"INVESTIGATION OF FRACTURE TOUGHNESS AND FRACTURE MECHANISMS USING ACOUSTIC EMISSION MEASUREMENTS"

Final Progress Report for the Period
1 March 1988 - 31 August 1991

- Prepared by -

Professor Steve H. Carpenter
Department of Physics
University of Denver
Denver, CO 80208

- Prepared for -

United States Department of Energy
ATTN: Dr. Joseph Darby
Agreement No. DE-FG02-85ER45182

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed, or represents that its use would infringe privately owned rights.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ABSTRACT

This report is the "FINAL PROGRESS REPORT" for the research program "Investigation of Fracture Toughness and Fracture Mechanisms using Acoustic Emission Measurements." The time period covered by this report is from 1 March 1988 through 31 August 1991. The research program consisted of three separate but closely related investigations:

- 1.- An Investigation of the Acoustic Emission Generated during the Deformation and Fracture of Premium Grade 4340 Steel as a function of Mechanical Properties.
- 2.- An Investigation of the Acoustic Emission Generated during the Deformation and Fracture of Ti-6Al-4V Alloys as a Function of Microstructure.
- 3.- An Investigation of the Acoustic Emission Generated from Second Phase Particles in Aluminum-Silicon Alloys as a Function of Second Phase Particle Size and Density.

A synopsis of each of the individual investigations including pertinent data and meaningful results will be given in the report. A listing of graduate student involvement, publications and presentations will also be provided.

RESEARCH PROGRESS

As mentioned in the abstract the research program consisted of three separate but closely related investigations. All of the investigations were concerned with the use of acoustic emission (AE) measurements to study and identify deformation and fracture mechanisms and the effects of different metallurgical variables on the acoustic emission generated. Each of the three investigations was brought to a satisfactory conclusion and either has been or is in the process of being published.

AN INVESTIGATION OF THE ACOUSTIC EMISSION GENERATED DURING THE DEFORMATION AND FRACTURE OF PREMIUM GRADE 4340 STEEL AS A FUNCTION OF MECHANICAL PROPERTIES

The goals of this particular investigation were to determine if ductile tearing could be detected and identified using acoustic emission measurements and to see if those measurements could be correlated with the fracture toughness of the material. The material chosen for this investigation was premium grade 4340 steel, which was supplied by Sandia National Laboratories. Four different heat treatments were employed to give a wide range of carbide sizes and distributions which in turn produced a significant range of mechanical properties. The acoustic emission was determined during tensile and compressive deformation as well as during uniform crack growth using double cantilevered beam (DCB) samples.

Significant acoustic emission is generated during tensile and compressive deformation of the 4340 steel. The acoustic emission produced during tensile deformation occurs at yield and during strain hardening and is consistent with the acoustic emission expected from inhomogeneous deformation, i.e., the initiation and propagation of Lueders bands. The acoustic emission generated during compressive deformation is consistent with that generated from homogeneous deformation. In both cases the acoustic emission is believed due to the avalanche motion of dislocations. The acoustic emission generated during deformation is strongly dependent upon the mechanical properties of the material. The stronger the material the higher the acoustic emission. The normalized acoustic emission peak height at yield for both tensile and compressive deformation is an approximately linear function of yield stress.

The acoustic emission generated during uniform crack growth was also measured and characterized for the four different heat treatments. The AE was characterized by bursts with an extremely wide range of signal amplitudes. Signals differing by as much as 80 dB were measured. Most of the larger signals occurred from large load drops before uniform crack motion was achieved. The stronger the material (lower fracture toughness) the higher the rate and number of signals for the same amount of crack advance and the lower the mean amplitude per AE signal. Using approximate values for the fracture toughness of 4340 steel from the "Structural Alloys Handbook", H.J.Hucek and J.S.Ward, Eds., produced by Metals and Ceramics Information Center, Battelle, Columbus, OH, 1983, Figure 1 below, shows the relationships between the fracture toughness and the mean amplitude of the AE signals. As well as the relationship between the fracture toughness and the rate of AE signals per 0.01 inch crack opening displacement.

Figure 1

It was also hoped in this investigation that the acoustic emission and fracture toughness could be correlated in some way with the ductile dimple size from SEM observations of the fracture face. It was believed that the dimple size would reflect the coarsening of the carbides during tempering. Unfortunately, only the highest strength material exhibited a uniform ductile dimple interface. The weakest material was characterized by regions of transgranular cleavage between areas of ductile dimples. The two intermediate samples had intermediate structures.

This work was reported on at the 10th International Acoustic Emission Symposium in Sendai, Japan, October 1990 and has been submitted for publication to the Journal of Acoustic Emission.

AN INVESTIGATION OF THE ACOUSTIC EMISSION GENERATED DURING THE DEFORMATION AND FRACTURE OF Ti-6Al-4V ALLOYS AS A FUNCTION OF MICROSTRUCTURE

The goal of this investigation was to investigate the acoustic emission from a material where the fracture toughness could be altered significantly by changes in the microstructure which produced only moderate changes in the strength of the material. The test material selected was Ti-6Al-4V alloy which was previously shown to meet the necessary strength and fracture toughness requirements. Heat treatments necessary to produce the desired microstructures were refined and used to give the desired microstructures in a repeatable way. The three microstructures used were:

- 1) Microstructure A, a microstructure of small spherical or equiaxed particles of alpha phase in a transformed beta matrix.
- 2) Microstructure B, a microstructure of needle or platelets of alpha (acicular alpha) in a transformed beta matrix.
- 3) Microstructure C, a microstructure somewhat intermediate between A and B, platelet and globules of alpha phase in a transformed beta matrix.

Microstructure A was a few percent (~ 10%) stronger than microstructures B and C. Microstructures B and C were essentially equal in strength. However, microstructure B had a significantly higher fracture toughness followed by A and then C.

Similar to the investigation of the 4340 steel, the acoustic emission was measured and characterized during tensile and compressive deformation and during uniform crack growth (DCB specimens). The acoustic emission generated during deformation was considerably different from that observed from deformation of the 4340 steel. The microstructure A, which was the strongest material had the lowest acoustic emission during deformation. It was determined that the acoustic emission generated during deformation was primarily due to deformation twinning in the alpha phase of the material. The acoustic emission results correlated very well with the volume and geometry of the alpha phase in the different microstructures.

The acoustic emission generated during uniform crack growth in the titanium alloys was quite different from that observed during deformation. During crack propagation the greatest number of acoustic emission signals for the same amount of crack advancement was from the C microstructure. The A microstructure was intermediate and the B microstructure produced the lowest number of signals. This result indicates that the number of acoustic emission signals for similar amounts of crack advance is inversely proportional to the fracture toughness, i.e., the higher the fracture toughness the smaller the number of signals generated as the crack advances. The number of acoustic emission signals correlated very well with the roughness of the crack interface as viewed using optical microscopy. The roughness of the crack interface could also be related to the microstructure of the material. The average or mean energy of the acoustic emission signals generated during uniform crack advance was found to correlate very well with the fracture toughness. The higher the fracture toughness the higher the mean energy of the AE signals generated during crack propagation.

In summary, microstructure B which had the highest fracture toughness was found to generate the lowest number of acoustic emission signals during crack propagation, but those signals had the highest average energy per signal. Microstructure C had the lowest fracture toughness but generated the highest number of signals during crack propagation and those signals had the lowest average energy per signal. Microstructure A had results intermediate to B and C. These results are summarized in Figure 2 below.

Figure 2

It should be pointed out that the fracture toughness data used in Figure 2 were determined from precracked Charpy samples which had similar microstructures but were not from identical material used to generate the acoustic emission data. Caution should be used in using the data for anything more than general trends.

The results of this investigation were presented at the "1st Symposium on Evaluation of Advanced Materials by Acoustic Emission" at the Research Center for Advanced Science and Technology, University of Tokyo, Japan, October, 1990 and is being submitted for publication in Metallurgical Transactions A.

AN INVESTIGATION OF THE ACOUSTIC EMISSION GENERATED FROM SECOND PHASE PARTICLES IN Al-Si ALLOYS AS A FUNCTION OF SECOND PHASE PARTICLE SIZE AND DENSITY

The goal of this investigation was to carry out a basic investigation of the AE generated from second phase particles during deformation and to correlate the results with deformation and fracture mechanisms. The primary material used was Al-Si alloys with which it was possible to get a wide range of second phase silicon particles using different alloy compositions and annealing schemes. Samples were made from aluminum with 2%, 5% and 19% silicon, giving silicon particles with mean diameters ranging from $\sim 4 \mu\text{m}$ to $\sim 50 \mu\text{m}$. The acoustic emission was measured during tensile deformation with the following results.

- 1.- Two distinct acoustic emission maxima were observed during tensile deformation. The first maxima results from the avalanche motion of dislocations. The second acoustic emission maxima which occurs just past yield is a result of the fracture and decohesion of the second phase silicon particles in the aluminum matrix.
- 2.- The acoustic emission signals generated by the fracture of the second phase silicon particles were found to be high energy signals which agree with current theoretical predictions regarding the energy released and the stress required for fracture as functions of particle size. Acoustic emission signals generated by the decohesion of the silicon particles from the aluminum matrix are more numerous, lower in energy and have no obvious correlation with particle size.

Attempts to measure the acoustic emission during crack growth were unsuccessful due to the low strength and high ductility of the materials used. During the course of this investigation, a series of well characterized samples of nodular cast iron with different nodule diameters became available. An added benefit was that the fracture toughness of these samples had been carefully measured previously. The acoustic emission was measured and characterized during compressive deformation of these materials. The measured acoustic emission correlated very well with theoretical predictions regarding particle size. The work on the nodular cast iron was presented at the "3rd World Symposium on Acoustic Emission" in Charlotte, N.C., March 1989 and a full paper has been published in an ASTM STP 1077, Acoustic Emission:

Current Practices and Future Directions. More importantly the measured acoustic emission was found to correlate very well with the fracture toughness. These results have been published in volume 26, (1991) of the Journal of Material Science, pp. 2057. The work on the Al-Si alloys has been submitted for publication in the Journal of Acoustic Emission and will be reported at the 11th International Acoustic Emission Symposium in Fukuoka, Japan in October 1992.

PERSONNEL ASSOCIATED WITH THE PROGRAM

The principal investigator for this program has been Professor Steve H. Carpenter of the Physics Department of the University of Denver. Professor Carpenter has had extensive experience in both acoustic emission and mechanical properties experiments and investigations.

A full time graduate student was associated with each of the major investigations discussed earlier. The results of those investigations formed the basis for their thesis.

Mr. Christian Pfliederer was associated with the investigation on the 4340 steel. He received a Masters degree from the University of Denver in March of 1990. The title of his thesis was "Acoustic Emission Generated during Fracture and Deformation of 4340 Premium Grade Steel. He is currently pursuing a doctoral degree in physics at Cambridge University.

Mr. Wei Xu was associated with the investigation on the Ti-6Al-4V alloys. He received a Masters degree from the University of Denver in June of 1990. The title of his thesis is, "An Investigation of the Acoustic Emission Generated during Deformation and Fracture of Ti-6Al-4V Alloys." He is currently working for a small firm in the San Francisco Bay area.

Ms Min Wu was associated with the investigation on Aluminum Silicon alloys. She received a Ph. D. in Physics from the University of Denver in March 1992. The title of her thesis was "An Investigation of the Acoustic Emission Generated from Silicon Particles in Aluminum Silicon Alloys." She is presently working on a postdoctoral appointment at the Royal Military College in Kingston, Ontario.

Nearly all of the work on the nodular cast iron was carried out by Dr, Zuming Zhu from the Institute of Metals Research in Shenyang, China. However, he received no compensation from or funding of any kind from this project.

PRESENTATIONS AND PAPERS

The following is a list of presentations and/or papers which have been given, published or submitted for publication during the time period from the last annual report. (Since February 1990)

- 1.- Correlation of the Acoustic Emission and the Fracture Toughness of Ductile Nodular Cast Iron, S.H.Carpenter and Zuming Zhu, Journal of Materials Science, 26, (1991), 2057-2062.
- 2.- An Investigation of the Acoustic Emission Generated during Deformation and Fracture of Ti-6Al-4V Alloys as a Function of Microstructure, S.H.Carpenter and W.Xu, Proceedings of the First Symposium on Evaluation of Advanced Materials by Acoustic Emission, Research Center for Advanced Science and Technology, University of Tokyo, October 20 1990, Japan. Proceedings contain extended abstracts only.
- 3.- An Investigation of the Acoustic Emission Generated during the Deformation and Fracture of Premium Grade 4340 Steel, S.H.Carpenter and C.Pfleiderer, presented at the 10th International Acoustic Emission Symposium, October 22-25, 1990, Sendai, Japan. Published in Progress in Acoustic Emission V, K.Yamaguchi, Ed., Japanese Society for Non-Destructive Inspection, (1990), pp. 492-500.

- 4.- An Investigation of the Acoustic Emission from Ti-6Al-4V Alloys as a Function of Microstructure, S.H.Carpenter and W.Xu, 34th Meeting of the Acoustic Emission Working Group, University of Illinois, Urbana, IL, November 12-15, 1990.
- 5.- An Acoustic Emission Investigation of 4340 Steel, S.H.Carpenter and C. Pfliederer, submitted for publication to the Journal of Acoustic Emission.
- 6.- An Acoustic Emission Investigation of Ti-6Al-4V as a Function of Microstructure, S.H.Carpenter and W. Xu, Submitted for publication to Metallurgical Transaction A.
- 7.- An Investigation of the Acoustic Emission Generated from Silicon Particles in Aluminum-Silicon Alloys, M. Wu and S.H.Carpenter, Submitted for publication to Journal of Acoustic Emission.
- 8.- Acoustic Emission from Second Phase Particles in Aluminum Silicon Alloys, M.Wu and S.H.Carpenter, to be presented at the 11th International Acoustic Emission Symposium, Fukuoka, Japan, October, 1992.

END

**DATE
FILMED**

6 104/92