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A REVIEW OF ULTRASONIC ADDITIVE MANUFACTURING FOR PARTICLE ACCELERATOR APPLICATIONS

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Abstract

Additive manufacturing (AM) technologies have been used for prototyping and production parts in many industries. However, due to process limitations and the unknown material properties of AM parts, there has been limited adoption of the technology in accelerator and light-source facilities.

Ultrasonic Additive Manufacturing (UAM) is a hybrid additive-subtractive manufacturing process that uses a solid-state ultrasonic bonding mechanism attached to a CNC mill to join and machine metal parts in a layer-by-layer manner. The solid-state and hybrid nature of UAM ensures base material properties are retained and mitigates process limitations which traditionally inhibit integration of parts produced by other AM processes.

This paper presents a review of the UAM process and its potential application to accelerator and beamline needs. Several specific areas are discussed including: replacement of traditional manufacturing approaches, such as explosion bonding to join dissimilar metals; improved internal cooling channel fabrication for thermal management; and imbedding of electronics and materials for more accurate remote sensing and radiation shielding.

INTRODUCTION

Components used in accelerators and beamlines operate in demanding environments which often require specialized and difficult fabrication processes to manufacture. Ultra-high vacuum (UHV) chambers may require explosion welding and beam stops and collimators utilize electrical discharge machining (EDM), both of which can be time consuming, costly, and are limited in their application.

As a hybrid, additive-subtractive manufacturing process, ultrasonic additive manufacturing (UAM) possesses unique capabilities which could make explosion welding or EDM options instead of necessities. The solid-state additive welding stage operates well below the melting temperature of the substrate materials, which ensures bulk material properties are largely retained.

Subtractive machining is completed by a computerized numerical control (CNC) mill to which the ultrasonic transducer and sonotrode are also mounted. This allows for both three and five-axis milling operations of complex geometries and retains the tolerances, surface finish, stability, and repeatability inherent to milling processes. In turn, parts printed using UAM can be more rapidly integrated without the need for time-consuming and costly post-processing operations that can include finish machining and surface finishing. A schematic depiction of both additive and subtractive stages of UAM is shown in Fig. 1.

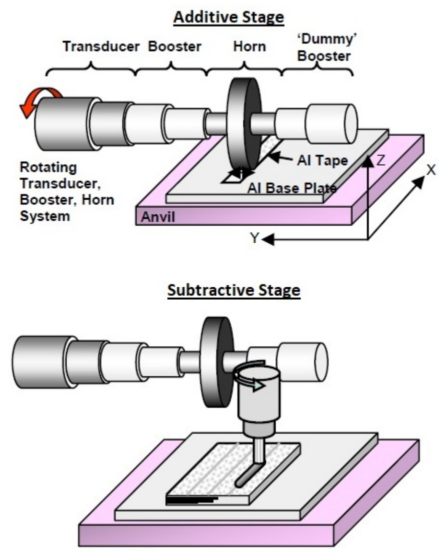

Figure 1: UAM process schematic showing additive and subtractive stages [1].

APPLICATIONS FOR ACCELERATORS

Accelerator facility adoption of parts printed with other metal additive manufacturing (AM) processes like selective laser melting (SLM), or electron beam melting (EBM) has been slow in part due to the uncertainty of printed parts' material properties. However, with the advantages of UAM, more rapid adoption of metal AM parts could occur for certain application areas.

Dissimilar Metal Welding

Bi-metallic joints are widely used for accelerator vacuum systems, thermal management components, and instrument feedthroughs with explosion welding serving as a common method of fabrication. Explosion welded joints are formed when a controlled explosion shockwave accelerates one material of the joint into the other [2]. The process is limited to simplistic geometries, which in turn limits the parts that can be fabricated.

The mechanisms for successful bonding during the UAM process are similar and generally believed to be shear deformation, inter-diffusion, and sometimes mechanical interlocking. The applied normal force from the sonotrode head compresses the foils ensuring good contact of the asperities which are subsequently sheared by the ultrasonic oscillations. Both the down force and ultrasonic oscillations also contribute to plastic flow of the material and breakdown and redistribution of surface oxide layers and impurities to promote a clean mating surface for solid joints [3]. Figure 2 shows several UAM welded dissimilar metal interfaces with varying bond topographies.

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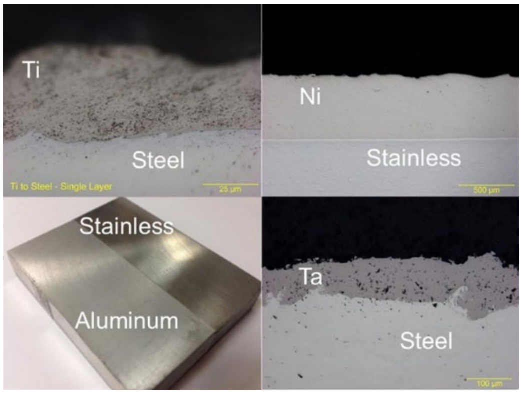

Figure 2: Example UAM dissimilar metal interfaces showing (a) titanium and steel (b) nickel and stainless steel (c) aluminum and stainless steel (d) tantalum and steel [4].

Explosion welding and UAM both form welds with comparable strengths and qualities due to their similar low-temperature, plastic deformation bonding mechanisms. What sets UAM apart is greater flexibility and control afforded by the integrated precision machinery. More complex geometries that could feature many multi-layered dissimilar metal interfaces are achievable and with greater speed and accuracy. Features normally requiring post-machining when using explosion welding, such as holes and knife edges, would be completed in-situ.

Another possible application is the manufacture of custom beryllium x-ray windows and vacuum flanges. As there exist a very limited number of beryllium window manufacturers, having the means to produce custom windows on demand could be incredibly valuable, especially for time-constrained projects.

Research examining beryllium window manufacture using ultrasonic welding was completed by NASA researchers in 1963 using 0.001” thick beryllium foil and an ultrasonic ring welder. Though the weld joint design and beryllium quality were called into question, the report ultimately determined that ultrasonic welding was feasible for obtaining vacuum-tight joints between thin beryllium disks and stainless steel rings [5]. With advances made in beryllium foil manufacture and quality since the 1960s, the chances of success using UAM for x-ray window fabrication seem plausible. However, little documentation exists on the generation of particulate during UAM, which would need to be investigated further to ensure beryllium could safely be processed.

Internal Features

The most common application for UAM is the optimization of heat exchangers. As radiation shielding component designs continue to evolve to meet the demands of greater beam energies, UAM could increase thermal efficiencies while decreasing weight and providing another avenue for fabricating critical components. Additionally, the footprint of UAM machines, that of a standard CNC machining center, could allow for easy integration into existing machine shop facilities and contribute to more rapid prototyping and production.

Traditionally, parts requiring internal features also require assembly of multiple constituents with welding or brazing to join them together. Water cooling channels or tubing in beam stops use machined channels in a block of copper which are then sealed using a brazed-on jacket or directly brazed to the copper to ensure water tightness and good heat transfer.

UAM can combine these two processes to create internal geometry without the need for extra assembly steps. Figure 3 shows UAM fabricated aluminum heat exchangers with internal cooling channels and machined recesses to reduce weight. Combining both dissimilar metal welding and internal feature integration, UAM could produce more thermally efficient beam stops and collimators or unique instrument feedthroughs tailored to better shield or route electronics.

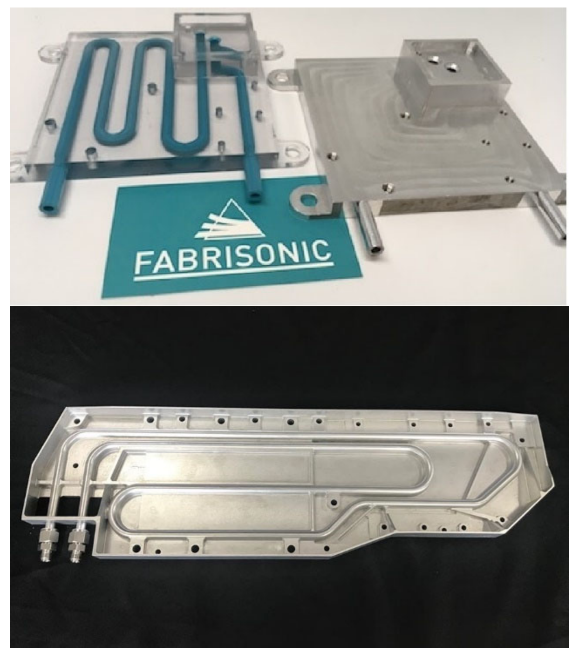

Figure 3: Aluminum heat exchangers showing complex internal geometry capabilities of UAM [4].

Embedded Electronics and Materials

Due to the lack of melting in the UAM process, materials which would otherwise be damaged by the heat of a traditional fusion welding or brazing application can be imbedded directly into UAM parts. Electronic sensors, such as thermocouples or strain gauges, can be strategically located closer to their points of interest enabling higher accuracy data acquisition.

An additional benefit of embedding electronics inside metal parts is the shielding that metal encasement affords. Electronics could potentially be shielded from beam or thermal radiation by clever layering of high-Z or less thermally conductive materials. Figure 4 shows the interface between an aluminum coated fiber optic cable embedded in an aluminum 6061 fatigue specimen. The metallized coating serves to promote a more homogenous bond and improve strength by reducing the possibility of defects at the weld interface.

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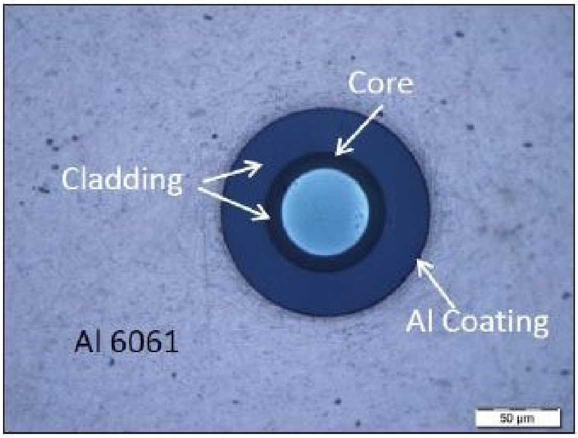

Figure 4: Metallized fiber optic cable embedded in aluminum 6061 fatigue specimen [6].

Materials not conducive to welding or that require precision placement within a part can also be embedded using UAM. Oak Ridge National Laboratory (ORNL) partnered with Fabrisonic, the primary manufacturer of UAM machinery, to fabricate control elements for use in the High Flux Isotope Reactor (HFIR). These control elements are curved and contain particles of Eu_2O_3 and Ta dispersed along their axis for neutron absorption. As such, they are costly to manufacture using traditional processes.

Using a 5-axis CNC mill with an attached UAM system, features were machined along a curved substrate plate. The neutron absorbing materials were then embedded in the machined holes and sealed by further layers of aluminum tapes. Figure 5 shows the layout of the neutron-absorbing disks just before they are further embedded underneath the remaining layers of aluminum required to complete the part.

Figure 5: Eu_2O_3 and Ta neutron absorbers embedded in a control panel used in a high-flux isotope reactor at ORNL [4,7].

A similar approach could be carried out for radiation shielding materials in accelerator systems. Tungsten or lead could be strategically added to locations in parts or used to encase sensitive electronics that would otherwise experience faster degradation from radiation damage.

PROCESS LIMITATIONS

Material Incompatibilities

As plastic deformation of asperities is one of the main mechanisms of the UAM process, harder materials are more difficult to process as they require greater energy to deform and collapse surface asperities. In order to achieve a high bonding density, high oscillation amplitude and/or high normal force will be required [3].

Additionally, some material combinations, particularly pure metals, are impeded by oxide layer interference. Pure titanium, for example, will gall during processing as the ductility of the titanium oxide layer tends to cause smearing at the sonotrode contact area and weld interface. Interlayers of softer materials, e.g. aluminum, may be required in these cases.

Post-Processing

UAM does suffer from mechanical strength anisotropy depending on the build direction and consequent layer orientation, which is a common feature of most AM processes. Anisotropies can be mitigated by post-process heat treatments which have been shown to increase bonding strength through controlled generation of intermetallics or relaxation of residual stress and promotion of inter-diffusion [3]. Hot isostatic pressing (HIP) is one heat treatment process that produces significant improvements in the density and mechanical strength of most AM parts.

Bi-metallic parts produced by UAM may require tailored heat treatments based upon the chemistry of the materials used. More complex, multi-metallic parts would thus require more extensive post-processing prior to integration.

CONCLUSION

UAM technology could provide multiple avenues for optimization of parts in accelerator applications. New and unique material constructions, more accurate thermal management, and improved sensing and data acquisition capabilities are some of the areas UAM welding could immediately affect. As with any new technology, further applications would only increase as more experience and familiarity are gained.

The Engineering and Technical Support Group (ETSG), part of the Enrico Fermi Institute at the University of Chicago, recently received funding to purchase a Fabrisonic SonicLayer1200 UAM machine. Due to the relationships ETSG has built with groups at both Argonne National Laboratory and Fermilab, future ETSG projects could enable testing of UAM parts to qualify the process for use in accelerator applications in the future.

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