

VERY HIGH POWER ULTRASONIC ADDITIVE MANUFACTURING (VHP UAM) FOR ADVANCED MATERIALS

K. F. Graff, M. Short and M. Norfolk

Edison Welding Institute, Columbus, OH 43221

Reviewed, accepted September 23, 2010

Abstract

To extend current ultrasonic additive manufacturing (UAM) to advanced materials, higher speeds and larger parts, it was essential to greatly increase the process ultrasonic power. EWI, with Solidica™, several industry, agency and academic partners, and support of Ohio's Wright Program, have developed a "Very High Power Ultrasonic Additive Manufacturing System" that greatly extends current technology. A key part was the design of a 9.0 kW "push-pull" ultrasonic system able to produce sound welds in materials such as Ti 6-4, 316SS, 1100 Cu and Al7075. The VHP system can fabricate parts of up to 1.5m x 1.5m x 0.6m, with process and software developments that enable forming contoured surfaces.

Introduction

The process of ultrasonic additive manufacturing (UAM), introduced by Solidica™ in 2000, has shown significant promise for a wide range of applications, such as rapid prototyping, low volume tooling, direct parts manufacture, tailored materials, embedded fibers, smart materials, cladding and thermal management. Specific examples include injection mold dies, embedded channels for thermal management or chemical processing, and the embedding of materials, e.g. wires, tapes or meshes, within a metal matrix.

In order to greatly extend the current technology to advanced materials, higher speeds and larger parts, it was essential to greatly increase the ultrasonic power applied to the process. Accordingly, EWI, with Solidica™, several industry, agency and academic partners, and the support of Ohio's Wright Program, have developed a "Very High Power Ultrasonic Additive Manufacturing System" that will greatly extend current technology. A key part was the design of a 9.0kW "push-pull" ultrasonic system able to produce sound welds in materials such as Ti 6-4, 316SS, 1100 Cu and Al7075. The VHP system can fabricate parts of up to 1.5m x 1.5m x 0.6m, with process and software developments that enable forming contoured surfaces. These various developments will be reviewed in the following.

Background

This section will cover the basics of UAM, describe certain limits faced by the process, and provide the basis for needing greater ultrasonic power for the current process.

Current UAM Process

The UAM process is one of building up solid metal objects through ultrasonically welding successive layers of metal tape into a three-dimensional shape, with periodic machining operations to create the detailed features of the resultant object (White, 2002). The key features of the process are shown in Figure 1.

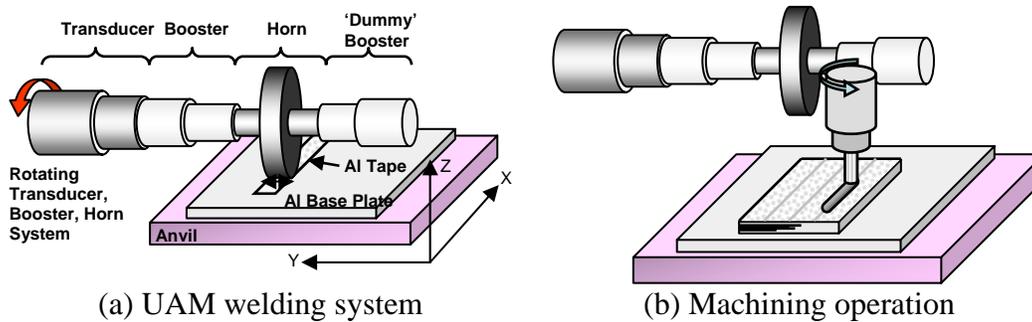


Figure 1. The UAM process

Figure 1(a) shows a rolling ultrasonic welding system, consisting of an ultrasonic transducer, a booster, the (welding) horn, and a second “dummy” booster. The vibrations of the transducer are transmitted to the disk-shaped welding horn (also referred to as the “sonotrode”) rolling in the x-direction, and from there to the tape-metal base, which creates an ultrasonic solid-state weld between the thin metal tape (shown as Al in the figure) and a base plate. The continuous rolling of the horn over the tape welds the entire tape to the plate.

By welding a succession of tapes, first side by side, then one on top of the other (but staggered so that seams do not overlap), it becomes possible to build a solid metal part, as shown in Figure 1(b). Through the course of the build, there will be periodic machining operations, using an integrated CNC system, to add features to the part, as suggested by the slot in Figure 1(b), to remove excess tape material and to true up the topmost surface of the part. Thus, the process also involves subtractive as well as additive steps.

As noted, a wide range of applications for UAM have been identified, including rapid prototyping, low volume tooling, direct parts manufacture, tailored materials, metal matrix composites, embedded fibers, smart materials, sensors, cladding, armor and thermal management. Specific examples include injection mold dies, embedded channels for thermal management or chemical processing, and the embedding of materials, e.g. wires, tapes or meshes, within a metal matrix.

Expanding UAM Capabilities

Current UAM systems typically operate at 1.5-3.0 kW and encounter some issues in seeking to bond advanced materials, such as Ti alloys, stainless steels, Cu alloys, advanced Al, and Ni-based alloys. Limits are also encountered in bonding thicker tapes and in increasing production speeds, which also tends to place limits on overall part sizes that can be considered.

To a significant extent, all of these issues can be related to the need to apply greater ultrasonic power to the bonding process. Since making the ultrasonic bond depends on being able to shear and plastically deform opposing asperities at the tape interfaces and to remove surface oxides, with increasing alloy strengths greater interface shearing forces are required to bring about the necessary interface deformations – which directly require increased ultrasonic power (de Vries, 2004). Likewise, the mass associated with increased tape thicknesses and/or widths requires increased power to be able to drive it in ultrasonic vibrations.

VHP UAM – Approach, Test Bed, Bonding

Approach

The approach for achieving higher levels of ultrasonic power is shown in Figure 2. Current UAM technology, shown in Figure 2(a), is powered by a single ultrasonic transducer of 1.5 to 3.0 kW, resulting in limitations in materials and parts that can be fabricated. It was determined that it would be possible to make a significant jump in ultrasonic power by combining two transducers, each of 4.5 kW, in a so-called push-pull configuration to arrive at 9.0 kW capacity as shown in Figure 2(b) (Short, 2008). In this early design concept, the two 4.5 kW transducers are shown in dark gray shading at either end of the setup. Two boosters (light gray) transmit the vibrations to the central sonotrode. Subsequent development of yet higher power transducers, configured for the UAM system, will permit yet higher powers, and hence greater performance, to be achieved.

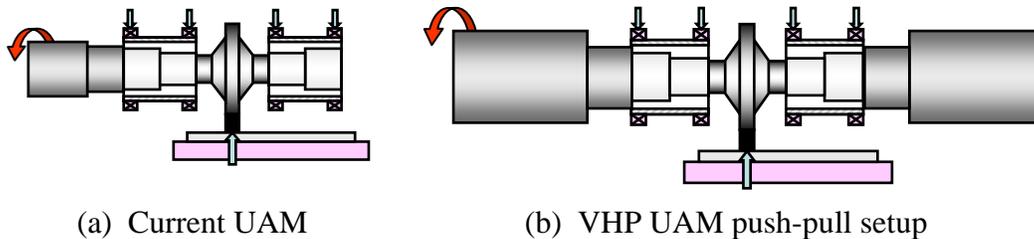


Figure 2. UAM, VHP UAM systems

Test Bed

It was important, before proceeding to the design/construction of the full VHP UAM system to prove out the operation of the push-pull ultrasonic system, including its welding characteristics. This was achieved by designing the 9.0 kW module and incorporating it into a test bed to test its welding capabilities.

A horizontal milling machine base was modified to accept the ultrasonic welding module, as shown in Fig. 3, thus serving as a system test bed. The 9.0 kW ultrasonic welding module, and its location on the test bed, is highlighted. This unit has only limited functionality, being able to lay down single tapes on flat plates, and does not have tape feed or machining capability.

A significant design innovation in the welding module was the elimination of the booster components between the transducers and the sonotrode (see Fig. 2(b) as reference), thus greatly reducing the length of the push-pull system.

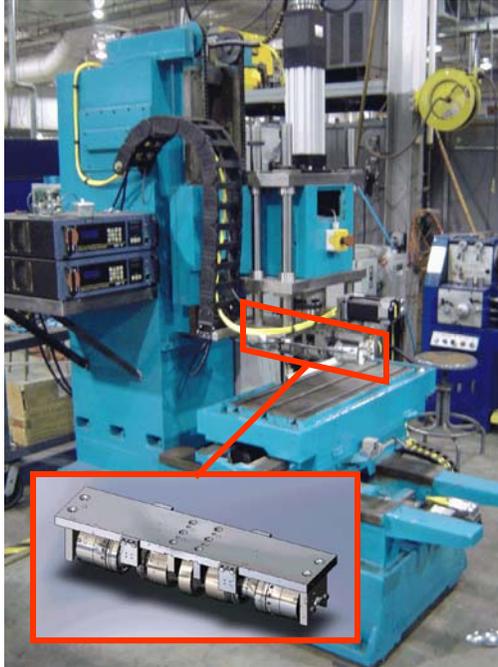


Figure 3. VHP UAM test bed

Bonding Trials

While the VHP test bed served to prove the 9.0 kW ultrasonic hardware, its most important role was to determine if the higher ultrasonic power did, in fact, permit the welding of advanced materials. This led to a number of weldability tests, some results which are summarized in Fig.

4. Referring to the numbered cross sections and welds of the figure:

- (1) bonding of five layers of 0.10-mm Ti CP-2 foil to a Ti base plate, while (2) shows the welded samples before testing
- (3) Al 3003-H18, 0.15-mm foil bonded with low-power UAM
- (4) bonding of 12 layers of Al 6061-H18 0.18-mm foil, while (6) is the cross section of that sample
- (5) bonding of 12 layers of Cu 1100, 0.18-mm foil, while (5a) shows the cross section of the bonded Cu. The horizontal white arrows indicate the interface locations between Cu layers
- (7) top view of three, 2-layer bonds of 0.13-mm 316L stainless steel, as well as the metallurgical section of one of the bonds

Special reference is made in Figure 4 to comparing the appearance of the 6061 bonding achieved with low-power UAM, (3) with the results from the VHP test bed, (6). The key feature is the great reduction in voids along the bond interface in the VHP results. Likewise, the Cu bonding of (5a) shows a near absence of interface voids. Tests are continuing on additional alloys, and in further improvement in bond quality of the resulting VHP welds. Extensive work has been done, and is ongoing, on characterizing the metallurgical and mechanical properties of materials bonded by the UAM and VHP UAM systems (Janaki Ram, 2006; Schick, 2010; Johnson, 2008; Dehoff, 2010; Ramanujam, 2010).

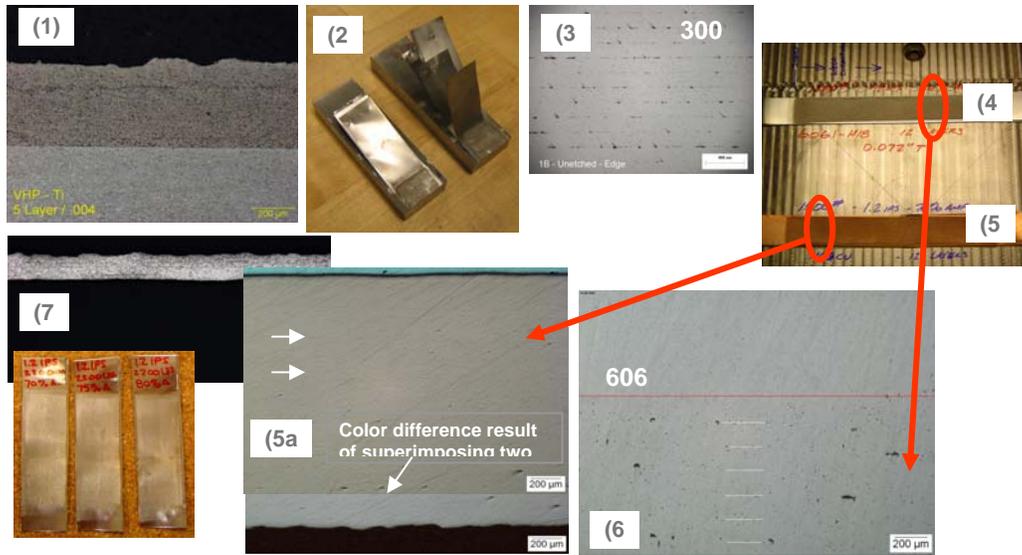


Figure 4. VHP welding tests on several advanced materials

VHP UAM System

There was a two-fold purpose in going to the higher ultrasonic power of the VHP system, the first of which was bonding advanced materials. The second purpose was increased productivity, meaning the ability to produce parts more rapidly, and in so doing, to make the production of larger parts feasible, both from a size and production time standpoint (thus, higher ultrasonic power permits better bonding of materials, but also faster speed of travel, and welding of thicker tapes). The initial machine concept having these features is shown in the upper left corner of Figure 5, where a large, moving gantry, fixed bed system was envisioned.

Once the sponsorship of the Wright Project was obtained, a detailed set of performance specifications were set and the design finalized, as shown in the lower left of Figure 5. The need for high mechanical stiffness of the system, both to withstand the high static forces needed by the higher power ultrasonics, as well as maintaining build accuracy for large parts, led to a fixed weld system, moving bed design. The system is shown at an intermediate stage of construction at the machine builder in the right of Figure 5.

At the time of this conference, the machine has been installed at EWI, as shown in Fig. 6, is operational and will be undergoing early welding trials. Thus, Fig. 6(a) shows the overall system, with viewing doors open, on EWI's laboratory floor, with the technician using the optional pendant operating control. The main VHP welding module with associated hardware is shown in Fig. 6(b). In this image, the operator has loaded the tape feed system, which accommodates 25-mm to 300-mm wide sheet stock, and is adjusting the alignment to the weld surface of the sonotrode.

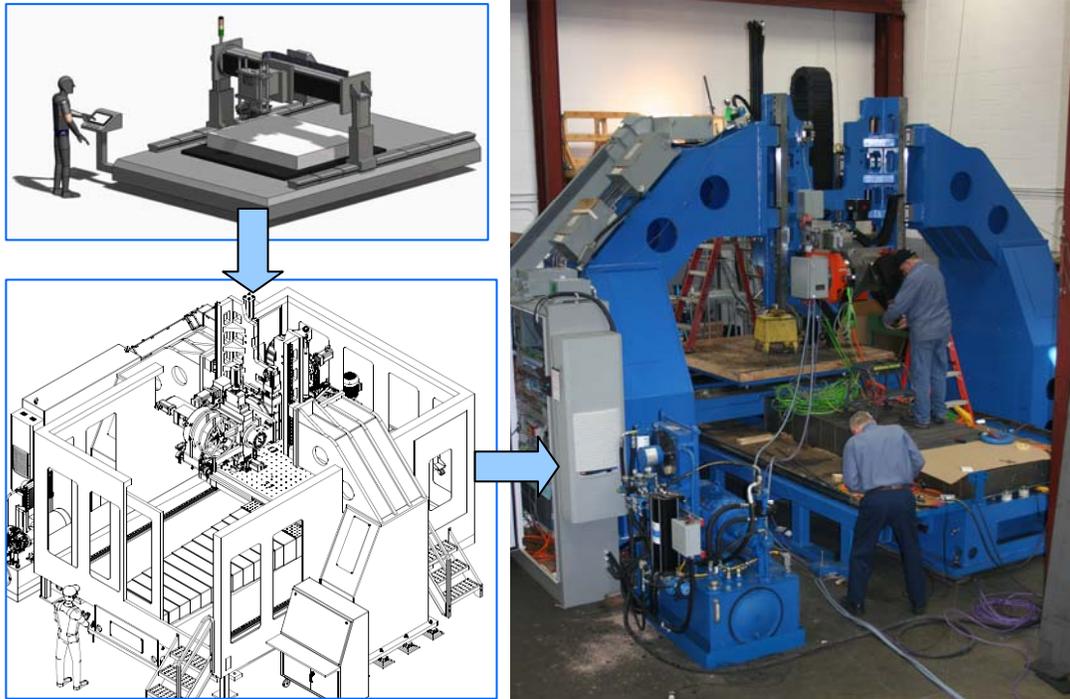


Figure 5. VHP UAM system – from concept to (near) final system

The machine specifications were drawn up to support the two primary objectives of increased ultrasonic power and a larger work envelop. The ultrasonic power increase required, as noted, the ability to deliver high forces at the weld interface, thus needing increased framework stiffness, as well as robust actuators capable of applying welding forces of up to 33-kN. This was accomplished with a two part gantry design in which large vertical columns support a horizontal bridge positioning the heavy z-axis actuators directly over the build table which is itself centered directly underneath the gantry.



(a) Overall VHP system under pendant operation



(b) VHP UAM main module

Fig. 6. VHP UAM system installed at EWI

As previously noted, a critical aspect of this new system is the ability to produce parts in the order of 1.8 m × 1.8 m × 0.9 m. This advance identifies many new opportunities for large scale manufacturing as well as large part hardware repair. Recognition of these applications is addressed with a multi-axis welding system and high speed machining center.

The multi-axis welding system is a large rotary table providing two additional degrees of freedom in the direction of pitch and roll (“A” and “B” axis’ respectively). Being that the rotary table is fixed and actuated by the z-axis, this design allows for 40 degrees of rotation in both pitch and roll. Maintaining consistent weld force is accomplished through a w-axis assembly which is tied to the rotary table, permitting high force application perpendicular to the surface normal direction at all times.

Fabrication of deliverable parts, whether they are new or repaired components, is accomplished by a custom three axis HSK-64 machining system. This subassembly is located on the opposite side of the gantry from the weld module and is also actuated by the z-axis. This design can accommodate a wide range of cutting tool sizes ranging from 0.5 mm to 100 mm operating at 10,000 rpm and feed rates as high as 10 mpm.

Programming of the machine is carried out by generating a CAD model of the desired part which is then imported into an offline software package, RPCam™, which develops the necessary G and M codes. All operations of the machine, including specialized welding features, are controlled by a Siemens 940D machine interface. Due to the critical placement and timing of welding functions, vital parameters such as amplitude, dwell time, force, and weld speed, are continuously monitored through a remote PC.

The quality of the fabricated part depends on the ability to produce sound welds in a repeated fashion. Therefore, a critical aspect of the VHP UAM technology is having the ability to determine weld quality before subjecting it to destructive testing methods (Short, 2010). A real time data acquisition system continuously monitors weld force, amplitude, power, frequency and position, and records the programmed and actual values in the form of a streaming graph. If a programmed value deviates outside of the acceptable window of operation, an alarm condition will occur indicating that the operator should check the part. Data from each weld operation for producing the desired part can be exported in common formats for further analysis.

Summary

The development of a “Very High-Power Ultrasonic Additive Manufacturing System” (VHP UAM), operating at up to 9.0 kW of ultrasonic power, has been described. The purpose of the development has been to expand the range of uses, in terms of materials, part sizes and rates of production and, ultimately, the total range of applications, of the basic ultrasonic additive manufacturing process. The technical aspects of the unique “Push-Pull” ultrasonic system were noted, including its first implementation in a very high power test bed. Using the test bed, welding of materials such as Ti 6-4, 316SS, 1100 Cu, and Al7075 has been demonstrated, with trials on other advanced materials in progress. The current status of the VHP UAM, recently installed at EWI was also described, noting that it will be capable of fabricating metal parts having lineal dimensions of up to 1.5 m × 1.5 m × 0.6 m.

Acknowledgements

The support of Ohio's Third Frontier Wright Project and team partners Boeing, General Electric, Lockheed-Martin, Army Research Laboratory, Solidica, and The Ohio State University in carrying out this development is acknowledged.

References

Dehoff, R., Babu, S.S. (2010, in press) *Characterization of Interfacial Microstructures in 3003 Aluminum Alloy Blocks Fabricated by Ultrasonic Additive Manufacturing*, Acta Materialia.

De Vries, E. (2004) *Mechanics and Mechanisms of Ultrasonic Metal Welding*, Ph.D. Dissertation, The Ohio State University.

Janaki Ram, J.D., Yang, Y., Stucker, B.E. (2006) Effect of Process Parameters on Bond Formation during Ultrasonic Consolidation of Aluminum Alloy 3003. *Journal of Manufacturing Systems*, 25:221–238.

Johnson, K. (2008) *Interlaminar Subgrain Refinement in Ultrasonic Consolidation*, Ph.D. Dissertation, Loughborough University, Loughborough, U.K.

Ramanujam, S.M., Babu, S.S., Short, M. (2010) *Bonding Characteristics During Very High Power Ultrasonic Additive Manufacturing of Copper*. Scripta Materialia, 62, 560-563.

Schick, D.E., Hahnen, R.M., Dehoff, R., Collins, P., Babu, S., Dapino, M.J., Lippold, J.C. (2010) *Microstructural Characterization of Binding Interfaces in Aluminum 3003 Blocks Fabricated by Ultrasonic Additive Manufacturing*. Welding Journal, 89(5), 105s-115s.

Short, M., Zhang, P.H., Graff, K. (2008) *Development of a VHP UAM System*, The Ultrasonics Industry Association.

Short, M. (2010) *Ultrasonic Additive Manufacturing*, American Welding Society Conference on New Welding Technologies, Ft. Lauderdale, FL, June, 2010.

White, D.R. (2002) *Object Consolidation Employing Friction Joining*, U.S. Patent 6,445,629, October 1, 2002.