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A novel molten metal deposition-based additive manufacturing technique for aluminum alloys

Angshuman Kapil [a]*, Vatsalya Sharma [b], Jan De Pauw [c], Abhay Sharma [a]

a. Department of Materials Engineering, Campus de Nayer, KU Leuven, Sint-Katelijne-Waver, 2860, Belgium
b. Center for Mathematical Plasma Astrophysics (CmPA), KU Leuven, Leuven, 3001, Belgium
c. ValCUN BV, Langerbruggestraat 33, Oostakker, 9041, Belgium

Abstract: Aluminum (Al) alloys have significant applications in many sectors, including but not limited to the automotive, aerospace, and aircraft industries. Although additive manufacturing (AM) of Al alloys has gained significant interest in the industry and academia, likewise, its full-scale implementation is currently restricted due to issues like porosity, low mechanical properties, large solidification shrinkage, etc. This study highlights a new molten metal deposition-based AM technique developed by 'ValCUN' that not only alleviates the aforementioned issues but also provides a pathway for fast and affordable Al 3D printing. The novel disruptive technique reduces capital investment and operating costs by foregoing the use of lasers and improves safety and sustainability by employing safe-to-handle wire feedstock (even in recycled conditions) instead of powders. The process employing continuous extrusion of molten metal at an adaptive resolution provides the possibility of high build rates that can enable the production of medium-sized and complex 3D-printed Al metal components like manifolds, heat exchangers, lightweight parts for robots, etc. To better comprehend the process, it is crucial to elucidate the post-deposition behavior of individual droplets. For this purpose, a parametric study is conducted to understand the influence of the initial conditions of molten Al droplet on the post-impingement (with a heated metal substrate) behavior and final shape. During experimentation, the temperature and size of the droplet before detachment is captured. Post-deposition droplet behavior and shape are then utilized to fine-tune the process parameters for more accurate AM of Al parts with complex shapes and features.

Keywords: Additive manufacturing; Molten metal deposition; Aluminum alloy; Droplet deposition; 3D printing

1. Introduction

Over the past two decades, metal additive manufacturing (AM) has made significant progress owing to the availability of cost-effective industrial lasers, high-performance computing software and hardware, and availability of a wide array of metal feedstock (in powder or wire form) [1]. Metal AM, providing the ability to fabricate parts with intricate geometries, is increasingly finding acceptance for applications in many critical fields, including medical implants and aerospace [1,2]. Although metal AM parts have attained fully certified production readiness for specific applications, it is warranted to have a comprehensive and fundamental understanding of the involved process, the employed feedstock, and structure and properties to fabricate reliable, i.e., defect-free and structurally sound metal AM parts.

The exponential rise in the research interest in metal AM is evident from the increasing number of comprehensive reviews available in the literature [1,3-11]. While there exist many metal AM technologies, the fusion-based AM technologies, i.e., powder bed fusion (PBF) and directed energy deposition (DED), utilizing high-energy-density beams, including lasers, electron beams, or electric arcs as the heat source, have garnered increased industry and academic interest. The wider acceptance of PBF and DED technologies for metal AM compared to the indirect and solid-state metal AM technologies (binder jetting, fused filament fabrication [12], cold spray AM [13], and ultrasonic AM [14]) is because of the ability of PBF and DED technologies to fabricate components with significantly superior performance owing to their inherent complicated thermal history [15].

In the area of metal AM, the most investigated material class after steels and titanium alloys are aluminum (Al) alloys [16,17]. Al alloys find widespread application in the automotive, aerospace, and rail transportation industry owing to their favorable properties like low density, high thermal conductivity, good mechanical properties and corrosion resistance, wide

*Corresponding author: E-mail address: angshuman.kapil@kuleuven.be

availability, and lower costs [18]. Despite the multiple advantages, the growth of Al alloy AM has been relatively slow compared to other metallic alloys [19], owing to the numerous technical challenges associated with the currently employed techniques. To date, the laser-based PBF process remains the most widely investigated technique for Al alloy AM, followed by the arc-based DED process [18]. The employed laser wavelength is an issue for Al alloy AM due to the high reflectivity of Al alloys [19]. Moreover, the laser-metal powder interaction involving a combination of mechanical, thermal, physical, metallurgical, and hydrodynamic phenomena makes the process control difficult. Al parts fabricated using the PBF process are subject to numerous defects like porosities, hot cracking, poor surface state or anisotropy, vapor plumes, spatter, and solute losses [20,21]. Arc-based DED is a suitable option for Al alloy AM due to the unconstrained build volumes, and the ability to use feedstock in the form of a wire that not only alleviates the cost but also reduces health and safety concerns [22]. However, there are certain critical issues when arc-based DED is employed for Al alloy AM. Firstly, the Al parts fabricated using arc-based DED have a significant presence of pores that leads to severe degradation of the mechanical properties [23]. Secondly, due to the high thermal conductivity of Al alloy, only a small portion of the arc energy is absorbed by the melt pool and the wire, leading to low thermal efficiencies and consequently lower deposition rate [24]. The use of the above-mentioned processes for generalized Al alloy AM is further limited due to issues like the propensity of Al alloys to form adherent oxides, the relatively wide solidification range, and the relatively poor flowability of Al metal powders [19].

The above discussion points out the overarching challenges in Al alloy AM. Over the last few years, research on Al alloy AM has been directed toward the development of alternative novel and efficient AM processes that can increase product quality, minimize defects and reduce the overall cost. This paper focuses on a novel molten metal deposition (MMD) based AM process for Al alloy printing. Section 2 of this paper provides a detailed description of the process under consideration and provides an overview of the capabilities of the process for Al alloy AM. The process considered in this study continuously deposits molten Al droplets to form 3D structures. To better understand the process basics, the attributes of the individual droplet were investigated in this work. Section 3 provides detail of the experimental procedure, followed by a discussion of the obtained results (Section 4). Finally, Section 5 provides concluding remarks and gives future research directions.

2. Background

2.1. MMD-based AM of Al alloys: The process

The novel, innovative, and proprietary metal 3D printing process developed by 'ValCUN' is disruptive to all existing metal 3D printers and is baptized as molten metal deposition (MMD). Similar to the commonly seen polymer fused deposition modeling (FDM) technology, the process uses Al filler wire instead of polymer, providing a pathway for fast and affordable Al 3D printing.

Figure 1 schematically describes the working principle of the developed MMD technique. The Al wire is fed and melted to a liquid state in the crucible through resistive heating. Liquid aluminum is then extruded through the nozzle. The temperature of the nozzle is controllable, which directly affects the temperature of the extruded Al. The extruded Al detaches from the nozzle due to gravity and surface tension forces, travels towards the substrate, and fuses with the previous layer, building the part. Note that the temperature of the substrate is also controllable. ValCUN's in-house developed software generates both the toolpath and the print parameters. Once the desired part is deposited, the parts are detached from the quick-release substrate.

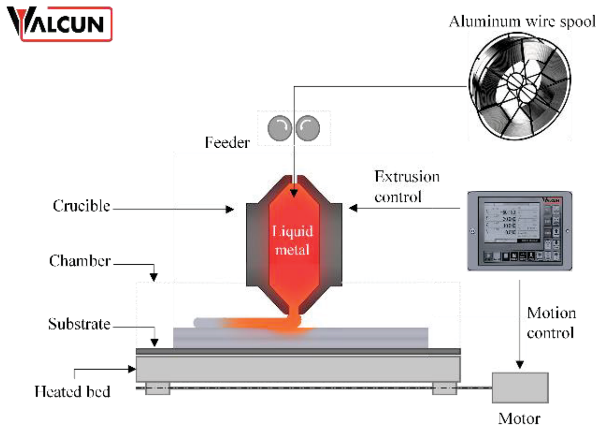

Figure 1 Schematic diagram representing the working principle of the MMD technique for Al alloy AM.

The developed proprietary technique for direct 3D printing of Al alloys is fast, simple, sustainable, and deployable. It allows direct, on-demand manufacturing of Al parts. The automatable pre and post-processing allows for a reduction in lead times and simultaneously ensures the availability of parts. The novel disruptive technique reduces capital investment and operating costs by foregoing the use of lasers and improves safety and sustainability by employing safe-to-handle wire and granular feedstock (even in recycled conditions) instead of powders which can be toxic. The process is energy efficient (up to 80% savings) and has a lower environmental impact. The process provides a greener AM solution by reducing waste and material usage and forgoes the use of any toxic chemicals.

3. Materials and methods

In this study, the single droplets of Al are deposited on Al substrates. ER4043 welding wire with a diameter of 1.2 mm is chosen as the filler wire and AlMgSi1 plates (50 mm X 50 mm X 2 mm) are used as the substrate. The chemical composition of the wire is provided in Table 1. The chemical composition is obtained from the product certificate provided by the supplier.

Table 1 Chemical composition of filler wire.

Elements (wt% composition)					
Mn	Si	Fe	Cu	Mg	Al
< 0.10	4.5-5.5	< 0.40	< 0.10	< 0.10	Balance

Figure 2 schematically depicts the experimental setup. For the deposition, three nozzle temperatures (N_T) (750, 850, 950 (°C)), three substrate temperatures (S_T) (400, 450, 500 (°C)), and three droplet travel distances (H), i.e., distance from the nozzle to substrate (20, 25, 30 (mm)) are considered. The experimental matrix is presented in Table 2. A total of 21 experiments (7 parameter sets with 3 repetitions at each set) were conducted to understand the influence on the deposited droplet attributes. Argon gas with a flow rate of 2 l/min was employed to shield the droplet and the substrate from atmospheric influence. The mass flow rate of the molten Al was kept constant at 500 mm/min. The nozzle temperature was measured using an infrared (IR) camera with a lens having a focal length (f) of 25 mm. The droplet temperature lies within ± 10°C of the nozzle temperature, and hence the nozzle temperature is considered to be the initial droplet temperature. An optical camera was employed to monitor the droplet formation and pinch-off. Figure 3 shows the state of the droplet just before pinch-off, along with the nozzle and droplet temperature measurements for experimental condition 4 provided in Table 2. The substrate temperature was measured using a Type K thermocouple Note that further details about the experimental setup cannot be shared at this stage due to intellectual property (IP) rights.

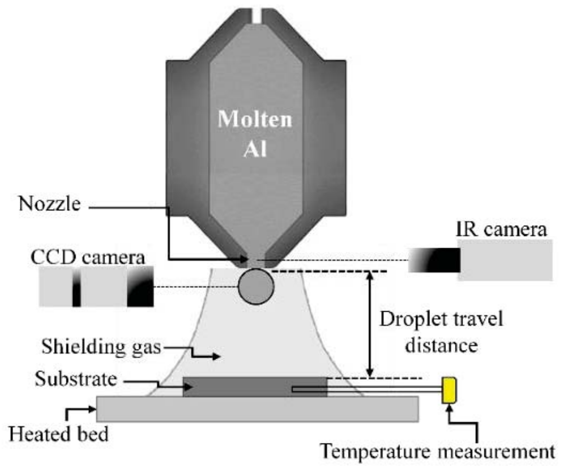

Figure 2 Experimental setup (schematic not drawn to scale)

Table 2 Experimental matrix.

Experimental conditions				
Exp. No	N_T (°C)	S_T (°C)	H (mm)	Repetitions
1	850	450	20	3
2	850	450	25	3
3	850	450	30	3
4	750	450	25	3
5	950	450	25	3
6	850	400	25	3
7	850	500	25	3

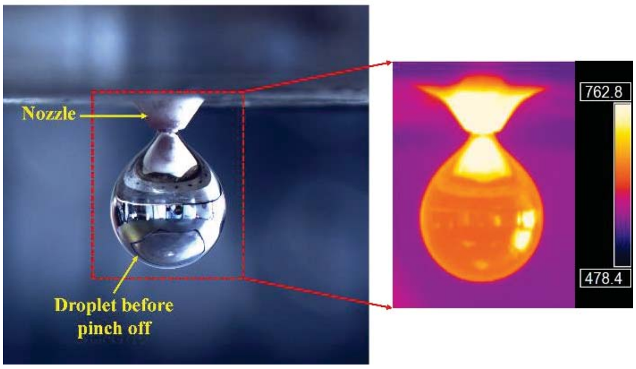

Figure 3 Representative image showing the droplet just before pinch off along with the nozzle and droplet temperature measurements

4. Results and discussion

Prior to the actual experiments, a few pilot experiments with varying substrate temperatures (nozzle temperature 850°C and droplet travel distance 25 mm) were conducted. It was observed that the droplet did not stick to the substrate when the substrate was kept at temperatures ranging from room temperature to 300°C. At 350°C substrate temperature, the droplet stuck to the substrate. This behavior could be attributed to the process type. The MMD process, unlike arc-DED, does not heat the substrate (presence of high-temperature arc in arc-DED). Even though the impinging droplet is at a high temperature (≥750°C) in this case, it is not enough to cause fusion with the substrate. Figure 4 depicts the droplet state for the substrate at 350°C and 300°C, respectively. The initial temperature of the impinging droplet and the substrate temperature are crucial for its proper adhesion to the substrate. For the droplet to remain sufficiently warm till its contact with the substrate, the droplet heat content is crucial. To avoid shrinkage stresses, the substrate must be rigid enough. In addition, the substrate's thermal properties (thermal conductivity and heat capacity) significantly affect the droplet morphology.

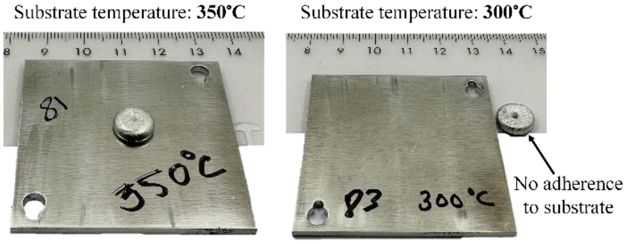

Figure 4 Droplet behavior at different substrate temperatures

Figure 5 provides the overall image of the droplet deposited for parameters viz., nozzle temperature 850°C, substrate temperature 500°C, and droplet travel distance 25 mm. Due to the lower surface tension of Al (both substrate and droplet), the droplet takes a flattened shape with a small contact angle. However, the contact surface is large, leading to faster cooling. The high thermal conductivity of the Al substrate also assists the higher cooling rate. Table 3 provides the droplet attributes (average width and height for all the experimental conditions). Note that the measurements provided in Table 3 are conducted using vernier calipers and hence represent approximate values only. More accurate measurements of droplet attributes will be conducted from micrographs of the droplet cross-section. It is observed from Table 3 that the process parameters have more influence on the droplet width, whereas the droplet height remains nearly the same for all the experimental conditions.

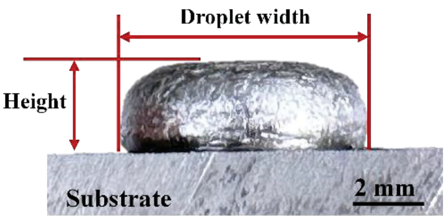

Figure 5 Overall view of the droplet (parameters: nozzle temperature 850°C, substrate temperature 500°C, and droplet travel distance 25 mm)

Table 3 Droplet attributes for different experimental conditions.

Droplet attributes (measurement of three droplets per experimental condition)		
Exp. No	Droplet width (mm)	Droplet height (mm)
1	9.2 ± 0.2	3.1 ± 0.1
2	9.8 ± 0.5	2.9 ± 0.2
3	9.9 ± 0.3	2.7 ± 0.1
4	9.3 ± 0.2	3.1 ± 0.0
5	10.3 ± 0.2	2.7 ± 0.1
6	9.5 ± 0.2	2.9 ± 0.1
7	9.7 ± 0.0	3.0 ± 0.1

Figure 6 provides the cross-section view of the droplet presented in Figure 5 and micrographs of the interface at various locations. The droplet is free from cracks or porosity, common issues when PBF and arc-DED processes are employed for Al 3D printing. A lack of fusion is observed along the edge of the droplet (location marked a and e in Figure 6). The interface at the center of the droplet (marked c in Figure 6) is free from any lack of fusion defect. On both sides of the center (marked b and d in Figure 6), the interface has regions of good bonding as well as regions where a lack of fusion can be seen. The interface state relates to the droplet's impact on the substrate, its subsequent spread outwards, heat transfer, and solidification behavior. The droplet first contacts the substrate at the center and then spreads outwards, leading to good bonding at the center. Evaluation of the droplet cross-sections for all the other experimental conditions listed in Table 2 will provide a detailed understanding of the droplet bonding with the substrate.

For AM, i.e., droplet-on-demand applications the common practice is to deposit multiple droplets on top of one another. Thus, the bonding quality of the first droplet with the substrate can be optimized based on the requirement, e.g., to facilitate the easy removal of the deposited part from the substrate.

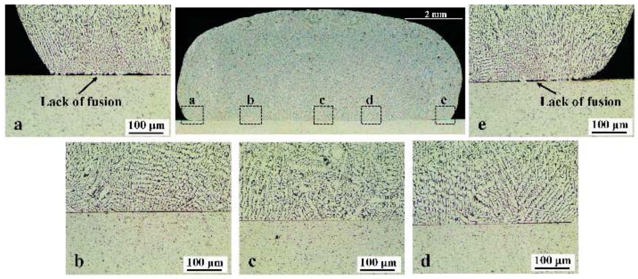

Figure 6 Cross-section view along with micrographs of the droplet-substrate interface

5. Conclusions and future directions

The proprietary MMD technique developed by 'ValCUN' provides a suitable alternative for direct on-demand Al 3D printing. The technique has a first-of-its-kind ability to print overhang and bridging structures without support structures. The technique also provides the unique ability to switch from continuous metal printing to individual droplet deposition. The experiments conducted in this study to investigate the individual droplet deposition for droplet-on-demand applications provide insight into the droplet morphology. For adhesion of the droplet, the substrate must be heated to a certain temperature (350°C in this study) even though the initial droplet temperature is around 750°C. The deposited Al droplet takes a flattened shape owing to the high surface tension. The droplet-substrate interface has regions of good bonding (center of the droplet) as well as regions where a lack of fusion is observed (edges of the droplet).

The early results presented in this study are very promising. Future work will focus on correlating the droplet morphology for a wider range of input process parameters. The authors' previous computational fluid dynamics-based multiphase simulation model (for arc-based DED process) will be modified for the MMD process considered in this study [25]. based on the conducted experiments. The developed model will provide a route for parametric optimization, process design, and reverse engineering. Additional techniques like process monitoring through sensor fusion and error and anomaly detection automation need to be developed. The mechanical properties of the printed parts must be quantified. The effect of post-processing steps (heat treatment, surface treatments, and machining) on the deposited part needs to be analyzed. Since Al is prone to rapid oxidation, a detailed study on the effect of surface oxides (on the droplet) needs to be conducted. There are wide-ranging opportunities for topology optimization and the development of unique print features and infill strategies focusing on real-world applications. The process also provides flexibility for new alloy designs (in-situ alloying) and the development of exotic microstructures. Finally, machine learning models can be developed for process parameter prediction.

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