Development of a new method utilizing semi-solid aluminum wires for extrusion based additive manufacturing

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Abstract. In the field of additive manufacturing (AM) technologies, the development of metal-based extrusion processes constitutes a significant industrial trend in the recent years. Respective processes are differentiated into powder bed, powder-fed and wire-fed depending on the used feedstock. Among those, powder-fed AM represents the most widely used approach, despite its physical limitations leading to intense thermal gradients and an uncontrollable defective microstructure of produced parts. In this context, extrusion-based AM using a wire semi-finished product in the semi-solid state offers a novel alternative for the direct processing of metallic alloys, avoiding the limitations mentioned. For this reason, a new method for consecutive extrusion of semi-solid AlSiMg aluminum wires has been developed at the Institute for Metal Forming (IFU, Stuttgart, Germany), particularly investigating the influence of the material´s microstructure on the process result. By modifying microstructure via heat treatment, a specific modification of the rheological material behavior can be achieved in terms of a pronounced shear-thinning characteristic, thus systematically affecting extrusion and deposition. First, an experimental setup for continuously extruding semi-sold aluminum wires was realized. Subsequently, experimental investigations were carried out on the extrusion of aluminum wires prepared via the strain induced melt activated (SIMA) process as well as untreated aluminum wires, using a conductively heated printhead concept. The objective was to determine process parameters necessary for successful extrusion and deposition of the modified aluminum material as well as the final proof of concept regarding a specific transformation of the material´s microstructure during the extrusion process.

Introduction

Additive manufacturing (AM) represents one of the most rapidly advancing manufacturing technologies in recent decades and has a particular importance for various industrial sectors, for example in the field of product design, automotive engineering as well as aerospace and bio-medical technology [1,2]. In this context, especially AM of metals has become substantial for producing industries. The AM processes applied here are categorized according to the raw material and the energy source used. In terms of the raw material, a distinction is made between powder bed, powder-fed and wire-fed processes. The energy sources used to melt the raw material as rapidly as possible include electron beam, laser or electric arc [3]. However, such AM processes still suffer from a wide variety of technological disadvantages. Due to the high energy input during the production of metallic AM parts, for example, complex thermal gradients can occur in the workpiece's volumes, leading to defects such as porosity, lack of fusion, part distortion, cracks and delamination [4]. In addition, especially powder bed-based melting or sintering methods entail high production costs and a long process duration [5].

Against this background, recent studies in the field of Additive Manufacturing (AM) focus on the development of a wire fed semi-solid AM process route. Wire as feedstock offers some significant advantages based on the simpler process set up and higher deposition rate in contrast to powder resulting in a shorter process duration on the one hand and overall reduced equipment and production costs on the other hand [6]. The general process methodology based on wire as a feedstock involves heating the material into semi-solid state inside of the print head as well as a subsequent deposition in layers onto a print bed, similar to conventional fused deposition modeling (FDM) with plastics. Thereby, the direct processing of metallic alloys in the semi-solid state can be achieved through the specific control of the microstructure present in the material and therefore the resulting rheological behavior. The pronounced shear-thinning characteristic of semi-solid metals with a globular microstructure enabling the production of three-dimensional structures due to a low viscosity during extrusion and a dimensional stability of the deposited material [7].

Initial investigations in the field of semi-solid AM have been done in respect to the processing of low melting lead alloys, showing the general feasibility of this approach [8,9,10]. In the following, the semi-solid extrusion of magnesium alloy wires on a modified FDM-printer was discussed by Lima et al. [11]. Here, focus was put on the transformation of the feedstock material into the required globular microstructure within the print head. For aluminum alloys, first investigations using a conductively heated print head and an Al4018 welding wire were carried out by Herhold [12]. However, due to high friction as well as an inappropriate temperature distribution inside the print head, no satisfying results were obtained. Sharma et al [13] applied a modified print head design utilizing induction heating to temper an iron core and through conductive heat transport thereby the actual aluminum wire that is passed internally. This approach resulted in a steady state extrusion of a four-layer rectangular test piece made of Al5356 wire. Englert et al. [14] adapted the aforementioned inductive heating approach by equipping an extrusion nozzle with a modified induction coil. In the process, though, no cross-section reduction of the wire in the printhead has been implemented, and only continuous heating was realized. In this way, an Al4018 wire could be heated directly within the nozzle to subsequently produce cubic shaped parts. In both cases, however, interactions between the induced magnetic field and the print bed, the deposited part and other components of the machine assembly occurred.

In order to improve the semi-solid wire-fed AM process of aluminum alloys, a deeper understanding of the material behavior during the process is needed. Current state of the art focused on inductive heating of the wire, thereby successful extrusion could be investigated. However, due to the induced electro-magnetic field, interactions with the layered specimen as well as the machine parts could be observed. Additionally, in semi-solid forming normally a solidification pressure is needed, to produce a defect-free microstructure, which is difficult to apply with an inductive heating coil. In this paper the evaluation of viable process parameters for semi-solid additive manufacturing utilizing aluminum wire and a conductive heated print head design is presented, to eliminate the mentioned negative effects of the inductive heating approach. Thereby, an implementation of the specific transformation of the material´s microstructure into the extrusion process itself and the conductive heating design can reduce the overall process complexity, allowing a low-cost production approach.

Material and Methods

Raw material. When additive manufacturing is performed with semi-solid metal wires, particular attention must be paid to the liquid phase content of the material structure, as this crucially influences the continuous extrusion process. Here, low liquid phase contents result into increased extrusion forces and possible clogging of the nozzle, whereas high liquid phase contents enhance the formation of droplets at the nozzle opening. The formation or presence of droplets during extrusion has been referred to as an undesirable factor by several authors [8,12,13] resulting in a reduced accuracy of the manufactured parts. Due to the strong correlation between the processing temperature or rather the liquid phase content associated therewith and the resulting material´s flow behavior, selection of a suitable aluminum alloy is a key issue. In this regard, suitable metal alloys for semi-solid metal forming processes usually offer following properties:

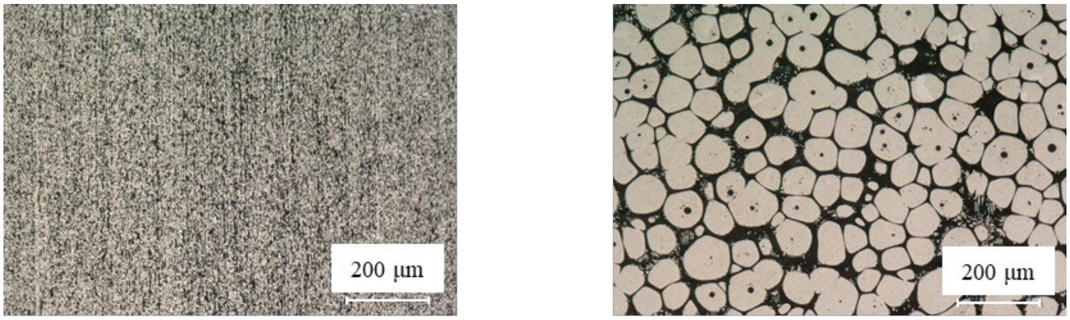
1. Solidification range (ΔT), defined as the temperature range between solidus and liquidus temperature, should found as extended as possible. Here, a range between 20 and 130 °C is recommended. [15]
2. Temperature sensitivity of solid phase content ($-d\varphi s/dT$), which indicates the change in solid phase content per temperature unit for a specific alloy composition, should not exceed 0.015 [16]. Thus, in general a 1.5 % change in solid phase content of the melt is permissible for every 1 °C change in temperature. [15]
3. Processing temperature specifies the temperature interval in which the required solid phase content of 0,4-0,7 for the respective semi-solid processing procedure is present. [17]
4. Globular microstructure leads to shear-thinning material behavior and is therefore a mandatory requirement for semi-solid forming processes. [18]

Based on the alloy-specific requirements described above, an Al4018 welding wire from Drahtwerk Elisental W. Erdmann GmbH & Co. [19] has been chosen as raw material for the investigations presented in this paper. Table 1 shows the chemical composition of the material used, according to Drahtwerk Elisental W. Erdmann GmbH & Co. [19] and its thermophysical properties in accordance to the above-mentioned selection criteria.

Table 1. Chemical composition of Al4018 welding wire in wt.% [19] and its thermophysical properties [20].

Si	Fe	Cu	Mn	Mg	Zn	Ti	Al
7,19	0,14	0,00	0,00	0,6	0,00	0,02	Base
ΔT = 65 °C			$-d\varphi s/dT = 0.004$			processing temperature = 565-595°C	

Fig. 1a) shows the microstructure of the wire material used, which is characterized by an enclosed silicon phase (dark) in an α-Al phase (bright). This cold worked microstructure is transformed to the necessary globular microstructure in the aluminum welding wire through heating into the semi-solid state as a sub step of the strain induced melt activated (SIMA) process [21]. In the present case of processing given Al4018 wire, a cross-section reduction of 44 % was performed in the last drawing stage, which means that the threshold value of 30% specified by Loué and Suéry [22] has been exceeded and a sufficiently high cold forming ratio with regard to optimal SIMA process requirements is reached. For heat treatment a convection oven was used to heat up the sample to a temperature of 575°C for a period of 15 minutes. In general, thixoforming operations require a solid phase content of 0,4-0,7 [17]. Therefore, within the corresponding temperature range for the present alloy (approximately 565-595°C), isothermal holding at 575°C has been chosen [20]. After heat treatment the aluminum filament was quenched in water. Fig.1b) illustrates the resulting microstructure, consisting of globular α-Al grains embedded in eutectic phase (intergranular) and eutectic phase enclosed within solid grains (intragranular).

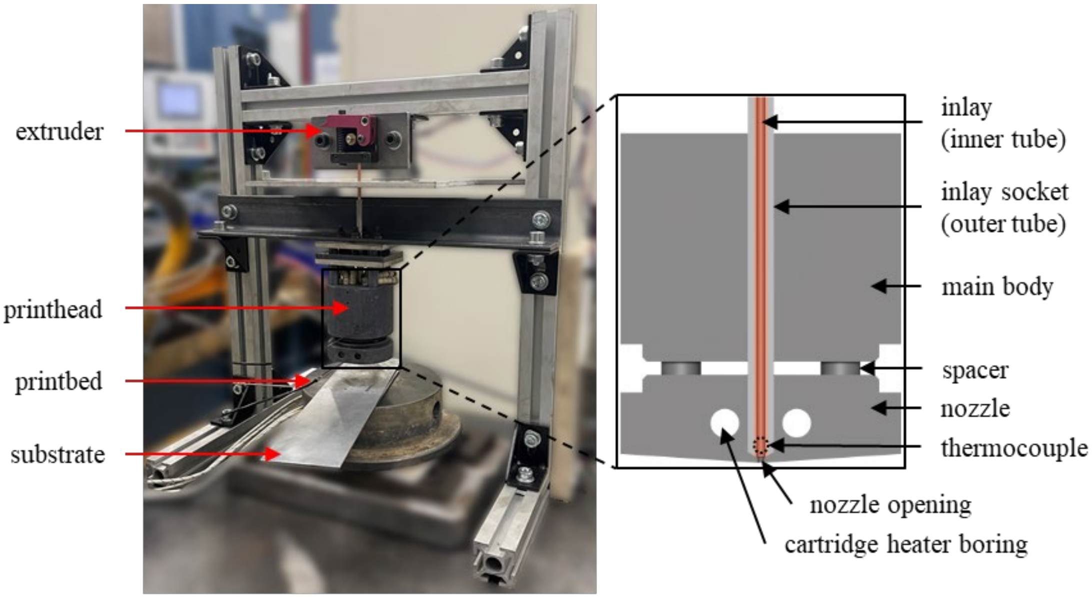


a) b)

Fig. 1. Microstructure of the utilized Al4018 welding wire as is a) and after heat treatment b).

As an evaluation criterion to determine suitability of the generated microstructure for semi-solid additive manufacturing, grain size and grain shape were calculated using the image analysis software Fiji. Perfect globular grains feature a shape factor of unity. In general, a globular microstructure that is suitable for semi-solid forming is considered to feature a shape factor between 0.6 and 1 and a grain size smaller than 100 µm [23]. Compared directly, the microstructure produced in the filament material by heat treatment with the chosen parameter combination has an average grain size of 71 µm and a shape factor of 0.75 and is therefore within the stated limits. The heat-treated welding wire with a globular microstructure is utilized for extrusion and deposition studies in the course of semi-solid additive manufacturing.

Additive manufacturing setup. A prototype 3D-printer equipped with wire-feed and conduction heating devices was developed and built up for the present study. This AM setup consists of custom as well as commercially available components. Fig. 2 shows the setup used on the left and a schematic illustration of the printhead cross section on the right.



a) b)

Fig. 2. Photograph of the additive manufacturing setup used a) and CAD rendering of the printhead cross section b).

The general design of the printhead includes a modular setup consisting of a main body and a nozzle separated by spacers. These spacers, between nozzle and main body, allow for thermal decoupling of these components from each other through the resulting air gap whereby a large temperature gradient as well as separate heating of the two components can be realized. The guidance inside the printhead has been designed with an exchangeable inlay, allowing guide sleeves from different materials and with different diameters to be investigated. A conventional pinch roller extruder, which is usually applied for FDM with plastics, is used for wire feeding. The extruder is driven by a stepper motor, whose speed and thus the wire feed rate is controlled through the open source software *Estlcam*. For tempering the nozzle, conventional cylindrical cartridge heaters with an electrical power of 200 watts are inserted in appropriately prepared mounting holes. Control of the heating cartridges and thus of the temperature distribution within the nozzle is performed via a control unit. Thereby, current nozzle temperature can be measured by means of a thermocouple (Type J) integrated into the printhead and connected to the control unit.

For extrusion objectives, the aluminum wire having a diameter of 2 mm and a section length of 1 m is first supplied to the pinch roller extruder. After leaving the extruder, the Inlay guides the wire until its heating into semi-solid state inside the nozzle and its subsequent extrusion through the nozzle opening. For the final deposition of the semi-solid aluminum, a heated print bed is used on which an additional 2 mm thick aluminum sheet is placed serving as a substrate. The relative movement of the substrate to the print head is performed manually. Entire extrusion and deposition of the semi-solid aluminum wire takes place without inert gas atmosphere.

Experimental procedure. The aim of the investigations presented in this paper was to produce primitive samples with a simple geometry using the principle of semi-solid AM to demonstrate the fundamental feasibility of the project at hand. These samples should feature a homogeneous microstructure without defects and metallurgical joint between the layers. For this purpose, the extrudability of the heat-treated welding wires having a globular material structure was first investigated using the AM setup described above. During these investigations, numerous process parameters were changed according to Table 2 in order to initially demonstrate feasibility of the semi-solid AM process and afterwards to determine its ideal parameter combinations.

Table 2. Parameter variation extrusion trials.

Experimental parameter			
Wire material	heat-treated (575°C, 15 min)		
Material of Inlay	stainless steel	copper	brass
Inner diameter of Inlay [mm]	Ø 2,1	Ø 2,4	
Nozzle temperature [°C]	565-630 (gradual increase in 5°C steps starting with 565°C)		
Main body temperature [°C]	540	560	

Due to the modular concept of the printhead, especially the influence of different materials and variations of the inner diameter of the inlay on the extrusion process could be investigated during the experiments. Here, copper, brass and stainless steel with internal diameters of 2.1 mm and 2.4 mm were analyzed. The inlay socket was made from stainless steel in all tests conducted and provided secure seating for the inlay inside the printhead as well as its reinforcement due to low wall thickness. Regarding the temperature distribution in the printhead, a constant main body temperature was maintained in all tests, while the nozzle was heated in 5°C increments, starting at 565°C. The starting temperature of 565°C at the nozzle corresponds to the required processing temperature range for the considered aluminum alloy in the semi-solid state, which is between

565°C – 595°C. The feed rate was set to 1 mm/s, corresponding to an approximate deposition rate of 3,1 mm^3/s, in all experiments carried out. The quality of the final extrusion samples was evaluated on the basis of the external appearance and microstructural analysis. For this purpose, a digital light microscope with a maximum magnification of 5000x was used. The preparation of the samples involved mechanical sanding and polishing followed by etching of the sections with 5 % NaOH solution for 60 s. Finally, a transfer of the ideal process parameters found, was performed to the processing of untreated welding wire. The objective behind this approach was the implementation of the necessary microstructural transformation into the extrusion itself and therefore eliminate the additional step of heat treatment.

Results and Discussion

Based on the experimental results obtained, the influence of, on the one hand, the design of the guidance (inlay) and, on the other hand, the printhead temperature control on the extrusion quality were evaluated. With regard to the guidance, the tests performed showed extrusion of the aluminum wire with an inner diameter of 2.1 mm rather than 2,4 mm. This is due to the fact that the bigger inner diameter results in a larger air gap between the tube wall and the wire having a diameter of 2 mm, leading to a significantly lower heat transfer. Actually, no melting and thus no extrusion of the aluminum welding wire was observed with the inlay variant having a diameter of 2.4 mm. Because of this, further investigations on the guidance material were only carried out using the inner diameter of 2.1 mm.

In the examinations on suitable materials for the guidance, stainless steel, copper and brass were investigated in combination with the temperature settings for nozzle and main body listed in Table 2. When combining brass as material for the inlay and a nozzle temperature of 590°C, as well as both main body temperatures listed in Table 2, continuous extrusion could be achieved. However, a more detailed analysis of the nozzle cross-section after the performed tests revealed the positioning of the melting zone located near the contact area between aluminum wire and extrusion shoulder, the entire brass inlay had been disintegrated (see Fig. 3). This disintegration of the brass guidance can be attributed to diffusion of alloying elements into the semi-solid aluminum in combination with subsequent mechanical abrasion. Therefore, a brass inlay is not suitable for the semi-solid AM process in terms of a reliable process control.

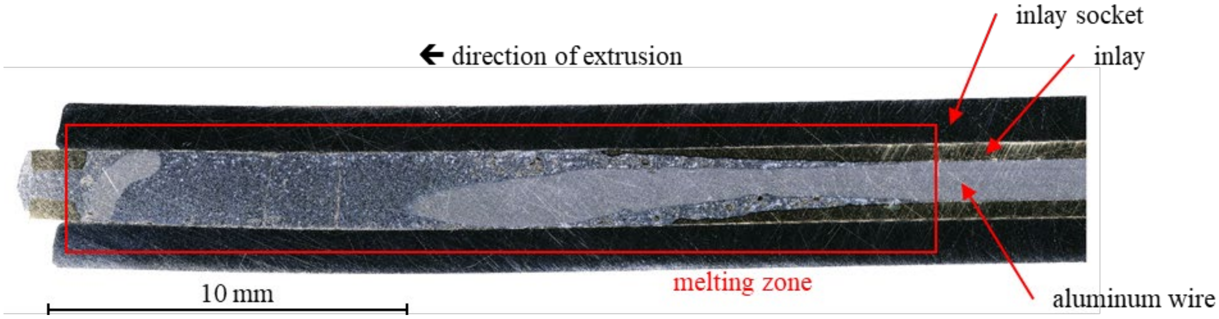


Fig. 3. Cross section of the inlay (brass) and inlay socket (stainless steel) with melted aluminum.

For stainless steel and copper as inlay materials, melting of the aluminum wire could be observed for a nozzle temperature of 590°C due to the formation of droplets at the nozzle opening, but no further extrusion. This can be attributed to the friction between the guidance and the semi-solid aluminum alloy itself, which prevented extrusion. However, by increasing the nozzle temperature up to 615°C in the case of stainless steel and 625°C for copper and simultaneously turning off active heating of the printhead main body, extrusion of the semi-solid aluminum gets feasible. The applied heating strategy relocated the melting zone closer to the extrusion shoulder and also decreased its dimensions. As a result, this led to reduced friction between guidance and wire, thus enabling extrusion.

The above described methodology for the extrusion of heat-treated wire also led to successful extrusion of untreated aluminum wires. Regarding this, Fig. 4 shows respective cross-sections of nozzles with a) stainless steel and b) copper as guiding material. The stainless-steel inlay reveals a gradual melting and simultaneous transformation of the untreated aluminum wire over a length of ~4,9 mm. The copper inlay, on the other hand, shows a significantly shorter melting and transformation zone, which is exclusively present at the immediate extrusion shoulder and nozzle opening. During the extrusion tests, the significantly larger melting zone within the stainless-steel inlay implied higher friction between the semi-solid aluminum and the guidance causing an increased force demand for the extrusion process in comparison to the copper inlay. Furthermore, when using the stainless-steel inlay, a nozzle temperature reduced by 10°C compared to the copper inlay had to be used in order to restrict the formation of the melting zone. Without reducing the nozzle temperature applied in the case of the steel inlay, no extrusion has been achieved using the extruder applied in the present study, since the required feeding force clearly exceeded the available capacities of the stepper motor. Even with an adapted temperature profile, steady-state extrusion was only present to a certain degree while using the stainless-steel inlay, as the force provided by the extruder was partially insufficient due to stick and slip effects and stagnation of the wire feed occurred. For the copper inlay, the forces required during the process to extrude the semi-solid aluminum did never exceed the extruder's capacity due to the already explained comparatively small melting zone (see Fig. 4).

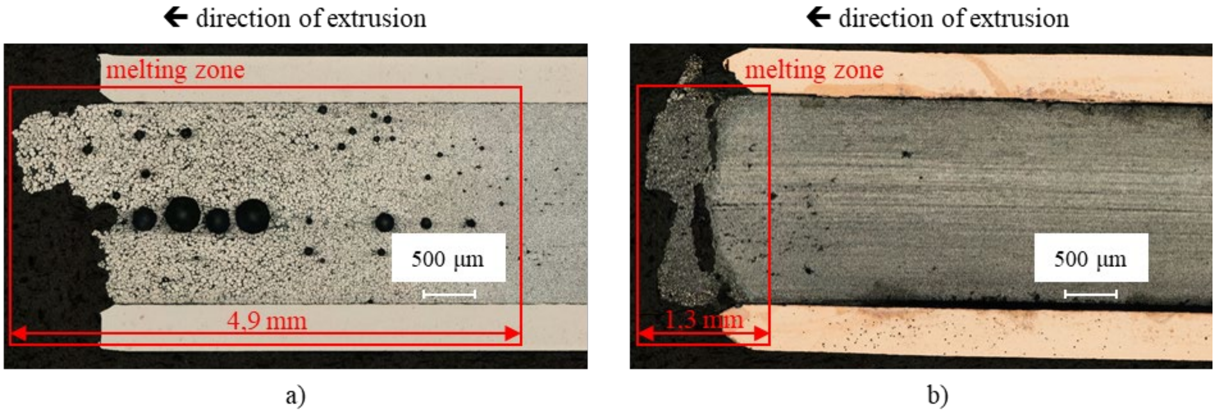


Fig. 4. Nozzle cross section with stainless steel a) and copper inlay b).

Table 3 shows the parameter combinations determined in the course of the extrusion studies providing a suitable operating window for steady state extrusion of aluminum welding wires.

Table 3. Best parameter combinations for extrusion and deposition.

Material Inlay 1	Inner diameter Inlay 1 [mm]	Temperatur nozzle [°C]	Temperature main body [°C]	Wire material
stainless steel	2,1	615	not heated	heat-treated, untreated
copper	2,1	625	not heated	heat-treated, untreated

Fig. 5 presents the resulting microstructure of fully extruded samples from untreated welding wires. In both cases, it can be seen that a complete transformed microstructure consisting of globular α-Al-grains embedded in an eutectic matrix is present. The smaller average grain size in the sample extruded with the copper inlay is attributed to the shorter holding time of the material in the semi-solid state caused by the reduced melting zone. This fact also contributes to the considerably finer porosity, since the coalescence occurring in the semi-solid state with advancing holding time leads to coarsening of pores. Both of the presented grain sizes are sufficiently small for semi-solid extrusion however the smaller grain size produced through extrusion with the copper inlay is generally considered a beneficial factor and has a positive effect on the extrudability of the semi-solid aluminum.

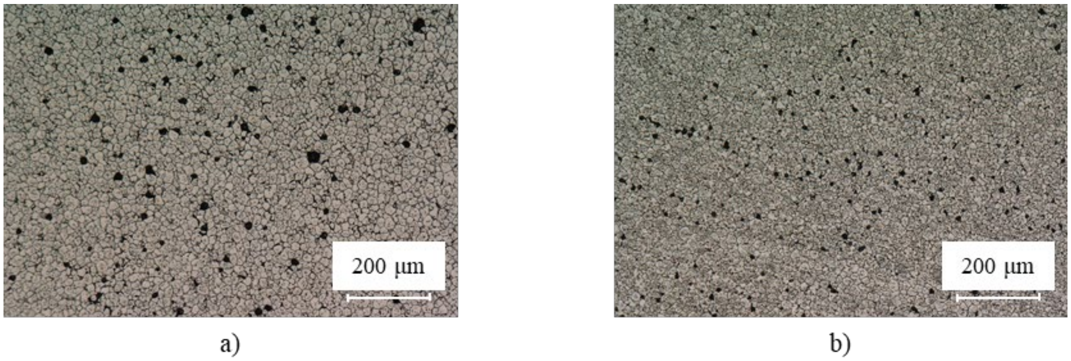


Fig. 5. Microstructure of extruded untreated aluminum wires with a) stainless-steel and b) copper inlay.

The manufacturing of a basic specimen took place using an untreated aluminum welding wire with the copper inlay as well as the corresponding process parameters listed in Table 3. Fig. 6a) shows the sample after extrusion and deposition of the semi-solid aluminum using the ideal process parameter combination. During the trials, a heated print bed with temperatures between 550-600°C was needed in order to achieve a good bonding of the layers. This can be attributed to the semi-solid state of both the already deposited and the just extruded aluminum, that enables an interface-free bonding of the two layers shown in Fig. 6b). The porosity described above is also found in the extruded specimen and can be classified as a defect in the material indicated by intergranular pores.

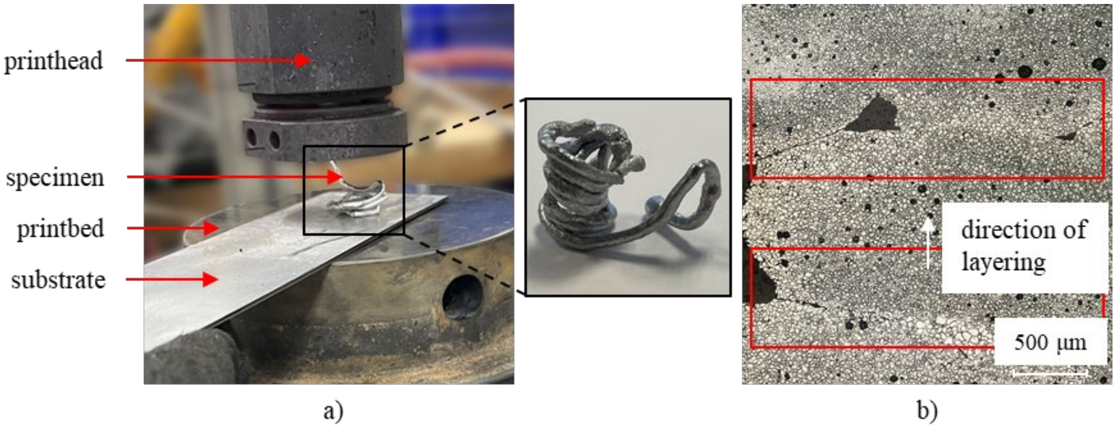


Fig. 6. Experimental procedure and specimen manufactured a), microstructural analysis of the specimen b).

Summary

In the present study, a novel manufacturing method has been presented enabling semi-solid additive manufacturing of aluminum wire utilizing a conductively heated printhead design. This also involved the fabrication of basic specimens by using a heated print bed as well as a manually moved aluminum substrate (6000 series) with a deposition rate of up to 3.1 mm^3/s. Thereby the required microstructural transformation of the untreated aluminum wire took place during heating inside the printhead, eliminating the need for an additional heat treatment. In the course of the experimental evaluation, three different inlay materials as well as variations of the inner diameter were tested. For 2.4 mm as an inner diameter no melting or extrusion could be observed due to an excessive air gap and therefore poor heat transfer between guidance and aluminum wire. With brass as guidance, disintegration of the inlay material occurred in the melting zone, while stainless steel led to stagnant extrusion caused by a large melting zone resulting in high friction along with stick-and-slip effects. Copper with an inner diameter of 2.1 mm was found to be the most suitable choice and consequently has been applied for the fabrication of simple specimens featuring a partial interface-free bonding of consecutive layers. However, the extruded material also exhibited defects in form of porosity.

In future studies, a dedicated machine setup will be developed, which enables a controlled movement of the print bed in x-, y- and z-direction at a pre-defined speed. In addition, a reworked printhead concept including a heat sink will be implemented in the system in order to be able to influence the dimensions of the melting zone.

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