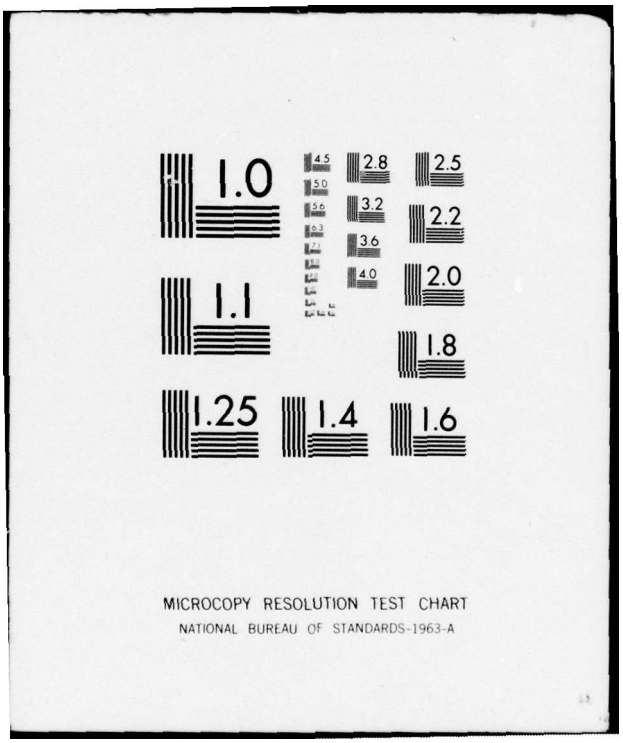
AD-A040 305 MASSACHUSETTS UNIV AMHERST MATERIALS RESEARCH LAB F/G 11/9
THE INFLUENCE OF EXTRUSION TEMPERATURE ON THE PROPERTIES OF ULT--ETC(U)
JUN 77 S KOJIMA, R S PORTER N00014-75-C-0686

UNCLASSIFIED TR-5 NL

| OF |
AD A040305

END

DATE FILMED
7-77


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6
6.3
7.1
8.0
9.0
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

(12) B.S.

OFFICE OF NAVAL RESEARCH

(15) Contract No. N00014-75-C-0686

Project No. NR 356-584

(9) TECHNICAL REPORT, NO. 5

(6) THE INFLUENCE OF EXTRUSION TEMPERATURE ON THE PROPERTIES OF ULTRA-DRAWN POLYETHYLENE,

by

(10) Shunji Kojima and Roger S. Porter
Polymer Science and Engineering
Materials Research Laboratory
University of Massachusetts
Amherst, Massachusetts 01003

(11) June 1, 1977

(12) 8p.

(14) TR-5

1472

408 988

THE INFLUENCE OF EXTRUSION TEMPERATURE ON THE PROPERTIES OF ULTRA-DRAWN POLYETHYLENE

Shunji Kojima* and Roger S. Porter
Polymer Science and Engineering
Materials Research Laboratory
University of Massachusetts
Amherst, Massachusetts

Abstract

In recent years, many studies have been made in this and other laboratories on the solid state extrusion of thermoplastics. The influence of extrusion conditions on the properties of the resultant fibers and films has not, however, been well examined and understood. A systematic study has thus been made to evaluate the influence of conditions for the extrusion of high density polyethylene. In this paper, extrusion temperature is the principal variable of evaluation. The temperature range for crystal formation prior to extrusion was held to a narrow range (132-136^{o}C). Related variables of molecular weight and draw ratio are discussed in detail in related studies.

*On leave from The Composite Research and Development Center of Toyo Seikan and Toyo Kohan Companies, 22-4, Okazawa, Hodogaya, Yokohama, Japan

Introduction

Many efforts have been made to study the deformation and morphology of polyethylene (1-3) and to make high-strength and/or high-modulus materials from a variety of polymers (4-39). Cold drawing (4-7), quench-rolling (8), hydrostatic (9-12) and direct (13-37) extrusion in the solid state have been the main methods employed.

Among the first investigation of solid state extrusion of high density polyethylene, HDPE, was by Southern in this laboratory (25) and by the research group headed by Professor Ward at Leeds University, England, and by Professor Takayanagi at Kyushu University in Japan (13). Many studies have been made on the extrusion process, on the resultant physical, mechanical and morphological properties, and on the use of the resultant fibers (13-37). The extrusion techniques has also been improved, and, in our hands, a continuous, steady-state extrusion has been developed for draw ratios to over ten (37).

In the perspective of prior work, it appears important to study the influence of extrusion conditions on the properties of the resultant fibers. Takayanagi (28) has reported on the influence of temperature for the extrusion of polypropylene. However, their techniques are quite different from ours. Capiati, et al. (41), recently reported on the influence of extrusion temperature and pressure for the extrusion of polyethylene. His results on the influence of extrusion temperature are meaningful but incomplete. This is because morphology perfection is influenced by both the temperature of crystal formation and the temperature of extrusion.

In the present study, the influence of temperature on extrusion over a relatively high and wide range is examined for its effect on the properties of the resultant HDPE fibers. The HDPE was crystallized in an Instron rheometer from the melt and then extruded at relatively high temperatures, which is the principal difference between our experiments and the excellent studies of Takayanagi.

Experimental

Two molecular weights of high density polyethylene (DuPont Alathon 7050 and 7026) were used. The weight average molecular weights of these samples are 56,000 and 135,000, respectively. The molecular weight and the distribution of molecular weight of these samples have been published (36).

For fiber preparation, three different brass capillaries were used with Teflon coating. All capillaries had 20 degree entrance angles but different draw ratios. The extrusion or draw ratios of the capillaries are calculated from the reduction ratio of cross-sectional areas. Polymer that does not pass the full entrance region is exposed to a draw ratio less than the maximum which is calculated from reservoir and capillary radii only. Thus, the actual draw ratio was calculated when steady-state extrusion was not achieved. The actual draw ratio and maximum draw ratio are shown in Table 1.

The HDPE samples were melted at 180^{o}C in an Instron rheometer and then cooled to the following two specific crystallization temperatures - 132^{o}C for Alathon 7050 and 136^{o}C for Alathon 7026.

The pressure was then increased to 2400 atms at the chosen constant temperature in the sealed rheometer. With crystallization complete, the temperature was changed to the extrusion temperature and the capillary exit unblocked. Extrusion was initiated at a constant pressure of 2400 atms.

The first 20 centimeters of each fiber were not used for the testing because the properties depend on the location along the fiber. This will be discussed later (38).

Young's modulus and tensile strength were determined using an Instron tensile tester. For the determination of modulus, an extensometer was also employed. The strain rates employed were 0.01 and 0.1 $min.^{-1}$ for modulus and strength determination, respectively, and moduli were determined below 0.2% strain.

The peak melting point and degree of crystallinity were determined using a differential scanning calorimeter (Perkin-Elmer DSC-1B) at a heating rate of $10^{o}C/min$. The peak melting point was corrected using an indium standard and the degree of crystallinity was calculated from the area under melting peaks. The heat of fusion for polyethylene and indium used for the calculation was 69.2 and 6.75 cal/g, respectively.

Results and Discussion

Table 2 shows the influence of extrusion temperature on the degree of crystallinity and peak melting point of resultant fibers. It is clearly shown that the degree of crystallinity increases with extrusion temperature and peak melting point stays constant. This may be due to the effect of annealing in the capillary itself.

It is well known (1) that the higher the crystal formation temperature, the thicker are the lamellae formed. In the present case, the polymer in the capillary cone region is under deformation and the deformation rate is a maximum at the cone exit, i.e. at the capillary entrance. After entering the capillary region, the polymer is not extended further and annealing occurs, which involves stress relaxation and crystal growth. It is, therefore, necessary to consider the effect of both deformation and annealing to discuss the formed morphology.

It is important to distinguish between deformation which merely changes the shape of the sample and deformation which changes the internal morphological structure. The ratio of the deformation which merely changes the shape of the sample should be greater when the polymer under deformation has greater movability, i.e. at higher temperature. Therefore, we can expect less chain orientation and fewer stressed tie molecules (i.e. a lower content of continuous crystal) for fibers drawn at higher temperature. A continuous crystal is the idealized model state in which all molecules are aligned and extended with chain ends buried randomly in the crystal lattice.

The effect of annealing is also greater at higher temperature, i.e. more chance of stress relaxation and recrystallization. This is a second reason why we can expect less chain orientation and less stressed tie molecules for fibers formed at higher temperature.

The data are consistent with these concepts. The crystals prepared and the fibers formed at higher temperatures exhibit a higher degree of crystallinity consistent with less chance for chain irregularities or stressed amorphous tie molecules; the polymer is thus effectively annealed after drawing. Peak melting point, however, is independent of the extrusion temperature because it does not depend on the amorphous structure. These trends hold for the different draw ratios and different molecular weight samples studied here. Figure 1 shows the influence of extrusion temperature on Young's modulus. Young's modulus increases slightly but significantly with decreasing extrusion temperature. There is a sharp drop in tensile modulus at the highest temperatures corresponding to incipient melting of the fibers on exiting the die.

Young's modulus depends essentially on the number of tie molecules which sustain stress on stretching. This corresponds to the fraction of continuous crystals. It is well known that the modulus of drawn fibers decreases on annealing due to the relaxation of stressed tie molecules. This can occur below the nominal melting point (42). A decrease in modulus with increasing extrusion temperature is likely due to this feature. At the highest extrusion temperatures, the modulus drops

precipitously due to actual filament melting on extrusion. Among the several studies of extrusion temperature in this lab, only one showed Young's modulus to increase with extrusion temperature. The data in the same study as a function of pressure, however, do indicate that Young's modulus decreases with increasing extrusion temperature. The difference is thus likely due to an increase in the degree of undercooling for extrusion due to the enhanced pressure.

Table 2 shows that tensile strength is insensitive to extrusion temperature. Tensile strength is influenced by the number and nature of weak points for stress concentration. The slippage between fibrils may, in this case, be the main reason for fracture as demonstrated by Capiati (41). These results thus suggest that the interaction between fibrils, following the tensile strength, is independent of extrusion temperature.

The optical clarity of fibers decreases at the highest extrusion temperatures. This suggests the formation of lamellae with perhaps spherulitic structure. This structure cannot be formed without an annealing or recrystallization process in highly-drawn fibers since related tests indicate that extrusion without annealing totally destroys the original spherulites.

These results show that the higher extrusion temperatures give fibers of higher crystallinity and lower modulus; the tensile strength and peak melting point are not affected by temperature over the range tested. It should be noted that extrusion rate decreases with decreasing extrusion temperature making it difficult to extrude

at lower temperatures than examined here. Exploration of extrusion is being explored at lower temperatures (43).

The molecular weight study by Perkins, et al. (36), shows a difference of peak melting point between extruded Alathon 7050 and 7026 of about 4°C. Polymer molecular weight is thus an important factor which influences both extrusion rate and properties of resultant fibers. A lower extrusion rate and increased tensile properties are expected for higher molecular weight samples.

At 5-10°C below the fiber melting point, the extrusion rate is reasonably fast, samples are defect free, and Young's modulus increases only modestly with further decrease in extrusion temperature. Takayanagi (19) has proposed that the best extrusion temperature is between the melting point and α transition temperature. He extruded mainly at lower temperatures near 110°C for high density polyethylene. It is, however, quite difficult to obtain high draw ratio at these temperatures. This is a principal difference between this work and that of Takayanagi.

Conclusions

These new data lead to several conclusions regarding the solid-state extrusion of high density polyethylene:

Lower extrusion temperatures yield filaments of higher Young's modulus with results insensitive to polymer molecular weight for extrusion draw ratios over

a wide range. Peak melting point and tensile strength are invariant for these extrusion conditions.

A convenient extrusion temperature for preparation of high-modulus fibers was determined to be between 5 to 10^{o}C below the melting point of the resultant fibers, dependent on polyethylene molecular weight and draw ratio.

Acknowledgment

The authors express appreciation for financial support of this research to the Office of Naval Research.

References

1. A. Peterlin, J. Mater. Sci. 6, 490 (1971).
2. D. P. Pope and A. Keller, J. Polym. Sci., Polym. Phys. Ed. 13, 533 (1975).
3. A. Keller and D. P. Pope, J. Mater. Sci. 6, 453 (1971).
4. G. Capaccio and I. M. Ward, Polymer 15, 233 (1974).
5. J. M. Andrews and I. M. Ward, J. Mater. Sci. 5, 411 (1970).
6. G. Capaccio and I. M. Ward, Nature Phys. Sci. 243, 143 (1973).
7. M. Takayanagi, K. Imada and T. Kajiyama, J. Polym. Sci. 15, 263 (1966).
8. T. K. Kwei, T. T. Wang and H. E. Bair, J. Polym. Sci. C, 31, 87 (1970).
9. K. Nakayama and H. Kanetsuna, Kobunshi-ronbunshu 31, 5, 321 (1974).
10. K. Nakayama and H. Kanetsuna, Kobunshi-ronbunshu 31, 4, 256 (1974).
11. K. Nakayama and H. Kanetsuna, Kobunshi-kagaku 30, 344, 713 (1973).
12. A. G. Gibson, I. M. Ward, B. N. Cole and B. Parsons, J. Mater. Sci., Letter 9, 1193 (1974).
13. K. Imada, T. Yamamoto, K. Ueno, D. Matsukuma and M. Takayanagi, Zairyo 19, 199, 32 (1970).
14. M. Takayanagi, K. Imada and T. Yamamoto, Asahi Garasu Kogyo Gijutsu Shoreikai Kenkyu Hokoku 17, 273 (1970).
15. K. Imada, T. Yamamoto, K. Shigematsu and M. Takayanagi, J. Mater. Sci. 6, 537 (1971).
16. M. Takayanagi and K. Imada, Asahi Garasu Kogyo Gijutsu Shoreikai Kenkyo Hokoku 19, 195 (1971).

17. K. Imada, T. Yamamoto, K. Kanekiyo and M. Takayanagi, Zairyo 20, 212, 52 (1971).

18. K. Nakamura, K. Imada and M. Takayanagi, Intern. J. Polymeric Materi. 2, 71 (1972).

19. K. Imada and M. Takayanagi, Intern. J. Polymeric Mater. 2, 89 (1973).

20. S. Maruyama, K. Imada and M. Takayanagi, Intern. J. Polymeric Mater. 2, 105 (1973).

21. S. Maruyama, K. Imada and M. Takayanagi, Intern. J. Polymeric Mater. 2, 125 (1973).

22. K. Imada, Sosei to Kako 14, 148, 413 (1973-5).

23. A. Makinouchi and N. Shimizu, Sosei to Kako 13, 134, 187 (1972-3).

24. P. Predecki and W. O. Statton, J. Polymer Sci. B 10, 87 (1972).

25. J. H. Southern and R. S. Porter, J. Appl. Polym. Sci. 14, 2305 (1970).

26. C. R. Desper, J. H. Southern, R. D. Ulrich and R. S. Porter, J. Appl. Phys. 41, 4284 (1970).

27. J. H. Southern and R. S. Porter, J. Macromol. Sci., Phys. B4, 541 (1970).

28. R. G. Crystal and J. H. Southern, J. Polym. Sci. A-2, 9, 1641 (1971).

29. J. H. Southern, N. E. Weeks, R. S. Porter and R. G. Crystal, Die Macromol. Chem. 162, 19 (1972).

30. J. H. Southern, R. S. Porter and H. E. Bair, J. Polym. Sci. A-2, 10, 1135 (1972).

31. P. J. Miller, J. F. Jackson and R. S. Porter, J. Polym. Sci., Polym. Phys. Ed. 11, 2001 (1973).

32. J. H. Southern and G. L. Wilkes, J. Polym. Sci. B 11, 555 (1973).

33. T. Niikuni and R. S. Porter, J. Mater. Sci. 9, 389 (1974).

34. N. E. Weeks and R. S. Porter, J. Polym. Sci., Polym. Phys. Ed. 12, 635 (1974).

35. R. S. Porter, J. H. Southern and N. E. Weeks, Polym. Eng. Sci. 15, 213 (1975).

36. W. G. Perkins, N. J. Capiati and R. S. Porter, Polym. Eng. Sci. 16, 200 (1976).

37. N. J. Capiati, S. Kojima, W. Perkins and R. S. Porter, J. Mater. Sci., accepted.

38. S. Kojima and R. S. Porter, paper in preparation.

39. E. S. Clark and I. S. Scott, Polym. Eng. Sci. 14, 682 (1974).

40. S. Kojima and R. S. Porter, paper in preparation.

41. N. J. Capiati and R. S. Porter, J. Polym. Sci., Polym. Phys. Ed. 13, 1177 (1975).

42. W. T. Mead and R. S. Porter, J. Appl. Phys. 47, 4278 (1976).

43. W. T. Mead and R. S. Porter, to be published.

TABLE 1

Draw Ratio for Capillary Entrance Zones

Capillary Draw Ratio		
Calculated Maximum	Actual	Sample Studied
10.7	10.7	After First 10 cm
11.8	11.8	After First 11 cm
35.9	31 ± 4*	Between 20 and 30 cm

*Samples did not pass through full capillary entrance extrusion draw region.

TABLE 2

Influence of Extrusion Temperature on Percent Crystallinity, Peak Melting Point and Tensile Strength

Sample	Draw Ratio	Extrusion Temperature, °C	Crystallinity, %	Peak Melting Point, °C	Tensile Strength x 10^9 /dynes/cm^2
Alathon 7050	10.7	110	81.8	136.5	2.59
(M_w = 59,000)		115	80.0	136.1	2.44
		120	81.7	136.2	2.31
		125	81.6	136.6	2.39
		130	82.2	136.3	2.37
Alathon 7026	11.8	110	78.0	138.0	3.75
(M_w = 147,000)		115	77.1	137.6	3.27
		120	77.5	138.1	3.98
		125	79.5	137.9	3.84
		130	81.4	138.4	3.90
Alathon 7050	31±4	132	86.1	138.0	3.85
(M_w = 59,000)		136	86.3	138.4	4.30

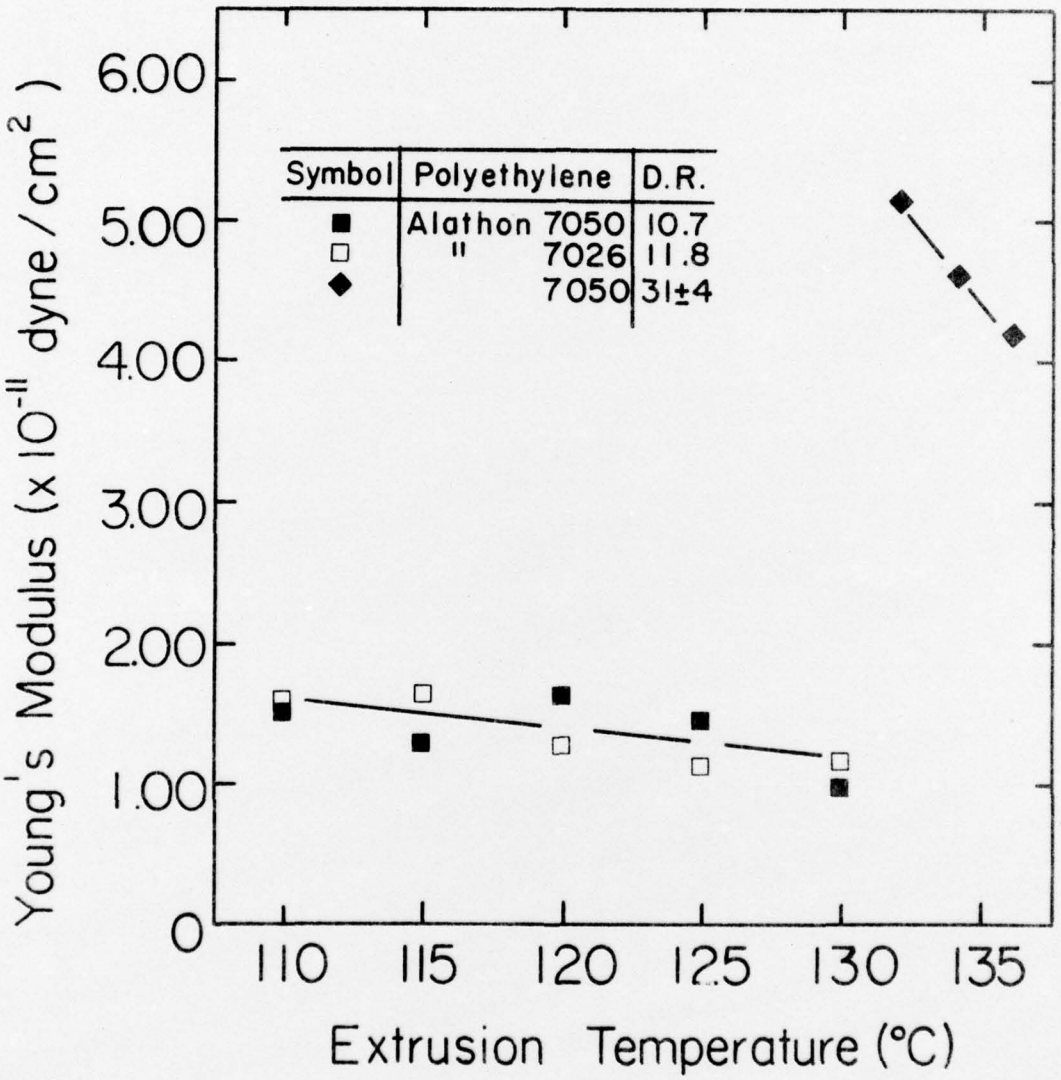


Figure 1

Young's Modulus as a Function of Extrusion Temperature

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report No. 5	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* The Influence of Extrusion Temperature on the Properties of Ultra-Drawn Polyethylene		5. TYPE OF REPORT & PERIOD COVERED Interim 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR*(s)* Shunji Kojima and Roger S. Porter		8. CONTRACT OR GRANT NUMBER*(s)* N00014-75-C-9686
9. PERFORMING ORGANIZATION NAME AND ADDRESS Polymer Science and Engineering University of Massachusetts Amherst, Massachusetts 01003		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NR 356-584
11. CONTROLLING OFFICE NAME AND ADDRESS ONR Branch Office 495 Summer Street Boston, Massachusetts 02210		12. REPORT DATE June 1, 1977 13. NUMBER OF PAGES 15 (incl. tables and figures)
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)*

Approved for public release; distribution unlimited

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

18. SUPPLEMENTARY NOTES

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

high-density polyethylene; solid-state extrusion; ultra-drawn fibers; temperature; molecular weight; draw ratio; crystallinity; melting point; tensile modulus; tensile strength

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

In recent years, many studies have been made in this and other laboratories on the solid state extrusion of thermoplastics. The influence of extrusion conditions on the properties of the resultant fibers and films has not, however, been well examined and understood. A systematic study has thus been made to evaluate the influence of conditions for the extrusion of high density polyethylene. In this paper, extrusion temperature is the principal variable of evaluation. The temperature range for crystal formation prior to extrusion was held to a narrow

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

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

range (132-136°C). Related variables of molecular weight and draw ratio are discussed in detail in related studies.

TECHNICAL REPORT DISTRIBUTION LIST

	No. Copies
Office of Naval Research Arlington, Virginia 22217 Attn: Code 472	2
Office of Naval Research Arlington, Virginia 22217 Attn: Code 102IP	6
ONR Branch Office 536 S. Clark Street Chicago, Illinois 60605 Attn: Dr. George Sandoz	1
ONR Branch Office 715 Broadway New York, New York 10003 Attn: Scientific Dept.	1
ONR Branch Office 1030 East Green Street Pasadena, California 91106 Attn: Dr. R. J. Marcus	1
ONR Branch Office 760 Market Street, Rm. 447 San Francisco, California 94102 Attn: Dr. P. A. Miller	1
ONR Branch Office 495 Summer Street Boston, Massachusetts 02210 Attn: Dr. L. H. Peebles	1
Director, Naval Research Laboratory Washington, D.C. 20390 Attn: Library, Code 2029 (ONRL) Technical Info. Div. Code 6100, 6170	6 1 1
The Asst. Secretary of the Navy (R&D) Department of the Navy Room 4E736, Pentagon Washington, D.C. 20350	1
Commander, Naval Air Systems Command Department of the Navy Washington, D.C. 20360 Attn: Code 310C (H. Rosenwasser)	1

	No. Copies
Defense Documentation Center Building 5, Cameron Station Alexandria, Virginia 22314	12
U.S. Army Research Office P.O. Box 12211 Research Triangle Park, North Carolina 27709 Attn: CRD-AA-IP	
Commander Naval Undersea Research & Development Center San Diego, California 92132 Attn: Technical Library, Code 133	1
Naval Weapons Center China Lake, California 93555 Attn: Head, Chemistry Division	1
Naval Civil Engineering Laboratory Port Hueneme, California 93041 Attn: Mr. W. S. Haynes	1
Professor O. Heinz Department of Physics & Chemistry Naval Postgraduate School Monterey, California 93940	
Dr. A. L. Slafkosky Scientific Advisor Commandant of the Marine Corps (Code RD-1) Washington, D.C. 20380	1

No. Copies

NASA-Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135
Attn: Dr. T. T. Serofini, MS-49-1 1

Dr. Charles H. Sherman, Code TD 121
Naval Underwater Systems Center
New London, Connecticut 1

Dr. William Risen
Department of Chemistry
Brown University
Providence, Rhode Island 02912 1

Dr. Alan Gent
Department of Physics
University of Akron
Akron, Ohio 44304 1

Mr. Robert W. Jones
Advanced Projects Manager
Hughes Aircraft Company
Mail Station D 132
Culver City, California 90230 1

Dr. C. Giori
IIT Research Institute
10 West 35 Street
Chicago, Illinois 60616 1

No. Copies

Dr. David Roylance
Department of Materials Science and Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts 02039 1

Dr. W. A. Spitzig
United States Steel Corporation
Research Laboratory
Monroeville, Pennsylvania 15146 1

Dr. T. P. Conlon, Jr., Code 3622
Sandia Laboratories
Sandia Corporation
Albuquerque, New Mexico 87115 1

Dr. Martin Kaufmann, Head
Materials Research Branch, Code 4542
Naval Weapons Center
China Lake, California 93555 1

Dr. T. J. Reinhart, Jr., Chief
Composite and Fibrous Materials Branch
Nonmetallic Materials Division
Department of the Air Force 1
Air Force Materials Laboratory (AFSC)
Wright-Patterson Air Force Base, Ohio 45433

TECHNICAL REPORT DISTRIBUTION LIST

	No. Copies
Dr. Stephen H. Carr Department of Materials Science Northwestern University Evanston, Illinois 60201	1
Dr. M. Broadhurst Bulk Properties Section National Bureau of Standards U.S. Department of Commerce Washington, D.C. 20234	2
Dr. C. H. Wang Department of Chemistry University of Utah Salt Lake City, Utah 84112	1
Dr. T. A. Litovitz Department of Physics Catholic University of America Washington, D.C. 20017	1
Dr. R. V. Submaranian Washington State University Department of Materials Science Pullman, Washington 99163	1
Dr. M. Shen Department of Chemical Engineering University of California Berkeley, California 94720	1
Dr. H. Freiser Department of Chemistry University of Arizona Tuscon, Arizona 85721	
Dr. V. Stannett Department of Chemical Engineering North Carolina State University Raleigh, North Carolina 27607	1
Dr. D. R. Uhlman Department of Metallurgy and Material Science Center for Materials Science and Engineering Massachusetts Institute of Technology Cambridge, Massachusetts 02139	1
Naval Surface Weapons Center White Oak Silver Spring, Maryland 20910 Attn: Dr. J. M. Augl Dr. B. Hartmann	1
Dr. G. Goodman Globe Union Inc. 5757 North Green Bay Avenue Milwaukee, Wisconsin 53201	1
Picatinny Arsenal SMUPA-FR-M-D Dover, New Jersey 07801 Attn: A. M. Anzalone Bldg. 3401	1
Dr. J. K. Gillham Princeton University Department of Chemistry Princeton, New Jersey 08540	1
Douglas Aircraft Co. 3855 Lakewood Boulevard Long Beach, California 90846 Attn: Technical Library C1 290/36-84 AUTO-Sutton	1
Dr. E. Baer Department of Macromolecular Science Case Western Reserve University Cleveland, Ohio 44106	1
Dr. K. D. Pae Department of Mechanics and Materials Science Rutgers University New Brunswick, New Jersey 08903	1