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PI/PD Name and Address

Arun Mahadeo Gokhale
School of Materials Engineering
~~GA Tech Res Corp - GIT~~
Georgia Institute of Technology
Atlanta GA 30332 0245

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: 07/9[illegible] To: 12/93

4. Institution and Address
GA Tech Res Corp - GIT
Administration Building
Atlanta GA 30332

5. Award Number 9013096

6. Project Title
Quanatitative 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 resonse 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	0	2	1				
B. Total, Permanent Residents	1	0	0	0	0	0				
U.S. Citizens or Permanent Residents[2]:										
American Indian or Alaskan Native										
Asian	1	0			0	0				
Black, Not of Hispanic Origin					0	0				
Hispanic					0	0				
Pacific Islander					0	0				
White, Not of Hispanic Origin	1	0			2	1				
C. Total, Other Non-U.S. Citizens	0	0	0		2	0				
Specify Country 1. India					2	0				
2.										
3.										
D. Total, All participants (A + B + C)	2	0	0	0	4	1				
Disabled[3]	0	0	0	0	0	0	0	0	0	0

☐ 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 fo 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 maintains cultural identification through tribal affiliation or community recognition.

ASIAN: A person having origins in any of the original peoples of East Asia, Southeast Asia or 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, and the Northern Marinas; the U.S. Trust Territory of Palau; the islands of Micronesia and 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.

A.M. Gokhale
DMR-9013098

PART - II

SUMMARY OF COMPLETED PROJECT

The basic objective of this research was to develop general, unbiased, efficient, and practical stereological and fractographic procedures for quantitative characterization of fracture surfaces and microstructural features in three dimensional space from the observations on the lower dimensional manifolds such as two dimensional sections and projections. These techniques were utilized to study the processes that govern the deformation and fracture of materials. The resulting information is useful to optimize the properties of the existing materials and for the development of new materials. As our stereological techniques are absolutely general, they are also applicable to biological structures. Some of the stereological methods developed during this project are being currently utilized by biologists to estimate length density of microvessels in brain, lengths of capillaries in heart, etc. The results of our research are reported in 17 technical publications, 10 conference presentations (6 invited papers), a theme lecture in 8th International congress for Stereology, two M.S., and one Ph.D. thesis.

The basic components of this project were analytical theoretical work, computer simulations/calculations, and experimental measurements to demonstrate the utility of the new stereological and quantitative fractographic techniques. The experimental portion of the project involved study of creep fracture and creep damage in copper, fatigue crack closure in inconel-718, impact and tensile fracture surfaces of AISI 4340 steel having different microstructure, and microcrack damage in thermally cycled metal matrix composite. We have developed new stereology based method for estimation of average growth rate of thermally induced microcracks in composite materials. A new method has been developed for estimation of length density of lineal features (e.g. dislocations) from projected images of foils of unknown and variable thickness. We have developed a general method for estimation of fractal dimension of anisotropic surfaces from profilometric data. These results are utilized to correlate fractal dimension to absorbed impact energy in AISI 4340 steel. The stereological measurements were utilized to develop a model for cavity nucleation during creep of copper. The image analysis techniques have been developed to quantify spatial arrangements of microstructural features.

A.M. Gokhale
DMR-9013098

PART-III

TECHNICAL INFORMATION

This project work concerns development of quantitative fractographic and microscopic techniques based on stereological principles, and applications of the new methods to the study of deformation and fracture of monolithic and composite materials to illustrate their utility and demonstrate their practical application. The results are useful for development of quantitative correlations of material microstructure to the operative deformation and fracture processes. The basic components of these research were analytical theoretical work, image analysis and software development, computer simulations and calculations, and experimental studies of fracture processes using the new quantitative techniques. The analytical theoretical research involved applications of stochaistic geometry, fractal geometry, and differential geometry to develop the techniques for the estimation of geometric attributes of nonplanar and rough fracture surfaces, and microstructures, in 3D space from the measurements performed on the random or design based 2D sections and projected images. The digital image profilometric techniques have been developed for acquiring the necessary data on fracture profiles. Computer simulations have been utilized to arrive at efficient sampling procedures for quantification of microstructures and fracture surfaces.

Our research has contributed significantly to the development of quantitative fractography and design based stereology. The results are reported in 17 publications in archival technical journals and conference proceedings (list of publications is enclosed), two M.S., and one Ph.D. thesis. The following is a brief summary of this progress.

(A) Analytical Theoretical Work:

(i) A new stereological equation has been derived to estimate the length density of lineal microstructural features such as dislocation lines, fibers, etc. from the measurements performed on the projected images of foils (slices) of unknown and variable thickness (1); the same data also yields average foil thickness. A new concept of sampling with "horizontal slice" is developed to estimate the total number of lineal feature end points from projected images (2).

(ii) A general and flexible procedure has been developed to calculate the evolution of bivariate size and shape (or orientation) distribution of particles/voids/cavities/microcracks during an evolution process, from modelled nucleation and growth kinetics of individual features (3). The development will be subsequently utilized to model the evolution of size and orientation distribution of microcracks and voids. A simple and general procedure is also developed to calculate individual bivariate particle/microcrack growth paths and growth rates from a series of experimentally measured bivariate distributions during an evolution process (3,4).

(iii) A general stereological equation has been derived to estimate the fractal dimension of anisotropic fracture surfaces, where profile fractal dimension may vary with the orientation of the sectioning plane (5,6).

(iv) A new fractographic parameter is defined to quantify the extent of overlaps (re-entrant regions) in fracture surfaces (7). These concepts are utilized to clearly distinguish between the topography of creep fracture and tensile fracture surfaces (6).

(v) Some new methods of grain size measurement have been critically analyzed (8).

(B) Computer Calculations and Simulations:

(i) Extensive computer calculations and simulations have been carried out to identify efficient sampling schemes for reliable estimation of fracture profile roughness parameter (and hence fracture surface roughness) when the measurements are performed only on limited number of short profile segments rather than the whole profile (9).

(ii) It is shown that sampling with "trisector" yields reliable estimates of total microstructural surface area per unit volume. Three vertical sections mutually at an angle of 120 deg. and having a common zone axis (called vertical axis) contain sufficient information for a reliable estimation of the total surface area per unit volume in a microstructure having arbitrary and unknown anisotropy and geometry (10). The intersection counting on trisector planes must be performed by using design based cycloid shape test lines. The computer simulations were also utilized to examine the effect of misorientation of the trisector planes on the precision of estimated surface roughness (11), and total microstructural surface area per unit volume (12).

(C) Feature Specific Digital Image Profilometry:

Software has been developed to extract some feature specific geometric information directly and automatically from set of (X,Y) coordinates of points that describe digitized fracture profile. Further work on feature specific Profilometry and the analysis of resulting data are a part of ongoing research.

(D) <u>Experimental Work:</u>

(i) Charpy impact tests and tensile tests were performed on a series of specimens of AISI 4340 steel having different hardness (produced by different tempering treatment). The profilometric measurements clearly showed that the fractal dimension of impact fracture surfaces decreases systematically with the distance from the initial notch: the correlation between impact energy and fractal dimension thus depends on where on the fracture surface the measurements are performed. The impact energy does not correlate to the average fractal dimension, but it shows strong correlation with the fractal dimension of the region of impact fracture surface adjacent to the charpy notch (5,6). This resolves some contradicting observations reported in the literature.

(ii) A new experimental technique is developed to estimate the average growth rate of microcracks in composites during the processes such as thermal cycling. The technique was applied to measure average growth rate of microcracks formed during thermal cycling of a metal matrix composite containing continuous alumina fibers distributed in the Al-Li alloy matrix (13). Such data should be useful to model microcrack damage evolution in composites.

(iii) The design based efficient stereological techniques were used to quantify evolution of population of cavities formed during high temperature creep of copper. The resulting stereological data were used to estimate cavity nucleation rate and growth rates (14). The fractographic measurements on the creep fracture surfaces were utilized to estimate extent of surface overlap and fractal dimension. It was shown that extent of fracture surface overlap can be used to distinguish between creep fracture and tensile fracture surfaces (6).

A.M. Gokhale
DMR-9013098

LIST OF PUBLICATIONS ACKNOWLEDGING NSF SUPPORT

(1) A.M. Gokhale: "Estimation of Length Density L_V From Vertical Slices of Unknown Thickness", **Journal of Microscopy**, 1992, Vol.167, PP. 1-8.

(2) A.M. Gokhale: "Utility of Horizontal Slice for Stereological Characterization of Lineal Features", **Journal of Microscopy**, 1993, Vol.170, PP. 3-8.

(3) A.M. Gokhale: "Evolution of Bivariate Particle Size Distributions", **Metall. Trans.-A**, 1992, Vol.23A, PP. 2973-2980.

(4)A.M. Gokhale: "Bivariate Growth Path Analysis", **Acta Stereologica**, 1992, Vol.11, Suppl.-1, PP. 255-463.

(5)W.J. Drury and A.M. Gokhale: "Measurement and Interpretation of Fracture Surface Fractal Dimension", **ASTM Standard Tech. Pub. No. 1165 : Metallography: Past, present, and Future**, G.F. Vander Voort, et. al., eds., ASTM, 1993, PP.295-309.

(6)A.M. Gokhale, W.J. Drury, and S. Mishra: "Recent Developments in Quantitative Fractography", **ASTM Standard Tech. Pub. No. 1203: Fractography of Modern Engineering Materials**, J.E. Masters and L.E. Gilbertson, eds., ASTM, 1993, PP. 3-22.

(7)E.E. Underwood: "Evaluation of Overlaps in Fracture Surfaces", **ASTM Standard Tech. Pub. No.1094: Micon-90: Advances in Video Technology for Microstructural Control**, G.F. Vander Voort, ed., ASTM, 1991, PP.340-353.

(8)G.F. Vander Voort and A.M. Gokhale: "Comments on Grain Size Measurements Using Point Sampled Intercepts", **Scripta Met. Mat.**, 1992, Vol.26, PP. 1655-1660.

(9)W.J.Drury and A.M. Gokhale: "Statistical Considerations in the Digital Profilometry of Fracture Surfaces", **ASTM Standard Tech. Pub. No. 1203: Fractography of Modern Engineering Materials,** J.E. Masters L.E. Gilbertson, eds., ASTM, 1993, PP. 125-133.

(10)A.M. Gokhale and W.J. Drury: "Efficient Measurement of Microstructural Surface Area Using Trisector", **Metall. Trans.-A**, in press (to appear in May 1994 issue).

(11)A.M. Gokhale and W.J. Drury: "Surface Roughness of Anisotropic Fracture Surfaces", **Materials Characterization**, 1993, Vol.31, PP. 115-123.

(12)A.M. Gokhale, W.J. Drury, and W.T. Whited: "Quantitative Microstructural Analysis of Anisotropic Materials", **Materials Characterization**, 1993, Vol.31, PP. 11-18.

(13)A.M. Gokhale and W.T. Whited: "Measurements of the Growth Rates of Thermally Induced Microcracks in a Metal Matrix Composite", **Proceedings of Symposium on " Developments in Ceramic and Metal Matrix Composites"**, K. Upadhya, ed., TMS, Warrendale, PA., 1992, PP. 273-286.

(14)A.M. Gokhale: "Utility of Stereological Measurements in the Study of Creep Cavitation", **ASTM Standard Tech. Pub. No. 1094: Micon-90: Advances in Video Technology for Microstructural Control**, G.F. Vander Voort, ed., ASTM, 1991, PP. 332-339.

(15)E.E. Underwood: "Directed Measurements and Heterogenous Structures in Quantitative Fractography", **Acta Stereologica**, 1991, Vol.10, PP. 149-165.

(16)E.E. Underwood: "Metallography", **McGraw-Hill Year Book of Science and Technology**, New York, NY, 1992, PP. 246-350.

(17)E.E. Underwood: "Treatment of Reversed Sigmoidal Curves for Fractal Analysis", **ASTM Standard Tech. Pub. No. 1094: Micon-90: Advances in Video Technology for Microstructural Control**, G.F. Vander Voort, ASTM, 1991, PP. 354-364.