metals

Editorial

Ultrasonic Additive Manufacturing of Metallic Materials

Chaoqun Zhang [1,2,*], Hongying Yu [1,2,*], Dongbai Sun [1,3,*] and Wen Liu [4]

1 School of Materials, Sun Yat-sen University, Shenzhen 518107, China
2 Innovation Group of Marine Engineering Materials and Corrosion Control, Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai 519082, China
3 School of Material Science and Engineering, Sun Yat-sen University, Guangzhou 510006, China
4 Department of Engineering, University of Cambridge, Cambridge CB3 0FS, UK
* Correspondence: zhangchq25@mail.sysu.edu.cn (C.Z.); yuhy26@mail.sysu.edu.cn (H.Y.); sundongbai@mail.sysu.edu.cn (D.S.)

Ultrasonic additive manufacturing (UAM), a solid-state additive manufacturing technology, was invented in 1999 by Dawn White [1]. UAM is a technique for creating solid metal objects by ultrasonically joining a series of metal foils into a three-dimensional structure [2]. To add internal features and complete the geometry of the printed part, computer numerical control (CNC) machining operations are applied interchangeably with the ultrasonic welding operation. Similar to ultrasonic metal welding, the procedure uses an ultrasonic transducer to activate a horn and produce a high frequency friction motion while a down force is exerted. The frequency of this friction motion is usually 20 kHz [3].

Similar to solid-state welding technologies (friction stir welding and ultrasonic welding [4]), melting does not take place during the UAM process. Because melting does not take place during the UAM process, it has many unique advantages compared with other "fusion" AM technologies, such as laser powder bed fusion (LPBF), wire arc additive manufacturing (WAAM). First, the low-temperature manufacturing feature of UAM can realize in situ embedding functional electronic components into UAMed metallic blocks [5,6], which gives the products functional and intelligent properties. UAM has been reported to successfully embed printed electrical circuitry [7], fiber-optic sensors [5,6], surface-mount resistors [8], and nickel–titanium (Ni–Ti)-shape memory alloys [9] into metal structures.

For example, in 2017, Li et al. [7] directly embedded printed electrical circuitries made of conductive and insulating materials within the interlaminar region of UAMed aluminium matrices to realize previously unachievable multifunctional metal-matrix composites. In 2019, Bournias-Varotsis et al. from Loughborough University [8] reported a new manufacturing route for integrating electronics with 3D through connectors in an aluminum matrix by UAM. In the route, the preparation of the electronics from the component consolidation was carried out separately from the UAM process using metal foils with printed conductors and insulators. The best mechanical and electrical insulating qualities were demonstrated by a dual material polymer layer, which also kept printed conductive tracks stable at temperatures up to 100 °C.

Schomer et al. from the Ohio State University [10] embedded fiber optic strain sensors (Fiber Bragg Grating sensors) into aluminum 6061 metallic structures via ultrasonic additive manufacturing. These embedded Fiber Bragg Grating (FBG) sensors are useful for real-time in situ measurement of strain and temperature. The embedded FBG sensors were found to trace the strain profile measured by foil gages with high accuracy during quasi-static cyclic load test.

Excitingly, very recently in 2022, in the high melting point metal area, which is very challenging for both UAM and UAM with embedded sensors, Hyer et al. [11] from Oak Ridge National Laboratory successfully made functional fiber-optic sensors embedded in stainless steel components by UAM for distributed temperature and strain measurements. To improve UAM bonding quality, stainless foils plated with a Ni coating were tried as

check for updates

Citation: Zhang, C.; Yu, H.; Sun, D.; Liu, W. Ultrasonic Additive Manufacturing of Metallic Materials. *Metals* **2022**, *12*, 1912. https://doi.org/10.3390/met12111912

Received: 4 November 2022
Accepted: 7 November 2022
Published: 8 November 2022

a new feedstock. Hyer et al. [11] found using SS304 + Ni foils resulted in better bonding between layers because of severe plastic deformation of the Ni interlayer observed at the interfaces, leading to grain sizes < 2 µm. It is reported that the embedded fiber in UAMed stainless steel can successfully measure the strain in the SS304 pipe test article throughout both transient and steady-state thermal testing, providing results with identical magnitudes to those of the anticipated strains that were calculated based on differential thermal expansion.

Second, since the materials do not melt during UAM, both inert gas shielding and vacuum condition are not required, which leads to low cost and makes the UAM operations easy to be carried out.

Third, due to the low-temperature manufacturing feature, the residual stress in UAM parts is usually lower than that in AM parts fabricated by "fusion" AM technologies.

Fourth, UAM is more suitable for AM of multi materials in one part, such as Al-Cu, Al-Ti and Al-Mg multi-material parts, than other "fusion" AM technologies, such as LPBF and WAAM, since in solid state the interfacial reaction between dissimilar metals can be greatly retarded. Wolcott et al. [12] successfully used a high power 9 kW UAM system to fabricate aluminum–titanium (Al 1100 and commercially pure titanium) laminar metal composite. To improve the mechanical properties of as-built Al–Ti laminar metal composite, Wolcott et al. [12] performed heat treatments on UAMed Al-Ti; it was found that heat-treated samples show twofold improvement in mechanical strength compared with as-built Al-Ti samples for both shear strength and push-pin tests, obtaining ultimate shear strengths over 100 MPa. In 2021, Zhou et al. [13] fabricated Cu/Al laminate metal composites using UAM. It is found that Cu foils initially in an annealed state become rolled state after the UAM process. The majority of the initially rolled, strip-like Al grains transform into equiaxed grains. While the foils' strip-like rolled Cu grains are predominately made up of different rolling texture and recrystallization texture components. Al_4Cu_9 intermetallic compound particles are found at the rough Cu/Al weld interface.

Fifth, the feedstock materials used for UAM are thin metallic foils, which are widely available and are usually low cost.

However, UAM also has some disadvantages. First, it is usually not suitable for the AM of materials with a high melting point and high hardness, since its low working temperature cannot process such materials, and severe plastic deformation occurs during UAM. Second, due to the large down force applied on the upper surface of UAM samples by the horn, UAM cannot fabricate parts with high geometry complexity, which can be easily realized by LPFB.

In summary, UAM, as an emerging AM technology, has potential applications in fabricating smart metal components with fully embedded sensors, actuators, and even microelectromechanical systems (MEMS) and nanoelectromechanical (NEMS) systems. UAM also has great potential in manufacturing multi-material metallic structures, such as Al-Cu, Al-Fe, Al-Ti structures. There are still many challenges for using UAM in industry. First, the quality stability needs to be improved for mass production, currently most reported UAM samples are small and in laboratory level. Second, the interfacial bonding quality between metal foil layers needs to be increased; the residual oxide film remains a concern. Further work on monitoring the manufacturing quality of UAM, heat treatments and other methods to improve interfacial bonding, investigating embedding more interesting intelligent components and sensors into various metal matrix, deserves greater attention in the future.

Author Contributions: Writing—original draft, review and editing, funding acquisition, C.Z.; Review and editing, funding acquisition, H.Y. and D.S.; Review and editing, W.L. All authors have read and agreed to the published version of the manuscript.

Funding: The authors are grateful for the finance support from Innovation Group Project of Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai) (No. 311021013). This work was also supported by the fund of State Key Laboratory of Long-Life High-Temperature Materials (No. DTCC28EE190933).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. White, D.R. Ultrasonic consolidation of aluminum tooling. *Adv. Mater. Process.* **2003**, *161*, 64–66.
2. Dehoff, R.R.; Babu, S.S. Characterization of interfacial microstructures in 3003 aluminum alloy blocks fabricated by ultrasonic additive manufacturing. *Acta Mater.* **2010**, *58*, 4305–4315. [CrossRef]
3. Hehr, A.; Norfolk, M. A comprehensive review of ultrasonic additive manufacturing. *Rapid Prototyp. J.* **2019**, *26*, 445–458. [CrossRef]
4. Zhang, C.Q.; Robson, J.D.; Prangnell, P.B. Dissimilar ultrasonic spot welding of aerospace aluminum alloy AA2139 to titanium alloy TiAl6V4. *J. Mater. Process. Technol.* **2016**, *231*, 382–388. [CrossRef]
5. Hehr, A.; Norfolk, M.; Kominsky, D.; Boulanger, A.; Davis, M.; Boulware, P. Smart Build-Plate for Metal Additive Manufacturing Processes. *Sensors* **2020**, *20*, 360. [CrossRef] [PubMed]
6. Chilelli, S.K.; Schomer, J.J.; Dapino, M.J. Detection of Crack Initiation and Growth Using Fiber Bragg Grating Sensors Embedded into Metal Structures through Ultrasonic Additive Manufacturing. *Sensors* **2019**, *19*, 4917. [CrossRef] [PubMed]
7. Li, J.; Monaghan, T.; Nguyen, T.; Kay, R.; Friel, R.; Harris, R. Multifunctional metal matrix composites with embedded printed electrical materials fabricated by ultrasonic additive manufacturing. *Compos. Part B Eng.* **2017**, *113*, 342–354. [CrossRef]
8. Bournias-Varotsis, A.; Han, X.; Harris, R.A.; Engstrøm, D.S. Ultrasonic additive manufacturing using feedstock with build-in circuitry for 3D metal embedded electronics. *Addit. Manuf.* **2019**, *29*, 100799. [CrossRef]
9. Hahnlen, R.; Dapino, M.J. NiTi-Al interface strength in ultrasonic additive manufacturing composites. *Compos. Part B Eng.* **2014**, *59*, 101–108. [CrossRef]
10. Schomer, J.J.; Hehr, A.J.; Dapino, M.J. Characterization of embedded fiber optic strain sensors into metallic structures via ultrasonic additive manufacturing. In *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2016*; SPIE: Las Vegas, NV, USA, 2016.
11. Hyer, H.C.; Sweeney, D.C.; Petrie, C.M. Functional fiber-optic sensors embedded in stainless steel components using ultrasonic additive manufacturing for distributed temperature and strain measurements. *Addit. Manuf.* **2022**, *52*, 102681. [CrossRef]
12. Wolcott, P.J.; Sridharan, N.; Babu, S.S.; Miriyev, A.; Frage, N.; Dapino, M.J. Characterisation of Al–Ti dissimilar material joints fabricated using ultrasonic additive manufacturing. *Sci. Technol. Weld. Join.* **2016**, *21*, 114–123. [CrossRef]
13. Zhou, Y.; Chen, J.; Wang, Z.; Jiang, F. Interfacial texture and bonding strength of Cu/Al laminate metal composite fabricated by ultrasonic additive manufacturing. *Sci. Technol. Weld. Join.* **2022**, *27*, 501–511. [CrossRef]