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Processing Aluminum Alloys with Piezoelectric Driven Molten Metal Jetting

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Abstract

Molten Metal Jetting (MMJ) belongs to the group of metal-based additive manufacturing processes, where components are built up layer by layer through repetitive material deposition. In contrast to most fusion-based methods, MMJ does not require a beam source for material melting or powders, as the material is supplied as wire, melted in a crucible, and deposited drop by drop. Utilizing a piezoelectrically driven actuator, near-net-shape manufacturing with droplet diameters ranging between 500 µm and 750 µm are achievable. Overall, the advantages of MMJ enable efficient, cost-effective, and high-quality component manufacturing. This paper focuses on establishing and qualifying, industry-relevant aluminum alloys to leverage MMJ´s potential for industrial production and applications in lightweight construction. Using the example of AlSi12, potentials and challenges regarding manufacturing parameters and mechanical properties are delineated. Based on this, requirements are derived to process higher magnesium-containing alloys such as AlSi10Mg and EN AW-7075 in the future.

1. Introduction

In additive manufacturing (AM) material is deposited layer-by-layer or voxel-by-voxel in contrast to subtractive or formative manufacturing approaches. This approach can be used for metallic or polymeric materials and is used in both domains. A variety of technologies is available and can be classified due to the material used, the principle applied for bonding or fusing, the used feedstock and how the material is transported in the machine [1]. Molten Metal Jetting (MMJ) is a novel AM process which according to ISO 52900 belongs to the category of Material Jetting (MJT), which is defined as a micro-casting process in which droplets of feedstock material are selectively deposited [1]. MMJ is a process, in which molten metal in the form of micro-sized droplets is emitted on demand (so called Drop on Demand, DoD) and applied precisely. To achieve this, feedstock in the form of wire is conveyed into a ceramic crucible, melted, and subsequently deposited onto a thermally controlled substrate plate using a piezo-actuated piston. The MMJ approach is currently commercially available for some aluminum alloys and has great potential for this material group since the investment costs – neigther laser, nor metal powder – can be reduced significantly compared to other AM processes [2]. Furthermore, the temperature gradients in the deposited material or during fusion can be controlled far better in contrast to other AM processes. MMJ achieves build rates up to 320 cm^3/h in comparison to powder bed-based processes (PBF-LB/M) with around 120–150 cm^3/h and wire-based processes, e.g. wire-arc addtive manufacturing (WAAM) with around 380–450 cm^3/h for aluminum [2, 3]. Of course, these specifications can vary for different set-ups and material properties, however, there are significant differences in the build rates, especially between powder bed-based processes and MMJ. An important advantage of MMJ over PBF-LB/M is the lack of post processing steps such as depowdering and residual heat destressing, which are often not considered in the total start-to-finish additive manufacturing process time. This highlights one of the central advantages of the novel approach with MMJ: It is possible to build parts considerably faster compared to PBF-LB/M, however, the design freedom is still considerably higher compared to WAAM since a single droplet in MMJ has diameters between 500–750 µm while the wire used in WAAM has a diameter typically of 1,000–1,200 µm [2, 3]. This puts the MMJ process in a sweet spot with respect to build rates and geometric freedom of the produced parts.

In this paper, the current state of the technology is highlighted based on observations of droplet actuation, droplet formation and stability, as well as the resulting mechanical properties. The material EN AW-4047 (AlSi12) is used for the investigations due to its good casting properties and the similarities of the MMJ process to (micro) casting processes. Attention is given to the setup of the process, the hurdles and influencing factors encountered, and strategies for future management to achieve high part quality. An overview of the initial trials with EN AW-4047 will be provided. This provides basic knowledge for understanding the manufacturing principles of this new technology, as well as identifying challenges that can be applied to other alloys.

2. State of the Art and Process Description

In MJT processes in a first step the material is molten in a crucible in which the metal is usually fed as wire. Once a small molten metal reservoir is formed, molten metal droplets are generated by pushing the material through a nozzle orifice [4]. After ejection, the droplets are added onto a heated movable build plate in accordance with the layer information of the digital computer-aided design (CAD) model. Through coordination between droplet ejection and build plate motion, the iterative approach yields a near-net shape part. For droplet ejection different approaches can be used: a gas pressure pulse, a magneto-hydraulic pulse, a piezoelectric driven actuator. The gas pressure pulse is applied to the surface of the molten metal to create a pressure pulse at the nozzle orifice, which causes a droplet ejection [5–9]. Another method is the magneto-hydrodynamic principle (MHD). A pulsed magnetic field is induced by an external coil surrounding the crucible. The induced eddy currents interact with the magnetic field and create an axial Lorentz force, which can be used to eject a droplet [10–12]. Alternatively, a piezoelectric driven actuator can be used to apply the necessary impulse to the nozzle orifice [6, 13, 14]. Those actuators need to be thermally decoupled by a transmitter piston from the molten metal as they cannot withstand the high temperatures. Piezoelectric ceramics, which are commonly used for DoD (Drop on Demand) print heads working at room temperature function like ink-jet print heads. Besides the magnetohydrodynamic, the piezoelectric DoD principle is the most widely used actuation principle (see figure 1).

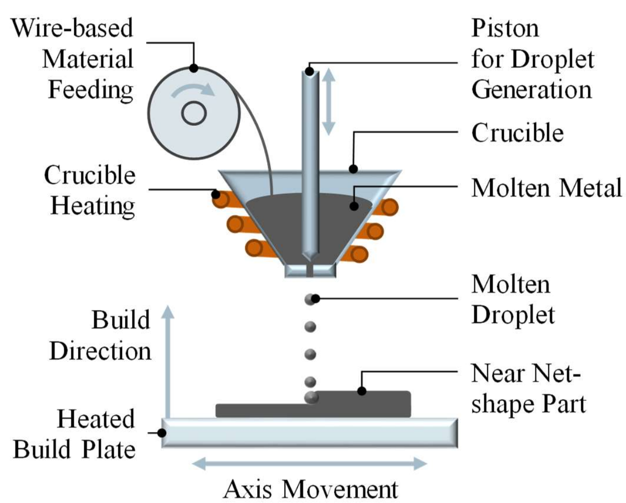


Figure 1: Wire-fed MMJ process with piezoelectric actuation

Up to now, metals with a low melting point have been processed. In addition to tin and bronze, the processing of aluminum alloys is in focus [15–17]. The influencing factors include environmental conditions (such as temperature, humidity, and atmospheric composition), hardware used (including nozzle geometry, material selection, and jetting parameters), and the physical and chemical properties of the alloy (such as viscosity, surface tension, alloy composition, and oxidation behavior) [10–13, 18–20]. However, is has been demonstrated that printed EN AW-4047 already achieves mechanical properties equivalent to or even surpassing those of cast materials [13]. Although there are numerous influencing factors, the parameters governing the process and their transferability to other alloys remain challenging.

3. Molten Metal Jetting Process of EN AW-4074 with Piezoelectric Driven Actuation

This paper aims to present initial correlations that can provide a basis for a more robust understanding of the process, focusing on the early stages of process development. The process is evaluated based on three successive stages, as summarized in Table 1: 1. wetting, 2. droplet formation and quality, and 3. part quality.

Table 1: Evaluation criteria of the printing process

Evaluation criterion	Description
1. Wetting	- Wetting of the nozzle channel - No clogging of the nozzle - No deformation of the nozzle orifice
2. Droplet generation and quality	- Constant droplets in terms of droplet size and velocity - Monodisperse droplets without satellite formation (detection by standard deviation of the droplet size) - Actuation parameters, e.g. voltage, current, frequence
3. Part quality	- Part density - Mechanical tensile properties

To focus the experimental investigations on the determination of a process window, hardware factors are not changed. The commercially available GMP300 MMJ system from the manufacturer GROB (Mindelheim, Germany) were used for the experiments. The tests were carried out using the following materials, hardware, and ambient conditions:

- The crucible heating temperature was set to 800 °C and the build plate temperature was 450 °C.
- The nozzle was made of graphite with an opening of a diameter of 500 µm.
- Both the piston and the crucible were made of ceramic. The flow channel had a distance between the piston and the crucible wall. The pisten had a diameter of 5.8 mm and the circumferential gap to the crucible was 0.1 mm.
- Nitrogen was used as the shielding gas in the machine area. The nozzle was purged with nitrogen at a flow rate of 2 l/min at an overpressure in the crucible of 5–6 mbar.
- The ambient temperature was kept constant at room temperature (approx. 20 °C) and the relative humidity at 30 % rH. The printing process took place in a bulid chamber under a nitrogen atmosphere, whereby a maximum of 1.6 % residual oxygen was obtained.

3.1. Wetting

Each manufacturing process begins with the complete wetting of the nozzle. Only then can droplets be generated in a targeted manner by activating the piston. The wetting is checked by camera images taken from the material output of the nozzle. These images also enable discrete tracking of the nozzle condition during and after the printing process. Figure 2 (left) shows an exemplary image of the nozzle after successful wetting. It can be seen that the nozzle orifice is filled with molten material (black in the image). This state represents the start of the droplet deposition cycle.

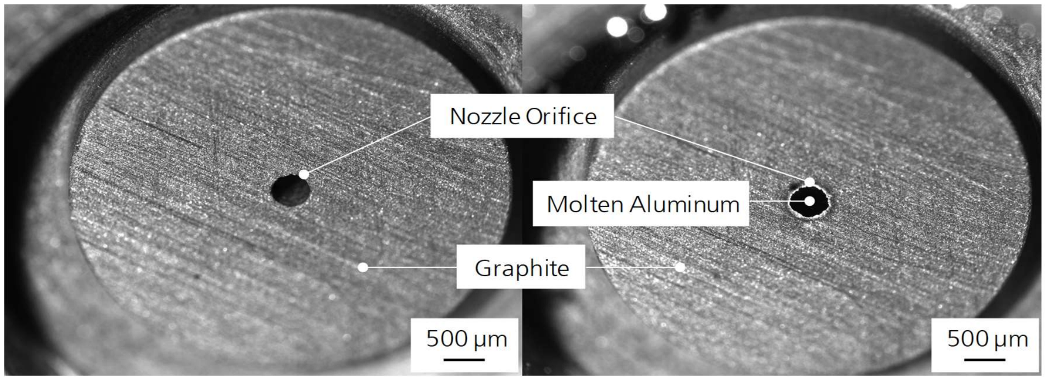


Figure 2: Wetting of the graphite nozzle. **Left:** Unwetted nozzle orifice. **Right:** Nozzle orifice after complete wetting.

3.2. Droplet Generation and Quality

When an electrical voltage is applied to the piezo actuator, the piezoelectric material expands or contracts. This movement can be used to move a membrane or mechanical system (as is the case here with the piston) to create a droplet. Piezo actuators offer very high precision and responsiveness to electrical signals. They are able to perform very small movements, in the micrometer or even nanometer range. The actuation of a piezo is linked to electromechanical equations, which are described below. The basic relationship for a piezoelectric actuator can be described with the piezoelectric equation (Eq.):

Eq. 1 $x = d \cdot V$, where: x is the mechanical displacement (expansion), d is the piezoelectric coefficient, V is the applied electrical voltage. The value of the piezoelectric coefficient d varies greatly depending on the material used and the specific material orientation. A piezo actuator also behaves like a capacitor whose capacitance C is given by:

Eq. 2 $C = Q/V$, where: Q is the charge, V is the voltage. The current I through the piezo actuator can be described as a change in charge over time:

Eq. 3 $I = dQ/dt = C\ dV/dt$. The velocity v of the expansion of the piezo actuator is the time derivative of the displacement:

Eq. 4 $x(t)= d \cdot V(t)$.

These equations describe the basic relationships between the electrical and mechanical properties of a piezo actuator. For more complex applications or more precise models, additional factors and corrections may be necessary that take into account, for example, the mechanical properties of the entire system or losses. Since the piezoelectric coefficient was unknown and the deflection of the entire system was currently unknown or could not be measured in interaction with the melt, the parameters of frequency, voltage, charge, and charging and discharging current were recorded to approximate the actuation.

To characterize the droplet, a camera system, which war already implemented in the machine, was used to record and measure the droplets. Features such as the diameter, velocity, trajectory, and satellite formation were be recorded in a measurement position, but not yet during printing. Figure 3 shows an exemplary image of droplet monitoring and measurement.

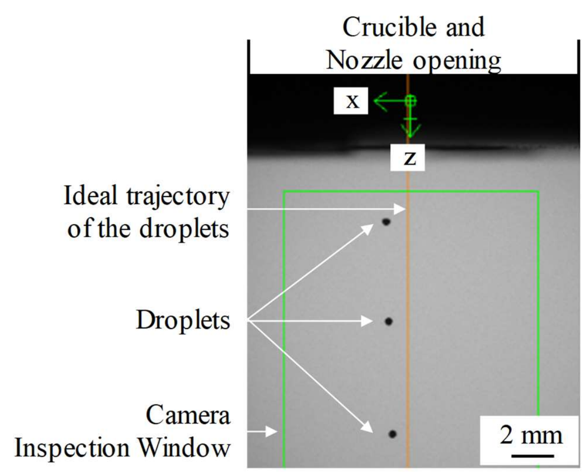


Figure 3: Recording of the droplets during accutation for quality control and measurement of the drop size and velocity.

In Table 2 the achieved droplet size and velocity are shown for the individual built jobs and actuation parameters. With the settings of the actuation parameters, stable droplets could be produced in the specified value ranges. In Figure 4 the droplet size and velocity are graphically shown for the individual build jobs. It is evident that the actuation parameters result in different, but stable droplet parameters. The initial droplet size (directly before printing) was between 505 µm up to 660 µm, with velocities between 1.3 m/s up to 2.5 m/s. So far, no clear correlation between the actuation parameters and the droplet parameters has been found. Further research is needed to understand how the actuation parameters relate to droplet size and velocity.

Table 2: Printing parameters and initially stable droplet parameters.

Built job	Droplet Size in µm	Droplet Velocity in m/s	Actuation Frequeny in hz	Actuation Voltage in V	Actuation Charging current in A	Actuation Discharge current in A	Actuation Charge in µC
1	525±6.8	1.5	160	190	3.8	-0.5	800
2	515±4.9	1.3	180	200	4.1	-0.7	950
3	640±7.3	1.6	170	150	3.6	-0.5	950
4	530±8.8	1.5	155	180	3.8	-0.4	850
5	630±2.4	1.3	150	150	3.4	-0.4	900
6	650±10.5	2.5	150	150	4.1	-0.3	900
7	660±18.4	2.4	150	150	3.8	-0.3	900
8	625±7.2	1.6	160	150	2.8	-0.5	950
9	600±4.0	1.6	150	150	3.9	-0.3	900
10	505±5.6	1.5	175	200	3.4	-0.4	1000

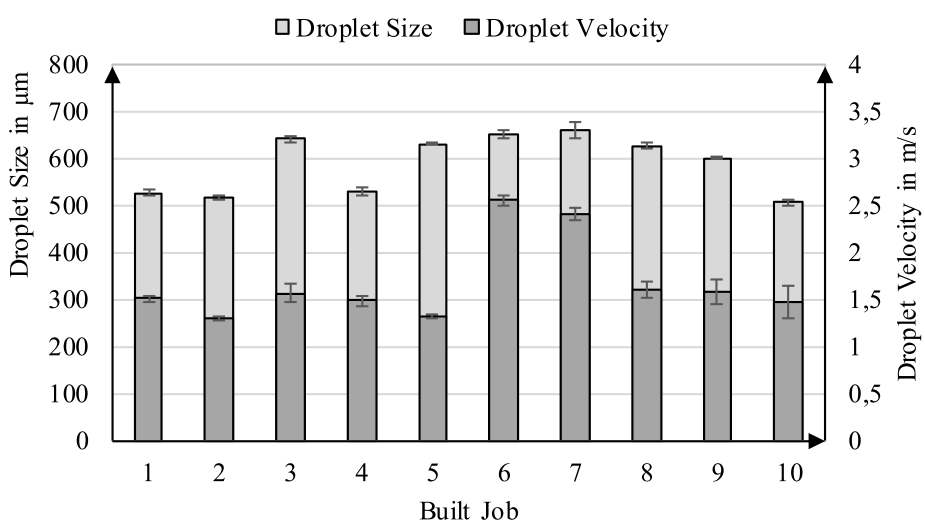


Figure 4: Achieved droplet size and velocity with actualtion parameters.

3.3. Part Quality

To determine the component quality achievable with the initial stable droplets, at least five test specimens are produced in both vertical and horizontal orientations. The distinction of the build direction serves to investigate the influence of orientation in the build process on component quality. It is assumed that vertically produced samples experience a greater temperature gradient than horizontally produced samples, as the build plane moves away from the build plate as a heat source with increasing component height. As a result, the component may exhibit inhomogeneity in its build direction in terms of its component and material properties. For example, increased pore formation and reduced component density as well as changes in the microstructure are conceivable. The test specimens were examined for their density due to micrographic images as well as static mechanical properties.

Figure 5 presents the results of the density measurements of the components across different build jobs in the vertical build direction. Figure 6 provides a comparative analysis of micrographs from two test specimens, which were sectioned for examination. The densities of all analyzed specimens ranged from 84 % to 99.9 %, with an average density of only 95 %. Notable differences in quality were observed between the lower and upper parts of the specimens. It is evident that the upper part of the test specimens often exhibits a significantly higher number of defects, leading to a lower overall density. This trend of an increasing number of defects in the upper region of the specimens may be associated with the greater build height and the increased distance from the build plate heating source. It was observed that droplet characteristics can change during the build process, which can lead to phenomena such as the formation of satellite droplets, corresponding to a reduction in overall density. Although droplet properties can be adjusted using actuation parameters, as previously demonstrated, a challenge remains due to the discrete nature of droplet measurement. By the time changes in droplet size, the presence of satellites, or velocity are detected, it is often too late to correct errors in already deposited layers. Consequently, defects arising from these deviations cannot be specifically corrected once they occur.

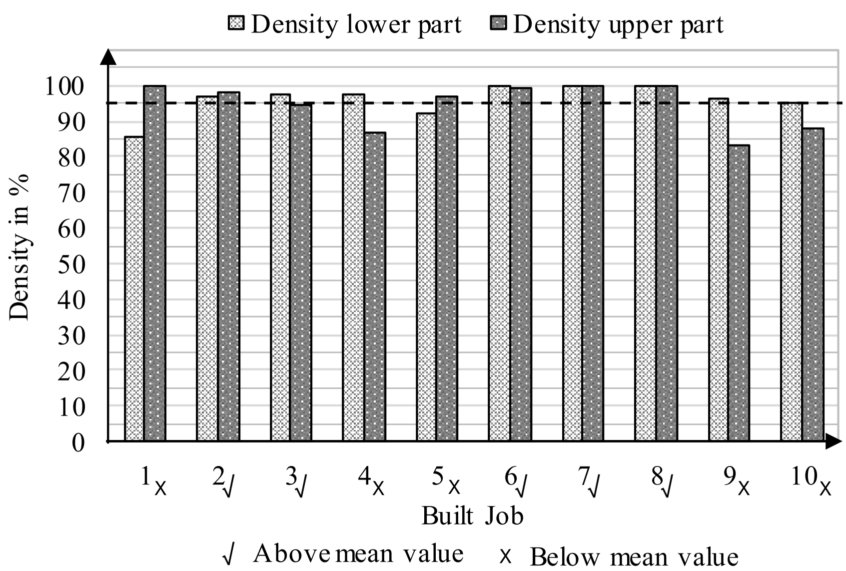


Figure 5: Comparison of the achieved density of the vertically built test specimens

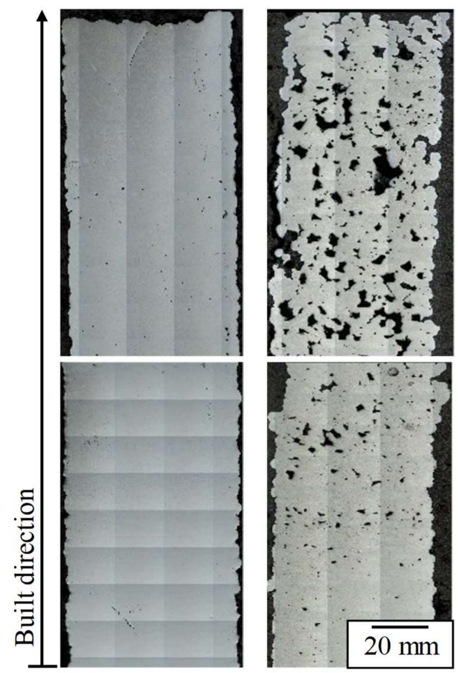
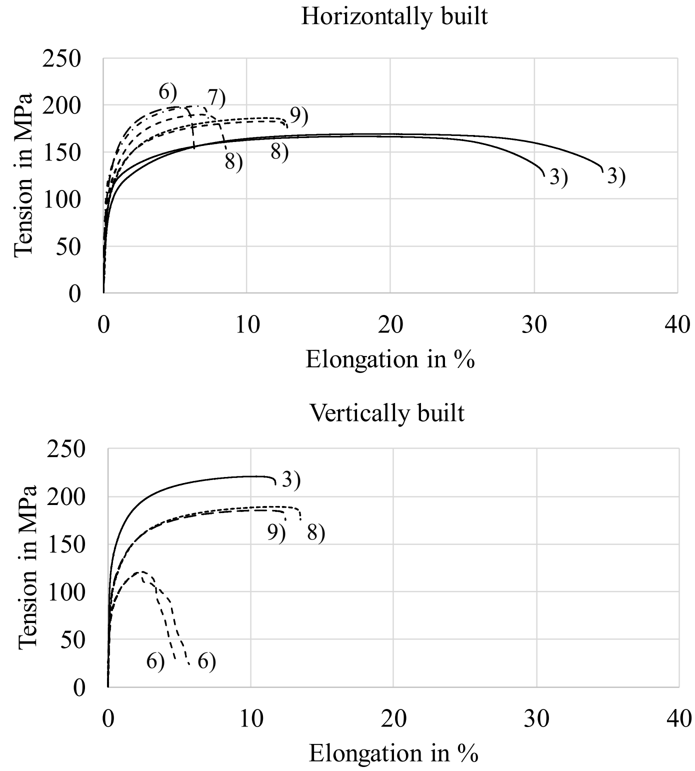


Figure 6: Micrographs of exemplary selected specimens, produced in a vertical orientation
Left: Built job 7, density upper part 99.9 %, lower part 99.7 %, droplet size 660±18.4 µm, droplet velocity 2.4 m/s
Right: Built job 4, density upper part 86.4 %, lower part 96.7 %, droplet size 530±8,8 µm, droplet velocity 1.5 m/s

This situation underscores the challenge of identifying the "sweet spot" in the process window to ensure consistent quality. The underlying reasons for and timing of droplet changes during printing are not yet fully understood and could be influenced by factors such as nozzle conditions, temperature fluctuations, or variations in inert gas composition. This leads to a first key objective for future research: achieving a constant and controllable process with monodisperse droplets for printing by carefully considering factors such as crucible temperature, actuation parameters, and droplet characteristics. To evaluate the static mechanical properties, samples were re-worked into tensile specimens and analyzed in their "as-built" state, without any surface milling or subsequent



BJ 3) Lower part 97.6 % | Upper part 94.4 % | 640 µm | 1.56 m/s
BJ 6) Lower part 99.9 % | Upper part 99.4 % | 650 µm | 2.55 m/s
BJ 7) Lower part 99.7 % | Upper part 99.9 % | 660 µm | 2.40 m/s
BJ 8) Lower part 99.9 % | Upper part 99.8 % | 625 µm | 1.57 m/s
BJ 9) Lower part 83.1 % | Upper part 96.4 % | 600 µm | 1.58 m/s

Figure 7: Results of the tensile tests

heat treatment. Out of 70 near-net-shape printed samples, only 23 % of horizontally printed samples and 16 % of vertically printed samples were successfully tested in tensile tests (see Figure 7).

Tensile testing was feasible only for samples with a density exceeding 95 %; most samples with densities below 95 % failed during processing, which precludes definitive conclusions about the mechanical properties since the evaluations was only possible in isolated cases. This issue is particularly significant for samples that were expected to have densities above 99.9 %, according to prior analysis. Indications of anisotropy and reduced strength were observed in vertically built samples. It can be determined that the literature strengths values for casted specimen of 150 MPa can be achieved sporadically with the printed samples [21]. Notably, the elongation at break of about 4–5 % is significantly higher than reported for EN AW-4047 in the literature [21]. As mentioned, the part temperature, which varies with the distance from the heat source and the build plate temperature, is expected to influence these results. The observed failures may also be attributed to the near-net-shape geometry and the reworking process. These findings lead to a second objective: achieving homogeneous material properties for high-quality parts, irrespective of geometry and orientation.

4. Conclusions and Expectations for Further Aluminum Alloys

In this study of the MMJ process with the aluminum alloy EN AW-4047 is demonstrated. Although there is still a large variance in the considered samples, which is due to the process not yet being fully robust. Several critical factors influencing process stability and material quality are observed, which lead to two main future objectives:

- Objective 1: To ensure a consistent and controllable MMJ process with monodisperse droplets, factors such as crucible temperature, actuation parameters, and droplet characteristics must be carefully managed.
- Objective 2: Achieving homogeneous material properties for high-quality parts, regardless of geometry and orientation, remains a key goal.

When transitioning the results with EN AW-4047 to other aluminum alloys, several factors, which are sometimes interlinked, are expected to play a critical role to achieve a constant and controllable process with monodisperse droplets:

Hardware and Environmental Conditions

- Nozzle Geometry and Material: The design and material of the nozzle, including factors such as diameter, orifice shape, and thermal properties, play a significant role in determining droplet size and flow rate, and in mitigating clogging tendencies [22].
- Substrate Material and Preheating: The choice of substrate and its preheating conditions affect droplet adhesion, spreading, and bonding quality. Mismatches in thermal expansion coefficients can cause warping or residual stresses
- Ambient factors: Such as temperature, humidity, and atmospheric composition can influence oxidation rates and process stability
- Cooling Rate and Solidification Behavior: The cooling rate impacts the microstructure and mechanical properties of the deposited material. Faster cooling can lead to finer microstructures, while slower cooling may result in defects such as cracks or pores
- Oxidation Control: The impact of oxidation at the nozzle orifice is likely to affect droplet quality. Effective measures to manage oxidation will be crucial for maintaining consistent droplet formation. Oxidation of aluminum and contamination from the environment or feedstock are significant concerns, as they affect flow behavior and part quality [23].

Ejection and Droplet Quality

- Droplet Velocity: The applied velocity is critical for achieving the desired droplet characteristics and deposition patterns [13].
- Viscosity and Surface Tension: The physical properties of the molten aluminum, including viscosity and surface tension, influence droplet stability and the wetting behavior on the substrate [10, 18, 19]
- Alloy Composition and Impurity Levels: The composition of the aluminum alloy, including alloying elements and impurity levels, impacts melting behavior and printability
- Alloy-Specific Properties: The choice of alloys such as EN AW-7075 or EN AW-6061, which have a solidification range rather than a eutectic point like EN AW-4047, may exhibit different melting behaviors and solidification characteristics, influencing both droplet quality and part properties

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