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A New Approach For A Flexible Powder Production For Additive Manufacturing

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Abstract

The technology of Additive Manufacturing (AM) is an enabler for more eco-friendly lightweight aircraft parts due to the possibility to use the freedom of design. Since the process of laser beam melting is powder bed based, there is a huge influence of the powder quality on the building process. The most common process for the AM powder production is the inert gas atomization based on molten material. There are different process types which are mainly used for a large scale powder production. In order to analyze new or expensive alloys for the AM process, small and flexible atomization plants to produce smaller amounts of powder are needed.

This work summarizes the required powder properties for aluminum alloys as well as the different suitable atomization processes. Current challenges concerning AM powder quality will be described and a new atomization plant concept for high-grade powder in small quantities, based on the process of thermal spraying, will be introduced.

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Keywords: additive manufacturing; powder; atomization; thermal spraying

Nomenclature

AM	additive manufacturing
SEM	scanning electron microscope

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1. Introduction

The transport volume in aviation is forecast to increase by 45 % between 2014 and 2035 [1]. In order to reduce the greenhouse gas emission, the efficiency of airplanes has to be increased. One option is to reduce the mass by lightweight constructions. This offers the possibility to carry more load with the same CO_2 emission or the same load with a lower CO_2 emission. Another possibility, besides the use of composite materials, is the implementation of topology optimized structural components. These complex geometries are more frequently produced by additive manufacturing (AM). The most common technology is the powder bed based laser beam melting due to the high freedom of design and the application of aviation relevant metallic materials like titanium, aluminum for structural components and high performance nickel-base alloys for engine parts (e. g. Inconel® Alloy 718). Since aluminum alloys are very common in aerospace industries, in particular in combination with alloying elements like silicon, due to their high specific strength [2], hardness [3] and at the same time light weight, the focus of this paper will be on laser beam melting of aluminum alloys. By the usage of AM and the associated topology optimization, part weight, e. g. of a fuel nozzle or a bracket, can be reduced by about 25 % or 54 % compared to the conventionally manufactured part [4,5]. It is estimated, that the aircraft basic weight could be reduced by 4 to 7 % by replacing conventionally parts with AM optimized lightweight components [6]. In particular aluminum alloy components have the highest mass reduction potential [6]. Besides the weight savings, assembly efforts could be decreased by functional integration and part consolidation. An exemplary traditional fuel nozzle consists of 18 individual parts. After design optimization, it can be manufactured in one piece [4].

2. Aluminum powder production for additive manufacturing

The possibilities to produce function integrated parts and one piece solutions instead of assemblies, are due to the layer wise build up of the additive manufacturing process. A laser beam melts up a thin powder layer on a building platform. This powder layer is usually 20 to 60 µm thick, in dependence of the required part quality and the affordable process time [7]. The eligible process parameters must be well adapted to the relevant material. Otherwise, objectionable effects such as a lack of fusion, balling, high porosity [8] and evaporation of alloying elements may occur [9]. Especially for aerospace industries, reliable processes are mandatory. Besides the influence of the process parameters, the initial powder material has an important influence on the resulting part and its surface finish and becomes increasingly important [10,11]. Due to this strong influence, the AM process cannot only be viewed separately, but upstream process steps, e. g. powder production, powder handling and transport, have to be considered.

Aluminum alloys have, compared to stainless steel, a higher reflectivity for laser radiation and a higher thermal conductivity, which makes process improvements more complicated [12]. In order to increase the build rate, a higher scan velocity and thus a higher laser power is necessary [13]. Furthermore, spherically shaped particles are recommended because they are beneficial for flowability and are more likely to result in a uniform powder bed [14].

A variation of the particle size will lead to a different distribution and packing density in the powder bed which influences the heat balance and affects the part density [15,16]. Oxide formations on the particles may result in oxide residues in the part since aluminum oxide has a higher melting temperature than pure aluminum [17]. The upper oxide film of the melt pool evaporates under the laser beam, the oxide films below remain intact or are disrupted by Marangoni forces that stir the melt pool [17]. A different effect is the explosion of the oxide layer due to the thermal gradient and the thermal expansion between the aluminum and the oxide layer [18]. The hydrogen content of the powder can produce hydrogen pores, if the melt pool solidifies faster than the gas evaporates [19].

Table 1 summarizes the influences of the powder particles and possible defects during the AM build up process and in the manufactured part. This information emphasizes the need for high quality powders and reliable processes for powder handling-, storage- and transport-conditions. The impact of the powder quality and the question of how much variation can be tolerated in the powder bed are areas of research [20].

Table 1. Powder characteristics and their influences on the additive manufacturing process

Powder characteristics	Description	Influence on process and part
particle size distribution	maximum particle size determines minimal powder layer thickness [16] balanced particle size distribution has a positive effect on packing density (small particles fill in small voids) [15,21] and powder compactibility [22] small particles are light and get easily thrown out of the process zone, furthermore due to their surface to volume ratio they are more likely to inflame or explode if making contact to reactive gas [16] small particle size and narrow particle size distribution leads to uniformity in the melt pool, and results in a higher part density [15,16,21] powder bed density influences the resulting heat transportation and thus the heat balance [16]	Process: minimal powder layer thickness, heat balance of the powder bed, consistency in melt pool, packing density, compactibility, spatter Part: density
flowability	affects the layer deposition and layer quality (e. g. homogeneous layers) [12,23]	Process: layer deposition
reflectivity, absorptivity	laser energy is absorbed (absorptivity) or reflected in the process chamber (reflectivity) by the powder bed [16] absorptivity of a powder depends on the wavelength of the laser and the condition of the powder bed [16] high reflectivity of the powder bed (> 91 % for aluminum) requires an increase in laser power [17,24,25]	Process: variations in energy input, required laser power and wavelength
thermal conductivity	high thermal conductivity increases the required laser power [24,25], this leads to a rapid dissipation of heat away from the melt pool [17]	Process: required laser power, melt pool temperature
oxidation	oxides form during the process (oxygen level 0.1 to 0.2 %) [17] theory: most predominant factor controlling the flowability is the amount of surface oxides on particle surface [26] rupture of the oxide layer of small powder particles is more difficult [27]	Process: obstacle for effective melting, adherent thin oxide films on molten Aluminum reduce wettability, powder flowability Part: entrapped oxide: region of weakness
humidity, hydrogen	single or multiple molecular layers can form on the particle surface, leading to hydrogen bonding [28,29] increased interparticular forces lead to a decrease in flowability [21,29,30] and the metal microstructure of the part [15] on the particle surface and in the powder material can lead to hydrogen porosity [19]	Process: powder flowability Part: metal microstructure, hydrogen pores
particle shape, morphology	typical powder defects are irregular shapes e. g. elongated particles, satellites, hollow or porous particles [14] affects flowability [21], spherical particle morphology is beneficial for powder flowability and helps to form uniform powder layers [14] excessive amounts of large pores or pores with entrapped gas can affect material properties [14] stacking density is a function of the powder morphology [16] surface roughness affects the absorptivity [16]	Process: layer deposition, absorptivity Part: material properties

Additive manufacturing is very demanding on the powder properties, especially for the manufacturing of aluminum based parts for the aerospace industry. Contaminations e. g. high fractions of aluminum oxide, potential residues of ceramic material from the crucible or other foreign material during the powder production, reduce the material properties of the part, e. g. strength, fatigue performance and ductility, significantly [18].

Metal powder material is typically produced in one of the following four ways: chemically, through electrolysis, mechanically or through atomization [30]. Powders for additive manufacturing are most commonly produced using gas atomization in an inert gas atmosphere. A high energy flow of gas atomizes the liquid metal upon impact [31]. The atomized liquid metal forms into spherical droplets and turns solid when cooling below the melting temperature. The solid particles are screened and sorted by their size. For reactive materials (e. g. aluminum) atomization and packaging is performed in a protective atmosphere. In all known processes for the production of aluminum powder, inert gas is used to preserve the spherical shape of the particles. Atomization in air leads to an immediate partial oxidation of the liquid material and prevents the liquid metal from transforming into spherical shape [32] making the powder unsuitable for additive manufacturing processes.

Atomization processes can be grouped by the method of melting the material, with or without the use of a crucible (Fig. 1), and by the type and geometry of the nozzle used (Fig. 2). When the material is melted in a crucible, inductive heating or a plasma torch are used. Subsequently, the melt is led through the nozzle into the atomization chamber.

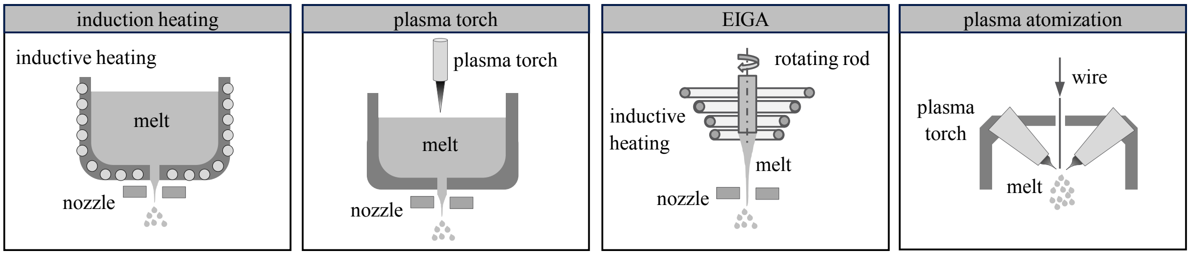

Fig. 1. Melting mechanisms for gas atomization [33–35]

The most common atomizer types are the free fall nozzle, the close coupled nozzle and the De Laval nozzle (Fig. 2). In the free fall nozzle, gravitation drives the melt into the atomization chamber, where it is atomized. The limited flow rate of the melt is a major disadvantage of the free fall nozzle. The diameters of the particles are typically higher than 50 µm [36], which is too large for additive manufacturing processes. In a closed coupled nozzle the atomization gas pulls the melt from the nozzle. In this configuration, the melt flow can be adjusted through a change in the atomization gas flow. In comparison to the free fall nozzle process, significantly higher flow rates and smaller particle sizes of approximately 10 µm [36] can be achieved.

In the De Laval nozzle a laminar gas flow is accelerated to supersonic speed [36]. Compared to the close coupled nozzle atomizer type, less gas is needed [36] and the resulting particle diameter is typically between 15 and 45 µm [37] with a narrow distribution of the particle diameter. A disadvantage of the free fall nozzle and the close couple nozzle is the possibility that a freezing of the melt inside the nozzle can occur and the process aborts.

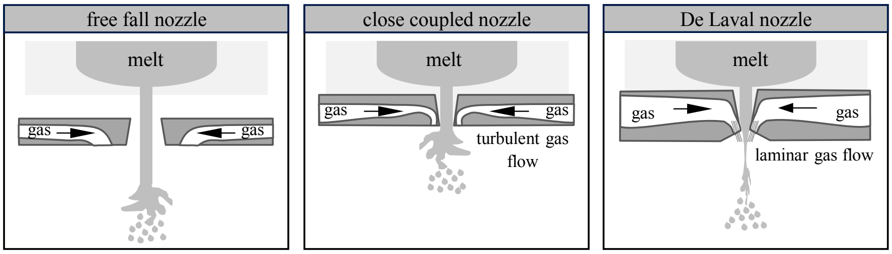

Fig. 2. Common gas atomization nozzle designs [36,38]

In the EIGA (Electrode Induction Melting Gas Atomization) process and in the plasma atomization process (Fig. 1) the material is not melted in a crucible and therefore contaminations by ceramic material or remains of foreign material from earlier process batches should not arise [39]. In the EIGA process, the metal is melted from an induction heated rod, from which the liquid metal drops into the atomization nozzle without any contact to the surrounding parts [34]. Despite the absence of a crucible in the EIGA process, Yablokova et al. describe a contamination of powder with residues from the previously atomized material [40]. In the plasma atomization process, a wire with a diameter of 3 mm is melted using three plasma torches [34], and directly atomized, using the heat and kinetic energy of the plasma. From this process, particles from 5 to 250 µm [39] with a particularly spherical shape are obtained.

Special AM applications demand for high and constant quality powders in relatively small amounts. Aerospace applications are especially demanding, not only on the powder quality, but also on transparency of processes and supply chains as well as storage condition monitoring. Current large powder production plants are optimized for high output of standard material, e. g. up to 300 kg per batch and also require lots of space. Common dimensions of such plants are 4.5 m in height and 1.5 m in diameter [41]. For the demand oriented production of powder from new tailored alloys, small but flexible powder atomization plants are needed. These smaller machines could be placed close to the respective additive manufacturing machine, allowing for quick reaction and short ways when new alloys for improved properties in the additive manufacturing process and the final part are developed.

3. A new approach based on thermal spraying

The process of thermal spraying is similar to the gas atomization process, due to the use of a gas flow for melt atomization, but it is more compact. Molten materials are dispersed on to a surface for coating. There are many process variations, which are listed in DIN EN 657:2005-06 e. g. according to their energy sources or spraying consumables [42]. Considering thermal efficiency, ease of maintenance, material and equipment costs, the process which is most preferable for the powder production is arc spraying. Arc Spraying is a wire based process which transfers the heat of the arc directly into the material [43]. In order to get the same temperature at anode and cathode, recent developments use fast commutating alternating current so that there are almost constant spatter sizes [44]. The particle velocity and the process temperature are lower compared to plasma spraying and reach about 3700 to 4700 °C and 100 to 150 m/s, depending on the process parameters. The coating performance is for aluminum about 6 to 8 kg per hour [45]. Comparing the properties of the arc spray process to the derived requirements of the AM powder, it can be assumed, that arc spraying is suitable for small volume AM powder production.

For a better understanding of the process of arc spraying for powder production, preliminary experiments were carried out. Samples were investigated using laser microscopy and scanning electron microscopy (SEM). Spraying was performed by a TAFA CoArc 9910 console in combination with an arc spray gun Model 9935. Aluminum alloy $AlSi_5Mg$ with a wire diameter of 1.6 mm was processed with common spray parameters for coatings, consisting of a voltage of 28 V, an amperage of 100 A, and a process gas pressure of 0.28 MPa (40 psi). In order to produce particles for AM, an adaption of the spray parameters is necessary. According to the conclusions of Krebs [46], the usage of low voltage, low amperage and a high process gas pressure generally lead the way to the production of small particle sizes under 63 µm, which are favorable for AM.

In the experiments conducted, compressed air ($O_2 \approx 21$ vol.-%) and Argon 4.6 ($O_2 \leq 4*10^{-4}$ vol.-%) [47] were used as atomizer medium. Spraying was performed into a thermal spray cabin and powder samples were collected directly out of the spray cone and sieved to the relevant size fraction ≤ 63 µm. When it comes to principal suitability of the produced powder for AM, the influences of the process gas are especially important. Fig. 3 (left side) shows SEM images of particles produced by the use of air and argon as atomization medium. An irregular particle shape of the air-sprayed powder can clearly be seen. The Argon-sprayed powder particles, however, show a more spheroidal shape. Occasionally rounded oblong (nodular) particles are present. The particle surface is considerably smother. The micro section images of the probes in Fig. 3 (right side) show a highly refined microstructure with a fine dispersed silicon phase at the grain boundaries. The formation of such fine microstructures, which is comparable to the one of industrial inert gas atomized particles, is supported by high cooling rates of the molten particles with cooling rates of 10^3 to

10^5 K/s [39,48]. Air sprayed particles show lots of two-dimensional and punctual structural defects. Argon sprayed particles, shown in Fig. 3 (right side), contain fewer punctual and no two-dimensional defects.

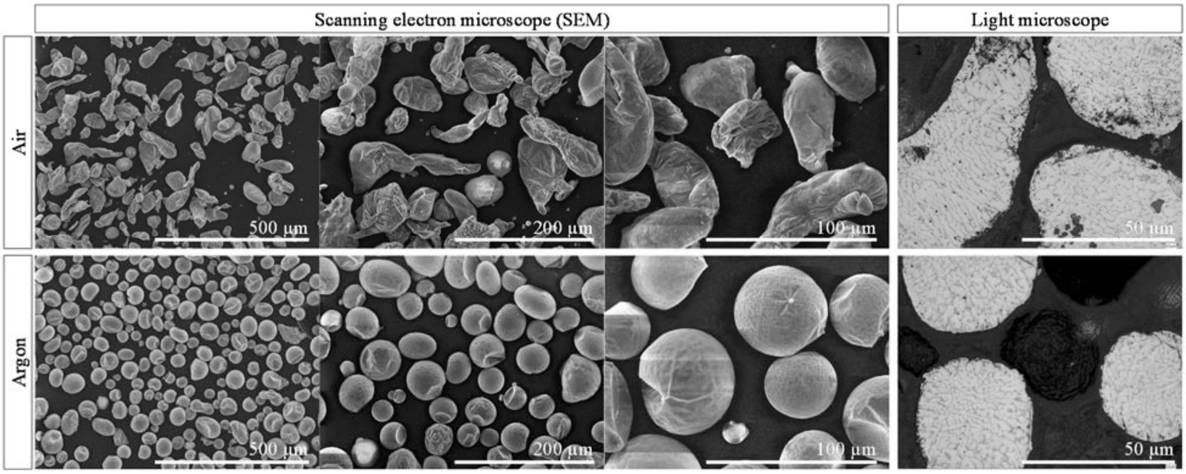

Fig. 3. Comparison of particles produced with air and argon as process gas, SEM images on the left and micro sections on the right side.

Concerning powder production by gas atomization or rather arc spraying, the use of compressed air leads to chemical reactions with molten particles [32]. Due to the strong oxygen affinity of aluminum, an oxide layer arises very quickly on the droplet surface and the surface tension of the molten material is insufficient to form spherical particles resulting in irregular particle shapes [49]. Assuming air is being swirled into the argon shielded spray cone, experimental results confirm that the influence of reactive air is being reduced, but not completely prevented. The appearance of structural defects is somehow similar. Thermal spraying into an inert gas atmosphere yields high powder quality, which could be comparable to inert gas atomized powders.

In the next step of these research activities, the spray cone from the arc spraying process will be inserted into a process chamber that is currently being developed. A schematic representation of the concept is shown in Fig. 4.

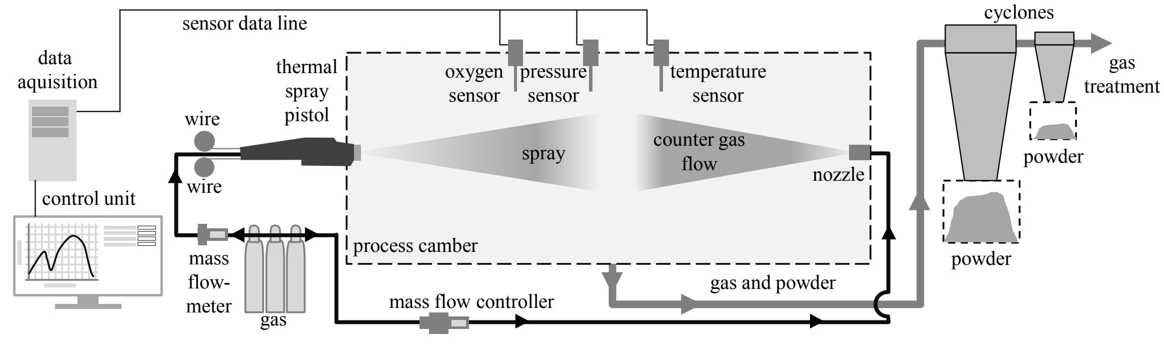

Fig. 4. Schematic representation of the planned process

The dimension of the chamber must be chosen with respect to the cooling distance and the spray cone width, so that the droplets will not hit the chamber walls or the bottom in liquid state and deform. Additionally the chamber dimension has to be minimized in order to save inert gas and space. There are two basic orientations for atomization chambers, a vertical and a horizontal layout. In industrial atomization plants the vertical layout is common, because the particles will fall with the gravity and the powder can be collected and forwarded at the bottom of the chamber. If the walls are even, the powder can settle harder and is more easily transported with the gas flow. A vertical concept has more preferable characteristics, but requires high ceilings. The concept of the arc spray atomization chamber for preliminary experiments has to be designed for a minimum space, therefore a horizontal concept will be realized. In order to cool down the droplets by a minimum distance, a counter flow will be integrated in the chamber to reduce the particle speed and to increase the cooling rate. The particles in the gas-particle atmosphere will be separated in cyclones. Due to the small dimensions and the wire based process, the atomization chamber can be used flexibly for new materials and located in close proximity to the AM process chain. This avoids unknown influences through handling and storage of the powder. Thereby the user knows the powder history of every single batch and can consider the previous influences while processing.

4. Conclusion

Due to AM, there is a variety of new challenges concerning powder production and the powder quality. Parameters such as the oxygen or hydrogen content of the powder can have a huge influence on the AM process and the resulting part quality, particularly when processing aluminum alloys. Therefore the powder production, handling and transport must be considered. A new small scale atomization chamber, based on arc spraying, shall help to get a better understanding of the process chain. First experiments with an arc spraying system showed, that the process is feasible for powder production, although the particle size and shape are not yet fully comparable to the already established powders for AM. These properties will be improved in further experiments with an adjustment of the thermal spray process parameters and a new experimental setup for atomization in an inert gas atmosphere with less than 3.0 vol.-% oxygen.

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