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Towards underwater additive manufacturing via additive friction stir deposition

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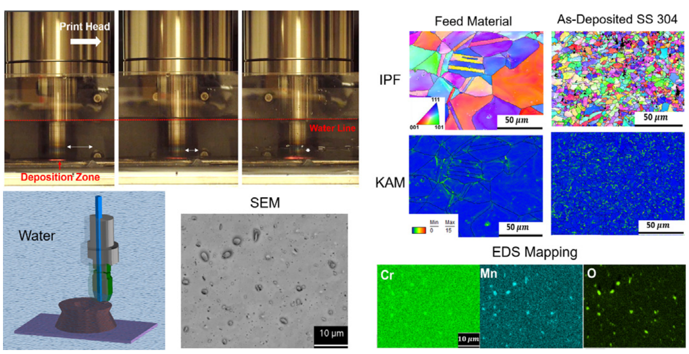
GRAPHICAL ABSTRACT



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ABSTRACT

Given the challenges in feed material supply and quality control, metal additive manufacturing has rarely been implemented in austere environments, especially underwater. This paper explores the underwater operation potential of an emerging solid-state additive technology: additive friction stir deposition, wherein material feeding and bonding are enabled by mechanical forces with minimal influences from water. It is demonstrated that additive friction stir deposition of 304 stainless steel can be successfully performed with the print head and substrate immersed in water. High temperature is reached in the deposition zone (>60% melting temperature); the material deposition behavior is similar to that in typical open-air operation. The as-deposited material is fully-dense, having fewer annealing twins and a substantially smaller grain size than the feed material (4.98 μm vs. 31.44 μm). Such microstructural changes stem from dynamic recrystallization caused by the large strain and high temperature introduced during deposition. In addition to grain refinement, small equiaxed dispersoids (~2–3 μm or less) are formed and evenly distributed in the austenite steel matrix. Rich in Cr, Mn, and O, these particles likely result from the reaction between the elements in stainless steel and water at elevated temperatures.

Submerged metal components are instrumental for transportation and energy infrastructures but are prone to accelerated damage. While the damaged components may be replaced or repaired *ex situ* on dry docks, the remote, inaccessible, and often hazardous locations make the process difficult as well as expensive, lengthy, and of high energy cost [1]. This necessitates a method that enables underwater additive manufacturing and repair via site-specific

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material deposition. Despite this urgent need, high-quality underwater metal additive manufacturing has rarely been demonstrated. Beam-based metal additive manufacturing and fusion welding rely on melting and solidification, making underwater operation difficult due to the molten pool instability [2]. As for non-beam-based, solid-state additive manufacturing, cold spray and additive friction stir deposition (AFSD) are two candidates that allow for continuous material feeding and deposition path control with great potential for structural repair [3]. Underwater cold spray has been attempted recently, in which water is found to slow the feeding particle velocity and worsen the deposition quality (porosity > 5%) [4]. Such issues could possibly be avoided using AFSD, in which material addition and bonding are governed by compression and shear. Here, the friction stir principle is integrated with a material feeding mechanism to enable site-specific deposition with full density and good interface bonding [5–7]. Given the dominant role of mechanical forces, the influence of water should be minimized, rendering AFSD promising for underwater operation like other friction stir-based processes [8].

The goal of this work is to explore the potential of underwater AFSD. As a feasibility study, a rig (305 mm long, 203 mm wide, 102 mm tall) was constructed consisting of an aluminum bottom plate, a 3D-printed PET three-sided wall, and a transparent plexiglass-based fourth wall for viewing purposes. This rig was sealed with caulk, mounted onto an AFSD machine (MELD R2, MELD Manufacturing Corporation, USA), and filled with room-temperature tap water to a depth of ~50 mm. Both the feed-rod (with a square cross-section of 9.53 mm × 9.53 mm) and substrate (3.18 mm thick) were made of wrought 304 stainless steel. AFSD was carried out at a rotation rate of 800 RPM with a travel velocity of 0.85 mm/s, a feed rate of 0.11 mm/s, and a target layer thickness of 0.25 mm, producing a 25 mm wide and 50 mm long deposition track. Both the print head (made of René 41 alloy) and substrate were immersed, and a continuous flow of water in and out of the chamber was balanced to maintain the target depth. The flow also effectively cooled the deposition, simulating an open-water situation. Microstructure characterization was performed on an FEI Helios Nanolab 600 SEM. For EBSD (electron backscatter diffraction) and EDS (energy dispersive spectroscopy), the scan area and step size were $140\mu m \times 100\mu m$ and $0.3\mu m$, respectively. TSL OIM Analysis was used for post-processing of the EBSD data, in which boundary misorientations from 2° to 15° were classified as low angle boundaries and those above 15° were identified as high angle boundaries. The kernel average misorientation (KAM) map was plotted between 0°–15°. Vickers hardness test was carried out on a Leco V-100-A2 hardness tester, with the applied load and dwell time being 9.8 N and 15 sec.

The graphical abstract shows three video snapshots, in which the print head is moving in-plane from the left to the right. The material beneath the print head is glowing, indicating a temperature >800 °C during deposition (>60% melting temperature of stainless steel). This is consistent with the finding that a vortex of steam bubbles is present around the print head. Despite intense local heating, the outflowing water remains cool and bubble-free. The setup thus well approximates the open-water condition. Scanning electron microscopy confirms that the as-deposited stainless steel is fully-dense; upon sectioning and polishing, the deposition appears sound without apparent interface delamination.

From EBSD, the as-deposited 304 stainless steel consists of fine austenite grains with an average size of 4.98 μm, which is significantly reduced from the feed material (average grain size ~31.44 μm). In addition, there are fewer annealing twins in the deposit than in the feed material. These microstructural changes stem from the dynamic recrystallization caused by the large strain and high temperature introduced during deposition. In the as-deposited steel (see the graphical abstract), higher KAM values are primarily seen as lines, which sometimes completely cut across individual grains. This indicates the formation of subgrains and evolution from low angle boundaries to high angle boundaries during deposition. Although the stacking fault energy of 304 stainless steel is low, the observation here suggests an important role played by continuous dynamic recrystallization in grain refinement. A similar conclusion has been reached in the previous work on AFSD of 316L stainless steel [9], which is also characterized by low stacking fault energy.

The 304 stainless steel deposited underwater shows one salient difference from conventional deposition: small dispersoids are formed in the austenite steel matrix with a size ranging from hundreds of nanometers to 2–3 μm. From EDS mapping, the dispersoids are rich in Cr, Mn, and O elements, possibly related to Cr_2O_3 and $MnCr_2O_4$ [10]. These oxide particles likely originate from the reactions between the elements in stainless steel (e.g., Cr and Mn) and water at elevated temperatures and can result in a substantially higher hardness value than the feed material (293 Hv vs. 249 Hv). The friction stir nature of AFSD, which results in particle fracture and dispersion, is the origin of the small size, even spatial distribution, and spheroidization of these oxide dispersoids.

In conclusion, the feasibility of underwater additive manufacturing using AFSD has been confirmed. The proof-of-concept work is demonstrated using 304 stainless steel, showing good deposition quality and notable microstructure changes. The austenite grain size is significantly reduced from the feed material and small spheroidized oxide particles are formed in the steel matrix. Future work may focus on process optimization to control the oxide formation and microstructure evolution, in order to improve the corrosion and erosion resistance in water environments.

CRediT authorship contribution statement

R. Joey Griffiths: Data curation, Formal analysis, Writing – original draft. **Nikhil Gotawala:** Data curation, Formal analysis. **Greg D. Hahn:** Data curation, Investigation. **David Garcia:** Data curation, Investigation. **Hang Z. Yu:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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