IREE: CAREER: Processing and Development of a New Ultra-Light High-Strength Material (a supplement to award #0238929)

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ABSTRACT: Composite metal foam (CMF) is a new, ultralight high strength material invented by Dr. Afsaneh Rabiei under the current NSF award and can be produced by casting and powder metallurgy techniques. Cast samples consist of an aluminum matrix surrounding hollow stainless steel or low carbon steel spheres, and powder metallurgy samples are either stainless steel or low carbon steel matrix and spheres. Using the IREE supplement, an undergraduate student, Judy Brown, traveled to The University of Tokyo to study the properties of CMF in 4 point bending tests with in-situ acoustic emission (AE) monitoring. Results showed high peak stress up to 82.1MPa—a significant improvement over the performance of existing metal foams. Foam performance and the type of AE observed are largely related to its microstructure. Fracture of intermetallic compounds present in cast samples resulted in a large number of AE events with high amplitude levels, while powder metallurgy samples exhibited much less AE events. Powder metallurgy samples don't have intermetallic compounds, and the primary AE source in these samples was debonding of spheres from the matrix. In addition to technical progress, the IREE award provided invaluable international research experience to an undergraduate student and opened opportunities for future collaboration with the host laboratory. Judy's success story in Japan was posted on NSF web site in Aug. 2008 (http://www.nsftokyo.org/ssr08-02.pdf).

INTRODUCTION

The current NSF CAREER award (#0238929) at North Carolina State University focuses on the processing and characterization of a new high strength composite metal foam material. Metal foams are a class of porous materials with unique combinations of properties desirable in many engineering applications. Their high strength and stiffness with low weight and density make them good candidates for applications including structural components in automotible and spacecraft, energy absorption, and acoustic and vibration damping. Currently available metal foams, however, have low strength, due to variations in cell size and general non-homogenity throughout the structure. This problem is partially solved by using pre-formed hollow spheres to create a uniform cell structure, but foams made in this manner still have low strength due to limited contact between the sphere walls. Composite metal foam (CMF), developed under the current award shows much more promising strength and energy absorption by filling the interstitial spaces between the pre-formed hollow spheres with a solid metal matrix. This foam is produced using similar materials (low carbon steel matrix and spheres or stainless steel matrix and spheres) through a powder metallurgy process and through gravity casting using dissimilar materials (Aluminum alloy A356 matrix and stainless steel or low carbon steel spheres). Our composite metal foam has been tested extensively in monotonic compression, loading-unloading compression, and compression-compression fatigue and shows properties greatly superior to those seen in other metal foams. It is notable that NSF has highlighted the outcome of the research funded by this CAREER award in October 2008 as one of NSF discoveries: (http://www.nsf.gov/discoveries/disc_summ.jsp?cntn_id=112486&govDel=USNSF_1, and http://www.radiospace.com/nsf133.htm).

Collaboration with Dr. Manabu Enoki's Reliable Materials Engineering Lab (RME) at The University of Tokyo allowed us to further characterize the composite metal foam in bending using in-situ acoustic emission tests as well as providing a platform for future interactions. The Reliable Materials Engineering Lab specializes in acoustic emission research in a variety of materials, and also in developing better systems to measure acoustic emission. A continuous wave memory system developed at RME was used to record acoustic emission data for our samples.

Under this IREE award, Dr. Rabiei's undergraduate student, Judy Brown, spent three months from May 15-August 12, 2008 at The University of Tokyo. Pre-travel preparation for the student was provided by the PI who is fluent in Japanese after living for 4 years in Japan, NCSU Office for International Affairs, and the NC Japan Center, a statewide resource to assist NC citizens and businesses to enrich their Japanese relationships through study of Japanese culture, political and societal systems and language. Judy worked as a member of Dr. Enoki's lab conducting bending tests with acoustic emission monitoring of composite metal foam samples. Dr. Rabiei also visited Japan from July 2008 to supervise not only Judy's work at The University of Tokyo (Todai), but also supervising her other graduate student's research at Japan National Institute of Materials Science (NIMS) as well as organizing a workshop between North Carolina State University (NCSU) and NIMS to start major collaborations between the two institutions. The effort was including a memorandom of understanding (MOU) signing and one day workshop plus tours to NIMS facility at Tsukuba. In addition to those, a major networking with people both at Todai and NIMS for future collaboration took place by Dr. Rabiei during her visit.

RESEARCH ACTIVITIES AND ACCOMPLISHMENTS OF THE INTERNATIONAL COOPERATION

Judy's research at The University of Tokyo consisted of conducting 4 point bending tests with acoustic emission monitoring on composite metal foam samples processed by casting and powder metallurgy techniques. Cast Al-SS (stainless steel) samples produced with air and water cooling methods were tested, as well as cast Al-LC (low carbon steel) samples cooled by air. Both stainless steel and low carbon steel samples produced by powder metallurgy were also tested. The samples were produced in Dr. Rabiei's Advanced Materials Research Laboratory at NC State University and cut into thin slices for the bending tests. In addition, one bulk sample of each type was left with the host laboratory at The University of Tokyo for evaluation of wave velocity and elastic constants with non-contact ultrasound techniques. The tests conducted at The University of Tokyo further characterize the properties of composite metal foam, which was developed by Dr. Rabiei under the current NSF award and has already been tested extensively in monotonic compression, loading-unloading compression, and compression-compression fatigue.

Judy was given desk space with other international students and full access to all host lab resources. This included access to lab equipment at any time as well as an account on the lab computer network. Everyone in the host lab was very helpful, and Dr. Enoki and his graduate students went out of their way to make her feel at home. Graduate students helped her learn how to use the equipment that she needed, and performed the experiment with her for the first few times. She gave presentations on her research progress at the weekly group meetings, and also was exposed to many areas of acoustic emission research during a weekly paper seminar where each member of Dr. Enoki's lab presented a paper relevant to their research area. She presented one of Dr. Rabiei's papers on composite metal foam project at one of these seminars as well, giving members of the host lab opportunity to become familiar with our project and goals.

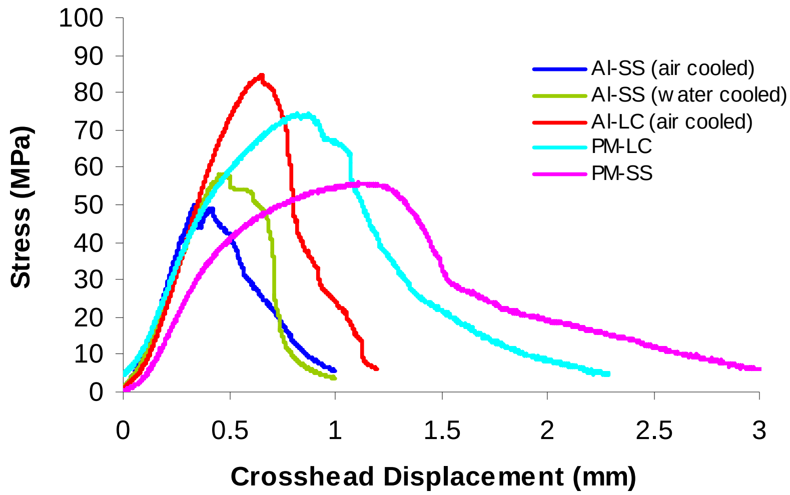

Figure 1: Stress vs. displacement curves for cast and powder metallurgy composite metal foam samples

Figure 1 shows the stress-displacement curves obtained from the bending tests of each type of composite metal foam. Three samples of each type were tested, and consistant results were obtained with a maximum variation of 16.2% in peak stress occurring for the cast Al-SS foam processed with water cooling method. All samples reached high peak stress values compared with other foams, with average values ranging from 54.5 MPa for air cooled Al-SS foam to 82.1MPa for air cooled Al-LC foam. Samples produced by powder metallurgy method showed a generally higher peak stress than the cast samples and exhibited more ductile behavior with a much longer test duration. This can be related to the presence of intermetallic compounds in the cast samples that result from diffusion around the sphere walls during cooling. These intermetallics are brittle and contribute to earlier fracture in the cast samples. The faster cooling rate experienced by the water cooled samples leave less time for intermetallic diffusion and results in higher peak stresses for the water cooled Al-SS sample compared with the air cooled Al-SS sample.

The differences in microstructure also affect the type of acoustic emission detected. Primary sources of AE in cast samples are microfractures occurring in the brittle intermetallic compounds, while acoustic emission in the powder metallurgy samples results from debonding of spheres and shifting of voids in the matrix. The cast samples show much more AE activity (1000 events or greater) throughout the bending test with much higher amplitudes, corresponding to the significant presence of intermetallics. In contrast, the powder metallurgy samples generally had around 100 events per sample.

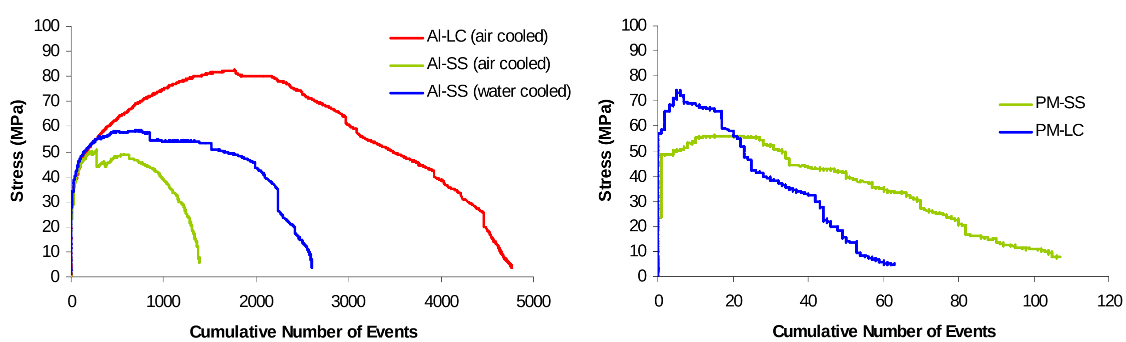

Figure 2: Stress vs. cumulative number of AE events for cast samples (left) and PM samples (right)

This can be seen in Figure 2, which shows the stress as a function of the cumulative number of events that have occurred for both PM and cast samples. We are currently working to characterize the type of events that occurred at different regions of the stress-displacement process and relating them to a specific fracture mechanism.

BROADER IMPACTS OF THE INTERNATIONAL COOPERATION

The research and travel conducted under the IREE supplement award has greatly enhanced the scope of our original award. Our composite metal foam had never been tested in bending before, and the data gathered during Judy's stay at The University of Tokyo further characterizes the behavior of this material. Evaluation of the acoustic emission behavior provided additional information about the correlations between the composite metal foam microstructure and its fracture mechanisms. The research also held great educational benefits for Judy, as she learned about acoustic emission and its applications as a valuable tool for characterizing material behavior. Participating in the program as an undergraduate also gave her valuable perspectives on research opportunities and inspired her to pursue graduate studies.

In addition to the research progress made with our composite metal foam project, collaboration with Dr. Enoki's lab through the IREE program greatly enhanced Judy's international perspectives. She was able to take a Japanese class for intenational students and researchers offered through The University of Tokyo. The class taught Japanese language skills and also familiarized participants with some aspects of the Japanese culture, including the tea ceremony, traditional dress, drama, and art. Participation in this class, as well as close work with the international students in Dr. Enoki's lab, allowed Judy to interact with people from a diverse range of cultures on a daily basis. This exposed her to a wide variety of cultural perspectives from over 10 countries.

Through travel on some weekends, she also had the opportunity to visit a variety of sites in Japan in both urban and rural settings. These included Nagano, Yokohama, Kamakura, many museums and famous sites of Tokyo, and also climbing Mt. Fuji. Some of this travel was done with Japanese friends, and some was done by herself, giving her the unique perspective of what it felt like to be an ethnic minority different from the native population. This experience gave her a better appreciation for the challenges faced by minorities in the United States. Overall the experience has given her a great appreciation for Japanese culture and encouraged her to look at issues with a broader global perspective.

DISCUSSION AND SUMMARY

The research conducted under the IREE supplement allowed comprehensive evaluation of composite metal foam samples in bending as well as study of their acoustic emission behavior. The foam showed excellent performance in bending, with peak stresses as high as 82.1 MPa. Significant differences were observed between samples of Al-SS and Al-LC foam processed by casting method and the stainless steel and low carbon steel samples processed with a powder metallurgy technique due to the presence of brittle intermetallic compounds in the cast samples. For cast samples, Al-SS samples processed with a water cooling technique achieved higher peak stress and showed more ductile behavior than samples processed with air cooling due to the faster cooling rate allowing less time for the intermetallic compounds to form. The acoustic emission behavior also reflected these differences in microstructure. Cast samples had many more AE events than the powder metallurgy samples, resulting as cracks occurred in the intermetallic areas. The more brittle behavior seen in the cast samples was also accompanied by AE events of high magnitude. Primary sources of AE in the powder metallurgy samples were debonding of spheres from the matrix and shifting of small voids, which produced fewer events with lower magnitudes. The ability to relate the type and ammount of acoustic emission observed with the different fracture methods of cast and powder metallurgy samples provides a valuable method for evaluating the integrity of these materials.

In addition to the significant technical accomplishments, the IREE supplement allowed an undergraduate student to experience the research environment in an international setting. The experience helped her to begin building Japanese language skills and to experience Japanese culture through weekend travel and daily interaction with members of the host laboratory. It also broadened her perspective of what can be accomplished through international research efforts and inspired her to continue her studies in graduate school. Opportunities for future interaction with the host laboratory were also discussed.

Overall, the IREE program provided us with a wonderful opportunity to expand the scope of the composite metal foam project as well as begin collaborative research efforts with the Reliable Materials Engineering lab at The University of Tokyo. It should definitely be continued.

ACKNOWLEDGEMENTS

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BRIEF BIOGRAPHIES OF RESEARCHERS

Judith A. Brown is a senior at North Carolina State University and will graduate in May, 2009 with a B.S. degree in aerospace engineering. She joined Dr. Rabiei's Advanced Materials Research Lab in January, 2008.

Afsaneh Rabiei received her Ph.D. in advanced materials at Research Center for Advanced Science and Technology, The University of Tokyo, Japan, in 1997 within the area of mechanics and non-destructive evaluation of metal matrix composites. Prior to that she gained over 8 years of industrial experiences in materials science & processing including casting, welding and non-destructive testing. She received her B.S. from the Department of Metallurgy & Material Science at Sharif University of Technology in Tehran, Iran in 1986. She worked at Harvard University as a post-doctoral researcher from 1997 until 2000. She is fluent in English, Japanese and Persian. Dr. Rabiei is the translator of the "Engineering Physical Metallurgy" book from English to Persian and she is the author of three other technical books, several international papers and booklets.