industry.

This collaboration developed a unique material in a class of composites that is expected to have a large market growth in the next five to ten years.

D. Expected Economic Impact

New high-performance, moderate-cost materials will result in economic strength for the participating industries, plus fuel savings, weight economy, and increased safety margins for the aerospace industry.

E. Benefits to DOE

Commercializing this technology will reduce the cost and improve the performance of aluminum and titanium-based materials now used in many DOE and Defense Program applications, including all military aircraft.

F. Industry Area

Transportation and Aerospace.

G. LLNL Point of Contact for Project Information

Donald Lesuer, (510) 422-9633.

H. Company Size and Point(s) of Contact

ALCOA	Ralph Bush	(412) 337-5990
United Technologies, Pratt & Whitney, CT	Craig Musson	(203) 565-8460
United Technologies, Pratt & Whitney, FL	Dave Alexander	(407) 796-6149
Rohr, Inc.	Brian Norris	(619) 691-3646
Sutek Corporation	Arthur Lee	(508) 562-4461

I. Project Examples

Tact Project Review #1, 12/8/93

J. Release of Information

I have reviewed the attached Project Accomplishment Summary prepared by Lawrence Livermore National Laboratory and agree that the information about our CRADA may be released for external distribution.

Ralph W Bush 7/15/97
Ralph Bush Date
ALCOA

J. Release of Information

I have reviewed the attached Project Accomplishment Summary prepared by Lawrence Livermore National Laboratory and agree that the information about our CRADA may be released for external distribution.

Brian Norris 11/20/97
Brian Norris Date
Rohr, Inc.

J. Release of Information

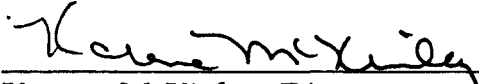
I have reviewed the attached Project Accomplishment Summary prepared by Lawrence Livermore National Laboratory and agree that the information about our CRADA may be released for external distribution.

Arthur Lee
Sutek Corporation

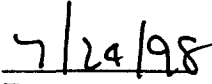
Date

RELEASE OF INFORMATION

I certify that all information contained in this report is accurate and releasable to the best of my knowledge.



Karena McKinley, Director
Industrial Partnerships
and Commercialization

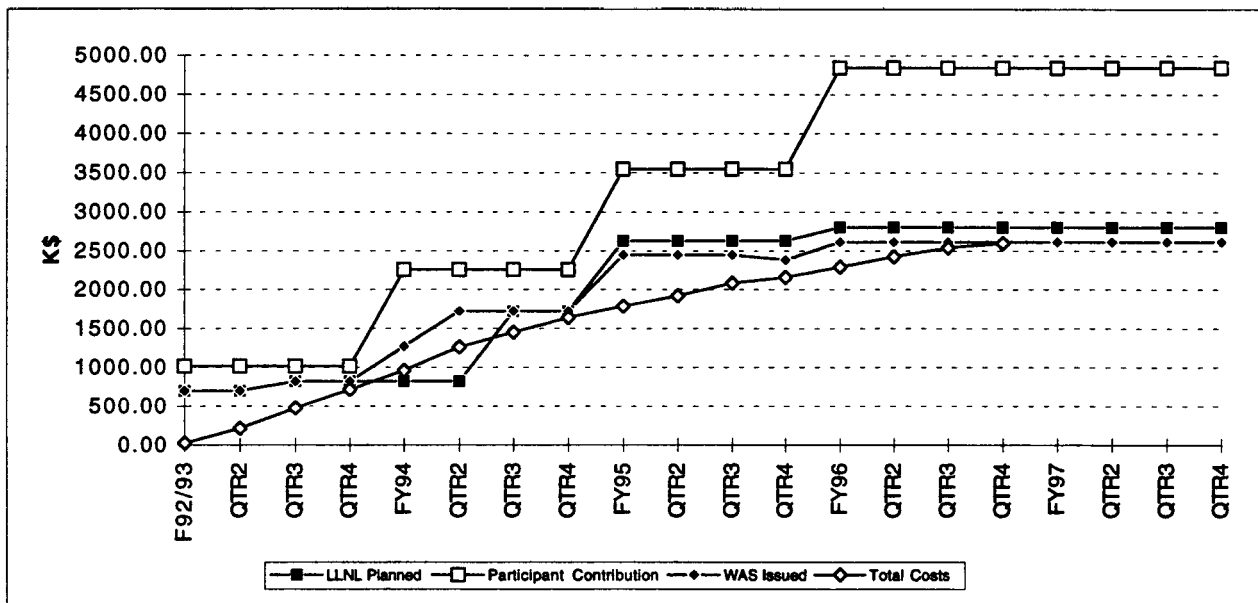


Date

**Lawrence Livermore National Laboratory
Final Quarterly Report (Attachment III)**

Title:	Laminated Metal Composites for Aero. Appl.	Reporting Period:	07/01/95 - 09/30/96
Participant:	Rohr Inc., Pratt-Whitney (Conn. & Fla.), Sutek Corp., Alcoa	Date CRADA Executed:	10/30/92
DOE TTI No.:	92-LLNL-002-B1	DOE Approval Date:	10/16/92
CRADA No.:	TC-0169-91	Scheduled Ending Date:	10/30/96
TACT:	AMPE	Project Completed:	09/30/96
Account Numbers	4782 -20 to 23, 7615-02	B & R Code (S):	DP0301
Accounts Closed:	#####		35DP03
Approved Funding Profile (\$K)			

	F92/93	FY94	FY95	FY96	FY97	Total
LLNL Planned	825	900	900	175	0	2800
Participant In-Kind	1020	1240	1290	1290	0	4840
Participant Funds-In	0	0	0	0	0	0
WAS DP0301	775	900	650	234	0	2559
WAS 35DP03	50	0	3	0	0	53
Total Costs	710	930	519	434	0	2593



DP0301	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	FYTD	2540
F92/93	0	0	27	59	59	70	96	83	76	64	48	76	657	
FY94	105	90	59	81	92	130	56	79	52	61	47	77	930	
FY95	49	52	45	33	56	50	28	64	69	42	14	17	518	
FY96	42	44	44	42	38	56	36	42	33	18	39	0	434	
FY97	0	0	0	0	0	0	0	0	0	0	0	0	0	

35DP03	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	FYTD	53
F92/93	0	0	0	0	0	0	0	3	0	0	58	-8	53	
FY94	0	0	0	0	0	0	0	0	0	0	0	0	0	
FY95	0	0	0	0	0	0	0	0	0	0	0	0	0	
FY96	0	0	0	0	0	0	0	0	0	0	0	0	0	
FY97	0	0	0	0	0	0	0	0	0	0	0	0	0	

STAFF w/phone:

Lab PI:	Don Lesuer (510) 422-9633	Participant:	Brian Norris (Rohr) (619)691-3646
Resource Manager:	Michelle Doggett (510) 422-3209		Craig Musson (Pratt-Whitney,CT) (203)565-8460
DOE OAK:	Jerry Scheinberg (510) 637-1653		Dave Alexander (Pratt-Whitney,FL) (407)796-6149
DOE HQ:	D. Bird (202) 586-0499		Arthur Lee (Sutek) (508) 562-4461
			Ralph Bush (Alcoa) (412) 337-5990

**Lawrence Livermore National Laboratory
Final Quarterly Report (Attachment III)**

Reporting Period: 07/01/95 - 09/30/96
DOE TTI No.: 92-LLNL-002-B1
CRADA No.: TC-0169-91

Page 2

Milestones and Deliverables:

List the complete set of milestones for all phases of the CRADA. Continue on a separate page if necessary.
Report any changes from the original CRADA or previous quarterly report on the CRADA Change Form.

	Completion Date:	
	Scheduled	Actual
1. Demonstrated ballistic performance superior to current technology.	05/94	05/94
2. Achieved mechanical property targets for medium & high strength aluminum metal matrix laminate.	06/94	06/94
3. Demonstrate property targets for medium strength laminates.	06/94	06/94
4. Demonstrate property targets for high strength laminates.	01/95	02/95
5. Establish structure-property correlations for medium & high strength laminates.	03/95	02/95
6. Establish scaling laws for ballistics tests.	06/94	06/94
7. Evaluate laminates for ballistics performance.	07/94	08/94
8. Complete metallographic analysis of 30 and 50 caliber tests	12/94	12/94
9. Complete additional testing of Al to determine the existence of a transition zone	05/95	06/95
10. Complete thick target testing - Ti data	05/95	04/95
11. Complete thick target testing - Al data	02/95	03/95
12. Identify key property variables for Ti & steel that influence ballistic performance	04/95	04/95
13. Developed model containing Johnson-Cook failure criteria	02/95	02/95
14. Use model capability developd in 11/determine mechanisms responsible for perf trends in 10	07/95	09/96
15. Characterization of Ti in the transition region	03/95	04/95
16. Milestone on Ti-Be/Al testing depends on delivery of material from Los Alamos (testing one month after receiving material).	dependent	*
17. Complete plan for 1/4 scale testing	06/95	06/95
18. Complete 1/4 scale tests on Ti targets	02/96	*
19. Complete 1/4 scale tests on Ti laminates targets	06/96	*

* Not completed due to lack of funding

Verification of participants' in-kind contribution was made in accordance with LLNL policy. Explain basis of verification: Please initial: YES X NO

- Participants' contributions validated by a) supply of material, b) supply of test data, c) completion of milestones and d) supply of a videotape showing test results.

List any subject inventions by either party (include I.L.# for LLNL inventions), additional background intellectual property, patents applied for, software copyrights, publications, awards, licenses granted or reportable economic impacts

Additional Background Intellectual Property, LLNL Invention #IL-9229B, US Patent #52429879, "Flow Constraining Ring Method for Deformation Bonding of Multilayer Laminates Containing Metals with Highly Dissimilar Flow Stresses at Bonding Temperature" by Chol K. Syn, et al.

Verification that all equipment and proprietary information has been returned to the initial owner or permanently transferred Please initial: YES X NO

Accomplishments

Describe Technical/Non-Technical lessons learned and other observations.
Summarize causes/justification of deviations from original scope of work.

See Final Report.

Reviewed by CRADA project Program Manager: _____ Date: _____

Reviewed by Karena McKinley, Director, LLNL/IP&C: Karena McKinley Date: 7/29/98

Direct questions regarding this Report to IP&C Resource Manager, Carol Asher, at (510) 422-7618

Papers and reports produced as a result of CRADA TC-169-91

1. R.P Gogolewski and B.J. Cuningham, "Terminal Ballistic Experiments for the Development of Turbine Engine Blade Containment Technology", UCRL-ID-120930, January 25, 1995.
2. Robert Riddle, Donald Lesuer, Chol Syn, Raymond Goglewski, Bruce Cunningham, "Application of Metal Laminates to Aircraft Structures; Prediction of Penetration Performance", *Finite Elements in Analysis and Design*, 23, 173-192 (1996).
3. Robert A. Riddle, Donald R. Lesuer and Chol K. Syn, "Damage Initiation and Propagation in Metal Laminates", in Recent Advances in Solids/Structures and Application of Metallic Materials, ASME, PVP-Vol. 342, MD-Vol. 72, 167-184 (1996).
4. R.W. Bush, "Extrinsic Toughening of Discontinuously Reinforced Aluminum: An Experimental Study of DRA Laminates", Report No. 57-95-08, Alcoa Technical Center, Alcoa Center, PA (1995).
5. Joseph D. Rigney and Ralph W. Bush, "Deformation and Fracture Behavior of 6013 // 6090/SiC/25p Laminates: Effects of 6013 Layer Volume Fraction and Thickness", Report No. ED-96-10, Alcoa Technical Center, Alcoa Center, PA (1996).
6. R.P. Gogolewski, B.J. Cunningham, R.A. Riddle, D.R. Lesuer and C.K. Syn, "On the Importance of Target Material Interfaces During Low Speed Impact", Proceedings 16th International Symposium on Ballistics, San Francisco (1996).
7. D.R. Lesuer, J. Wadsworth, R.A. Riddle, C.K. Syn, J.J. Lewandowski and W.H. Hunt, Jr., "Toughening Mechanisms in Al/Al-SiC Laminated Metal Composites", in *Layered Materials for Structural Applications*, edited by J.J. Lewandowski, C.H. Ward, M.R. Jackson and W.H. Hunt, Jr., Materials Research Society Symposium Proceedings Volume 434, Materials Research Society, Pittsburgh PA, 205 (1996).

Papers resulting from PhD Thesis of Todd Osman
Case Western Reserve University
(completed as part of CRADA TC-169-91)

1. T.M. Osman, J.J. Lewandowski and D.R. Lesuer, "The Fracture Resistance of Layered DRA Laminates: Influence of Laminae Thickness", accepted for publication *Materials Science and Engineering A*, (1996).

2. T.M. Osman, J.J. Lewandowski, D.R. Lesuer and R.A. Riddle, "Constrained Flow in Bi-Material Systems: Effects of Property Mismatch", accepted for publication in *Scripta Metallurgica and Materialia* (1996).
3. T.M. Osman, J.J. Lewandowski, D.R. Lesuer and W.H. Hunt, "Deformation and Fracture Processes in DRA Laminates", *Micromechanics of Advanced Materials: A Symposium in Honor of Professor James Li's 70th Birthday*, edited by S.N.G. Chun et al, The Minerals, Metals and Materials Society, 135 (1995).
4. T.M. Osman, J.J. Lewandowski, W.H. Hunt, Jr., D.R. Lesuer and R.A. Riddle, "Extrinsic Toughening in DRA Laminates", in *Intrinsic and Extrinsic Fracture Mechanisms in Inorganic Composite Systems*, edited by J.J. Lewandowski and W.H. Hunt, Jr., The Minerals, Metals and Materials Society, 103 (1995).