CORROSION FATIGUE OF IRON-CHROMIUM-NICKEL ALLOYS: FRACTURE MECHANICS, MICROSTRUCTURE AND CHEMISTRY

Progress Report

for Period December 1, 1990 - December 31, 1992

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REFERENCE: Grant No. DE-FG02-88ER45354, "Corrosion Fatigue of Iron-Chromium-Nickel Alloys: Fracture Mechanics and Chemistry"

SUBJECT: Progress Report for Period 1 December 1990 to 31 December 1991

This progress report briefly summarizes the research performed under the referenced grant for the period from 1 December 1990 to 31 December 1991, and contains a cumulative listing of technical presentations and publications dating back to 1 June 1988.

Technical Report of Progress

Under this grant, a multi-disciplinary research program is undertaken to address certain fundamental issues relating to corrosion fatigue crack growth in structurally important alloys in aqueous environments. The principal goal of the research is to develop and expand the scientific understanding of the processes that control corrosion fatigue crack growth, particularly for ferrous alloys in terms of the controlling mechanical and chemical/electrochemical processes and their interactions with the microstructure.

Focus is placed upon the austenitic iron-chromium-nickel (FeCrNi) alloys because of the need to resolve certain mechanistic issues and because of extensive utilization of these alloys in the power generation and chemical industries. Emphasis is given to the growth of short (small) cracks at low growth rates because crack growth in this regime is expected to be more sensitive to changes in external chemical/electrochemical variables. The slower growth rates would also facilitate critical testing of mechanistically based models in terms of their ability to predict long-term response from short-time data. The ongoing research utilizes a combined mechanics, materials science and chemistry/electrochemistry approach.

The program was initiated on 1 June 1988, and was extended for an additional 3 years, effective 1 June 1991. Principal efforts during the past 13 months are as follows: (1) resolution of fundamental issues relating to measurement of kinetics of electrochemical reactions with bare steel surfaces and publication of these findings; (2) additional measurements of the kinetics of electrochemical reactions for the annealed Fe18Cr12Ni alloy in aqueous environments, and their correlation with corrosion fatigue crack growth response as a function of solution pH; (3) studies of fracture surfaces produced by corrosion fatigue in aqueous solutions and in hydrogen to identify the crack

growth enhancement mechanisms, and the susceptibility of specific boundaries; (4) studies of microstructural changes that result from hydrogen charging; and (5) further development of techniques for preparing bicrystals of the Fe18Cr12Ni alloy. Progress in each of the areas is given in the following executive summary, and is then briefly described.

Executive Summary

Principal findings from research conducted during this period are as follows:

1. The fundamental question of "what is being measured in a scratched electrode test?" has been resolved, and the findings have been published in the Journal of the Electrochemical Society. A separate note has been accepted for publication in Corrosion, a journal of the National Association of Corrosion Engineers. In essence, the scratched (or strained) electrode test that had been used to study the kinetics of reactions with bare metal surfaces over the past 10 years provided gross overestimates of the peak bare-surface current densities and the rates of repassivation for stainless steels. Overestimation had resulted from not recognizing double-layer charging of the filmed portion of the specimen surface as the principal contributor to the initial current transient, and of the transient action of the potentiostat upon the sudden exposure of a new surface. Overestimation of the repassivation rates is a consequence of this oversight, and of the very limited duration (about 10 ms) selected for making the current measurements in the scratched electrode technique.

The aforementioned papers (see attachments 1 and 2) represent revised and expanded versions of the preprints that were submitted with the progress report last year, and provide clarifications of the role of the filmed surface and the interaction with the potentiostat. This finding has been discussed with and is supported by the work of Dr. R. Oltra, University of Dijon, Dijon, France, who is well regarded for his work in transient electrode kinetics. The important contribution of double layer charging in the scratched electrode test has now been affirmed also by the recent work of researchers at the Brookhaven Laboratories.

2. Additional studies of the influences of potential and pH on the reactions of bare surfaces of annealed Fe18Cr12Ni alloys with deaerated 3.5% NaCl solution have been completed. The amount of charge transferred was found to increase with increased (i.e., more noble) applied potential and solution pH (i.e., more caustic), which reflected increases in free corrosion potential with pH. The charge transfer results correlated with the corrosion fatigue crack growth data at room temperature. The correlation suggests that the electrochemical condition at the crack tip approximated that of free corrosion.

Crack growth response was essentially identical at pH 2 and 6.5, but the crack growth rates were slower at pH 12. The slower rates are attributed to a lower hydrogen fugacity associated with the reactions at pH 12. This important influence of solution pH is consistent with results from hydrogen permeation studies, but is not well understood. Further investigations are planned and are included in the proposed continuation of research.

3. To further clarify the mechanisms for corrosion fatigue crack growth, a direct comparison is made of the morphology of fracture surface of the Fe18Cr12Ni alloy that had been produced by corrosion fatigue in 3.5% NaCl solutions (at pH 2 to 12) and in hydrogen at room temperature. The results show that the fracture surface morphology was identical in these environments. The fracture paths consisted of intergranular cracking along the austenite boundaries, twin boundary separation, and quasi-cleavage of transformed martensite. The austenite and twin boundaries appear to be preferred paths for cracking. The amount of intergranular (IG) and twin boundary (TB) separation depended upon solution pH; the amount at pH 12 was essentially equal to that observed in hydrogen at 100 kPa. The areal fractions of IG/TB separation are correlated with the corrosion fatigue crack growth rates, and their dependence on solution pH is interpreted in terms of its influence on hydrogen fugacity. These observations confirm hydrogen embrittlement (rather than anodic dissolution) as the micromechanism for corrosion fatigue crack growth in the aqueous environments. These results have been summarized and have been submitted to Scripta Metallurgica et Materialia for publication (see Attachment 3).

4. Strong correlation was established between the morphology of corrosion fatigue fracture surfaces and cracking in hydrogen charged samples (austenite grain boundary and twin boundary separation, and transgranular cracking along preferred planes within the austenite grains). A study was initiated during this period to investigate microstructural changes that result from hydrogen charging using x-ray diffraction analyses. Initial results show that an apparent "hydride" phase formed upon charging of the annealed Fe18Cr12Ni alloy; the amount of which depended on charging conditions. Upon aging at room temperature, this phase decomposed to form α' and ϵ martensites. These findings suggest that charging can serve as an important additional tool for studying the mechanisms for crack growth. These studies are being continued and are included in the proposed continuation of research.

5. Attempts at growing bicrystals by an active strain annealing technique have not been successful thus far. The procedure is time-consuming and does not appear to offer the desired degree of consistency. As a part of a new NSF/MRG program at Lehigh, a modified Bridgman crystal growing furnace will be available for use this spring. The modified Bridgman technique has been used successfully by General Electric and HOWMET to grow large (10x80x100 mm) single crystals and bicrystals of nickel base alloys. It is planned to make use of this facility to grow bicrystals by this technique for the proposed grain boundary sensitivity studies.

Peak Bare-Surface Current Density Measurements

Results from electrochemical experiments conducted during the previous period clearly showed that the peak bare-surface current densities and the rates of repassivation reported by previous investigators [1-3] on the basis of scratched (and strained) electrode tests are seriously in error. The peak bare-surface current densities and the estimated repassivation rates of stainless steels are one to 3 orders of magnitude higher than those indicated by the in situ fracture experiments [4,5]. The error in the magnitude of the current densities arose, apparently, as a result of incorrect understanding of how a potentiostat functions and of the nature and distribution of current between the bared and filmed portions of the specimen surfaces. Overestima-

tion of the repassivation rates is a consequence of this misunderstanding, and the very limited duration (about 10 ms) chosen for these experiments.

These results served to remove much of the ambiguities regarding the mechanisms for crack growth enhancement, and suggested that a careful reassessment of the conclusions, drawn on the basis of scratched electrode data, is needed. The essential results were summarized and submitted for publication as a paper and a technical communication (see previous progress report dated 29 November 1990). During the publication review process, a more detailed explanation of the interactions between the bared and filmed portions of the specimen surface and the potentiostat was requested. Accordingly, the papers were expanded and revised. The main paper has been published in the Journal of the Electrochemical Society [6] (see Attachment 1), and the technical communication will appear in Corrosion in January [7] (see Attachment 2).

In essence, as a portion of the originally "passive" surface is bared by scratching (or straining), current flows between the bared and surrounding filmed surfaces as a result of their differences in electrochemical potential. This current flow serves in part to form a double layer over the bared surface and to effect repassivation, and is supplied by discharge of the double layer over the filmed portion of the specimen surface. Concurrently, the potentiostat senses the reduction in potential (becoming more cathodic) caused by the bared surface, and responds by increasing current flow to the specimen. This current is partitioned between the bared and filmed surfaces. The relative magnitudes of the charging and repassivation currents depend on the electrolyte and reaction kinetics, among others. The actual magnitude and distribution of current between the two portions of the surface depend on the configuration of the cell, etc.

These papers [6,7] (see Attachments 1 and 2) essentially serve to clarify the issues, and address the concerns raised by Kelly and Newman in [8], and, more recently, by Bernstein and Gao [9]. To further solicit opinions from the electrochemistry community, Dr. R. P. Wei visited Dr. R. Oltra at the University of Dijon in Dijon, France in August. Dr. Oltra is a principal contributor to research in transient electrode kinetics, and is currently active in this area. He has been focusing a part of his research on the distribution of initial currents between the double layers, and his results are in agreement with this assessment of the scratched electrode technique. Further support of the influence of the double layer over the filmed surface on the measured initial current transient is provided by recent results of computer simulation at Brookhaven [10].

It is hoped that further advances in understanding of various electrochemical processes will now follow.

Electrochemical Reactions and Corrosion Fatigue Crack Growth

Measurements of the kinetics of electrochemical reactions with bare surfaces of the Fe18Cr12Ni alloy have been made and verified, using the in situ fracture technique [1,11]. The influences of applied potential (-400, -480 and -700 mV SCE) and pH (2, 6.5 and 12) were determined for the reactions in deaerated 3.5% NaCl solution at room temperature. The results were summarized in the previous progress report (dated 29 November 1990).

To examine the relationship between electrochemical reactions and corrosion fatigue, crack growth experiments were conducted on the Fe18Cr12Ni alloy to investigate principally the influence of pH. The experiments were carried out under constant ΔK control, principally at $\Delta K = 15 \text{ MPa}\sqrt{\text{m}}$, in a deaerated 3.5% NaCl solution at room temperature and an applied potential of -700 mV SCE. The experiments spanned frequencies from 0.1 to 10 Hz. Correlation of the crack growth and charge transfer data is shown in Fig. 1.

Fig. 1: Correlation of charge transfer data with corrosion fatigue crack growth response (at an applied potential of -700 mV SCE) for Fe18Cr12Ni alloy in deaerated 3.5% NaCl solution (pH 2, 6.5 and 12) at room temperature.

Figure 1 shows the crack growth data at pH 2 and 6.5 conformed to estimated charge transfer data for applied potentials of -420 and -550 mV SCE, respectively, rather than the applied potential of -700 mV SCE for the fatigue crack growth tests. The data at pH 12.0 correlated well with the charge transfer data at -700 mV SCE. Each of the potentials approximates the free corrosion potential at the particular pH level. These correlations, therefore, are consistent with the previous observation that showed the crack-tip potential tended to remain close to the free corrosion potential [11]. The difference in the amount of charge transferred was not sufficient to account for the observed difference in crack growth rates between pH 12.0 and the other pH values. The lower growth rates at pH 12.0 is now attributed to a lower hydrogen fugacity relative to that at the lower pH levels (see following section). The results are being summarized and will form the basis of a M.S. thesis for Mr. S. F. Chen.

There are indications of chemically-short-crack effect, which depended on pH and applied potential. The variation in corrosion fatigue crack growth rate with crack length is complex, and extended to about 7.5 mm. Depending on electrochemical and loading conditions and crack lengths, the rates may be faster (at less than 3 mm), or slower (from about 3 to 7.5 mm), or remain unchanged (at -1000 mV SCE) relative to that observed at the longer crack lengths. Further crack growth and fractographic studies are being made to understand this phenomenon.

Mechanisms for Corrosion Fatigue Cracks in Fe18Cr12Ni Alloy

To further clarify the mechanism for corrosion fatigue crack growth in ferrous alloys in aqueous environments, a direct comparison is made of the morphology of fracture surfaces of a high-purity metastable (Fe18Cr12Ni) stainless steel that had been produced by corrosion fatigue in deaerated 3.5% NaCl solutions (at pH 2, 6.5 and 12) and in hydrogen at room temperature. Fractographic examinations were conducted on specimens that had been tested at a constant ΔK of $15 \text{ MPa}\sqrt{\text{m}}$ and $R = 0.1$, using a frequency of 10 Hz for the aqueous solutions, and 8 Hz for hydrogen and vacuum.

Representative SEM micrographs of the fatigue fracture surfaces produced in deaerated 3.5% solutions were given in the previous progress report (dated 29 November 1990), and are compared against those produced in hydrogen in the attached paper (Attachment 3). They showed the essential features of the fracture surface morphology (FSM) for the various deleterious environments to be identical, and indicated that they were produced by the same micro-cracking mechanisms. The FSM consisted of intergranular (IG) separation, twin boundary (TB) cracking, and irregular appearing regions of quasi-cleavage (QC) that surround IG and TB separation. Some evidence of secondary cracking was also observed. These features are essentially the same as those observed in 304 stainless steels in aqueous solution and in air [13]. There is one-on-one matching across the mating fracture surfaces, with no evidence of corrosion attack (or metal dissolution). The FSM of fatigue surfaces produced in vacuum was different and was "ductile" in appearance, with no evidence of IG or TB separation. The crystallographic nature of the fracture surfaces, the absence of discernible corrosion attack, and the identity of FSM with that produced in gaseous hydrogen provide unequivocal support for hydrogen embrittlement as the mechanism for crack growth in aqueous environments.

To quantify the microstructure-environment interactions, the areal fractions of IG and TB separation in the different environments were determined, and compared against the corresponding fatigue crack growth rates in Table I. Both the overall crack growth rates, (da/dN) , and the environmental contributions, $(da/dN)_{cf}$, are included [12]. It can be seen that the areal fraction of IG and TB separation and the corresponding crack growth rates at pH 12 are comparable to those in hydrogen, but are less than one-half of those at pH 2 and 6.5. The crack growth rate was the lowest in vacuum, with no evidence of IG and TB separation. These results imply that grain and twin boundaries are the preferred paths for hydrogen assisted cracking (or embrittlement). They suggest that hydrogen fugacity was highest at the lower pH values, and was comparable at pH 12 to gaseous hydrogen at 100 kPa.

The indicated effect of pH is consistent with that observed in hydrogen permeation experiments [14]. For iron-based alloys, the average concen-

Table I: Areal Fraction of IG and TB Separation and Associated Fatigue Crack Growth Rates in Various Environments

Environment	Crack Growth Rate* (10^{-9} m/cycle)		Areal Fraction (IG + TB) %
	(da/dN) _e	(da/dN) _{cf}	
Vacuum	3.2 ± 0.2	0	0
Hydrogen (100 kPa)	10.7 ± 0.7	7.5 ± 0.7	8.9 ± 1.3
3.5% NaCl pH = 12	10.4 ± 1.0	7.2 ± 1.0	10.6 ± 0.3
pH = 6.5	16.5 ± 3.8	13.0 ± 3.8	24.7 ± 2.2
pH = 2.0	18.9 ± 1.1	16.0 ± 1.1	29.2 ± 1.9

*Crack growth tests were conducted at 10 Hz, except in vacuum and hydrogen (f = 8 Hz).

trations of hydrogen in the material for a low pH solution (0.1N H₂SO₄, at pH = 1.29) were found to be more than one order magnitude higher than those for a high pH solution (0.2N NaOH, at pH = 13.3) at same charging current densities [14]. It should be noted that the observed effect of pH on crack growth rates cannot be reconciled with the dissolution-based models, because the amount of charge transferred at pH 12 is higher than, or comparable to, those at the lower pH values (2.0 and 6.5) at the same applied potential.

These results clearly show that hydrogen embrittlement is the mechanism for corrosion fatigue crack growth in the austenitic Fe18Cr12Ni steel in 3.5% NaCl solutions. The austenite and twin boundaries appear to be preferred paths for cracking. The amount of intergranular (IG) and twin boundary (TB) separation depended upon solution pH; the amount at pH 12 was essentially equal to that observed in hydrogen at 100 kPa. The areal fractions of IG/TB separation are correlated with the corrosion fatigue crack growth rates, and their dependence on solution pH is interpreted in terms of its influence on hydrogen fugacity. Solution pH appeared to influence crack growth rates and the amount of grain and twin boundary separation through its effect on hydrogen fugacity. Further studies to understand this influence are underway and are included in the proposed continuation of research.

A paper, summarizing the foregoing results, has been submitted for publication in Scripta Metallurgica et Materialia (see Attachment 3).

Microstructural Changes in Fe18Cr12Ni Alloy Following Hydrogen Charging

To better understand the mechanisms for crack growth and the influence of microstructure, 0.2 mm thick specimens of the Fe18Cr12Ni alloy were cathodically charged with hydrogen in a 1N H₂SO₄ solution, containing 0.25 g/L of

Na_2AsO_2 as a hydrogen recombination poison. Charging was carried out at a current density of 100 mA/cm^2 for up to 4 hours. These conditions are quite severe. If all of the hydrogen entered the specimens, the estimated average hydrogen concentration would be about 5×10^{23} atoms/cm³.

Scanning electron micrographs showed extensive cracking of the austenite grain boundaries and twin boundaries, following 60 minutes of charging. There was considerable cracking within the austenite grains, and the appearance of many of the grains suggested that martensitic transformation had taken place. Charging at shorter times induced the same cracking features (albeit to a much smaller degree), and suggested certain of the boundaries might be more susceptible than others to hydrogen embrittlement.

To complement these SEM studies, changes in microstructure of the Fe18Cr12Ni alloy were monitored by x-ray diffraction. Representative x-ray spectra, showing the influence of room-temperature aging after charging at 100 mA/cm^2 for 4 hours, are given in Figs 2 and 3. The spectrum in Fig 2 corresponds to a sample that had been charged, cooled in liquid nitrogen, and then warmed to room temperature for 2 minutes prior to x-ray analysis. The spectrum in Fig 3 corresponds to the same sample that had been aged at room temperature for 24 hours.

Comparison of Figs 2 and 3 shows the presence of a prominent peak at $2\theta = 45.3$ degrees, following charging, which disappeared completely after prolonged aging at room temperature. This peak is not associated with any of the known x-ray peaks of this austenitic steel, and is tentatively identified

Fig. 2: Representative x-ray spectrum of Fe18Cr12Ni alloy specimen electrolytically charged at 100 mA/cm^2 for 4 h and cooled to liquid nitrogen temperature; taken 2 min. after warming to room temperature.

Fig. 3: Representative x-ray spectrum of specimen in Fig. 2; after 24 h.

as a "hydride" peak. The presence of α' , ϵ and γ phases following charging shown in Fig 2, is indicated by the corresponding x-ray diffraction peaks. It is to be noted that the γ peak is shifted to a smaller 2θ relative to the uncharged material. Following aging, the disappearance of the "hydride" peak is accompanied by increases in the α' and ϵ peak intensities, while the γ peak-height remained essentially unchanged. The results indicated gradual shifts of 2θ to larger values for the γ and ϵ peaks with aging, while that of α' remained essentially unchanged.

The SEM and x-ray diffraction results indicated substantial uptake of hydrogen by the lattice, and extensive hydrogen related changes in microstructure. The x-ray results suggested the formation of an apparent "hydride" phase, and the decomposition of this and other phases and transfer of hydrogen amongst the different phases. The strong correlation between the crack paths for corrosion fatigue and the cracking pattern in hydrogen charged specimens, taken together with the changes in microstructure indicated by x-ray diffraction, suggest that further study of hydrogen charged specimens would help in understanding the mechanisms for cracking. Further studies, combining scanning and transmission electron microscopy, and electron channeling, are being continued, and are also included in the proposed continuation of research.

Preparation of Bicrystals on the Fe18Cr12Ni Alloy

To examine the influence of grain boundary orientation and structure on hydrogen concentration in the boundaries and on their fatigue properties, a

limited number of experiments were planned for Fe18Cr12Ni bicrystals. These bicrystals are not available commercially and need to be specially produced. Attempts were continued during this period to prepare bicrystals of Fe18Cr12Ni alloy by a "strain-annealing technique". This work is intended to serve the following two purposes. Firstly, the preparation of small bicrystals that can be used for characterization of grain boundary orientation and structure and for preliminary studies of grain boundary effects. Secondly, the preparation of small single crystals that can be used as seeds for growing bicrystals by using a "floating zone electron beam melting technique" (with the modified match-up seed method).

Although grain diameters of up to 8 mm have been obtained as before, the technique still proved to be time consuming and ineffective in producing bicrystals with control. Effort during this period was concentrated on using active straining during the annealing treatment. An alternative for producing bicrystals is now available. As a part of a new NSF/MRG program at Lehigh, a modified Bridgman crystal growing furnace will be available for use this spring. The modified Bridgman technique has been used successfully by General Electric and HOWMET to grow large (10x80x100 mm) single crystals and bicrystals of nickel base alloys. It is planned to make use of this facility to grow bicrystals by this technique for the proposed grain boundary sensitivity studies. Preparation and characterization of low-angle boundary bicrystals are planned, and are included in the proposed continuation of research.

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"The Kinetics Aspects of Hydrogen Embrittlement", R. P. Wei, 2nd National Aero-space Plane (NASP) Workshop: Hydrogen-Materials Interactions, Scottsdale, AZ, June 2, 1988.

*"Bare Surface Reactions and Crack Growth in Steels: A New Perspective", R. P. Wei, Gordon Research Conference on Corrosion, New London, NH, July 21, 1988.

"Deformation and Subcritical Crack Growth Under Static Loading", Hui Yin, Ming Gao and R. P. Wei, 1988 TMS Fall Meeting, Chicago, IL, September 27, 1988.

"Stress Corrosion Cracking of High-Strength Steels in Aqueous Environments", H. C. Chu, Ming Gao and R. P. Wei, 1988 TMS Fall Meeting, Chicago, IL, September 28, 1988.

*"Chemically-Induced Crack Length Effects in Corrosion Fatigue of AISI 304 Stainless Steel", D. E. Allison, A. Alavi, M. Gao and R. P. Wei, 1988 TMS Fall Meeting, Chicago, IL, September 28, 1988.

*"In Situ Fracture Techniques for Studying Transient Reactions With Bare Steel Surfaces", R. P. Wei and A. Alavi, 174th Fall Meeting of Electrochemical Society, Chicago, IL, October 10, 1988.

"Electrochemical Considerations of Crack Growth in Ferrous Alloys, R. P. Wei, Seventh International Conference on Fracture (ICF7), Houston, TX, March 20-24, 1989.

"Corrosion Fatigue Crack Growth and Reactions With Bare Steel Surfaces", R. P. Wei, CORROSION/89, New Orleans, LA, April 17-21, 1989.

"Identification of Hydride Phases in Thermally Charged Titanium Aluminides", Ming Gao, Bart Boodey and Robert P. Wei, 3rd NASP Workshop: Hydrogen-Materials Interactions, Scottsdale, AZ, May 31-June 2, 1989.

"Phase Transformation and Moisture Induced Crack Growth in Yttria Stabilized Zirconia", R. P. Wei, International Conference on Mechanistic Aspects of Fracture, Irsee, W. Germany, June 19-23, 1989.

*"Environmental and Microstructural Considerations of Corrosion Fatigue Crack Growth", R. P. Wei, FRACTURE '89, Johannesburg, South Africa, June 29, 1989.

"Corrosion Fatigue Crack Growth and Electrochemical Reactions for A X-70 Linepipe Steel in Carbonate-Bicarbonate Solution, R. P. Wei, FRACTURE '89, Johannesburg, South Africa, June 29, 1989.

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*"Bare Surface Reactions and Mechanisms for Corrosion Fatigue Crack Growth", R. P. Wei, DOE/BES/DMS Contractors' Meeting, Oakland, CA, September 21, 1989.
"Environmentally Assisted Fatigue Crack Growth in an Alumina Reinforced Aluminum Alloy", R. P. Wei, ALCAN Meeting, Chicago, IL, September 28, 1989.

"Identification of New Precipitates in Peak Aged Al-Mg-Si (6061-T6) Aluminum Alloy", M. Gao and R. P. Wei, 1989 TMS Fall Meeting, Indianapolis, IN, October 2, 1989.

*"Crack Paths and Corrosion Fatigue Crack Growth in 304 Stainless Steels", Ming Gao, Shuchun Chen and R. P. Wei, 1989 TMS Fall Meeting, Indianapolis, IN, October 2, 1989.

"Environmentally Assisted Crack Growth and Predictions of Service Life", R. P. Wei, ONR Workshop on Life Predictions, National Institute of Standards and Technology, Gaithersburg, MD, October 27, 1989.

"Mechanistic Considerations of Corrosion Fatigue of Steels", R. P. Wei, International Conference on Evaluation of Materials Performance in Severe Environments (EVALMAT 89), November 20, 1989.

*"Bare Surface Reactions and Mechanisms for Corrosion Fatigue Crack Growth in Steels", R. P. Wei, Nippon Steel Corporation, R & D Laboratories II, Sagami-hara, Japan, November 24, 1989.

*"Rate Controlling Processes and Corrosion Fatigue Crack Growth", Robert P. Wei, Materials Science Colloquia, University of Virginia, Charlottesville, VA, April 2, 1990.

"Phase Transformation and Sustained-load Crack Growth in Yttria Stabilized Zirconia", Hui Yin and R. P. Wei, American Ceramic Society, Dallas, TX, April 24, 1990.

*"Bare Surface Reactions and SCC and CF Crack Growth in Ferrous Alloys: A New Approach to Understanding", R. P. Wei, Seminar at the University of Erlangen, Erlangen, Germany, July 27, 1990.

*"Scratching Electrode Technique -- What is Being Measured", Ming Gao, DOE/BES Contractors' Meeting, Minneapolis, MN, September 13, 1990.

*"Bare Surface Reactions and SCC and CF Crack Growth in Ferrous Alloys: A New Approach to Understanding", R. P. Wei, Keynote lecture for the 1990 Annual Meeting of the Chinese Society of Corrosion Engineering, Sun-Moon Lake, Taiwan, ROC, September 13, 1990.

"Phase Transformation and Sustained-load Crack Growth in Yttria Stabilized Zirconia", R. P. Wei, Industrial Technology Research Institute, Materials Research Laboratories, Taiwan, ROC, September 14, 1990.

"Environmentally Assisted Crack Growth in Ceramic Particle Reinforced Metal Matrix Composites", R. P. Wei, Alcan Meeting, Kingston, Ontario, Canada, September 26, 1990.

"Misfit Strains and Mechanism for the Precipitation of Hydrides in Thermally Charged Alpha-2 Titanium Aluminides", Ming Gao, J. Bart Boodey and Robert P. Wei, TMS/ASM Fall Meeting, Detroit, MI, October 8, 1990.

"Hydrogen Solubility and Hydride Formation in a Thermally Charged Gamma Based Titanium Aluminide", J. Barton Boodey, Ming Gao and Robert P. Wei, TMS/ASM Fall Meeting, Detroit, MI, October 8, 1990.

"Environmentally Assisted Fatigue Crack Growth in Aluminum and Titanium Alloys", Robert P. Wei, Institut fur Werkstoffwissenschaften, Erlangen, Germany, February 5, 1991.

*"Hydrogen Embrittlement and Environmentally Assisted Crack Growth in High Strength Steels", Robert P. Wei, GKSS-Forschungszentrum Geesthacht GmbH, Geesthacht, Germany, February 22, 1991.

*"Electrochemical Reactions With Bare Surfaces and Corrosion Fatigue Crack Growth in Steels", Robert P. Wei, MPI-Stuttgart, Germany, February 25, 1991.

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Personnel

During the past 13 months, the following personnel were associated with this grant in addition to Dr. Robert P. Wei, Principal Investigator: Dr. Ming Gao and Messrs. Shuchun Chen and Shyuan-Fang Chen. Dr. Gao is a Senior Research Scientist from the People's Republic of China and is participating in the program on a part-time basis. He is responsible for the mechanical and microstructural aspects of the program. He assists Dr. Wei in addressing the problems of corrosion fatigue mechanisms and modeling of corrosion fatigue crack growth. Mr. S. C. Chen is a Ph.D. candidate in Materials Science and Engineering, and is studying the microstructural aspects of corrosion fatigue crack growth. Mr. S. F. Chen is a M.S. candidate in Applied Mechanics in the Department of Mechanical Engineering and Mechanics, is studying corrosion fatigue crack growth response in relation to electrochemical reactions with bare surfaces.

Dr. Wei assumed the position of Chairman of the Department of Mechanical Engineering and Mechanics on 1 July 1990. In this capacity, he has administrative responsibility for a department with 34 full-time faculty, 370 undergraduate and 100 graduate students.

Awards and Honors

Dr. Robert P. Wei was granted an Alexander von Humboldt Foundation Award for a Distinguished Senior U. S. Scientist in December 1989 for a 12-month period of research studies in Germany. As a part of this award, Dr. Wei is conducting cooperative research on corrosion fatigue in aqueous environments with scientists at the GKSS Forschungszentrum, a German government laboratory, located in Geesthacht (near Hamburg). He spent the summer there in 1990 principally for planning, and completed his tenure from January to the end of August, 1991 at GKSS.

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