AD-A155 530 METALLURGICAL ORIGINS OF FRACTURE TOUGHNESS AND MICROSTRUCTURE AND FRACTU..(U) BATTELLE COLUMBUS LABS OH A R ROSENFIELD ET AL. 31 MAY 85 ARO-15689.9-MS 1/1

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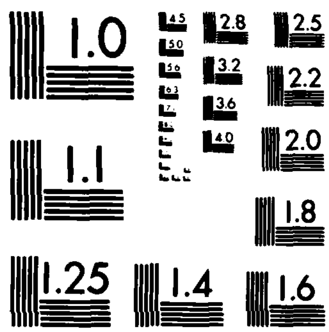

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: ARO 15689.9-MS ARO 18399.7-MS	2. GOVT ACCESSION NO.: N/A
3. RECIPIENT'S CATALOG NUMBER: N/A	
4. TITLE (and Subtitle): METALLURGICAL ORIGINS OF FRACTURE TOUGHNESS and MICROSTRUCTURE AND FRACTURE TOUGHNESS OF AN HSLA STEEL	5. TYPE OF REPORT & PERIOD COVERED: 15 Aug 78 - 14 Aug 81, 1 Jan 82 - 31 Dec 84, Final Report
	6. PERFORMING ORG. REPORT NUMBER: N/A
7. AUTHOR(s): A. R. Rosenfield, J. P. Hirth, and J. G. Schroth	8. CONTRACT OR GRANT NUMBER(s): DAAG-29-78-C-0031, DAAG-29-82-K-0033
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Battelle's Columbus Laboratories, Columbus OH 43201-6424	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: N/A
11. CONTROLLING OFFICE NAME AND ADDRESS: U. S. Army Research Office, Post Office Box 12211, Research Triangle Park, NC 27709	12. REPORT DATE: 31 May, 1985
	13. NUMBER OF PAGES: 7
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Same	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

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

NA

18. SUPPLEMENTARY NOTES

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

Fracture Toughness
Steel, High-Strength/Low-Alloy
Microstructural Effects
Compositional Effects
Fracture Statistics
Constitutive Modelling

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

The report discusses effects of composition and heat treatment on the fracture behavior of a group of steels based on ASTM A710A. Very low transition temperatures were observed in a number of cases. However, adverse effects of Cu on the K_{IC} value for cleavage and on the sharpness of the ductile/brittle transition are noted. At ambient temperatures, overaged Cu particles are beneficial for ductile fracture resistance.

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A new experimental method for evaluating the relative contributions of opening and shear to ductile crack growth was developed, along with a superdislocation model of the process.

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ARO 18399.7-MS

METALLURGICAL ORIGINS OF FRACTURE TOUGHNESS

and

MICROSTRUCTURE AND FRACTURE TOUGHNESS OF AN HSLA STEEL

Final Report

by

A.R.Rosenfield, J.P.Hirth, and J.G.Schroth

May 31,1985

U. S. ARMY RESEARCH OFFICE

Grant Nos. DAAG-29-78-C-0031 and DAAG-29-82-K-0033

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STATEMENT OF THE PROBLEM STUDIED

The major objective of this research has been to define the relations between fracture toughness and microstructural variables for a group of closely related HSLA steels. These steels are low-carbon, copper-bearing compositions based on ASTM A-710A. Since the steels chosen for study generally are exceedingly tough at ambient temperatures, appropriate test techniques to characterize fracture toughness were not available. Furthermore, the project steels exhibit two main fracture mechanisms (cleavage and dimpled rupture), and it was anticipated that the effects of microstructure on toughness would depend on mechanism and, consequently, on temperature.

SUMMARY OF THE MOST IMPORTANT RESULTS

Effect of Composition and Microstructure on Toughness

Resistance to cleavage fracture (lower-shelf toughness) appears to be adversely affected by both sulfur and copper. The sulfur effect is attributed to providing sites for localized crack initiation; copper additions can result in decreased fracture-surface roughness, thus decreasing the energy of crack propagation.

Resistance to dimpled rupture (upper-shelf toughness) was exceedingly high, with many specimens being too tough to satisfy the ASTM J-integral (E813) size requirements. Overaged copper particles appear particularly beneficial to toughness, because of inhibition of plastic instability associated with shear localization.

All heat treatments increased the sharpness of the ductile/brittle transition (i.e. the extent of the temperature range between fully brittle and fully ductile behavior) of as-rolled alloys. In contrast, addition of copper and nickel promoted a broader transition. Generally, sharp transitions were associated with uniform microstructures.

Since the position of the ductile/brittle transition temperature reflects a combination of all of the above effects, no simple trends based on composition and heat treatment could be discerned. However, when compared to most steels, the ductile/brittle transition temperatures were quite low.

Fracture Mechanics of Tough Steels

A controlled-angle slant-notch fracture specimen was developed to model stable crack growth in the upper-shelf temperature regime. The specimen allows the ratio of Mode I (opening) to Mode III (transverse shear) components of toughness to be controlled. Special formulations of the J-integral (designated J_i and J_{iii}) were developed to quantify the resulting combined-mode fracture behavior. It was found that an applied Mode III loading component reduced the Mode I component necessary to produce crack initiation (and vice versa). For all loading geometries, large initiation values of J corresponded to large crack-growth resistance.

The fracture mechanism is dimpled-rupture throughout the spectrum of Mode I-Mode III conditions. As the J_{iii}/J_i ratio is varied, the stress state ahead of the crack changes. The resultant fracture-surface dimples are equiaxed for Mode I conditions, but become increasingly elongated in the transverse-shear direction as the relative Mode III component is increased. Two heat-treated conditions of ASTM A710-A both show tendencies for transverse-shear flow during mixed-mode loading. The heat-treated condition exhibiting the greater resistance to plastic instability in uniaxial tension was tougher for all crack-growth geometries.

Combined-mode elastic-plastic fracture initiation has been modeled using an elastic analog in which the plastic zone is represented by two super-dislocations, one screw and one edge, lying ahead of the crack tip.

Statistical Analysis of Scattered Temperature-Dependent Data

There are many situations where test data are both temperature-dependent and severely scattered. A statistical analysis, developed on this grant to handle such situations, combines mathematical convenience with fracture theory. The analysis has found application to a variety of fracture data and has been developed further by various other users. In addition to percentiles, confidence limits can now be calculated. The data set can be also broken up into subsets, each of which can be analyzed individually.

While all applications to date have involved fracture toughness and impact energy, other phenomena are amenable to the analysis. Possible applications include analysis of the effects of stress on fatigue life, the effect of load on wear rate, and the effect of temperature on chemical-reaction rate.

Constitutive Modeling

Several tangential results were obtained in the area of mathematical descriptions of deformation and fracture behavior.

Equations have been developed to describe strain gradients in a tensile specimen with non-uniform cross section. The analysis results in an equation which successfully relates fracture elongation to constitutive parameters.

Key curves have been derived to represent power-law relations among load, displacement, and remaining ligament in standard fracture-mechanics test specimens. This approach simplifies analysis of the raw data to provide both path-independent (J) integrals and tearing moduli.

LIST OF PUBLICATIONS

Effect of Composition and Microstructure on Toughness

M.T. Miglin, I.-H. Lin, J.P. Hirth, and A.R. Rosenfield, "Mixed-Mode Crack Growth Using the Compact Specimen", ASTM STP 791, (1983), II-353--II--369*

M.T. Miglin, J.P. Hirth, and A.R.Rosenfield, "Effects of Microstructure on Fracture Toughness of a High-Strength Low-Alloy Steel", Metallurgical Transactions A, Vol.14A (1983), 2055-2061

M.T. Miglin, J.P. Hirth, A.R. Rosenfield, and W.A.T. Clark, "Microstructure of a Quenched and Tempered Cu-Bearing High-Strength Low-Alloy Steel", to appear in Metallurgical Transactions A

D.M. Kindel, R.G. Hoagland, J.P. Hirth, and A.R.Rosenfield, "Characterizing Brittle-Fracture Resistance of Steel", to appear in Materials Characterization for Systems Performance and Reliability, J.A. McCauley and V. Weiss,eds., Plenum Press

Fracture Mechanics of Tough Steels

M.T. Miglin, J.P. Hirth, and A.R. Rosenfield, "Estimation of Transverse-Shear Fracture Toughness for an HSLA Steel", International Journal of Fracture, Vol. 22 (1983), R65-R67

M.T. Miglin, J.P.Hirth, and A.R.Rosenfield, "Development of Fractographic Features During Shear Failure of an HSLA Steel", Res Mechanica, Vol. 11 (1984), 85-95 (invited highlight paper)**

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* This paper also contains information on fracture testing of tough materials.

** This paper also contains information on effects of composition on microstructure and toughness.

J.G. Schroth, R.G. Hoagland, J.P.Hirth, and A.R. Rosenfield, "Tensile and Shear Fracture of an HSLA Steel", Scripta Metallurgica, Vol. 19 (1985), 215-219

Statistical Analysis of Scattered Temperature-Dependent Data

T.A. Bishop, A.J. Markworth, and A.R. Rosenfield, "Analyzing Statistical Variability of Fracture Properties", Metallurgical Transactions A, Vol. 14A (1983), 687-693

Constitutive Modeling

I.-H. Lin, J.P.Hirth, and A.R.Rosenfield, "J-Integral Analysis of Stable Crack Growth", International Journal of Fracture, Vol. 16 (1980), R11-R14

I.-H. Lin, J.P.Hirth, and A.R.Rosenfield, "Response: Discussion of J-Integral Analysis of Stable Crack Growth", International Journal of Fracture, Vol.16 (1980), R157-R161

I.-H. Lin, J.P. Hirth, and E.W. Hart, "Plastic Instability in Uniaxial Tensile Tests", Acta Metallurgica, Vol. 29 (1980), 819-827

I.-H. Lin and A.R.Rosenfield, "Key Curve Analysis of Crack-Growth Resistance Curves", International Journal of Fracture, Vol.20 (1982), 103-115

Other

A. R. Rosenfield, "Stress Intensity Factors for Non-Uniform Applied Stresses", Engineering Fracture Mechanics, Vol. 13 (1980), 1031-1032.

A. R. Rosenfield, "Discussion of 'Critical Fracture Stress and Fracture Strain Models for the Prediction of Lower and Upper Shelf Toughness in Nuclear Pressure Vessel Steels'", Metallurgical Transactions A, Vol. 12A (1981), 545

SCIENTIFIC PERSONNEL AND ADVANCED DEGREES

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J.G.Schroth (OSU; M.S. Awarded, Dec.,1984; Ph.D. Awarded, May,1985, Thesis abstracted on next page)

*** The research contained in the theses of Drs. Lin and Miglin and of Mr. Kindel has been reported in the papers cited in the "List of Publications" section of this report.

THESIS ABSTRACT

"Combined Mode I - Mode III Fracture Toughness of a High-Strength Low-Alloy Steel"

J.G.Schroth, Ohio State University, May, 1985

Combined Mode I- Mode III fracture behavior was investigated for two heat treated conditions of a copper-bearing high-strength low-alloy steel. Special formulations of the J integral, denoted J_i and J_{iii} for the opening mode and transverse shear modes respectively, were used to characterize crack initiation while Paris' tearing modulus was used to characterize J-resistance behavior during stable crack extension. Combined-mode fracture initiation data define a linear fracture envelope in J_i-J_{iii} space. This behavior is predicted qualitatively by a superdislocation model of combined mode elastic-plastic fracture in which the plastic zone is modeled by two superdislocations ahead of the crack tips, one of edge character with Burgers vector equal to the Mode I CTOD, the other of screw configuration with Burgers vector equal to the Mode III CTOD. For all loading modes, the overaged condition containing incoherent face-centered-cubic copper precipitates exhibited superior toughness as compared to the peak aged condition which had a similar grain size and carbide distribution, but contained coherent body-centered-cubic copper-containing clusters. For all loading geometries, large J-component initiation values were accompanied by large tearing modulus values (large resistance to crack growth). This correspondence between crack initiation resistance and growth resistance agrees with commonly observed Mode I behavior. Both heat treated conditions displayed tendencies for transverse shear flow and the overall greater toughness of the overaged material probably results from its greater resistance to plastic instability as evidenced by its greater elongation at fracture in uniaxial tensile tests. Fractographic examination reveals that crack extension occurred by dimpled rupture in all loading, but that dimple morphologies changed markedly. For pure Mode III loading, friction between the specimen halves may have contributed significantly to measured toughness values.

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