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NATIONAL SCIENCE FOUNDATION FINAL PROJECT REPORT

PART I - PROJECT IDENTIFICATION INFORMATION

1. Program Official/Org. Bruce A. MacDonald - DMR

2. Program Name METALS, CERAMICS, & ELECTRONIC MATERIALS

3. Award Dates (MM/YY) From: 08/85 To: 01/91

4. Institution and Address
Georgia Tech Research Corp
Administration Building
Atlanta GA 30332

5. Award Number 8504167

6. Project Title
Quantitative Analysis of Fracture Surfaces using Stereological Methods

This Packet Contains
NSF Form 98A
And 1 Return Envelope

PART IV — FINAL PROJECT REPORT — SUMMARY DATA ON PROJECT PERSONNEL

(To be submitted to cognizant Program Officer upon completion of project)

The data requested below are important for the development of a statistical profile on the personnel supported by Federal grants. The information on this part is solicited in response to Public Law 99-383 and 42 USC 1885C. All information provided will be treated as confidential and will be safeguarded in accordance with the provisions of the Privacy Act of 1974. You should submit a single copy of this part with each final project report. However, submission of the requested information is not mandatory and is not a precondition of future award(s). Check the "Decline to Provide Information" box below if you do not wish to provide the information.

Please enter the numbers of individuals supported under this grant.
Do not enter information for individuals working less than 40 hours in any calendar year.

	Senior Staff		Post-Doctorals		Graduate Students		Under-Graduates		Other Participants[1]	
	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.
A. Total, U.S. Citizens	1		0	0	1	1	0	0	0	0
B. Total, Permanent Residents	1		0	0	1	0	0	0	0	0
U.S. Citizens or Permanent Residents[2]:										
American Indian or Alaskan Native . . .										
Asian	1				1					
Black, Not of Hispanic Origin										
Hispanic										
Pacific Islander										
White, Not of Hispanic Origin										
C. Total, Other Non-U.S. Citizens										
Specify Country 1.										
2.										
3.										
D. Total, All participants (A + B + C)	2	0	0	0	2	1	0	0	0	0
Disabled[3]										

☐ Decline to Provide Information: Check box if you do not wish to provide this information (you are still required to return this page along with Parts I-III).

[1]Category includes, for example, college and precollege teachers, conference and workshop participants.

[2]Use the category that best describes the ethnic/racial status for all U.S. Citizens and Non-citizens with Permanent Residency. *(If more than one category applies, use the one category that most closely reflects the person's recognition in the community.)*

[3]A person having a physical or mental impairment that substantially limits one or more major life activities; who has a record of such impairment; or who is regarded as having such impairment. *(Disabled individuals also should be counted under the appropriate ethnic/racial group unless they are classified as "Other Non-U.S. Citizens.")*

AMERICAN INDIAN OR ALASKAN NATIVE: A person having origins in any of the original peoples of North America, and who maintain cultural identification through tribal affiliation or community recognition.

ASIAN: A person having origins in any of the original peoples of East Asia, Southeast Asia and the Indian subcontinent. This area includes, for example, China, India, Indonesia, Japan, Korea and Vietnam.

BLACK, NOT OF HISPANIC ORIGIN: A person having origins in any of the black racial groups of Africa.

HISPANIC: A person of Mexican, Puerto Rican, Cuban, Central or South American or other Spanish culture or origin, regardless of race.

PACIFIC ISLANDER: A person having origins in any of the original peoples of Hawaii; the U.S. Pacific Territories of Guam, American Samoa, or the Northern Marianas; the U.S. Trust Territory of Palau; the islands of Micronesia or Melanesia; or the Philippines.

WHITE, NOT OF HISPANIC ORIGIN: A person having origins in any of the original peoples of Europe, North Africa, or the Middle East.

THIS PART WILL BE PHYSICALLY SEPARATED FROM THE FINAL PROJECT REPORT AND USED AS A COMPUTER SOURCE DOCUMENT. DO NOT DUPLICATE IT ON THE REVERSE OF ANY OTHER PART OF THE FINAL REPORT.

A.M. Gokhale
DMR - 8504167

PART - II

SUMMARY OF COMPLETED PROJECT

The basic objective of this research was to develop unambiguous, unbiased, assumption - free, and practically feasible as well as flexible stereological techniques for quantitative characterization of the geometric attributes of fracture surfaces and microstructural features in three dimensional space. The quantification of structural and fractographic properties is expected to provide important input concerning the deformation and fracture processes that are responsible for material fracture and failure; these studies are crucial for the improvement of existing materials, and for the development of new materials. The basic components of the research work were analytical theoretical work, digital image analysis, computer simulation and calculations, and experimental measurements on the fracture surfaces of a low alloy steel, aluminum - copper alloy, and a metal matrix composite. As the characterization techniques are absolutely general, they are equally applicable to biological, pathological, botanical, and geological structures. Some of our results are being used by biologists for the characterization of blood vessels, microtubules, neurons, etc. (see enclosed copies of SQM news letters). A very general method has been developed for the measurement of roughness of a fracture surface of any arbitrary geometry. A stereological method has been also developed for quantification of anisotropy of symmetric fracture surfaces. We have utilized digital image analysis for characterization of fracture profiles. These methods were utilized to study the role of processing defects in the fracture of a metal matrix composite, detection of temper embrittlement in steel via fractal dimension measurement, and effect of microstructure on the fracture processes in an aluminum alloy, etc.

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PART - III

TECHNICAL INFORMATION

The end point of deformation and fracture processes is the generation of fracture surface. It may be said that the geometric attributes of fracture surface and the associated microstructural features contain quantitative information concerning the processes that lead to fracture. In order to develop such correlations among fractographic attributes, fracture behavior and properties, and material microstructure, it is essential to utilize the structure characterization techniques that are assumption free and unbiased, so that the observed correlations are real, <u>and</u> the real correlations <u>are</u> observed. The main objective of this research was to develop the general, assumption free, and unbiased stereological techniques for quantitative characterization of fracture surfaces and microstructures in three dimensional space from the observations and measurements that can be performed on the associated lower dimensional manifolds. The basic components of this research were analytical theoretical work involving the applications of stochaistic geometry, fractal geometry, differential geometry, and integral geometry, digital image analysis for quantitative measurements, computer simulations, and experimental measurements on the fracture profiles and microstructures. A very significant progress has been made during the course of this project work. This research has provided very important input in the development of new science of quantitative fractography. Our results are reported in more than twenty publications in prestigious journals and conference proceedings (the publication list is enclosed). The following is a very brief summary of this progress.

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(1) The experimental techniques for the vertical section profilometry and digital image analysis of fracture profiles were established for the quantification of fracture surface Profiles (publication no. 9,10,11,15)

(2) A computer code was developed to calculate profile roughness, fractal dimension, and profile line element angular orientation distribution function from the digitized profile co-ordinate data obtained by digital image analysis. (Publication no.11, 12)

(3) The above experimental methods were successfully applied to the fracture profiles of low alloy steel, aluminum-copper alloy, and metal matrix composite material (publication no. 5,19,11,13,15,16)

(4) Resolution dependent fracture profile roughness parameter was studied in detail to establish the reverse sigmoidal behavior which describes the ruler length or resolution dependence of profile roughness. A computer program was developed to calculate the fractal dimension of fracture profile and the saturation roughness from the experimental data (publication no. 6,12,18,19,21)

(5) The techniques established in (1) to (4) were utilized to study variation of the fractal dimension of fracture profile of test fracture surfaces with the tempering temperature in a low alloy steel. It was shown that the temper embrittlement leads to a significant decrease in the profile fractal dimension (publication no. 11, 12)

(6) The profile roughness data was successfully utilized to analyze fatigue crack growth behavior in a low alloy steel.

(7) The utility of quantitative fractographic techniques was demonstrated via experimental

work on the fracture profiles from the fracture surfaces of Al-Cu alloy (publication no. 10)

(8) A computer program was developed to calculate anisotropy of symmetric fracture surfaces from the profile line element angular orientation distribution function (publication no. 10)

(9) A computer program was developed to calculate spatial distribution of fibers in a metal matrix composite from digitized certroid co-ordinate data, and it was utilized to quantify the spatial distribution of continuous unidirectional Al_2O_3 fibers in Al-Li alloy matrix.

(10) Quantitative SEM fractography was utilized to analyze the role of processing defects in the fracture of metal matrix composite material (publication no. 5, 8).

(11) A general, assumption - free, and unbiased stereological relationship has been derived to estimate roughness (and hence the surface area) of any arbitrary fracture surface from the measurements performed on the corresponding vertical section fracture profiles; the result is a fundamental equation of quantitative fractography (publication no. 3)

(12) The efficiency and precision of the above general method for surface roughness measurement was studied in detail via extensive computer simulations. It was shown that just three vertical sections which are mutually at an angle of 120°, contain sufficient structural information for estimation of surface roughness of anisotropic fracture surface (publication no. 4)

(13) A design based efficient stereological method was developed to estimate the length densities of the lineal microstructural feature from the measurements performed on their projected images; this result is utilized by biologists for the estimation of the length density of blood vessels, microtubles, neurons, etc. (see pub. no 2, and enclosed copies of SQM news letters).

(14) A set of design based test line shapes have been theoretically calculated for efficient quantification of anisotropy of lines in two dimensional plane; the intersection counts with these test lines directly yield the Fourier coefficients that quantify the anisotropy.

(15) The stereological techniques were utilized to characterize the anisotropic fracture surfaces of metal matrix composite materials (publication 4,5, 14).

(16) The stereological methods were utilized to quantitatively analyze the creep fracture processes (publication no. 1).

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LIST OF PUBLICATIONS ACKNOWLEDGING NSF SUPPORT

1. A.M. Gokhale, "Utility of Stereological Counting Measurements in the Study of Creep Cavitation Kinetics", Proceedings of MiCon-90, ASTM Special Tech. Pub. No. 1049, George F. VanderVoort ed., pp. 332-339, 1991.

2. A.M. Gokhale, "Unbiased Estimation of Curve Length in 3D Using Vertical Slices", Journal of Microscopy, vol. 159, pt. 2, pp. 133-141, 1990.

3. A.M. Gokhale and E.E. Underwood, "A General Method for Measurement of Fracture Surface Roughness - I; Theoretical Aspects", Metall. Trans., vol, 21A, pp. 1193-1199, 1990.

4. A.M. Gokhale and W.J. Drury, "A General Method for Measurement of Fracture Surface Roughness - II; Practical considerations." Metall. Trans., vol. 21A, pp. 1201-1207, 1990.

5. S.D. Antolovich, A.M. Gokhale and C. Bathias, "Application of Quantitative Fractography and Computed Tomography to Fracture Processes in Materials", ASTM Special Tech. Pub. No. 1085, B.M. Strauss and S.K. Patatunda, eds., pp. 3-25, 1990.

6. A.M. Gokhale and K. Banerji, "Criteria for Selecting Optimum Resolution For Quantitative Analysis of Fracture Surfaces", Microstructural Science, vol. 17, pp. 67-79, 1989.

7. A.M. Gokhale and E.E. Underwood, "A New Parametric Roughness Equation For Quantitative Fractography", Acta Stereologica, vol. 8, pp. 43-52, 1989.

8. W.J. Drury, "Involvement of Processing Defects in Failure of FP.Al-Li", Metall. Trans., vol. 20A, pp. 2175-2178, 1989.

9. E.E. Underwood, "Estimating Feature Characteristics by Quantitative Fractography", Jnl. of Metals, vol. 38, No. 4 (1986) 30-33.

10. K. Banerji and E.E. Underwood, "On Estimating the Fracture Surface Area of Al-4% Cu Alloys", Microstructural Science, vol. 13, ed. by S.A. Shield, et al., 17th Annual Technical Meetings of the Inter. Metallographic Soc., Philadelphia, (1987) 537-551.

11. E.E. Underwood and K. Banerji, "Quantitative Fractography", in Fractography, vol. 12, Metals Handbook, 9th Edition, ASM International, (1987) 193-210.

12. E.E. Underwood and K. Banerji, "Fractal Analysis of Fracture Surfaces", ibid., 211-215.

13. E.E. Underwood, "Stereological Analysis of Fracture Roughness Parameters", 25th Memorial Volume of the Inter. Soc. for Stereology, ed. by R.E. Miles, Publ. by Acta Stereologica, Ljubljana, Yugoslavia, (1987) 169-178.

14. W.J. Drury and E.E. Underwood, "Quantitative Fractographic Analyses of Oriented Fracture Surfaces", Proc. 7th Inter. Congr. for Stereology, Pt. II, ed. by J.-L. Chermant, Vol. 6, Suppl. III, (1987) 549-554.

15. E.E. Underwood, "The Analysis of Nonplanar Surfaces Using Stereological and Other Methods", ibid., 855-876.

16. W.J. Drury, K. Banerji and E.E. Underwood, "Quantitative Metallographic and Fractographic Analyses of MMC Microstructures", Proc. Advanced Mats. Conf., ed. by J.G. Morse, Publ. by The Met. Soc., Warrendale, PA (1987) 279-287.

17. E.E. Underwood, "The Current Status of Modern Quantitative Fractography", Advances in Fracture Research, vol. 5, ed. by K. Salama, et al., Seventh Int. Conf. on Fracture, Pergamon Press, (1989) 3391-3409.

18. E.E. Underwood, "Recent Advances in Quantitative Fractography", Fracture Mechanics: Microstructure and Mechanisms, ed. by S.V. Nair, et al., ASM International, (1989) 87-109.

19. E.E. Underwood, "The New Quantitative Fractography for Analyzing Metallic Surfaces", Jnl. of Metals, vol. 42, No. 10 (1990) 10-15.

20. E.E. Underwood, "Evaluation of Overlaps in Fracture Surfaces", MiCon 90: Advances in Video Technology for Microstructural Control, ASTM STP 1094, ed. by G.F. Vander Voort, American Society for Testing and Materials, Philadelphia (1990) 340-353.

21. E.E. Underwood, "Treatment of Reversed Sigmoidal Curves for Fractal Analysis", ibid., 354-364.

22. E.E. Underwood, "Directed Measurements and Heterogeneous Structures in Quantitative Fractography", Proc. STERMAT '90, Third Conf. on "Stereology in Materials Science", Szczyrk, Poland Publ. by Polish Soc. for Stereology (1990) 100-115.