QUANTITATIVE DETERMINATION OF THE EFFECTS OF YIELD STRENGTH, MODE MIXITY, AND CRACK LEGNTH ON CRACK FACE INTERACTIONS DURING SHEAR LOADING

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Project Summary

A collaborative project to continue our studies of the effect of fracture surface interference on the driving force for shear crack growth is proposed. Specifically, we will use in situ, phase shifted speckle interferometry techniques to measure the displacement field around a Mode I fatigue pre-crack loaded in shear as a function of load. The effective Mode II stress intensity factor and the induced Mode I stress intensity factor will be determined by fitting the displacement fields to near tip analytical expressions. The crack face shear and normal traction distribution will be estimated by using the experimentally observed crack face displacement as boundary conditions to boundary element and finite element models of the specimen.

These methods will be used to evaluate the effect of crack length, yield strength, and mode mixity on both the driving force for crack growth and on the crack face traction distribution as a function of applied Mode II stress intensity factor for several tempers of 4340 steel and of 7075 aluminum. The evolution of crack face displacements and tractions will be analyzed to generate a nonlinear, macroscopic spring model of the fracture surface interaction that will be correlated to statistical descriptions of the fracture surface profile. This model could then be used to predict the crack face displacements and tractions for any loading and crack geometry in the same material. This nonlinear contact interaction will be incorporated into an element designed for use in conventional FEM and BEM codes to make our results accessible to those who want to predict crack growth under shear and mixed mode loading in which the crack faces are either partially or entirely in contact.

I. Introduction

There is an increasing interest in the effect of fracture surface interaction in shear and mixed-mode loading situations as evidenced by Refs. [Li and Sakai, Reardon, Tong 1995, Tong 1995, Shang, Li 1995, Egami, Tanaka, Tschegg], all by other researchers and all published during the last project period. The important, and as yet not fully understood, role of fracture surface interaction in each of these studies is clearly brought out, and some of our previous work is cited in Refs. [Li and Sakai, Reardon]. We are therefore even more dedicated to the goal of our research, which is to characterize and model the effect of fracture surface interference on the driving force for shear modes of crack growth. Our recent efforts lead us to believe that we can provide unique and detailed information that will help to understand and describe this complex phenomenon.

Since fracture surfaces are microscopically rough, they interact as they are displaced in shear. The interdigitated fracture surface asperities must either ride up on one another and/or smear over one another. Both of these processes depend on the magnitude and spatial distribution of the contact stress normal to the fracture surface caused by the elastic hinge of the remaining ligament. The two primary effects of this interaction are that the crack tip is shielded from the applied shear and a Mode I stress field is induced [Mendelsohn, Gross, and Zhang 1995, Gross 1995, Goulet]. We have previously predicted that the magnitude of the resistance is much greater for interlocked asperities that ride up on one another than for smeared asperities, [Gross 1988, Gross 1989]. The specific goal of our research during the current project period was to characterize the effect of yield strength and elastic modulus on the nature and magnitude of the fracture surface interaction.

Our initial thinking was that the normal stress would be linearly proportional to elastic modulus for a given opening displacement. Therefore, the normal contact stress and, hence the shielding, would be greater for materials with higher elastic modulus. However, as we analyzed our results and thought more carefully, we realized that, for a given Mode II stress intensity factor, the crack face shear displacements are also proportional to elastic modulus. The crack would open less for a given applied Mode II and generate less resistance. So, one might expect to find offsetting effects and that the shielding would not depend on modulus. In fact, we found that the interaction is more complex.

The effect of yield strength was expected to manifest itself in two ways. First, the maximum contact stress near the tip must be limited by the yield strength. Therefore, at the tip, where the shielding is expected to be the greatest, the magnitude of the shielding should be roughly proportional to the yield strength. Second, the transition from asperity locking to asperity smearing is expected to be proportional to yield strength. Again, however, this transition depends on the magnitude of the normal contact stress for a given combination of opening and shear displacements, both of which are proportional to elastic modulus. So, the transition should also be affected by the effective driving force as well as yield strength.

II. Summary of Previous Work

The following sections describe what we have done to answer these questions during the previous contract period. We were able to infer the spatial dependence of the crack face tractions resulting from fracture surface interference using a hybrid analytical-experimental approach that utilizes unique, interferometric measurements of displacement fields around cracks loaded in shear in conjunction with a boundary element model of the specimen. The magnitude of the shielding and the induced Mode I stress intensity factor was determined as a function of applied Mode II stress intensity factor for two tempers of 7075 Al and for three different strength steels by fitting the displacement fields to the near tip field expressions. This study necessitated the re-analysis of the impact of boundary conditions on the loads applied by the asymmetric four point bend specimen.

II. A. Estimation of Crack Face Traction Distribution from Crack Face Displacement Fields

Figure 1 compares the experimentally obtained crack face shear and opening displacement fields with what was expected from the applied loading acting on a flat, smooth crack. For this specimen, the crack position was such that the applied loads held the crack faces in contact near the crack tip. Note that the observed shear displacements are less than the applied and that opening is observed where the applied opening is zero.

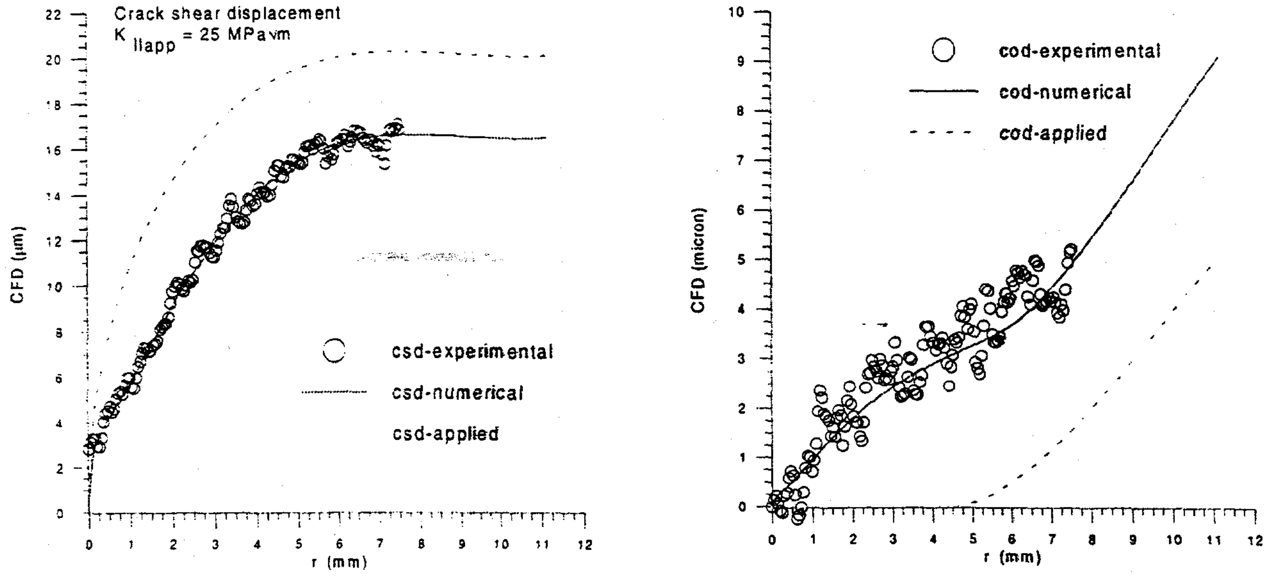

Figure 1 – Comparison of predicted and observed crack face opening and shear displacement profiles.

Figure 2 shows the analytical predictions of the crack face tractions that are necessary to generate the observed displacement field with the applied loading. The interaction parameter $\Gamma = \tau_R / \sigma_N$ is shown in Figure 3. Besides a small region near the tip ($r=0$ to $r \approx 0.25$ mm) where the crack faces are pinched out of contact, the crack is in contact to $r \approx 6$ mm. The shear tractions are maximum at the closest contact point to the tip and monotonically decrease with distance from the tip. In contrast, the normal tractions are nearly zero at the tip, reach a maximum at 2-4 mm from the tip, and then decrease with distance. The plot of the interaction parameter shows the "strength" of the interaction decreases with increasing distance from the tip.

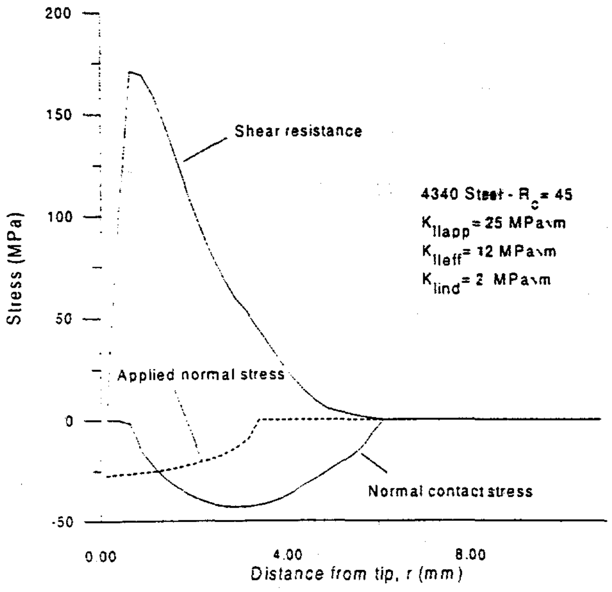

Figure 2

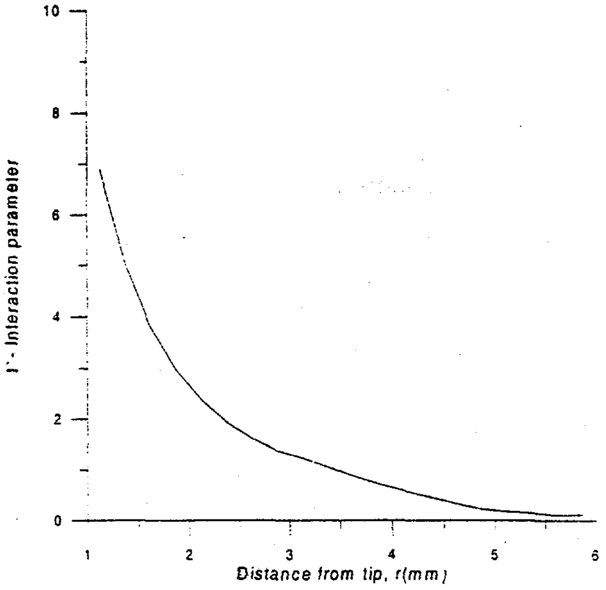

Figure 3

If the asperities are smeared or no longer interdigitated, then the proportionality constant becomes simply the Coulomb friction coefficient, μ. For a given friction coefficient, the resistance from interlocking is much greater than that for friction alone. If either of these situations were correct, then the shear and normal tractions in Figure 2 would be proportional to one another over the entire crack face. Both of these situations must be at least approximately correct on a local basis. The error is assuming that the interaction occurs everywhere and in the same way over the entire macroscopic crack. This assumption is common to much of the contact, wear and friction literature. It is only recently that researchers have begun to investigate the variable local nature of the frictional interaction across a rough surface [Bogy, Dally]. The proportional interaction neglects the fact that the crack tends to remain flat as it opens up - it does not curve to conform and remain in proportional contact. This nearly planar crack face opening can be clearly seen in both the analytical predictions and the experimental observations Figure 1.

So, what do the tractions in Figure 2 mean? Near the tip, the shear tractions are large indicating that the crack faces are interlocked. The peaking of the normal tractions coupled with the diminution of the shear tractions strongly suggests that the asperities have smeared in the 2-4 mm range from the tip. Furthermore, the peak in the normal tractions coupled with the fact that the crack cannot substantially bend to conform indicates that the crack faces are riding on this high point and attempting to lift off both at the tip and the mouth. If the crack faces conformed, as assumed in most models, then the normal tractions would be greatest at the tip. The fact that the normal compressive tractions at the tip are less than that predicted from the applied loading further supports the contention that the crack faces are lifting off of one another at the tip. ***This observation represents a major change in the way we must think about crack face interaction under shear loading.***

II. B. Analysis of the Asymmetric Four-Point-Bend Specimen

The asymmetric four point bend specimen is shown in Figure 4. All of the calculations made in the analysis of the experimental results discussed above, including the analysis of the applied problem without the interaction, were made possible by extensive studies of the effects of specimen geometry and load point boundary conditions [Mendelsohn 1997, Chen, Mendelsohn and Gross 1995]. The original design of the specimen and its previous use and calibration were based on expectations of the crack plane stresses found from a strength of materials approximation which is valid only in the limit of small ratio of the width to the load span. When this approximation is violated, it results in an additional normal stress component on the crack plane that increases in magnitude with the increase in the relative width. This tends to warp the crack plane resulting in an increased COD and, if the crack is open at the tip, an increased Mode I stress intensity factor as well.

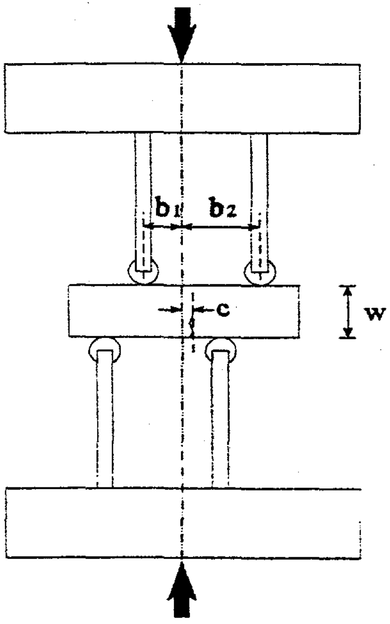

Figure 4 – Schematic of asymmetric four point bending setup.

Both normal and tangential interaction conditions between the load pins and the specimen were studied as well. We found that the load pins cause an observable indentation that prevents slip between the load pin and the specimen during loading. Therefore, the contact is modeled as a no-slip linear elastic spring acting tangent to the specimen at the load pin contact point. When all four load points are modeled this way, the lateral restraint induces compression on the crack plane which reaches a maximum at the limit of zero tangential motion. The resulting crack closure effect is most prevalent in the middle of the specimen near the crack tip. Only moderate values of the spring stiffness are sufficient to close cracks that would otherwise be open at the tip. There is also an increase in the warping of the crack plane with lateral restraint. In order to minimize these complications, a load apparatus was designed to have very small tangential stiffness. Once fabricated the measured stiffness of the load apparatus was used in the calculations and found to induce almost no compression. This small stiffness value was used throughout the remainder of the calculations.

It was also found that the lateral restraint had no effect on the Mode II response if the specimen is allowed to rotate. However, if it is prevented from rotating, lateral restraint can cause up to a 30% reduction in the Mode II response. Interestingly though, the constraint provided by the load frame necessary to prevent rotation also relieves some of the lateral restraint induced compression. Since we feel that allowing the rotation is more realistic, this is the condition used in all of the calculations that followed.

II. C. Effect of Yield Strength and Elastic Modulus on Shielding and Induced Opening

We investigated the effect of elastic modulus by comparing 7075-T6 Al and 8642 hot rolled steel which have nearly the same strength level. In addition, two stronger tempers of 4340 steel were studied and softer, annealed 7075-O aluminum was studied. The yield strength range in this study was 105 MPa to 1325 MPa. The modulus of aluminum is 1/3 that of steel (70.3 GPa and 210 GPa). Mode mixity was an additional variable in this study by variation of the position of the crack plane with respect to the loading axis. Experiments were conducted where a compressive load was applied to the crack faces and compared to those where a Mode I load was applied or was zero. The displacement fields were collected for decreasing loads and for multiple cycles, as well [Goulet 1997, Gross, Goulet, and Mendelsohn 1996]. These results are currently being analyzed and will not be discussed in this proposal.

The dependence of the resistance stress intensity factor, K_{IIR}, on the applied stress intensity factor, K_{IIapp}, is shown in Figure 5 on the next page. In the higher strength alloys, the K_{IIR} is equal to the K_{IIapp} up to a critical value (5-6 MPa$\sqrt{m}$ for Al and 10-12 MPa$\sqrt{m}$ for the steel). After this point, the K_{IIR} is roughly constant with increasing K_{IIapp}. The crack faces are locked at the lower K_{IIapp}. In contrast, the lower strength alloys exhibit no locking, the K_{IIR} increases with increasing K_{IIapp} but is of significantly lower magnitude. ***Lower strength alloys exhibit considerably less shielding.***

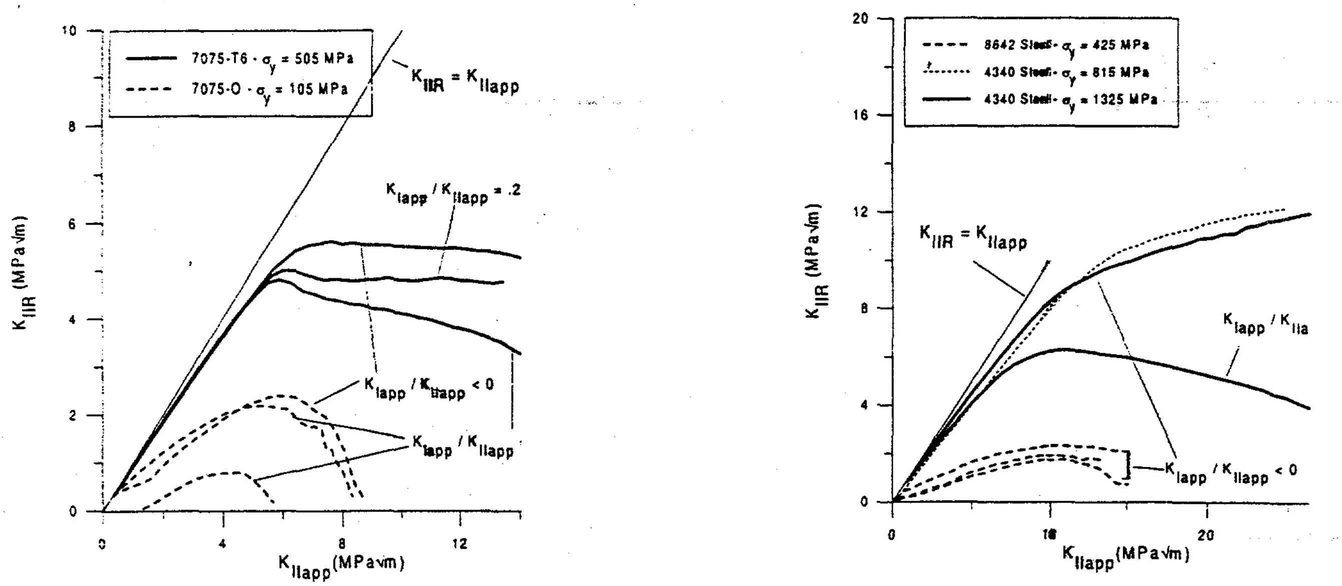

Figure 5 – Resistance stress intensity factor vs. Mode II applied stress intensity factor.

The plots of K_{Iind} vs. K_{IIapp} are shown in Figure 6 below. For the higher strength of each metal, the induced opening is suppressed until the crack faces slide past one another. The fact that the induced opening continues to increase without a concomitant increase in resistance suggests that the crack face interaction is in transition from a steep slope, short wavelength asperity interaction to a shallow slope, longer wavelength interaction.

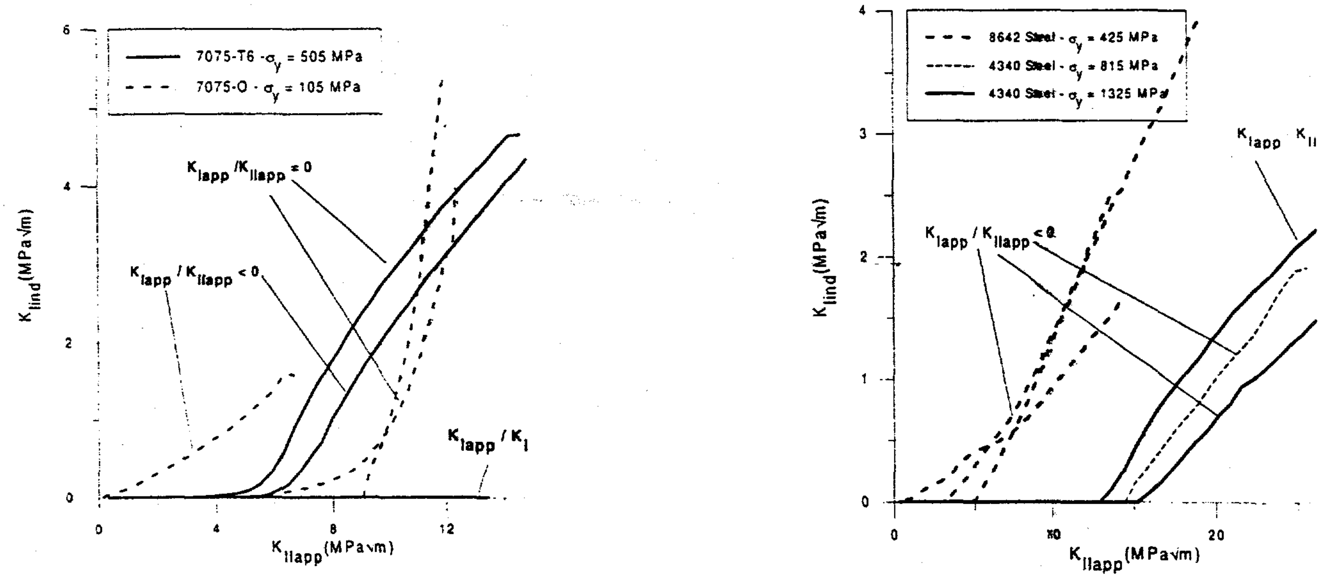

Figure 6 – K_{Iind} vs. K_{IIapp} for aluminum and steel.

Between the inference of the crack face traction distribution from the experimentally measured crack face displacements and the calculation of the effective Mode II and induced Mode I stress intensity factors, we have developed a powerful set of tools to study fracture surface interaction. These tools have been automated so that we can analyze large amounts of data in 1/10th the amount of time it took at the beginning of this project. We have uncovered a considerable amount of unique information that changes the way we must think about the way fracture surface interaction affects mixed mode crack growth. However, we have just scratched the surface and there are some key variables that need to be explored before we can say we understand the effect of fracture surface interference in shear. The next section summarizes our approach for the next funding period.

III. Proposed Work

III. A. Experimental Studies

In our previous work, we developed accurate techniques to measure the displacement field around a crack loaded in shear, as a function of applied load. The full displacement fields were analyzed to estimate the effective Mode II and induced Mode I stress intensity factors. The crack face displacement fields were analyzed to estimate the crack face tractions. This method was utilized to show that both elastic modulus and yield strength have a significant and measurable effect on crack tip shielding and crack face interaction for selected materials for approximately 10-12 mm long cracks. While our previous results were informative, much work must be done before our understanding of crack face interactions has broad application and significance. Specifically, the effect of *crack length* must be studied. It is necessary to understand the effect of mode mixity if we expect to be able to model multiaxial fatigue crack growth, where we know fracture surface interference plays a role. Obtaining a more detailed understanding of the effect of yield strength is very important too. Relating fractographic information to macroscopic behavior is necessary to correlate micromechanisms of interaction to the applied driving force. Finally, our measurements suggest that low strength materials have little resistance to the applied shear. We will attempt to grow Mode II fatigue cracks for low strength materials.

Effect of Crack Length: The effect of crack length is a variable that has not yet been explored in our studies. Other investigators have shown that the Mode III fatigue crack growth rate at constant ΔK_{IIIapp} decreases one to two orders of magnitude as the crack length increases from 0.5 mm to 3 mm. The estimate of crack face tractions shows that most of the crack face interaction occurs between 2-4 mm from the tip. This suggests that the shielding will be crack length dependent for crack lengths less than 5 mm. We will investigate the crack length dependence of the shielding for cracks in the 1-5 mm range for a “low” strength and a “high” strength aluminum and steel. This data will be used to formulate the crack length dependence of the constitutive law describing the shielding.

Mode Mixity Studies: Figure 5 and 6 contain data that was obtained at different degrees of mode mixity ranging from compressive loads on the crack faces to a positive Mode I. The results do not exhibit a clear and consistent trend. There are two possible reasons for this. First, the data is fairly sparse at a given strength level. Second, we need to make sure that our alignment methods are precise enough. We will refine the alignment technique and will then study the effect of positive and negative mode mixity for low and high strength steel. The data will be obtained for multiple specimens to evaluate repeatability.

More detail on yield strength effects: As previously mentioned, the amount of shielding decreases with a decrease in yield strength. Also, little or no locking is observed for "low" yield strengths while locking persists to a K_{IIapp} of 6 MPa$\sqrt{m}$ for "high" strength aluminum and to 10-12 MPa$\sqrt{m}$ for higher strength steels. This transition seems to depend on the ratio of yield strength to elastic modulus rather than the actual value of the yield strength. However, we do not currently have enough data to determine if the transition is distinct or gradual and if it occurs at the same yield strength-to-modulus ratio for both aluminum and steels. We propose to answer these questions by extending our measurements on 4340 steel and 7075 aluminum to a denser range of yield strength.

Fractographic Studies: To date, we have concentrated our efforts on the analysis of the displacement fields to estimate the effective Mode II and induced Mode I stress intensity factors and to estimate the crack face tractions. It has been a consuming, difficult, but extremely rewarding task. The crack face tractions suggest that the interaction changes from interlocking near the tip to smearing and/or compressive deformation of the asperities further away. This transition should be evident in the fracture surface by the appearance of abrasion and flattening of the asperities at some distance from the tip. We will conduct fractographic studies on all specimens to detect evidence of a transition in the nature of the crack face interaction. Sections through the fracture surface will be analyzed to detect flattening of asperities from the increased presence of reentrant features. Fracture surface matching studies will be performed on selected samples. The information from these studies will provide a bridge relating the macroscopic driving force to the microscopic asperity interactions.

Mode II Fatigue Crack Growth: We found that the resistance to the applied Mode II was small for low yield strength metals. This strongly suggests that Mode II fatigue crack growth in low strength metals cannot be suppressed by fracture surface interaction. B. Gross of NASA-Lewis Research Center communicated to us that he observed Mode II fatigue crack growth in an unspecified, but low strength aluminum alloy. Qian et. al. reported that they were unable to get Mode II cracks to extend in the Mode II orientation, but they studied austenitic stainless steel with yield strength of 310 MPa. The Mode II fatigue growth studies cited in Qian's review section typically involves complex specimens where the stress state may or may not be what the investigators expected. Shang was able to grow shear cracks in solder which is clearly a low strength material. We will attempt to grow Mode II fatigue cracks from Mode I fatigue precracks for the low strength tempers of the 4340 and an annealed 7075 aluminum using our well-characterized asymmetric four point testing jig. If Mode II fatigue cracks *cannot* be grown, then we know that Mode I fatigue crack growth is preferred for some other reason than suppression of Mode II or Mode III fatigue crack growth by fracture surface interaction.

III. B. Analytical Studies

The calculation of the crack face traction distribution has only been completed for one sample at one load. At this point, the process is very slow and tedious because we must iteratively determine where the crack face is in contact and we must arbitrarily smooth the data. To analyze the displacement data from even one sample would be prohibitive at present, so we propose to automate the process. The resulting sets of crack face tractions and displacements will be fitted to interaction relationships which track the transition from interlocking at low loads to sliding on worn surfaces. Once the different materials in the experiments have been characterized in this way, the interaction relationships can be used in predictive calculations, knowing only the applied loading and geometry, elastic modulus, yield strength, and a minimum of statistical information about typical roughness profiles for that material. To do this, we will develop general element and solution algorithms incorporating these interaction relationships in standard FEM or BEM codes. This will make our results accessible to those who intend to model multiaxial crack growth.

Automation of Traction Estimation from Experimental Displacements: As Fig. 1 shows, there is noise in the experimental data for the crack face displacements (CFDs). If the actual data were input into a BEM or FEM model for the specimen and loading, the resulting crack face tractions (CFTs) would have unrealistically large peak magnitudes and first, second, and even higher derivatives. Therefore, smooth fits of the experimental CFDs are used instead. Even then, there are still several obstacles to overcome in obtaining "realistic" and "smooth" crack face traction distributions. First, we must deal with the region near the tip where small changes in the input CFDs near the tip cause very large changes in the CFTs. Another sensitive region is the contact/no-contact boundary. Small changes in the location of the boundary and the distribution of the CFDs there can cause large changes in the CFTs.

An additional problem is the fact that the crack face data collected so far does not extend all the way to the mouth, necessitating "guessing" what the CFDs are past the range of the data. This is further complicated by the fact that, for some of the samples, the contact/no-contact boundary is in the vicinity of where the data stops. Therefore all future measurements will include the entire crack face.

Fett, et al. (1994) and Fett (1995) has used a similar inverse procedure to estimate Mode I crack face tractions due to whisker bridging. But, we are the first to apply this method to a mixed mode frictional setting where the state of contact or interaction is uncertain. It is important to note that the solutions obtained by Fett and by us are non-unique as a result of the uncertainties in measurement and knowledge of the crack face compliance relationships.

An automated iterative process (similar to the manual one used to obtain Figs. 1 and 2) for inputting "smoothly" corrected CFTs or CFDs and calculating CFDs or CFTs is proposed. At each step, the candidate distributions will be subjected to several constraints and conditions. First, there can only be compression (no tension) on the crack faces and the shear traction can only resist the relative sliding motion of the crack faces. Second, the tractions must satisfy certain well-known generic smoothness conditions at the contact/no-contact boundary. Namely, provided that the displacements are smooth, both tractions must have small second and third derivatives and the shear traction must come into the boundary with zero slope. Similar conditions at the crack tip have also been used, but the primary problem has been unrealistically large first derivatives of the shear traction.

As mentioned, the process has been manual up to now involving polynomial fits of hand drawn sets of smoothed candidate distributions. In order to automate this we need to first quantify all smoothness conditions and establish a "goodness of fit" criterion when fitting the experimental CFDs. We will use local polynomial fitting or cubic splines to automate the creation of families of candidate CFT or CFD distributions where the local features are required to change in a specified smooth fashion (i.e. 2D morphing). We expect that the development of the algorithm and the analysis of the large amount of experimental runs to be a significant portion of the entire proposed computational effort.

Characterization, Interaction Modeling and Element Development: One of our goals has been to develop a micromechanical model which would be able to ***characterize*** and ***predict*** the surface interaction from basic physical principles and the microstructural geometry, knowing only the modulus, yield strength, and some statistical or fractal measure of the roughness, slope and curvature profiles of a typical fracture surface of the material. Based on our own attempts to do this, and on discussions with members of the wear and tribology community, we now feel that this is an elusive goal, see e.g. a recent review of metallic sliding friction and wear [Black]. We turn instead to a macroscopic and phenomenological approach which recognizes that ***the measurable features of the interaction occur mostly on the same scale as the crack length and the features of the roughness with wavelengths at approximately this scale.***

The same, very general, model framework will be used for three tasks. The first task is to characterize the interaction using the sets of estimated tractions and experimental displacements. The second task is to use the resulting fleshed out models to predict the results in other situations. The third task is to develop an element for this type of model for use in FEM and BEM codes.

The general principle for the incremental interaction model is that, increments in the normal contact pressure and the resistance shear stress, are related to increments in the COD and CSD through independent, nonlinear springs. The focus of this stage of the research will be on the first cycle of loading during which the major interaction transition discussed above occurs, followed by sliding back on the worn surface. We propose that for a given material the compliances of the interaction springs at a given point along the contact are functions of the material properties, the displacement history at a given point, and the point's position along the contact relative to the nearest asperity peak. Simple functional forms for the stiffnesses based on previous concepts from tribology and on our own observations from the experiments have already been developed. For a given point in contact, the constants for the independent stiffness functions will be fitted by tracking the estimated ratios of normal contact pressure to COD and resistance shear stress to CSD. This will give us a map of the interaction behavior along the crack surface which evolves from the initial strong resistance of the interlocked asperities through the transition to smeared surfaces.

It is expected that the maps will correlate to the predominant wavelength of the intact surface roughness in the millimeter range. The maps will reflect the extent of smearing through the change in interaction. We will use the model in forward predictive calculations of the tractions and displacements assuming a similar wavelength of roughness but different load and/or geometry. These forward computations necessitate the development of a general nonlinear interaction element.

While many contact and interface elements exist, there are none which account for the complex interaction and history dependence that we will surely end up with based on the knowledge gained so far. The interface models and elements closest to our needs have been developed for rock or concrete interfaces under compression which exhibit shear strain softening as they degrade, Navayaogarajah, et al. (1992), Yang, et al. (1996). While we too expect shear strain softening as the opposing metallic surfaces wear, the existing elements involve constants which will be very difficult to determine from our experiments. We also don't know how these elements will work near or at the crack tip. We feel that developing our own model and element designed for use in a crack setting and based on our results is more efficient than adapting one of the previous models. The element, unlike all standard contact elements, must also allow for the wedging effect of asperities riding up on one another, which results in a positive COD and crack face contact at the same time. Also, an iterative algorithm will be developed, using the constraints mentioned above governing rough frictional contact, for determining whether a point is in contact or not, and, if in contact, whether or not the contact tractions are admissible.

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Goulet, R. U., (1997), *An Experimental Investigation of the Effect of Elastic Modulus and Yield Strength on Fracture Surface Interference in shear Loaded Cracks*, Ph.D. Thesis, University of New Hampshire.

Chen, F., (1997), *Analysis of a Four-Point-Bend Mixed-Mode Fracture Specimen*, M.S. Thesis, The Ohio State University.

Goulet, R. U., Gross, T. S. and Mendelsohn, D. A., (1996), "Evidence of Fracture Surface Interference for Cracks Loaded in Shear Detected by Phase Shifted Speckle Interferometry," *Metall. and Mater. Trans.*, **26A**, 1711-1717.

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Gross. T. S., Mendelsohn, D. A. and Tschegg, E. K., (1997), "Progress Towards Understanding the Effect of Fracture Surface Interference on Shear Modes of Crack Growth," to be presented at 5th International Conference on Biaxial and Multiaxial Fatigue and Fracture, September 8-12, 1997

Mendelsohn. D. A. and Gross, T. S., (1995), "Analysis of a Mixed Mode Four-Point Bend Fracture Specimen: Effect of Loading Pin Contact Conditions," *Developments in Mechanics*, **18**, 129-131.

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Mendelsohn, D. A., Young, L. J., Gross, T. S., and Zhou, M., (1995), "Analysis of Mode II Specimens For Studying Fracture Surface Interference", The Mining, Metals, and Materials Society (TMS) Annual Meeting, Cleveland.

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Mendelsohn, D. A., Young, L. J. and Gross, T. S., (1996), "Effects of Crack Roughness on Mixed-Mode Interface Crack Tip Plasticity," 3rd Int. Conf. on Composites in Eng., New Orleans.

Students supported by this project

UNH

1. Current: Christopher M. Prindle, M.S. candidate 1997

Chris has recently started on this project. He is a very hard worker and is expected to produce a large amount of information. His vitae is on the following page.

2. Ronald U. Goulet, 1994-1997, Ph.D. May 1997

OSU

1. Fei Chen 1995-1997 - M.S. June 1997

2. Mingxing Zhou 1995-present - will finish M.S. late 1997

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EDUCATION:

B.S. in Mechanical Engineering, University of New Hampshire, 1997
Cumulative GPA: 3.54/4.00

Related Coursework:

Thermodynamics
Materials Science
Machine Design
Experimental Measurement & Data Analysis
Systems Modeling, Simulation, and Control
Thermal System Analysis & Design
Fluid Mechanics
Vibration Theory
Finite Element Analysis
Engineering Graphics
Heat Transfer
Senior Design Experience
Corrosion of Materials
Electronic Properties of Materials
Kinematics & Dynamics of Machines

TECHNICAL SKILLS:

Software Tools: Mathcad, MATLAB, Grapher, Quattro-Pro, SilverScreen (Solid Model Based CAD), Microsoft Word, Excel and PowerPoint, Marc Finite Element Software
Operating Systems: UNIX, DOS, Windows, Windows 95
Computer Language: FORTRAN

RELATED EXPERIENCE:

MATERIALS SCIENCE LAB RESEARCHER
Materials Science Laboratory, Mechanical Engineering Department
University of New Hampshire, Durham, NH
Conducted research with a professor in the field of materials science; specifically, used interferometry techniques to study fracture mechanics of materials. Gained proficiency in the operation of an Instron servohydraulic loading machine, in addition to various machine tools, such as the mill and surface grin
(January, 1996 - Present)

OTHER EMPLOYMENT:

ASSISTANT TO SENIOR GRANT AND CONTRACT OFFICER
Office of Sponsored Research, University of New Hampshire, Durham, NH
Assisted Senior Grant & Contract Officer in preparation of subcontracts for faculty research, responsib
for basic office tasks.
(September, 1994 - December, 1995)

RETAIL SALES CLERK/EVENING SHIFT MANAGER
Meredith Trading Post, Meredith, NH
Managed evening shift, received and priced merchandise, responsible for opening and closing store and making daily deposits.
(Summers, 1994-1996)

MEMBERSHIPS/ AFFILIATIONS:

Certified Engineer-In-Training, NH Certificate #3383
Tau Beta Pi National Engineering Honor Society, NH Alpha Chapter
American Society of Mechanical Engineers (ASME)
Golden Key National Honor Society

EXTRACURRICULAR ACTIVITIES:

Tufts Design Fest '95 at Tufts University; community service at Chase Home for Children in Portsmouth, NH; Peer Outreach Program at Horne Street Elementary School in Dover, NH; Habitat For Humanity in Manchester, NH; Peer tutoring for the UNH College of Engineering.

INTERESTS:

Skiing, soccer, weightlifting, mountain climbing, inline skating, racquetball.

Description of Facilities and Resources

The experimental work will be performed at the University of New Hampshire.

UNH has developed a unique phase shifted speckle interferometry system (PSSI) that is mounted on an (ancient) screw driven Instron machine (20kip). The PSSI system is capable of resolving in-plane displacements of 0.05 μm and out-of-plane displacements of 0.01 μm. The spatial resolution has been demonstrated at 5 μm, but testing is typically done at 50 μm spatial resolution. The asymmetric, four point bending jig has compliant fingers to minimize the effect of lateral loads on the applied Mode I loading component. Papers detailing the accuracy and features of the PSSI system can be obtained on request.

Other relevant facilities at UNH

Complete metallography and specimen preparation facility
Amray 3300-FE field emission SEM (purchased 1997)
Digital Instruments, Dimension 3000 Scanning Probe Microscope.
Rigaku 2 kW x-ray diffractometer
Silicon Graphics Indy 133 MHz workstation for image processing

Facilities at OSU

Ohio Supercomputer Center - Cray Y-MP8/864
Ohio State University College of Engineering Computer Graphics Laboratories
(Several Vax systems)

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ACADEMIC BACKGROUND

1979, Ph. D.: Theoretical and Applied Mechanics, Northwestern University
1976, M. S.: Theoretical and Applied Mechanics, Northwestern University
1973, B. A.: Mathematics, Boston University.

PROFESSIONAL EXPERIENCE

1979 - 1982, Senior Engineer, Materials Engineering, Halliburton Services, Duncan, Oklahoma.
1982 - 1988, Assistant Professor, Department of Engineering Mechanics, The Ohio State University.
1988 - present, Associate Professor, Department of Engineering Mechanics, The Ohio State University

PROFESSIONAL ACTIVITY

Elasticity Committee, Engineering Mechanics Division, American Society of Civil Engineers (ASCE): Chair (1994-1996), Vice-Chair (1993 & 1997)

Associate Editor, *Journal of Engineering Mechanics (ASCE)*, 1994-1996.

Member: American Society of Mechanical Engineers, American Academy of Mechanics, International Association of Boundary Element Methods

RECENT JOURNAL PUBLICATIONS

D. A. Mendelsohn, T. S. Gross and Y. Zhang, "Fracture Surface Interference in Shear, Part I: A Model Based on Experimental Surface Characterizations," *Acta Metallurgica et Materialia*, Vol 43, 893-900, 1995.

C. Pecorari, D. A. Mendelsohn, and L. Adler, "Ultrasonic Wave Scattering from Rough, Imperfect Interfaces, Part I: Stochastic Interface Models, and Part II: Incoherent and Coherent Scattered Fields," *Journal of Nondestructive Evaluation*, Vol. 14, 109-128, 1995.

S. Muju, P. M. Anderson, and D. A. Mendelsohn, "Shielding due to Aligned Microcracks in Anisotropic Media," *Mechanics of Materials*, Vol. 22, 203-217, 1996.

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