(4)

OFFICE OF NAVAL RESEARCH

Contract: N00014-85-K-0222

Work Unit: 4327-555

Scientific Officer: Dr. Richard S. Miller

Technical Report No. 19

COMPARISON OF PEEL AND LAP SHEAR BOND STRENGTHS FOR ELASTIC JOINTS WITH AND WITHOUT RESIDUAL STRESSES

by

A. N. Gent and C.-W. Lin

Institute of Polymer Science
The University of Akron
Akron, Ohio 44325

May, 1989

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER Technical Report NO. 19	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Comparison of Peel and Lap Shear Bond Strengths for Elastic Joints With and Without Residual Stresses		5. TYPE OF REPORT & PERIOD COVERED Technical Report 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) A.N. Gent and C.W. Lin		8. CONTRACT OR GRANT NUMBER(s) N00014-85-K-0222
9. PERFORMING ORGANIZATION NAME AND ADDRESS Institute of Polymer Science The University of Akron Akron, OH 44325		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 4327-555
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Power Program Arlington, VA 22217-5000		12. REPORT DATE May 1989 13. NUMBER OF PAGES 30
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

According to attached distribution list.
Approved for public release; distribution unrestricted.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Submitted for publication in the Journal of Adhesion

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Adhesion, Bonding, Debonding, Peel, Shear, Strength, Stress (Residual), Stress, Shrinkage. (mgr-1)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Fracture energies have been calculated from peel and lap shear experiments on rubber strips bonded together with a pressure-sensitive acrylic adhesive layer. In some cases, one strip was held stretched during bonding, to create joints with built-in stresses. Good agreement was obtained in all cases,

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-LF-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) cont'd

provided that elastic strain energy was taken into account, the work of detachment being about 180 J/m^2. sq. m. For thick rubber layers, about 3 - 4 mm. or greater, the strain induced by peel or shear forces was rather small and the assumption of linear elastic behavior was found to be satisfactory. Good agreement was then obtained with the relations derived by Kendall (1,2).

Keywords:

S/N 0102-LF-014-6601

1. Introduction

Peel and lap shear tests are simple and widely-used methods of measuring the strength of an adhesive bond. But the results are not easily compared. The peel force per unit width of the joint can be directly interpreted as an energy G_a required to bring about separation per unit area of interface. On the other hand, it is usual to describe the strength of a lap shear joint by the mean shear stress causing fracture. But the joint does not fail in shear by simultaneous rupture of the entire bonded area. Instead, the bond fails first at a highly stressed site, usually at one edge, and failure then spreads across the interface.

Kendall calculated the strength of a lap-shear joint on this basis (1,2), using Griffith's energy-balance approach, and showed that the fracture energy deduced from lap shear measurements on model joints agreed well with that given by a simple peeling experiment. However, Kendall assumed that the stress-strain relationship in tension for the two adhering layers was a linear one and the strains were small. These assumptions are not necessarily true for thin layers, which might be stretched to large strains during bonding or detachment. The theory is reviewed here and measurements on extensible rubber layers are compared with predictions made with and without the assumption of small strains.

If one of the adherends is stretched when it is bonded to the other, the joint is made more resistant to separation, at least for prestrains below a critical level at which the layers spontaneously separate on release. Both the strengthening effect of initial prestrains and the critical degree of prestrain at which spontaneous delamination occurs can be calculated on the basis of elastic strain energy contributions to the work of separation, assuming that the intrinsic strength of adhesion is unchanged by prestretching. Some measurements are reported of the peel and lap shear strengths of joints prepared by bonding a stretched rubber strip to an unstretched one. Such joints can be regarded as models of adhesive joints prestressed due to a variety of causes; for example, by shrinkage of one layer on setting or by differential thermal contraction.

2. Theoretical Considerations

Work is expended in two ways in peeling. First, the detached strip is stretched, to a strain of e, say, requiring input of strain energy U per unit volume. If it was already stretched to a strain of e^* in the bonded state, before detachment, with a corresponding amount of strain energy U^* per unit volume stored in it, then the additional energy supplied is $U - U^*$. Secondly, an amount of energy G_a is expended per unit area of interface in separating the adhering surfaces. (It is assumed that G_a is the same for stretched and unstretched adhering surfaces, but we note that unit area of surface becomes $(1 + e^*)^{1/2}$ in the stretched state.) Thus, the work done by the peel force F during detachment of a strip of unit length in the unstrained state (given by Fx where x is the displacement of the point of application of the force) is equal to the sum of these two terms,

$$F x = [G_a(1 + e^*)^{1/2} + (U - U^*)t]w \quad (1)$$

where t is the unstrained thickness and w the unstrained width of the detaching layer.

From geometrical considerations (Figure 1) x is given by

$$x = [1 + e - (1 + e^*)\cos\theta] \quad (2)$$

where θ is the peel angle. The fracture energy G_a is then obtained from Equations 1 and 2,

$$G_a(1 + e^*)^{1/2} = (F/w)[1 + e - (1 + e^*)\cos\theta] - (U - U^*)t. \quad (3)$$

In the case of linear elasticity, the strains e and e^* are given by F/wtE and F^*/wtE, where E is the tensile (Young) modulus of the strips, F^* is the residual tension in the strip before separation, corresponding to the strain e^*, and the strain energies U and U^* are given by $(F/wt)^2/2E)$ and $(F^*/wt)^2/2E$. Thus, for peeling a linearly-elastic strip, the fracture energy is given by

$$G_a(1 + e^*)^{1/2} = (F/w)[1 - (1 + e^*)\cos\theta] + (F^2 + F^{*2})/2w^2tE. \quad (4)$$

If the strip is not prestressed, $e^* = F^* = U^* = 0$, and Equations 3 and 4 become

$$G_a = (F/w)[1 + e - \cos\theta] - Ut \quad (5)$$

and

$$G_a = (F/w)[1 - \cos\theta] + F^2/2w^2tE. \quad (6)$$

If the strip is relatively inextensible, the second term in Equations 5 and 6 is negligibly small in comparison with the first, unless θ is close to zero. The relation for the fracture energy then takes its simplest form

$$G_a = (F/w)[1 - \cos\theta]. \quad (7)$$

For lap shear debonding, $\theta = 0$ in Equation 3. Considering only one layer of the sandwich to be extensible, the fracture energy can be expressed as:

$$G_a(1 + e^*)^{1/2} = (F/w)(e - e^*) - (U - U^*)t \tag{8}$$

Again, if it is assumed that the layer is linearly-elastic, this relation becomes

$$G_a(1 + e^*)^{1/2} = (F - F^*)^2/2w^2tE. \tag{9}$$

And if the layer was not prestressed at the time the joint was made, $e^* = F^* = 0$, and

$$G_a = F^2/2w^2tE. \tag{10}$$

When two strips are pulled apart, Figure 2, with strain energy imparted to both, then Equation 8 becomes

$$G_a(1 + e^*)^{1/2} = (F/w)(e - e_2) - [U - U_{e_2} - (1 + e^*)U_{e_1}]t \tag{11}$$

where e_2 denotes the strain in the bonded portion of the prestressed strip during detachment and e_1 denotes the corresponding strain in the other strip, Figure 3. They are related to the prestrain e^* at the time of bonding and to the detachment force F by the relations

$$e_2 = e^* + (1 + e^*)e_1 \tag{12}$$

and

$$F = F_1 + F_2 \tag{13}$$

where F_1 and F_2 are the tensile forces in the two bonded strips.

For linearly-elastic strips, Equation 11 becomes

$$G_a(1 + e^*)^{1/2} = (F - F^*)^2/2(2 + e^*)w^2tE. \tag{14}$$

When the prestrain e^* is zero, $e_1 = e_2$, $F_1 = F_2$, and $U_{e_1} = U_{e_2}$. Equations 11 and 14 then become

$$G_a = (F/w)(e - e_1) - (U - 2U_{e_1})t \tag{15}$$

$$G_a = (F/w)^2/4tE. \tag{16}$$

The above relations for fracture force based on linear elastic behavior (Equations 9 and 14) were originally derived by Kendall (3) with e^* assumed to be much smaller than unity. He pointed out that the detachment force F increased linearly with the magnitude of the preload F^*, up to a value of F^* equal to the original failure force. For values of F^* of this amount or greater, detachment will occur spontaneously on releasing the joint from the force F^* applied during bonding.

We now compare the predictions of these various relations with experimental measurements of the forces required to detach soft rubber layers, adhering together.

3. Experimental Details

Sheets of vulcanized rubber having a wide range of thickness were prepared using the mix recipe and vulcanization conditions given in the Appendix. Experimental relations between tensile stress and elongation e, and between elastic strain energy U per unit volume and e, are shown in Figures 4 and 5. Strips about 20 mm wide and 200 mm long were cut from the rubber sheets and coated with a thin layer, about 0.2 mm thick, of an acrylic adhesive emulsion (Monsanto Gelva Multipolymer Resin Emulsion RA-2397, kindly supplied by Mr.J.M.Questel, Adhesive Consultants, Inc., Akron, Ohio). After drying in an air oven at 50°C for 2 h, two similar coated rubber strips were pressed into contact to form a model joint.

Measurements of peel force and lap shear failure force were made at the same rate of propagation of the debond, about 0.1 mm/sec. In peeling, one rubber layer was bonded to a steel plate and the other layer was peeled away from it at an angle of 45°, Figure 1. Lap shear measurements were carried out symmetrically, as shown in Figure 2.

The experiments were carried out at room temperature, about $25^{\circ}C$.

4. Experimental Results and Discussion

(i) Joints prepared without a prestress

(a) Peel strength

The measured peel forces and lap shear failure forces are given in Tables 1 and 2 for rubber layers having thicknesses ranging from 0.6 to 12 mm. Values of fracture energy were calculated from the peel forces, using three different assumptions: that the layers were inextensible (Equation 7), that they were extensible but linearly elastic (Equation 6), and that they were non-linearly elastic (Equation 5). The results are plotted in Figure 6 against the thickness of the rubber layer being peeled away. As can be seen, the results calculated assuming zero extension or assuming linear elasticity are not constant. Values obtained with thin rubber layers are considerably smaller than those from thick layers. On the other hand, values calculated taking into account the non-linearly elastic character of rubber are constant over the whole thickness range. We rubber strips for various amounts of prestrain $\underline{e}^*$. When the strips were assumed to be linearly-elastic the results were not constant but depended on the strip thickness, especially for thin strips. On the other hand, when non-linearly elastic behavior of the strips was taken into account, then the calculated values were approximately constant, independent of the strip thickness. Moreover, the average value, about 210 J/m^2, was close to that obtained from peeling and lap shear measurements on unprestressed joints, Figures 6 and 7.

(b) Lap shear strength

In order to calculate fracture energy for prestressed lap shear joints in the most general case, Equation 11, it is necessary to deduce the strains $\underline{e}_1$ and $\underline{e}_2$ in the two bonded strips under the failure force $\underline{F}$. This was done by trial and error, using Equations 12 and 13. Values obtained in this way are given in Table 4, together with the results for $\underline{G}_a$ calculated from them. As can be seen in Figure 9, these values of $\underline{G}_a$ are approximately constant at about 160 $\pm$ 20 J/m^2, close to the value deduced from peeling measurements, and independent of the strip thickness, whereas values calculated on the basis of linearly elastic behavior using Equation 14 are much smaller for thin strips and not independent of the strip thickness. We conclude that it is necessary to take into account non-linear elastic behavior of rubber strips to predict the effect of large prestrains on peel and lap shear strengths.

(c) Strengthening effect of prestresses

As shown by the failure forces given in Tables 3 and 4, conclude that it is necessary to employ the accurate non-linear relationship, Equation 5, in order to obtain correct values for the fracture energy from peeling experiments with unreinforced rubber strips, even when the thickness is 3 mm or more.

(b) Lap shear strength

Values of fracture energy calculated from lap shear measurements are plotted in Figure 7. Again, results obtained assuming linear elasticity are found to depend upon the thickness of the adhering rubber layers up to about 8 mm. When a non-linear relation is used to deduce the fracture energy, the results become constant over the whole thickness range, and they agree well with the corresponding value obtained from peeling measurements, about 180 J/m^2.

We conclude that the present well-bonded rubber layers stretch too much in peeling and lap shear measurements for the elementary theory of fracture based on linear elasticity to apply. Instead it is necessary to take into account non-linear behavior in tension to obtain accurate values of the work of detachment.

(ii) Joints prepared with a prestress

(a) Peel strength

Peel forces for prestressed joints prepared using strips of a wide range of thickness are given in Table 3, with values of fracture energy $\underline{G}_a$ calculated from them assuming that the strips were linearly elastic, Equation 4, or that they were non-linearly elastic, Equation 3. The results are plotted in Figure 8 against the thickness of the rubber strips for various amounts of prestrain $\underline{e}^*$. When the strips were assumed to be linearly-elastic the results were not constant but depended on the strip thickness, especially for thin strips. On the other hand, when non-linearly elastic behavior of the strips was taken into account, then the calculated values were approximately constant, independent of the strip thickness. Moreover, the average value, about 210 J/m^2, was close to that obtained from peeling and lap shear measurements on unprestressed joints, Figures 6 and 7.

(b) Lap shear strength

In order to calculate fracture energy for prestressed lap shear joints in the most general case, Equation 11, it is necessary to deduce the strains $\underline{e}_1$ and $\underline{e}_2$ in the two bonded strips under the failure force $\underline{F}$. This was done by trial and error, using Equations 12 and 13. Values obtained in this way are given in Table 4, together with the results for $\underline{G}_a$ calculated from them. As can be seen in Figure 9, these values of $\underline{G}_a$ are approximately constant at about 160 $\pm$ 20 J/m^2, close to the value deduced from peeling measurements, and independent of the strip thickness, whereas values calculated on the basis of linearly elastic behavior using Equation 14 are much smaller for thin strips and not independent of the strip thickness. We conclude that it is necessary to take into account non-linear elastic behavior of rubber strips to predict the effect of large prestrains on peel and lap shear strengths.

(c) Strengthening effect of prestresses

As shown by the failure forces given in Tables 3 and 4, prestressed joints were more resistant to separation than non-prestressed joints. The maximum increase in strength was about 50 percent. But, at a critical amount of prestrain, denoted in Table 4 by e_c^*, the joints spontaneously separated on releasing them from the prestress. Values of fracture energy have been calculated from the corresponding pre-tension forces F_c^*, using Equation 11. They are included in Table 4. They are seen to be in good agreement with values determined directly from measurements of failure forces. Thus, the maximum amount of prestress that a joint can withstand is also given correctly by fracture energy considerations.

5. Conclusions

Peel and lap shear debonding forces are related by a common failure criterion: that a critical amount of energy G_a is needed for debonding. This conclusion of Kendall has been verified again for adhering rubber strips of a wide range of thickness, bonded together with various amounts of residual stress. But it has proved necessary to take into account both the relatively large strains that rubber can undergo during detachment, especially when the strips are thin, and the non-linear elastic response of rubber. Otherwise, the inferred fracture energies are too small, by factors of up to 3 or 4 in the present experiments.

Acknowledgements

This work forms part of a program of research on adhesion supported by the Office of Naval Research (Contract N00014-85-K-0222) and by research grants-in-aid from Lord Corporation, 3M Company and Westvaco.

References

1. K. Kendall, "Elastic Dislocations in Lap Shear Joints", Adhesion 2, (K. W. Allen, Ed.), Applied Science Publishers Ltd, London, 1978 Chap. 8, pp 121-131.
2. K. Kendall, J. Phys. D: Appl. Phys. 8, 512(1975).
3. K. Kendall, J. Phys. D: Appl. Phys. 8, 1722(1975).

Appendix

Mix formulation in parts by weight and vulcanization conditions were as follows: natural rubber, 100; zinc oxide, 5; stearic acid, 2; accelerator (Santocure), 1; sulfur, 2.5. Vulcanization was effected by heating for 30 min. at 150^{o}C.

Table 1 : Peeling Results

Strip thickness t [mm]	Failure force F [N]	Elongation e	Fracture energy G_a [J/m^2] calc. from (Eq. 7)	(Eq. 6)	(Eq. 5)
0.64	6.1	0.71	89	145	182
0.91	6.9	0.57	100	154	193
1.23	9.4	0.77	138	163	175
2.10	10.2	0.27	150	179	195
4.31	12.2	0.28	180	186	188

Table 2: Lap Shear Results

Strip thickness t [mm]	Failure force F [N]	Elongation e	Fracture energy G_a [J/m^2] calc. from (Eq. 16)	(Eq. 15)
0.58	9.6	1.42	100	175
0.88	12.5	0.92	112	173
2.10	21.5	0.77	138	189
4.30	32.4	0.57	153	169
12.50	58.1	0.25	169	172

Table 3: Peeling Forces for Pre-stressed Joints

Strip thickness t [mm]	Prestrain e^*	Preload F^* [N]	Failure force F [N]	Fracture energy G_a [J/m^2] calc. from (Eq. 4)	(Eq. 3)
0.85	0.25	3.7	7.9	126	184
	0.30	4.3	9.0	142	195
	0.60	6.6	12.0	169	239
1.20	0.25	5.3	10.3	155	189
	0.30	5.9	11.9	181	218
	0.60	9.2	15.2	202	247
2.10	0.25	9.2	13.6	188	215
	0.30	10.5	15.9	217	234
4.30	0.10	6.2	12.4	183	200

Table 4: Lap Shear Failure Forces for Pre-stressed Joints

Strip thickness t [mm]	Pre-strain e^*	Failure strains e_1 (calc.)	e_2 (calc.)	Failure forces [N] F (meas.)	F_1 (calc.)	F_2 (calc.)	Fracture energy G_a [J/m^2] calc. from (Eq. 14)	(Eq. 11)
0.85	0.25	0.44	0.80	13.2	5.5	7.7	53	139
	0.30	0.50	0.95	14.6	6.1	8.5	56	127
	0.60	0.55	1.48	17.9	6.4	11.5	69	171
	0.80[a]							202[b]
1.25	0.25	0.48	0.85	20.1	8.6	11.5	91	135
	0.30	0.61	1.09	23.6	9.9	13.7	128	189
	0.65[a]							209[b]
2.10	0.25	0.42	0.78	31.9	13.1	18.8	128	129
	0.30	0.45	0.89	34.0	13.8	20.2	132	192
	0.45[a]							209[b]
4.30	0.10	0.22	0.34	40.7	16.9	23.8	155	191
	0.25[a]							162[b]

a: prestrain e_c^* causing spontaneous debonding on release.

b: calculated from Eq. 11, putting F = e = U = 0; $U_{e_2} + (1 + e^*)\, U_{e_1} = U^*$.

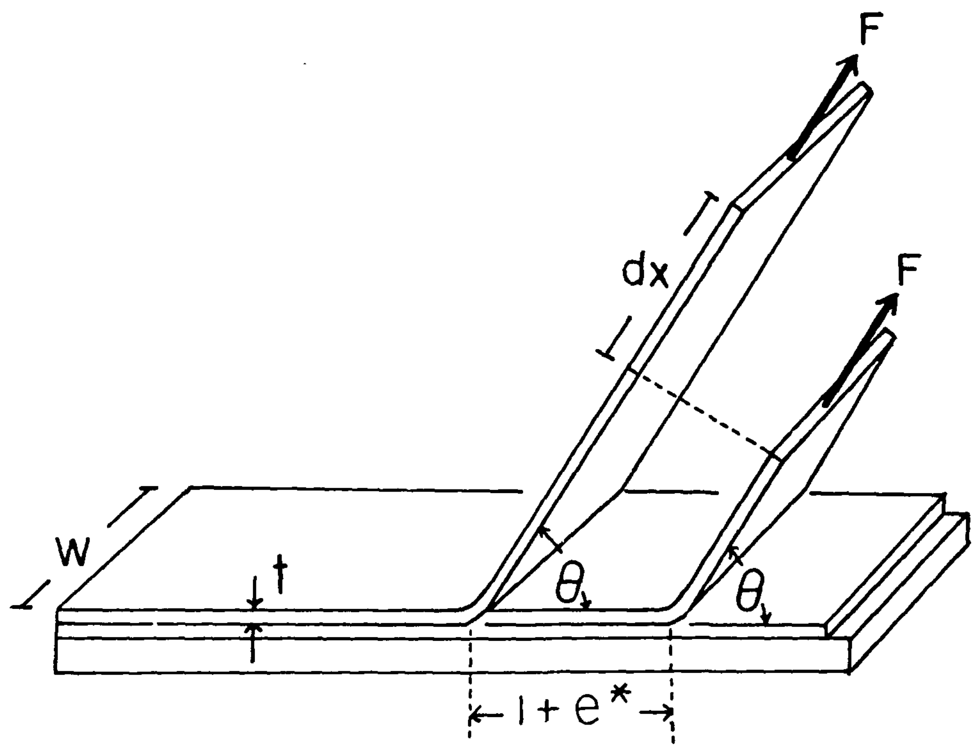

Figure 1

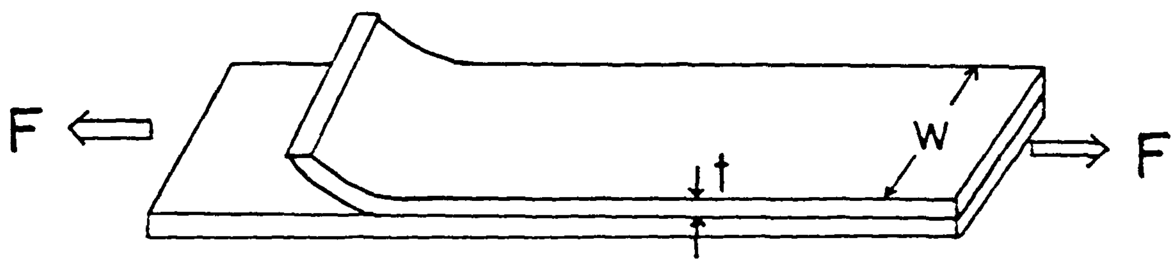

Figure 2

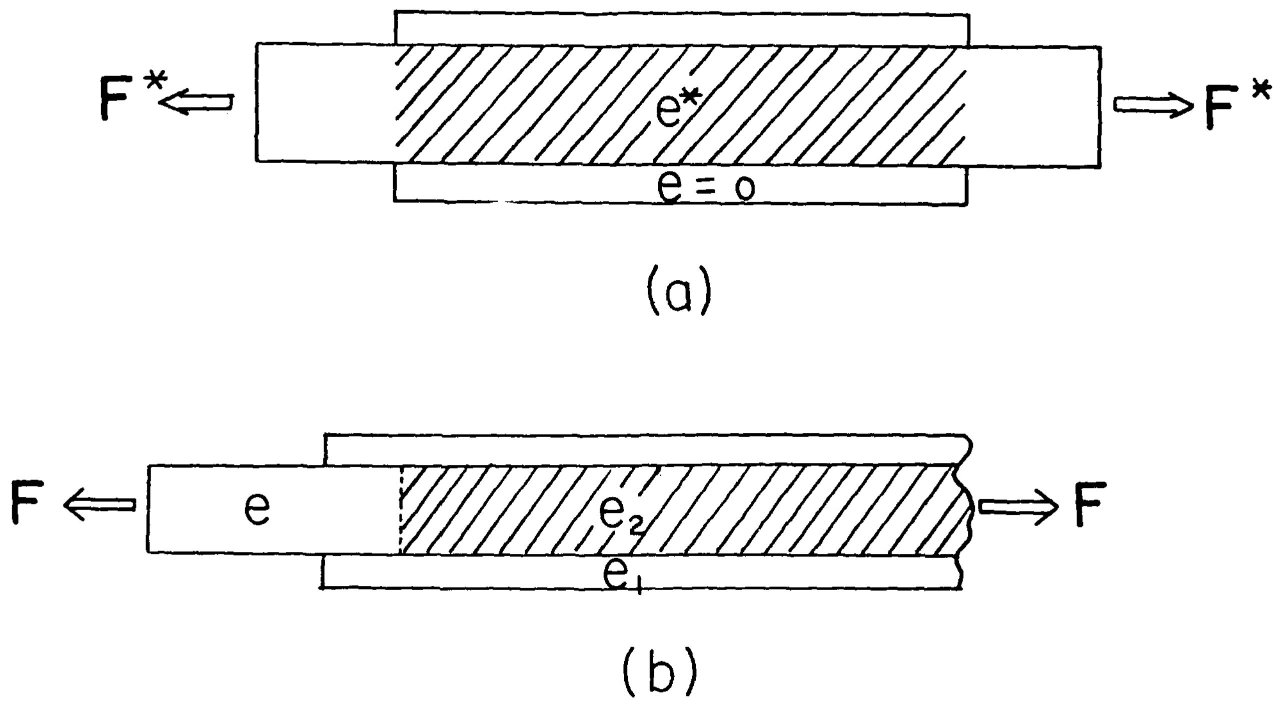

Figure 3

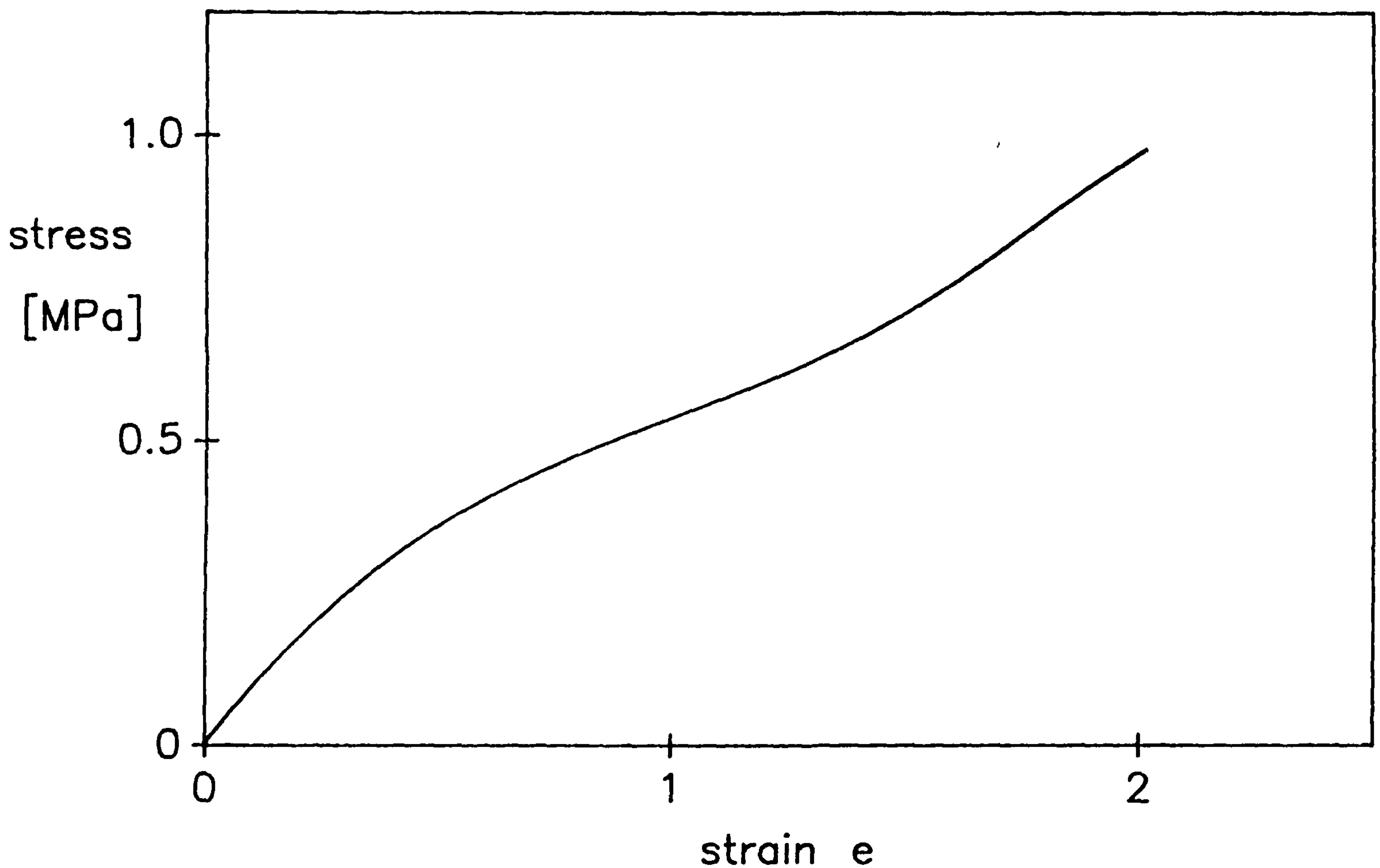

Figure 4

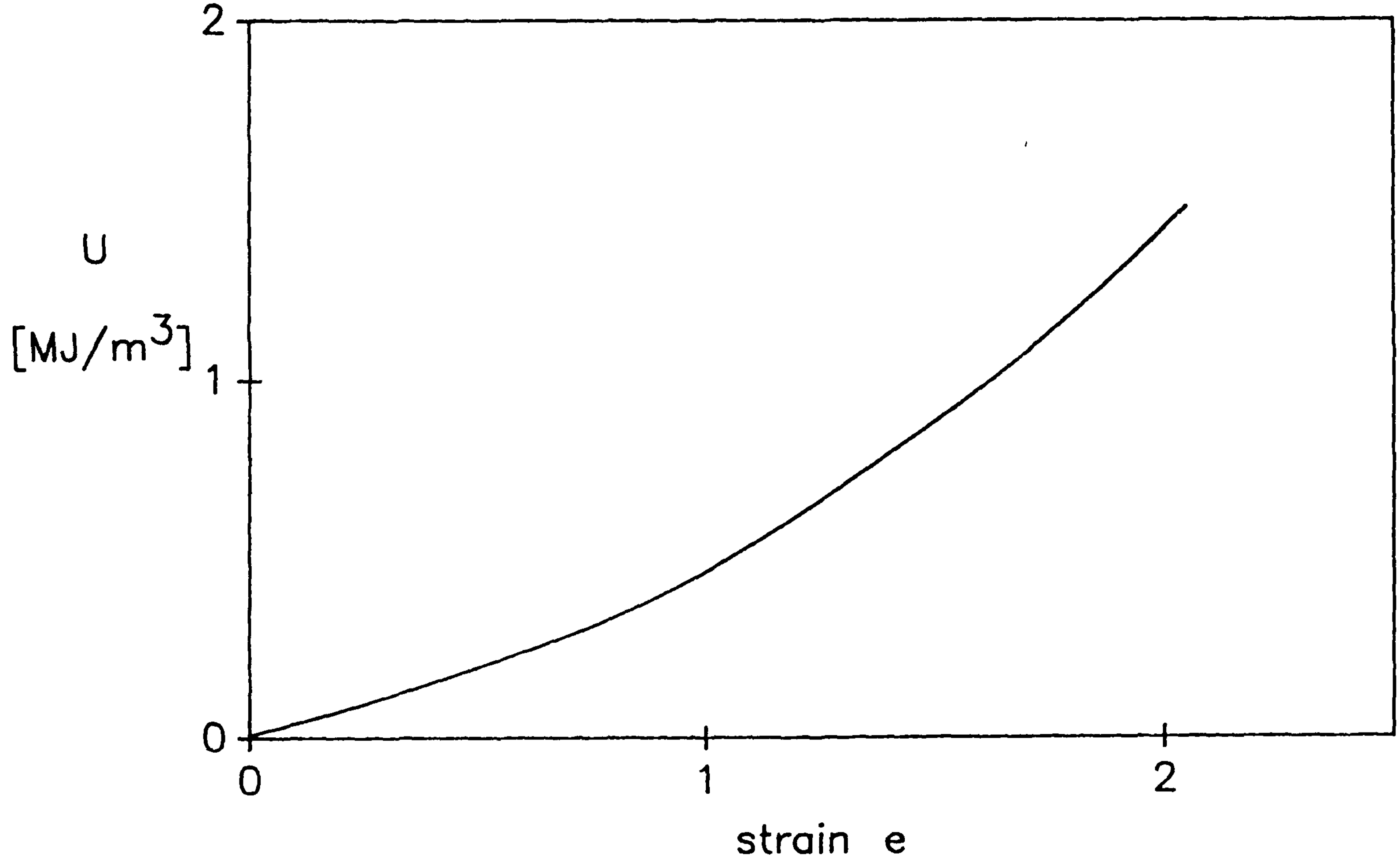

Figure 5

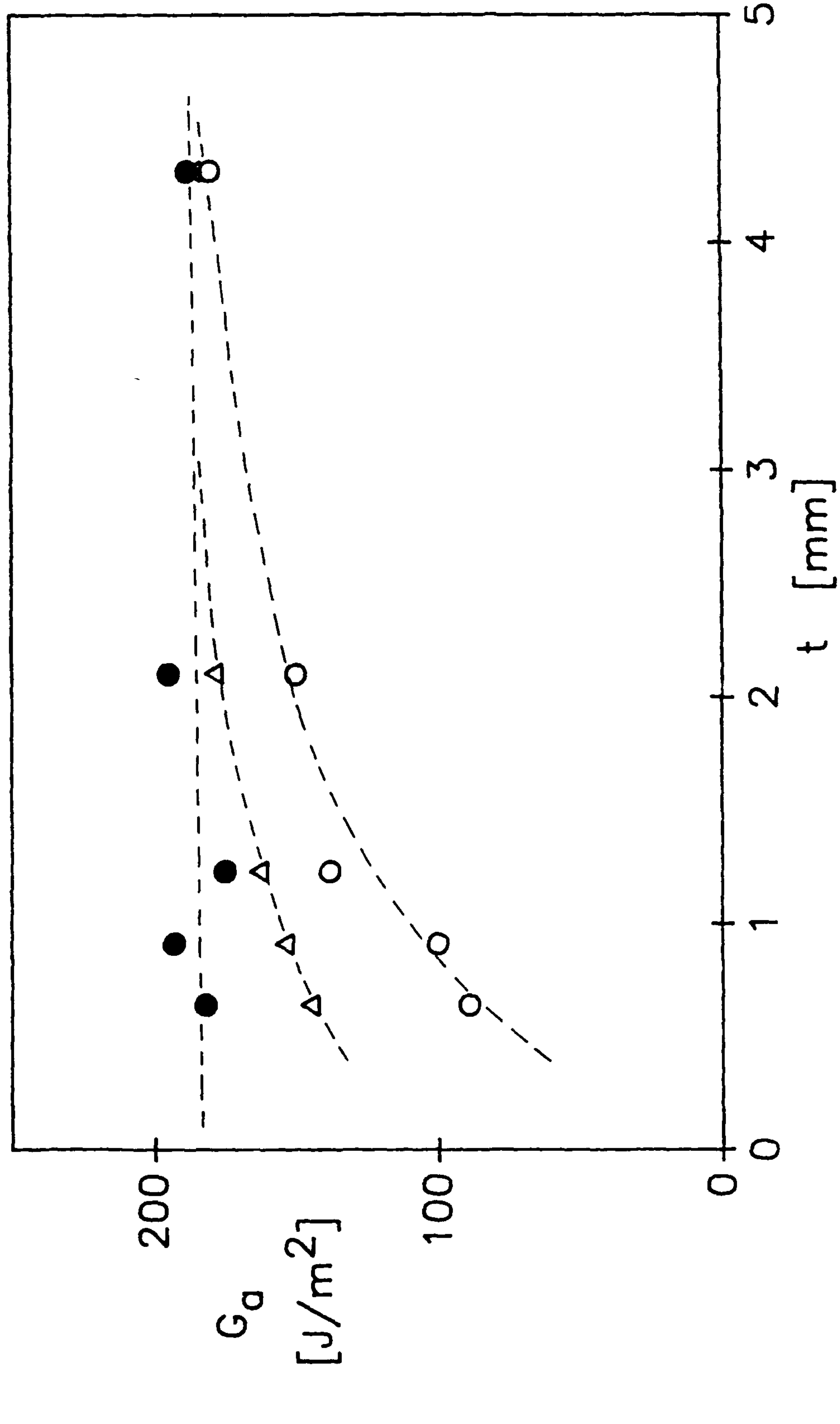

Figure 6

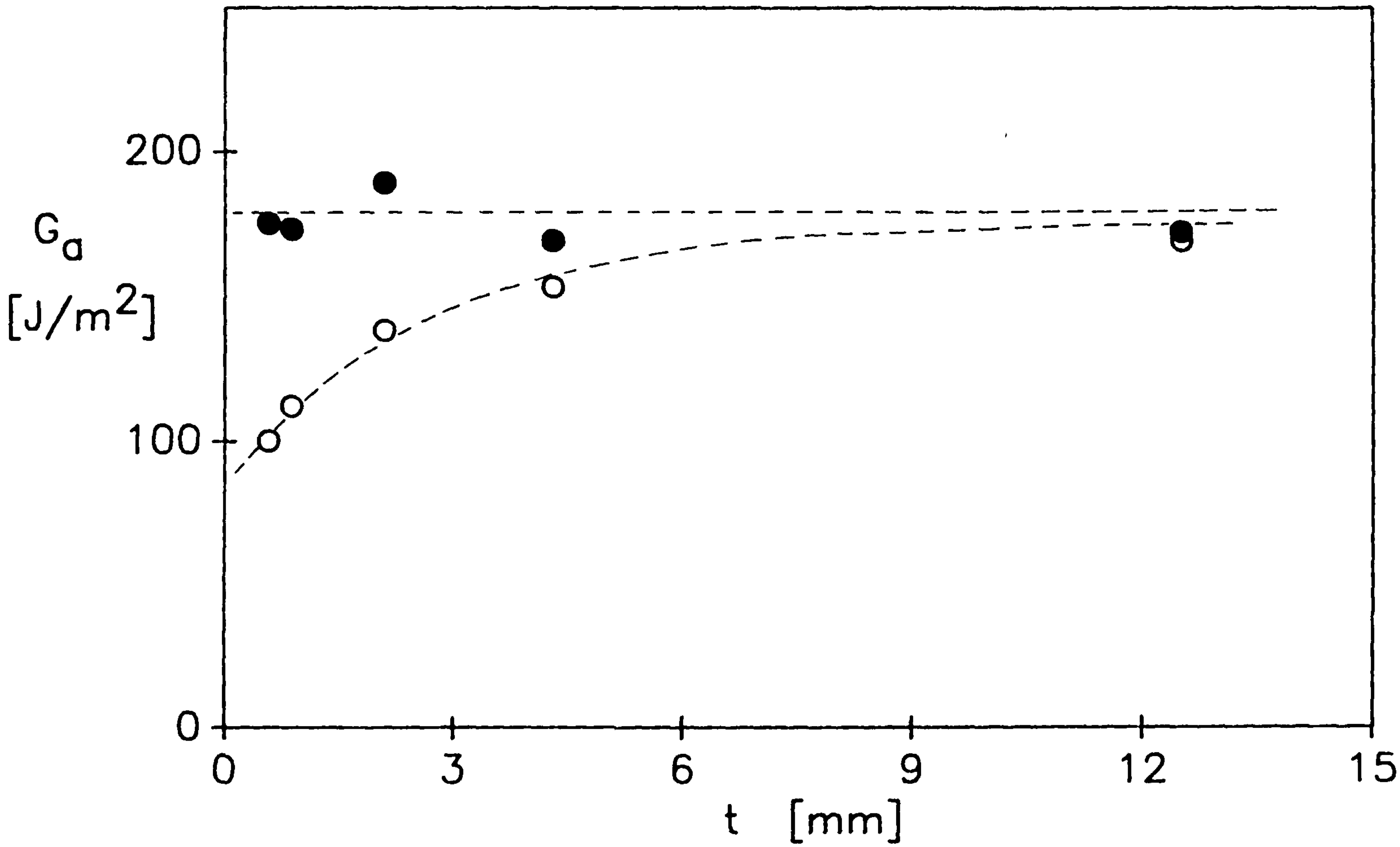

Figure 7

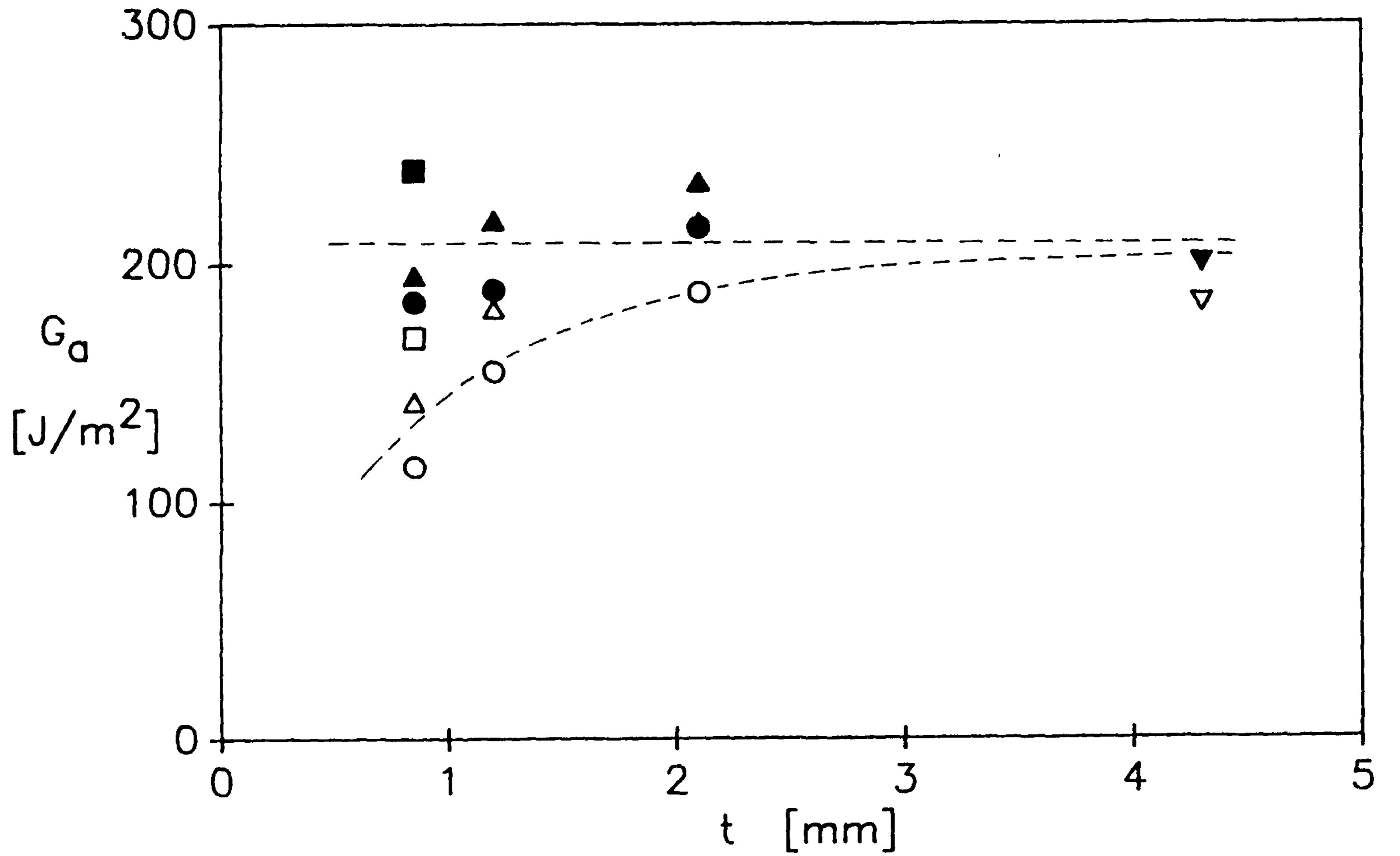

Figure 8

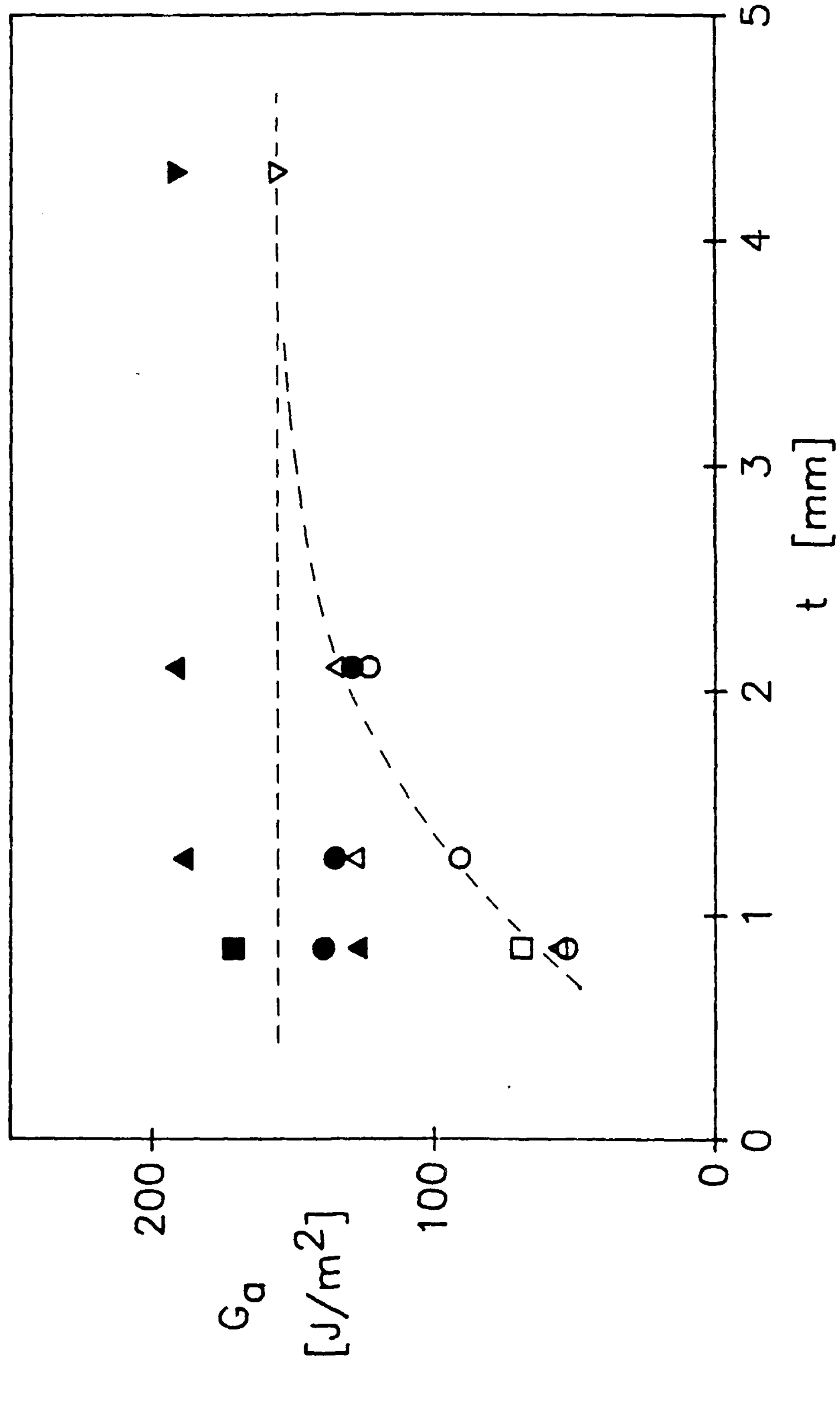

Figure 9

(DYN)

DISTRIBUTION LIST

Dr. R.S. Miller
Office of Naval Research
Code 432P
Arlington, VA 22217
(10 copies)

Dr. J. Pastine
Naval Sea Systems Command
Code 06R
Washington, DC 20362

Dr. Kenneth D. Hartman
Hercules Aerospace Division
Hercules Incorporated
Alleghany Ballistic Lab
P.O. Box 210
Cumberland, MD 20502

Mr. Otto K. Heiney
AFATL-DLJG
Elgin AFB, FL 32542

Dr. Merrill K. King
Atlantic Research Corp.
5390 Cherokee Avenue
Alexandria, VA 22312

Dr. R.L. Lou
Aerojet Strategic Propulsion Co.
Bldg. 05025 - Dept 5400 - MS 167
P.O. Box 15699C
Sacramenta, CA 95813

Dr. R. Olsen
Aerojet Strategic Propulsion Co.
Bldg. 05025 - Dept 5400 - MS 167
P.O. Box 15699C
Sacramento, CA 95813

Dr. Randy Peters
Aerojet Strategic Propulsion Co.
Bldg. 05025 - Dept 5400 - MS 167
P.O. Box 15699C
Sacramento, CA 95813

Dr. D. Mann
U.S. Army Research Office
Engineering Division
Box 12211
Research Triangle Park, NC 27709-2211

Dr. L.V. Schmidt
Office of Naval Technology
Code 07CT
Arlington, VA 22217

JHU Applied Physics Laboratory
ATTN: CPIA (Mr. T.W. Christian)
Johns Hopkins Rd.
Laurel, MD 20707

Dr. R. McGuire
Lawrence Livermore Laboratory
University of California
Code L-324
Livermore, CA 94550

P.A. Miller
736 Leavenworth Street, #6
San Francisco, CA 94109

Dr. W. Moniz
Naval Research Lab.
Code 6120
Washington, DC 20375

Dr. K.F. Mueller
Naval Surface Weapons Center
Code R11
White Oak
Silver Spring, MD 20910

Prof. M. Nicol
Dept. of Chemistry & Biochemistry
University of California
Los Angeles, CA 90024

Mr. L. Roslund
Naval Surface Weapons Center
Code R10C
White Oak, Silver Spring, MD 20910

Dr. David C. Sayles
Ballistic Missile Defense
Advanced Technology Center
P.O. Box 1500
Huntsville, AL 35807

(DYN)

DISTRIBUTION LIST

Mr. R. Geisler
ATTN: DY/MS-24
AFRPL
Edwards AFB, CA 93523

Naval Air Systems Command
ATTN: Mr. Bertram P. Sobers
NAVAIR-320G
Jefferson Plaza 1, RM 472
Washington, DC 20361

R.B. Steele
Aerojet Strategic Propulsion Co.
P.O. Box 15699C
Sacramento, CA 95813

Mr. M. Stosz
Naval Surface Weapons Center
Code R10B
White Oak
Silver Spring, MD 20910

Mr. E.S. Sutton
Thiokol Corporation
Elkton Division
P.O. Box 241
Elkton, MD 21921

Dr. Grant Thompson
Morton Thiokol, Inc.
Wasatch Division
MS 240 P.O. Box 524
Brigham City, UT 84302

Dr. R.S. Valentini
United Technologies Chemical Systems
P.O. Box 50015
San Jose, CA 95150-0015

Dr. R.F. Walker
Chief, Energetic Materials Division
DRSMC-LCE (D), B-3022
USA ARDC
Dover, NJ 07801

Dr. Janet Wall
Code 012
Director, Research Administration
Naval Postgraduate School
Monterey, CA 93943

Director
US Army Ballistic Research Lab.
ATTN: DRXBR-IBD
Aberdeen Proving Ground, MD 21005

Commander
US Army Missile Command
ATTN: DRSMI-RKL
Walter W. Wharton
Redstone Arsenal, AL 35898

Dr. Ingo W. May
Army Ballistic Research Lab.
ARRADCOM
Code DRXBR - 1BD
Aberdeen Proving Ground, MD 21005

Dr. E. Zimet
Office of Naval Technology
Code 071
Arlington, VA 22217

Dr. Ronald L. Derr
Naval Weapons Center
Code 389
China Lake, CA 93555

T. Boggs
Naval Weapons Center
Code 389
China Lake, CA 93555

Lee C. Estabrook, P.E.
Morton Thiokol, Inc.
P.O. Box 30058
Shreveport, Louisiana 71130

Dr. J.R. West
Morton Thiokol, Inc.
P.O. Box 30058
Shreveport, Louisiana 71130

Dr. D.D. Dillehay
Morton Thiokol, Inc.
Longhorn Division
Marshall, TX 75670

G.T. Bowman
Atlantic Research Corp.
7511 Wellington Road
Gainesville, VA 22065

(DYN)

DISTRIBUTION LIST

R.E. Shenton
Atlantic Research Corp.
7511 Wellington Road
Gainesville, VA 22065

Mike Barnes
Atlantic Research Corp.
7511 Wellington Road
Gainesville, VA 22065

Dr. Lionel Dickinson
Naval Explosive Ordinance
Disposal Tech. Center
Code D
Indian Head, MD 20340

Prof. J.T. Dickinson
Washington State University
Dept. of Physics 4
Pullman, WA 99164-2814

M.H. Miles
Dept. of Physics
Washington State University
Pullman, WA 99164-2814

Dr. T.F. Davidson
Vice President, Technical
Morton Thiokol, Inc.
Aerospace Group
3340 Airport Rd.
Ogden, UT 84405

Mr. J. Consaga
Naval Surface Weapons Center
Code R-16
Indian Head, MD 20640

Naval Sea Systems Command
ATTN: Mr. Charles M. Christensen
NAVSEA-62R2
Crystal Plaza, Bldg. 6, Rm 806
Washington, DC 20362

Mr. R. Beauregard
Naval Sea Systems Command
SEA 64E
Washington, DC 20362

Brian Wheatley
Atlantic Research Corp.
7511 Wellington Road
Gainesville, VA 22065

Mr. G. Edwards
Naval Sea Systems Command
Code 62R32
Washington, DC 20362

C. Dickinson
Naval Surface Weapons Center
White Oak, Code R-13
Silver Spring, MD 20910

Prof. John Deutch
MIT
Department of Chemistry
Cambridge, MA 02139

Dr. E.H. deButts
Hercules Aerospace Co.
P.O. Box 27408
Salt Lake City, UT 84127

David A. Flanigan
Director, Advanced Technology
Morton Thiokol, Inc.
Aerospace Group
3340 Airport Rd.
Ogden, UT 84405

Dr. L.H. Caveny
Air Force Office of Scientific Research
Directorate of Aerospace Sciences
Bolling Air Force Base
Washington, DC 20332

W.G. Roger
Code 5253
Naval Ordance Station
Indian Head, MD 20640

Dr. Donald L. Ball
Air Force Office of Scientific Research
Directorate of Chemical & Atmospheric Sciences
Bolling Air Force Base
Washington, DC 20332

(DYN)

DISTRIBUTION LIST

Dr. Anthony J. Matuszko
Air Force Office of Scientific Research
Directorate of Chemical & Atmospheric
Sciences
Bolling Air Force Base
Washington, DC 20332

Dr. Michael Chaykovsky
Naval Surface Weapons Center
Code R11
White Oak
Silver Spring, MD 20910

J.J. Rocchio
USA Ballistic Research Lab.
Aberdeen Proving Ground, MD 21005-5066

B. Swanson
INC-4 MS C-346
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Dr. James T. Bryant
Naval Weapons Center
Code 3205B
China Lake, CA 93555

Dr. L. Rothstein
Assistant Director
Naval Explosives Dev. Engineering Dept.
Naval Weapons Station
Yorktown, VA 23691

Dr. M.J. Kamlet
Naval Surface Weapons Center
Code R11
White Oak, Silver Spring, MD 20910

Dr. Henry Webster, III
Manager, Chemical Sciences Branch
ATTN: Code 5063
Crane, IN 47522

Dr. A.L. Slafkosky
Scientific Advisor
Commandant of the Marine Corps
Code RD-1
Washington, DC 20380

Dr. H.G. Adolph
Naval Surface Weapons Center
Code R11
White Oak
Silver Spring, MD 20910

U.S. Army Research Office
Chemical & Biological Sciences
Division
P.O. Box 12211
Research Triangle Park, NC 27709

Dr. John S. Wilkes, Jr.
FJSRL/NC
USAF Academy, CO 80840

Dr. H. Rosenwasser
AIR-320R
Naval Air Systems Command
Washington, DC 20361

Dr. Joyce J. Kaufman
The Johns Hopkins University
Department of Chemistry
Baltimore, MD 21218

Dr. A. Nielsen
Naval Weapons Center
Code 385
China Lake, CA 93555

(DYN)

DISTRIBUTION LIST

K.D. Pae
High Pressure Materials Research Lab.
Rutgers University
P.O. Box 909
Piscataway, NJ 08854

Dr. John K. Dienes
T-3, B216
Los Alamos National Lab.
P.O. Box 1663
Los Alamos, NM 87544

A.N. Gent
Institute Polymer Science
University of Akron
Akron, OH 44325

Dr. D.A. Shockey
SRI International
333 Ravenswood Ave.
Menlo Park, CA 94025

Dr. R.B. Kruse
Morton Thiokol, Inc.
Huntsville Division
Huntsville, AL 35807-7501

G. Butcher
Hercules, Inc.
P.O. Box 98
Magna, UT 84044

W. Waesche
Atlantic Research Corp.
7511 Wellington Road
Gainesville, VA 22065

Dr. R. Bernecker
Naval Surface Weapons Center
Code R13
White Oak
Silver Spring, MD 20910

Prof. Edward Price
Georgia Institute of Tech.
School of Aerospace Engineering
Atlanta, GA 30332

J.A. Birkett
Naval Ordnance Station
Code 5253K
Indian Head, MD 20640

Prof. R.W. Armstrong
University of Maryland
Dept. of Mechanical Engineering
College Park, MD 20742

Herb Richter
Code 385
Naval Weapons Center
China Lake, CA 93555

J.T. Rosenberg
SRI International
333 Ravenswood Ave.
Menlo Park, CA 94025

G.A. Zimmerman
Aeroject Tactical Systems
P.O. Box 13400
Sacramento, CA 95813

Prof. Kenneth Kuo
Pennsylvania State University
Dept. of Mechanical Engineering
University Park, PA 16802

T.L. Boggs
Naval Weapons Center
Code 3891
China Lake, CA 93555

(DYN)

DISTRIBUTION LIST

Dr. C.S. Coffey
Naval Surface Weapons Center
Code R13
White Oak
Silver Spring, MD 20910

D. Curran
SRI International
333 Ravenswood Avenue
Menlo Park, CA 94025

E.L. Throckmorton
Code SP-2731
Strategic Systems Program Office
Crystal Mall #3, RM 1048
Washington, DC 23076

R.G. Rosemeier
Brimrose Corporation
7720 Belair Road
Baltimore, MD 20742

C. Gotzmer
Naval Surface Weapons Center
Code R-11
White Oak
Silver Spring, MD 20910

G.A. Lo
3251 Hanover Street
B204 Lockheed Palo Alto Research Lab
Palto Alto, CA 94304

R.A. Schapery
Civil Engineering Department
Texas A&M University
College Station, TX 77843

Dr. Y. Gupta
Washington State University
Department of Physics
Pullman, WA 99163

J.M. Culver
Strategic Systems Projects Office
SSPO/SP-2731
Crystal Mall #3, RM 1048
Washington, DC 20376

Prof. G.D. Duvall
Washington State University
Department of Physics
Pullman, WA 99163

Dr. E. Martin
Naval Weapons Center
Code 3858
China Lake, CA 93555

Dr. M. Farber
135 W. Maple Avenue
Monnovia, CA 91016

W.L. Elban
Naval Surface Weapons Center
White Oak, Bldg. 343
Silver Spring, MD 20910

Defense Technical Information Center
Bldg. 5, Cameron Station
Alexandria, VA 22314
(12 copies)

Dr. Robert Polvani
National Bureau of Standards
Metallurgy Division
Washington, D.C. 20234

Director
Naval Research Laboratory
Attn: Code 2627
Washington, DC 20375
(6 copies)

Administrative Contracting
Officer (see contract for
address)
(1 copy)