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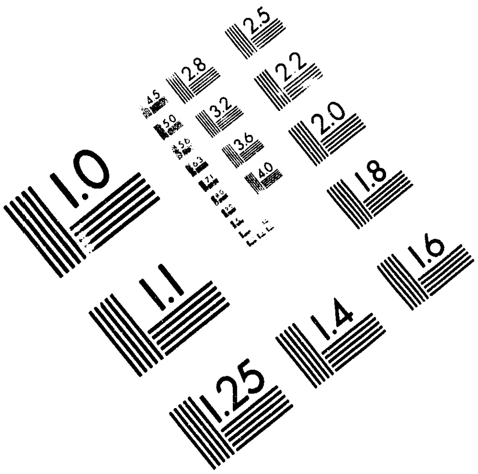

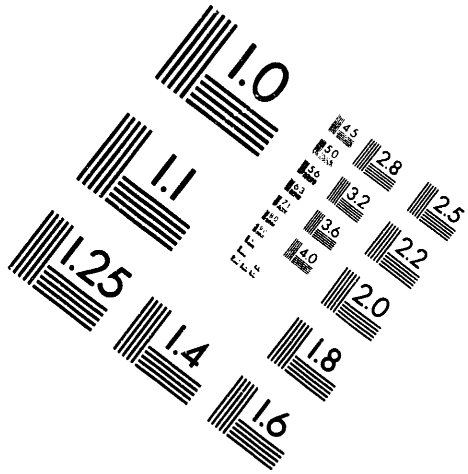

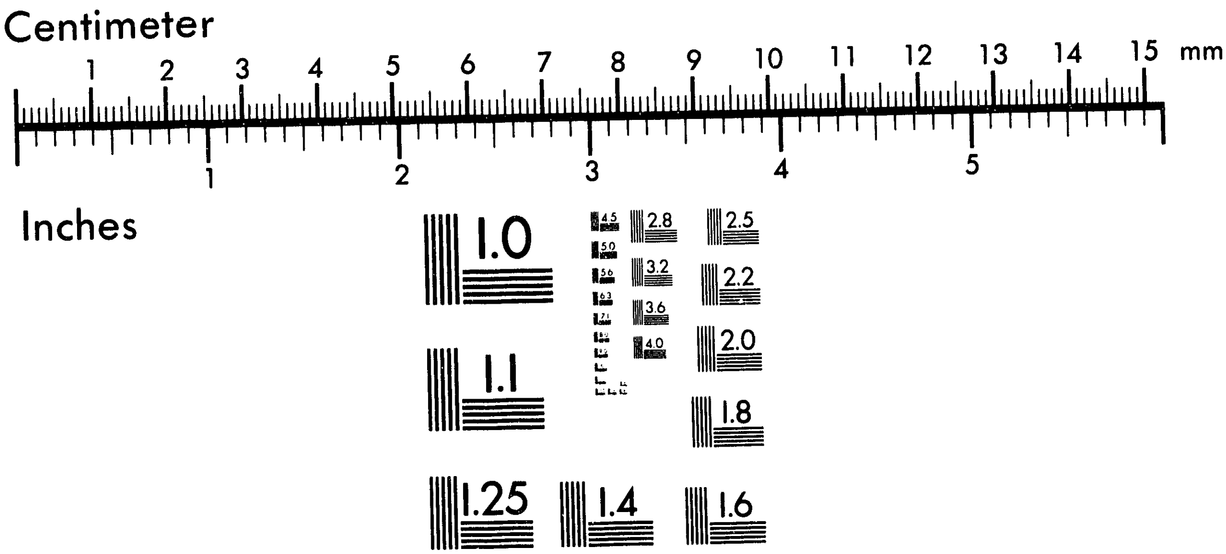

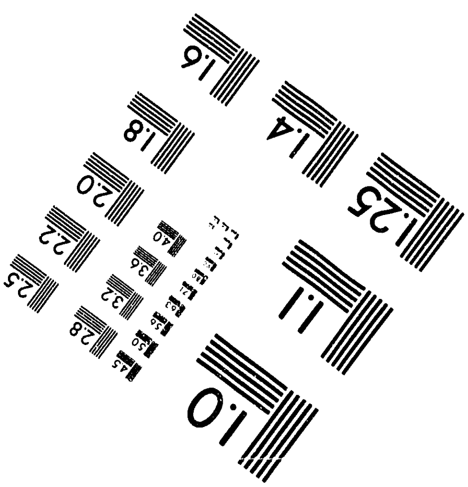

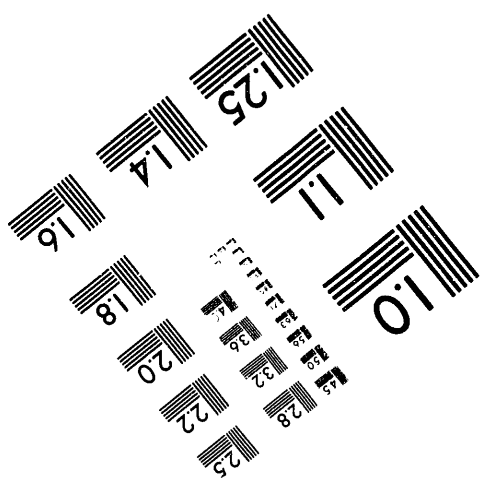

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I. PROGRESS REPORT

I.1. Funding History

The origins of this work, initiated with funding in 1984, were predominantly associated with fatigue studies where it was noted that a combination of low temperature and cyclic loading produced cyclic cleavage in BCC iron-base systems. To gain a fundamental understanding of these processes, it was decided that it was necessary to probe both the dislocation dynamics and quasi-statics of crack growth processes. In the first three years, this led us to investigations of both quasi-static and dynamic cleavage of poly- and single crystals of iron and titanium base systems. Approximately 15 papers were published, the two most significant being:

W.W. Gerberich and E. Kurman, "New Contributions to the Effective Surface Energy of Cleavage," *Scripta Metall.* **19** (1985) p. 295.

W.W. Gerberich, T. Livne and X. Chen, "A Transient Model for Sub-Critical Cracking in BCC Alloys," in *Modeling Environmental Effects on Crack Growth Processes*, R.H. Jones and W.W. Gerberich, eds., TMS-AIME, Warrendale, PA (1986) pp. 243–258.

The first of these led us to a concentrated effort in studying ligament effects in process zones, particularly associated with the ductile-to-brittle transition (DBTT) in steels. The second of these, as a consequence of introducing sharp cracks into Fe-3wt%Si single crystal by hydrogen-assisted fatigue, led us to the discovery that both sustained-load cracking and very definitive crack arrest markings (CAM) could also be produced. This inaugurated a concentrated 6-year effort in quantifying both the sub-microstructural and macroscopic aspects of hydrogen embrittlement by decohesion along $\{100\}\langle 011\rangle$ crack planes and localized crack growth directions. These two areas along with a new thin film area started in 1990 are summarized below.

While still incomplete, these three areas of research, single-crystal cleavage, hydrogen-induced cleavage and brittle fracture in small volumes, poise us for this next effort. While we still have major aspects of the brittle fracture problem needing better definition, there are new questions associated with small volume and kinetic effects. As will be shown in the proposal, this has implications from materials development, e.g. tougher and more hydrogen resistant aluminides, to phenomena associated with fretting fatigue initiation or composite interface fracture. The next two sections review the progress over the past six years.

I.2. Accomplishments '87–'90

There were four major accomplishments in the three-year effort to July 1, 1990. These dealt with understanding hydrogen embrittlement thresholds, with computational studies which assist in understanding both thresholds and cleavage onset, with crack-tip dislocation emission and instability, and with process zone concepts in brittle fracture.

I.2.1. Hydrogen embrittlement

Since it was known from Vehoff and Rothe's studies[1] that hydrogen-induced crack growth in Fe-3wt%Si single crystals was on the {100} cleavage plane, this was an ideal system for studying discontinuous cleavage. For the first time, a large scale program on large single crystals of iron was conducted where stress intensity levels, crack velocities and acoustic emission signals gave quantitative details on the micromechanistic process. From these investigations, the following can be summarized:

i) hydrogen-nucleated cleavage very near the root of a sharp crack is consistent with existing concepts of decohesion;

ii) embrittlement thresholds depend on both a critical hydrogen level being achieved in a local volume near the crack tip and a local stress which appears to approach the theoretical crystal strength;

iii) the threshold condition is different for plane stress and plane strain as verified by crack tunneling in a macroscopic ⟨110⟩ growth direction, which should maintain a straight crack front if there were not state of stress effect;

iv) there is evidence of anisotropic plasticity on the fracture surfaces strongly suggesting that dislocation shielding is an important contribution;

v) while thresholds as low as 16 MPa-m$^{1/2}$ have been observed, this may be slowly increased to K_I values as large as 50 MPa-m$^{1/2}$ without failure;

vi) hydrogen cracking above threshold is discontinuous with 1 μm steps involved as verified by fractography and acoustic emission;

vii) the effect of test temperature on stage II growth kinetics is directly analogous to those observed in higher strength steels with either internal or external hydrogen environments.

This investigation led to a major review and a number of papers listed below.

1. W.W. Gerberich, C.E. Hartbower and X. Chen, "Internal Carbon Embrittlement," in *Environmental Degradation of Engineering Materials, III*, M.R. Louthan, Jr., R.P. McNitt and R.D. Sisson, Jr., eds., The Pennsylvania State University, University Park, PA (1987) pp. 105–119.
2. W.W. Gerberich, T. Livne, M. Kaczorowski and X.F. Chen, "Crack Growth from Internal Hydrogen — Temperature and Microstructural Effects in 4340 Steel," *Met. Trans. A*, May (1988) pp. 1319–1334.
3. W.W. Gerberich, X. Chen and R. Caretta, "Carbon Segregation Induced Grain Boundary Embrittlement," MRS Symposium Vol. 122 (1988) pp. 399–404.
4. W.W. Gerberich, "The Micromechanics and Kinetics of Environmentally Induced Failures," ASM Materials Science Seminar, 1987, S.V. Nair, J.K. Tien, R.C. Bates and O. Buck, eds., ASM International, Metals Park, OH (1989) pp. 201–228.

I.2.2. Computational studies

These were primarily aimed at obtaining a better description of the local stress field near a crack tip since there was a concern that continuum models did not necessarily give the local maximum. For example, it was difficulty to understand bond breaking (cleavage) by stresses which were 1/100 of the shear modulus. Atomistic studies had not been developed sufficiently and it was felt that the continuum mechanics of small-scale yielding solutions were both too far field and too smooth to represent microstructural discontinuities. For these reasons, an intermediate scale discretized dislocation model after Atkinson and Clements[2] was utilized to simulate the stresses. This was chosen since it allowed an anisotropic elastic solution, with dislocation point forces, appropriate to iron. It was also of interest since it allowed the stress tensor to be evaluated for this model which is similar to those of Rice and Thomson,[3] Burns,[4] Li,[5] Argon,[6] Brede and Haasen[7] and others. Although a large number of papers have been written on this subject, few had attempted to calculated the stress tensor associated with the crack and dislocations at equilibrium. Thus, a major accomplishment of this study was utilizing the power of the supercomputer to analyze the local stress distribution as a function of slip character. Some of the following findings were quite surprising to us:

i) in a single-slip system, the number of dislocations in a localized slip band and the length of the band required for equilibrium increased with increasing stress intensity;

ii) with two slip systems, the local slip band length was controlled by the macroscopic slip angle. This length increased by a factor of six as the slip angle deviated from the crack plane to 90 degrees to the crack plane. Correspondingly, the maximum normal stress decreased by a factor of six;

iii) for applied stress intensities as low as 2 MPa-$m^{1/2}$, near theoretical stresses (20 GPa) were reached at the crack tip. These stresses only existed over a narrow 1 nm region;

iv) the critical region over which this stress was achieved increased as to the square of the applied stress intensity;

v) a simulation of prior overloads and the attendant far-field residual plasticity provided a rationale for the experimental observations.

Such crack/dislocation equilibrium simulations of stress distributions provided background for several analytical descriptions of brittle instabilities as described in several overview papers in preparation and the following:

5. M. Lii, T. Foecke, X. Chen, W. Zielinski and W.W. Gerberich, "The Effect of Low Energy Dislocation Structures on Crack Growth Onset in Brittle Crystals," *Mat. Sci. Engng.* **A113** (1989), pp. 327–338.

6. X. Chen, T. Foecke, M. Lii, Y. Katz and W.W. Gerberich, "The Role of Stress State on Hydrogen Cracking in Fe-Si Single Crystals," *Engng. Fract. Mech.* **35**, No. 6 (1990), pp. 997–1017.

7. W.W. Gerberich, T. Foecke and M. Lii, "Dislocation Crack-Tip Interactions: Influence on Subcritical Crack Growth," in *Constitutive Laws of Plastic Deformation and Fracture*, A.S. Krausz, J.I. Dickson, J.-P.A. Immarigeon and W. Wallace, eds., Kluwer Academic Publ. Hague, Netherlands (1990) pp. 197–205.

I.2.3. Dislocation emission

Our early studies dealt with dislocation emission from grain boundaries and how this might influence fatigue substructure and fatigue life. This has more recently gravitated toward fundamental issues of dislocation emission at crack tips. Specifically, what type of character did dislocation emission have in model materials such as NaCl and how did this influence cleavage stability in single crystals? Some of the important accomplishments were:

i) fatigue structure evolution can be followed at a surface with selected area channeling patterns (SACP);

ii) surface and bulk substructures are different in magnitude and morphology during fatigue;

iii) SACP observations assist in theoretical modeling of cyclic work-hardening behavior;

iv) anisotropic slip across interfaces at cracks or grain boundaries can be analyzed by electron channeling;

v) theoretical models of the stress intensity for dislocation emission K_{Ie} predicted values a factor of three higher than the extensive observations in {100} NaCl which demonstrated K_{Ie} to be $0.067^{+0.003}_{-0.007}$ MPa-m$^{1/2}$;

vi) birefringence can be used for probing internal slip band emission from crack tips;

vii) as many as eight separate slip bands were found to emit from the tip of a crack in NaCl. These dislocations, being internal would not form surface etch pits, making some of the previous calculations by Narita, *et al.*[8] in this material questionable.

These and other observations have been published in the following:

8. W.W. Gerberich, J.K. Sheth and M. Kaczorowski, "Fatigue-Induced Nanoscale Patterns and Microstructures," in NATO Adv. Workshop on Pattern Defects and Microstructures in Nonequilibrium Systems, D. Walgraef, ed., NATO ASI Series E, No. 121, Martinus Nijhoff, The Netherlands (1987) pp. 237–256.
9. M. Kaczorowski and W.W. Gerberich, "The Degradation of Selected Area Channeling Patterns as a Function of Glide Anisotropy," *J. Mat. Sci.* **22** (1987) pp. 3227–3230.
10. J.K. Sheth and W.W. Gerberich, "The Effect of Test Frequency and Geometric Asperities on Crack Closure Mechanisms," in ASTM STP 982, J.C. Newman and W. Elber, eds., Philadelphia (1988) pp. 112–120.

I.2.4. Process zones

While our process zone efforts date back more than 10 years ago, more recent application had been toward the brittle fracture problem.[9] This approach had been prompted by early acoustic emission events when cracking was initiated from sharp cracks. This type of process was observed in the range of 130 and 193 K suggesting that weakest link approaches did not apply in the temperature range associated with the lower shelf.[10] This was recently supported by Rogers and Clayton[11] on slightly different plain carbon steels. This and other evidence by Irwin[12] suggested that more detailed measurements of cleavage onset in many polycrystalline microstructures were needed. This was accomplished in the program with the following findings:

i) Acoustic emission detection of discontinuous microcrack events initiate at K_I values as low as 15 MPa-m$^{1/2}$ at 193 K, even though $K_{Ic} \simeq 45$ MPa-m$^{1/2}$;

ii) process zone models are useful in modeling the microstructural details of a discontinuous brittle fracture process in a polycrystalline solid;

iii) based on the temperature dependence of yield stress, $\sigma_{ys(T,\dot{\epsilon})}$ and a proposed grain size dependence of fracture stress, $\sigma^*_{f(d)}$, the K_{Ic} dependence on these variables were predicted. However, this was based upon one *ad hoc* assumption and three adjustable parameters;

iv) the geometrical arrangement and size distribution of grains was suggested to be the controlling process in HSLA steels rather than weakest link considerations;

v) discontinuous cleavage patches were identified and related to the magnitude of the stress intensity over and above that necessary to nucleate a coplanar crack.

These and other observations were published in the following:

11. W.W. Gerberich, "Novel Techniques as Applied to Fracture Process Zone Theory," in NATO-Adv. Workshop on Chemistry and Physics of Fractures, R.M. Latanision and R.H. Jones, eds., NATO ASI Series E, No. 130, Martinus Nijhoff, The Netherlands (1987) pp. 419–436.
12. W.W. Gerberich, "Substructural and Microstructural Influence on Crack Closure," in *Fatigue '87*, R.O. Ritchie and E.A. Starke, Jr., Eds., E MAS, U.K. (1987).
13. W.W. Gerberich, S.-H. Chen, C.-S. Lee and T. Livne, "Brittle Fracture: Weakest Link or Process Zone Control?," *Met. Trans. A* **18A** (1987) pp. 1861–1875.
14. W.W. Gerberich, R.H. Jones, M.A. Friesel and A. Nozue, "Acoustic Emission Monitoring of Stress Corrosion Cracking," *Mat. Sci. Engng.* **A103** (1988) pp. 185–191.
15. R.H. Jones, M.A. Friesel and W.W. Gerberich, "Acoustic Emission from Intergranular Subcritical Crack Growth," *Metall. Trans. A* **20A** (1989) pp. 637-648.
16. W.W. Gerberich, "Metallurgical Aspects of Crack-Tip Failure Processes," ASTM STP 945, D.T. Read and R.P. Reed, eds., Am. Soc. Test. Mat'ls., Philadelphia (1988) pp. 5–18.

I.3. Accomplishments '90–'93

In this time frame there were three major thrust areas associated with (1) hydrogen embrittlement, (2) brittle fracture at the atomistic and dislocation scale and (3) brittle fracture at the microscopic and macroscopic scales.

I.3.1. Hydrogen embrittlement

With funding limitations, some aspects of the program had to be eliminated so that this aspect was in the process of phasing out. Nevertheless, five papers were published on various aspects of hydrogen-enhanced decohesion. One of the primary ones was the intimate relationship between localized plasticity and cleavage onset as detected by a combination of selected area channeling, acoustic emission and laser interferometry. These experimental results clearly demonstrated to us how anisotropic slip (selected area channeling and laser interferometry) precedes a brittle instability (acoustic emission and scanning electron microscopy). They further showed us the way in which atomistic and microscopic fracture criteria could be connected to the continuum world through appropriate discretized dislocation modeling. The experimental aspects are predominantly in the publications below with theoretical aspects in the next section.

Some of the specific accomplishments of this work were:

i) For either internal hydrogen, as provided by prior gas phase charging, or an atmosphere of external hydrogen, the threshold stress intensity for Fe-3wt%Si was 16 MPa-$m^{1/2}$ at room temperature;[13]

ii) for both internal and external hydrogen, cracking is predominantly brittle, decohesion and discontinuous with 1 μm steps growing locally in $\langle 110 \rangle$ directions in the $\{001\}$ cleavage plane;[13,14]

iii) a strong plane-stress versus plane-strain effect existed for hydrogen-induced slow crack growth in Fe-3wt%Si as reflected by both crack tunneling and the local plastic strain distributions;[15]

iv) crack velocity observations as a function of test temperature were consistent with a kinetic model based upon hydrogen transport, collection and decohesion.

These and other observations were published in the following:

17. W.W. Gerberich and S.-H. Chen, "Environment-Induced Cracking of Metals, Fundamental Processes: Micromechanics," Intern. Conf. on Environ. Induced Cracking, Oct. 1988, National Association of Corrosion Engineers, Houston, TX (1990) pp. 167–187.

18. S.L. Robinson, J.C. Costa, N.R. Moody, A.E. Pontay and W.W. Gerberich, "Hydrogen Isotope Concentration Enhancements at a Blunt Notch," *Scripta Metall.* (1989).

19. S.-H. Chen, Y. Katz and W.W. Gerberich, "Crack Tip Strain Fields and Fracture Microplasticity in Hydrogen Induced Cracking of Fe-3wt%Si Single Crystals," *Philos. Mag. A* **63**, No. 1 (1990) pp. 131–155.

20. X. Chen and W.W. Gerberich, "The Kinetics and Micromechanics of Hydrogen Assisted Cracking in Fe-3wt% Single Crystals," *Metall. Trans. A* **22A** (1991) pp. 59–70.

21. W.W. Gerberich and T.J. Foecke, "Hydrogen Enhanced Decohesion in Fe-Si Single Crystals: Implications to Modeling of Thresholds," in *Hydrogen Effects on Material Behavior*, N.R. Moody and A.W. Thompson, eds., The Minerals & Materials Society (1990) pp. 687–702.

I.3.2. Understanding brittle fracture at the atomistic and dislocation scales.

Regarding the crack-tip dislocation emission problem, we have shown this to be critical to understanding ductile-brittle transition temperature (DBTT) phenomena. First, it has been shown that multiple nucleation sites for dislocation emission exist along the crack front in bulk crystals. This has been accomplished *in situ* with depth imaging optical birefringence in NaCl and *ex situ* with TEM foil sections from crack tips in Fe-3wt%Si. This culminated in two position papers.[16] While initially developed for Fe-3wt%Si single crystals, this has since been applied to intermetallic crystals and polycrystalline mild steel.[17] From atomistic simulations we have shown that hydrogen inhibits dislocation emission out of grain boundaries while Baskes and Daw[18] had previously indicated that hydrogen enhances dislocation emission at crack tips. We have discussed that such behavior is not necessarily inconsistent.[19] While still in the formative stages, such approaches could be key to full-scale modeling of how hydrogen triggers transitions from transgranular to intergranular cracking in materials, ranging from relatively tough superalloys to relatively brittle intermetallics.[19] Two tools, which are presently being developed to probe defects at the atomistic and dislocation levels, are scanning tunneling and atomic force microscopes. Although we are only starting with the latter, some accomplishments with the STM have been imaging crack morphologies around indentations in silicon and following the dislocation motion, *in situ*, associated with the hexagonal to rhombohedral transformation in highly ordered pyrolytic graphite. While we are still learning to use such instruments, the potential for probing the nanomechanical behavior of small volumes is enormous.

Some of the specific accomplishments of this work were:

i) dislocation emission in NaCl crystals gave values of k_{Ie} approximately one-third of theoretical predictions;

ii) acoustic emission methods are capable of resolving discontinuous microevents which scale with 1 μm extensions observed by fractography;[16]

iii) a discretized dislocation simulation allowed a local stress analysis which could be used to understand initiation, arrest and reinitiation events on the $\{100\}$ cleavage plane in local $\langle 011 \rangle$ directions of Fe-3wt%Si single crystals;

iv) the simulation, which leads to local stresses greater than 20,000 MPa near the theoretical strength, implies that a decohesion volume is a viable approach to brittle fracture;[16,17]

v) scanning tunneling microscopy (STM) can be a useful instrument in studying both line and planar defects at surfaces. Specifically, STM tip forces can promote phase transitions at a free surface.[20]

These and other observations were published in the following:

22. T.J. Foecke and W.W. Gerberich, "Birefringence Observations of Dislocation Emissions at Crack Tips in NaCl Single Crystals," *Scripta Met. et Mat.* **24** (1990) pp. 553–558.

23. M.-J. Lii, X.-F. Chen, Y. Katz and W.W. Gerberich, "Dislocation Modeling and Acoustic Emission Observation of Alternating Ductile/Brittle Events in Fe-3wt%Si Crystals," *Acta Metall.* **38** (1990) pp. 2435–2452.

24. T.J. Foecke, R. King, A. Dale and W.W. Gerberich, "Imaging of Cracks in Semiconductors Using Scanning Tunneling Microscopy," *J. Vac. Sci. Techn.* **B9**(2) (1991) pp. 673–676.

25. T.J. Foecke, R. King, A. Dale and W.W. Gerberich, "Imaging of Cracks in Semiconductor Surfaces Using Scanning Tunneling Microscopy," *Mat. Res. Soc. Symp.* **209** (1991) pp. 617–622.

26. S. Snyder, T.J. Foecke, H.S. White and W.W. Gerberich, "Imaging of Stacking Faults in HOPG using Scanning Tunneling Microscopy, *J. Materials Research* **7**(2) (1992) pp. 341–344.

27. W.W. Gerberich, H. Huang and W. Zielinski, "Crack-Tip Dislocation Grain Boundary Interactions Near the Ductile-Brittle Transition," in *Symposium on Quasi Brittle Fracture* submitted *Metall. Trans.* (1992).

I.3.3. Understanding brittle fracture at the microscopic and macroscopic scales

In terms of the interactions between crack tips, tip-emitted shielding dislocations, redundant or work-hardening dislocations and grain boundaries, we have begun to comprehend how a model might link these together. We have first seen how anisotropic slip naturally develops at crack tips as a consequence of dislocation shielding requirements for stability.[21] Second, it is possible to quantify the interaction of emitted dislocations with the crack tip force on one side and a grain boundary on the other using a simplification[22] of Li's[23] approach. This leads to a good prediction of fracture toughness in the lower shelf regime. Here, toughness ranged from 20–40 MPa-m$^{1/2}$ for slow rate and dynamic tests of mild steel with room temperature yield strengths of 200 and 280 MPa for coarse and fine grain microstructures. Through a combination of electron channeling and acoustic emission, we have also analyzed the approximate sequence of microcleavage events leading up to instability at a test temperature in the transition temperature regime.[24] Here, the stress intensity values ranged up to 45 MPa-m$^{1/2}$ for a 360 MPa yield strength HSLA steel. This was not nearly so successful as the detailed sequence of events in the process zone, compared to the previous onset of cleavage in the first few grains, makes this a much more difficult mechanism to describe. As such, there are two interacting phenomena here. On the microscopic level, different grains along the crack front first cleave as governed by crack-tip/dislocation/grain orientation and boundary arrangements in equilibrium with the applied stress intensity. With a number of grains in the process zone cracked, however, the effective applied K_I on the remaining grains must be considered for further calculation of local cleavage instability. This evolutionary fracture process, while not a simple one, in principle should be predictable[22,24]

Some of the specific accomplishments of this work were showing that:

i) microcleavage is a discontinuous process at temperatures near the DBTT in HSLA steel;

ii) electron channeling methods can be used to orient individually cleaved facets in a process zone;

iii) the largest and most nearly coplanar grains near the crack tip failed at the lowest applied stress intensities in fracture toughness tests;

iv) a simplified dislocation shielding model can represent the low temperature fracture toughness of mild steel as a function of grain size and test temperature in the lower shelf regime;

v) in dynamically indented coarse grained nickel, backscattered electron channeling verified that microcracks around the indentation were transgranular. Whatever the origin of these, it would appear that transgranular dynamic crack extension of brittle cracks is possible in nickel, of importance to film-induced cleavage models in stress corrosion cracking.

These and other observations were published in the following:

28. S.-H. Chen, Y. Katz and W.W. Gerberich, "On the Directional Dependency of Microplasticity for {100} Cleavage in Fe-3wt%Si Single Crystals," *Scripta Met. et Mat.* **24** (1990) pp. 1125–1130.

29. W.W. Gerberich, J.A. Kozubowski, T.J. Foecke and C.S. Lee, "Crystal Orientation Effects on the Process Zone During Brittle Fracture of Steel," in *Proc. of the Morris Fine Symposium*, TMS, Warrendale, PA (1990) pp. 327–336.

30. J.W. Hoehn, T.J. Foecke and W.W. Gerberich, "Brittle Fracture of Nickel by Dynamic Indentation," *J. Mater. Res. Rapid Commun.* **7**(8) (1992) pp. 1973–1975.

31. Y. Katz, R.R. Keller, H. Huang and W.W. Gerberich, "A Dislocation Shielding Model for the Fracture of Semi-Brittle Polycrystals," *Metall. Trans. A*, accepted (1992).

I.4. Previous Students and Colleagues (last six years)

X.-F. Chen (PhD 1989) – First PhD student to graduate on this grant dealt with the kinetic aspects of sustained-load cracking in Fe-3wt%Si single crystals. Is currently at Singapore Institute of Standards and Industrial Research.

T. Livne (1985–86) – Visiting researcher dealt with macroscopic fracture mechanics and acoustic emission of discontinuous cleavage. She is currently at RAFAEL in Haifa, Israel.

C.-S. Lee (1986–87) – Post-doctoral associate investigated crystallographic aspects of the process zone. He is currently a Professor at Postfach in South Korea organizing a research program on the mechanical behavior of titanium alloys.

J.K. Sheth (MS 1986) – Investigated cyclic-cleavage fatigue crack growth in Fe-3wt%Si single crystals. Returned to Bombay to manage his family business.

B. Wilfahrt (MS 1990) – Analyzed liquid metal embrittlement of brazed joints. Brian did this fracture mechanics study in conjunction with industry (salary support). Part of this led to ideas on how stacking fault energy may play a role in several embrittlement mechanisms.

S.-H. Chen (PhD 1990) – Did the first analysis of state of stress effects on the plastic strain gradient very near crack tips using selected area channeling methods. She is currently in charge of failure analysis on a number of projects at INTEL Corporation in Chandler, Arizona.

T.J. Foecke (PhD 1991) – Analyzed cracks in silicon with scanning tunneling microscopy and dislocation emission in alkali halides. Tim won an NRC Fellowship and is two years with Robb Thomson and Dave Lashmore at NIST performing *in situ* TEM experiments on multilayer structures.

W. Zielinski (MS 1991) – Transmission electron microscopy of crack-tip dislocation arrangements – he will return to Warsaw in November, 1992.

Y. Katz (1988–89) – Visiting professor from Ben Gurion University and the Nuclear Research Establishment, Beer Sheva, Israel. Was responsible for many of the ideas associated with the dynamics of crack initiation and arrest in semi-brittle fracture.

Appendix I: Other Sponsored Program References on Microscratch Toughness

Preprints & reprints removed & cycled separately.

DATE

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END