Modeling & Manufacturing of Multi-Functional MMCs through Ultrasonic Consolidation (UC)

Yanzhe Yang[1], and Brent Stucker[2]
[1,2]Utah State University, Mechanical & Aerospace Engineering, Logan, UT, 84322-4130, USA. E-mail: brent.stucker@usu.edu

ABSTRACT: Using IREE funding, Utah State University (USU) personnel traveled to Loughborough University in England, U.K. One Ph.D. student went for 3 months as a visiting researcher to the Rapid Manufacturing Research Group, and his graduate advisor paid a short supervisory visit. The main research tasks during this international cooperation were to experimentally study thermal and physical phenomena during fiber embedment within metal matrix matrices using the ultrasonic consolidation process. Through this international experience the awardees benefited by gaining experience with varying educational systems, engaging in innovative experimental discussions, developing a more fundamental understanding of bond formation during ultrasonic consolidation, and initiating a more formal collaboration between complementary research groups at Loughborough University and Utah State University.

INTRODUCTION

The Advanced Manufacturing and Materials Laboratory at Utah State University is actively engaged in research aimed at developing a more fundamental understanding of the mechanisms which govern bonding and advanced structure fabrication using ultrasonic consolidation (UC). The National Science Foundation (through grant CMMI 0522908) funded the current project, which focuses on the manufacturing and modeling of fiber-reinforced metal matrix composites (MMCs) made using UC. This investigation includes studying the effect of processing parameters on mechanical properties of MMCs, and developing a reliable combination of processing parameters for fully-functional MMCs. In parallel, numerical models are being developed which focus on the fundamental bond formation mechanisms which occur during MMC fabrication using UC, and which accurately predict the properties of the resulting MMCs.

As part of this NSF-funded work, optimum processing parameters for fabrication of UC structures in both the presence and absence of fibers were developed using design of experiment (DoE) methodology. Samples produced using these optimum parameters are being studied using standard metallurgical techniques, and the linear welding density (LWD) was found to be as high as 98% (Fig.1a). Successful embedment of silicon carbide (SiC) fibers of 0.1 mm diameter within an Al 3003 matrix was achieved without physical gaps or discontinuities between the fiber and metal matrix (Fig.1b). A thin-slice push-out test was implemented to characterize the interfacial mechanical behavior between the fiber and metal matrix.

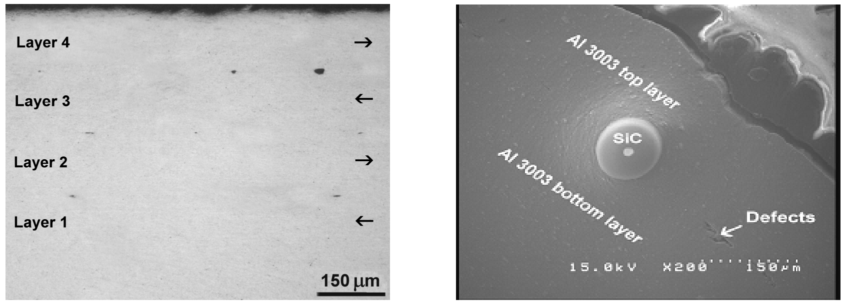

Figure 1 (a) Microstructure of UC deposit with 98% LWD (b) SEM image of single SiC fiber within Al 3003(X200)

Using IREE funding, Yanzhe Yang, a Ph.D. candidate in Mechanical & Aerospace Engineering at USU, worked at the Rapid Manufacturing Research Group (RMRG) within the Wolfson School of Mechanical & Manufacturing Engineering at Loughborough University in England for three months, starting May 10th 2007. The RMRG was chosen as the international research partner due to their complementary expertise in Ultrasonic Consolidation. The RMRG was amongst the first to initiate research on fiber embedment using UC, which led to a number of early journal and conference papers in this area [1,2,3,4,5]. The experimental apparatus used at Loughborough is different from that used at USU, and thus, an IREE supplement was sought to enable travel to England to perform experiments designed shed light on the similarities and differences between the early experimental results achieved at Loughborough and those at USU, and to enable Mr. Yang to more fully explore the difference between educational and research approaches used in Europe versus America.

RESEARCH ACTIVITIES AND ACCOMPLISHMENTS OF THE INTERNATIONAL COOPERATION

To expand the research scope of our NSF award, three activities were proposed for this international cooperation, which were:

- Task 1. To compare the different sets of optimum processing parameters developed at Loughborough University and USU, to better understand the reasons for differing results;
- Task 2. To perform experimental studies to better understand the temperature profile present at the interface during UC; and
- Task 3. To investigate differences between fiber embedment when placing a fiber between similar and dissimilar metal foils.

These tasks were considered critical for developing a better understanding of bond formation mechanisms during UC, which is a core part of our research. These activities were successfully completed as a result of this collaboration with Loughborough University, according to the schedule in Table 1.

Table 1 Schedule of research tasks

Task ID	1st month				2nd month				3rd month			
	1	2	3	4	1	2	3	4	1	2	3	4
Task 1	↔	↔										
Task 2		↔	↔	↔	↔	↔						
Task 3							↔	↔	↔	↔	↔	
Report											↔	↔

In general, the fundamental physical mechanisms which govern UC processing are agreed upon between research groups at Loughborough University and USU. However, it became apparent that dissimilar optimized processing parameters were achieved between the groups. As a result of data sharing and enlightening discussions between the research groups, a fundamental understanding of the reasons for the discrepancies between the optimum parameters were developed, and will likely form the basis for future journal articles, thus completing Task 1.

Characterization of processing temperature is important in order to understand the various physical phenomena which occur during UC. Processing temperature was measured by embedding ultra-small thermocouples between metal foils under various combinations of processing parameters. The maximum processing temperature of *98°C* was captured when oscillating amplitude was set to *12µm* and clamping pressure to *30psi*. Effects of oscillating amplitude and clamping pressure on the mean of maximum processing temperature are depicted in Fig. 2. Both parameters have positive influences on temperature, while amplitude has a more significant effect on temperature rise.

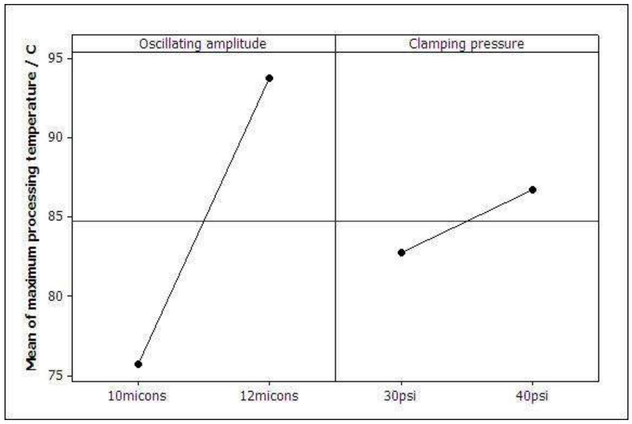

Figure 2 Main effects of processing parameters on processing temperature

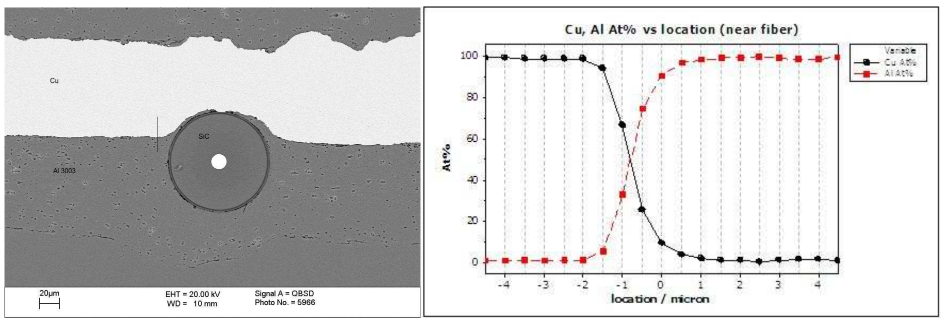

Figure 3 (a) SEM result of single SiC fiber embedded between Al3003/Cu; (b) element line mapping across metal interface

Single SiC fibers were embedded within Al 3003/Cu sandwich structures. Those samples were microstructurally examined using scanning electron microscope (SEM) and energy dispersive X-ray (EDX), as shown in Fig. 3. The fiber was found to embed into the Al 3003 matrix, and the Al matrix material was deformed plastically to fully fill the gaps between fiber and foils. Element line mapping demonstrated no obvious evidence on element diffusion through the metal interface. The broader implications of these results are still being discussed and investigated.

BROADER IMPACTS OF THE INTERNATIONAL TRAVEL

Ultrasonic consolidation is an extension of ultrasonic metal seam welding. Thus, a fundamental knowledge and understanding of ultrasonic metal welding is critical for understanding UC. However, the fundamentals of ultrasonic metal welding have not been thoroughly investigated. Through our studies, it has become clear that a more fundamental understanding of bond formation mechanism during ultrasonic welding is critical to further develop the UC process. This international cooperation helped to shed light on important bond formation mechanisms during UC, as well as give direction for future research priorities.

Various experimental methodologies have been used to study bond formation mechanisms during UC. For both groups, microstructural analysis is the primary method used to investigate the bond quality of UC fabricated samples. At USU, a thin-slice push-out test was utilized to examine bond quality for fiber-embedded samples. At Loughborough University, researchers implemented nano-indentation technology to characterize metal plastic deformation during processing. Other experimental method, such as micro hardness testing and micro X-ray diffraction (μXRD), were jointly identified as potentially beneficial characterization methods for future research.

The RMRG at Loughborough University and the Advanced Manufacturing and Material Laboratory (AMML) at Utah State University are both active research groups in the field of UC. During the period of cooperation, copies of publication from both sides were shared freely. Experimental methods for sample fabrication using UC and sample properties testing methods were identified and discussed. Good relationships were established between researchers at both groups, which have subsequently led to collaborative proposals and discussion of other opportunities for collaboration.

DISCUSSION AND SUMMARY

The IREE experience for awardees is not just an opportunity to experience travel in a foreign country for several months, it is a great opportunity to more fully understand and appreciate research expertise in a broader, world-wide context. In addition it allows one to personally experience the variety and diversity of educational systems available.

To increase the benefits to existing and future NSF awardees, we recommend that the IREE program utilize not only these standardized reports, but also conduct tele-conferences between awardee institutions and their host universities (with NSF representatives present via teleconference). This would provide an opportunity to identify best practices and to understand the benefit of these exchanges to all parties involved.

In conclusion, three research tasks were proposed for this international collaboration. All three tasks were successfully completed.

1. The differences between optimized processing parameters for UC were studied. The reasons for the differences were explained based on dissimilarities in machine settings and work piece conditions and a joint understanding of the important bond formation mechanisms at work.
2. Temperature history during UC processing was investigated experimentally. Effects of processing parameters on the temperature history were studied. It was found that both clamping pressure and oscillating amplitude have positive influences on processing temperature, where oscillating amplitude has a more significant effect.
3. Bond formation mechanisms during fiber-embedment using UC were explored. The primary bonding mechanism was identified as metal plastic deformation, whereas diffusion was not found to play a major role.
4. An excellent relationship was established between the RMRG at Loughborough University and AMML at USU. Further research projects involving UC and other solid freeform fabrication technologies were discussed and are planned.

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BRIEF BIOGRAPHIES OF RESEARCHERS

Yanzhe Yang received the BSE degree in Mechanical Engineering from Beijing University of Aeronautics and Astronautics in 2003. He is a Ph.D candidate in Department of Mechanical & Aerospace Engineering at Utah State University. Research interests include rapid prototyping and metal matrix composites.

Brent E. Stucker received a B.S. in Mechanical Engineering from the University of Idaho in 1993 and a PhD in Mechanical Engineering from Texas A&M University in 1997. He is a faculty member in the Department of Mechanical & Aerospace Engineering at Utah State University. He conducts research in the field of additive manufacturing, with a current research focus on aerospace and biomedical applications.