LASER METAL DEPOSITION WITH METAL POWDER IN MICROGRAVITY

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Abstract

The applications of the additive manufacturing process Laser Metal Deposition include the production of near-net-shape parts, coating, joining, feature addition and, above all, repairs. This potential makes the technology interesting not only for applications on earth, but also for use in space. In the case of future space missions to Mars and beyond, the process can be used to react much more flexibly to emergencies and the total mass of spare parts on the spaceship can also be significantly reduced. This work shows the research project in which Laser Metal Deposition with metal powder for operation under the environmental conditions of space is being researched for the first time. For this purpose, the experiment is placed in the *Einstein-Elevator* (next generation drop tower). While the *Einstein-Elevator* performs a vertical parabolic flight, the experiment carrier is in free fall and the samples can be manufactured under microgravity. These samples should provide information about the influence of gravity on manufacturing and how it may need to be adjusted for an optimal process. In addition, this work provides an insight into the new development of a powder feeder that can convey powder in a targeted manner in zero gravity.

Keywords

Laser Metal Deposition; Additive Manufacturing; Repair in Space; Einstein-Elevator; Microgravity

1. INTRODUCTION

More and more people and companies, like SpaceX and NASA, have the vision to colonize the Moon and Mars and to make mankind a multiplanetary species. Before this vision can become a reality, a number of problems still need to be solved. These include the development of additive manufacturing processes that can operate in the environmental conditions of the Moon, Mars and space. For long-duration space missions toward Mars, the flight takes at least 6 months. In addition, the launch window for Mars missions opens only every 26 months due to the planetary constellation [1]. If components fail during the mission, there is no way to reship spare parts from Earth. With the help of additive manufacturing processes, the required components could be produced very flexibly and in a very short time. In this case, the mass of spare parts on board could also be significantly reduced, leaving more capacity for other important components. [2]

Some additive manufacturing processes have already been researched under other gravitational conditions. These include, for example, the Powder Bed Fusion process. In the *MOONRISE* research project, selective laser melting was used to melt lunar regolith under microgravity and lunar gravity [3] [4] [5]. In another research project, a so-called gas-flow-assisted powder deposition process was developed in which the metal powder does not move even in microgravity due to an air-flow platform and can be melted with the aid of a laser beam [6].

The additive manufacturing process Laser Metal Deposition is being researched for the first time in this research project for operation under the environmental conditions of space with metal powder [7]. This process uses a laser beam to melt a thin layer of the base material in a controlled manner. This ensures that a metallurgical bond is formed between the coating and the base material. The metal powder is then injected with a coaxial nozzle through a gas stream containing inert gas. The flexible positioning of the coaxial nozzle makes the process very versatile. Possible applications include the production of near-net-shape parts, coating, joining, adding features and, unlike all other additive manufacturing processes, components can also be repaired. This feature of the manufacturing process brings enormous potential for use in space. [8]

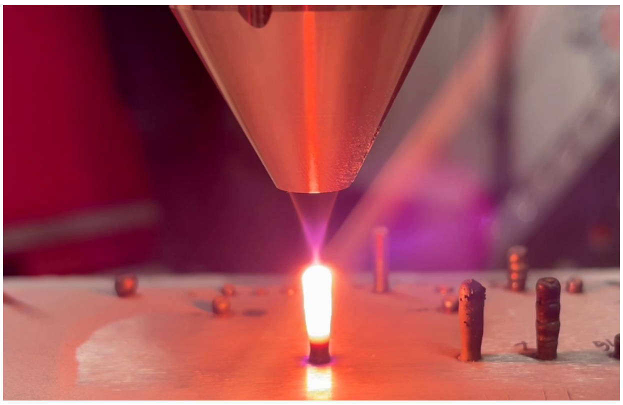

FIG 1. Seed sticks additively manufactured under earth gravity by Laser Metal Deposition (Photo: Leibniz University Hannover/Christoph Lotz)

The research objective includes the production of cylindrical components (3 mm in diameter and 100 mm long, according to DIN EN ISO 6892-1:2017-2 [9]), the so-called seed sticks, by the Laser Metal Deposition process in mi-

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crogravity (see figure 1). The environmental conditions of space are generated with the help of the *Einstein-Elevator*, a drop tower of the latest generation. The experimental setup has to be adapted accordingly for installation in the drop tower. In addition to the generation of a stable and reproducible melting process in the *Einstein-Elevator*, the second main objective is the development of a powder feeder for use in weightlessness. Handling metal powder in the absence of gravity is a prerequisite for successful application in space. The two materials commonly used in space applications, titanium (Ti-6Al-4V) and nickel alloys (Inconel 625), will be tested.

2. THE EINSTEIN-ELEVATOR

One way to perform experiments under different gravity conditions offers the drop tower of the Leibniz University Hannover (LUH), called the *Einstein-Elevator*. The facility is located at the Hannover Institute of Technology (HITec) and is able to generate different gravity conditions from microgravity to hypergravity (up to 5 *g*). Compared to other facilities, it also features an excellent repetition rate. In an eight-hour work shift, 100 experiments can be performed, which is a consequence of the unique design and thus also enables the collection of statistical measurement data. [10]
The *Einstein-Elevator* essentially consists of three parts: the gondola, the drive and the guide system (see figure 2). The gondola, which is a vacuum chamber made of carbon fiber-reinforced plastic, is used to set up the experiments together with the experiment carrier. To achieve microgravity, a vertical parabolic flight is required. Therefore, the gondola is first accelerated to 5 *g* from the ground using linear motors, resulting in a velocity of 20 m/s and a microgravity time of 4 s, followed by the deceleration time. An experiment carrier lifts off inside the gondola during the microgravity time and is recentered after this process via an automatic mechanism. To increase the microgravity quality, a vacuum of up to 10^{-2} mbar can be created inside. [11]
Furthermore, this design ensures a high repetition rate compared to other freefall facilities where the drop zone is completely evacuated. In addition, the gondola provides space for experiments with a height of up to 2 m and a diameter of 1.7 m. The facility allows a payload of up to 1000 kg. However, in terms of weightlessness quality, the unique drive and guidance system is the key to the *Einstein-Elevator*. The system is based on a tower-in-tower design [12]. Thus, the drive and the gondola guide each have a tower, which are built on two separate foundations so that vibrations caused by the drive system are prevented from being transmitted to the guide system of the gondola. As a result, the only connection between the drive and guide components with the gondola is a single coupling rod. The guided gondola is actively driven by a linear synchronous motor over the whole length of the tower. By compensating the rolling resistance and the air drag, the experiment carrier is decoupled from the carrier. This ensures a residual acceleration at the experiment less than 10^{-6} *g*. [10]
For microgravity conditions, the experiment carrier is not attached to the gondola, so during a flight the carrier is detached from the gondola by a few millimeters. In the range of µ*g* to 1 *g* (hypogravity) and 1 *g* to 5 *g* (hypergravity), the carrier is attached to the gondola. An adjusted trajectory profile is created so that the required acceleration results from thrust (upward) or deceleration (downward) by the gondola. Very fast acceleration changes in less than 50 ms are possible in this case. The associated test duration depends on the desired acceleration. [11]

3. EXPERIMENT CARRIER

As a platform for experiments a new experiment carrier system is being developed. This system will be able to provide a residual acceleration of less than 1 µ*g* while offering a maximum payload volume. With the carrier's features such as an active cooling system and logging of basic telemetry data will be available. The carrier consists of the elements shown in table 1.

Part	Weight
base (mandatory)	180 kg
pressure tight shell (optional)	120 kg
payload level (1 - 5 mandatory)	50 kg
stiffening element (optional)	3 kg

TAB 1. carrier elements

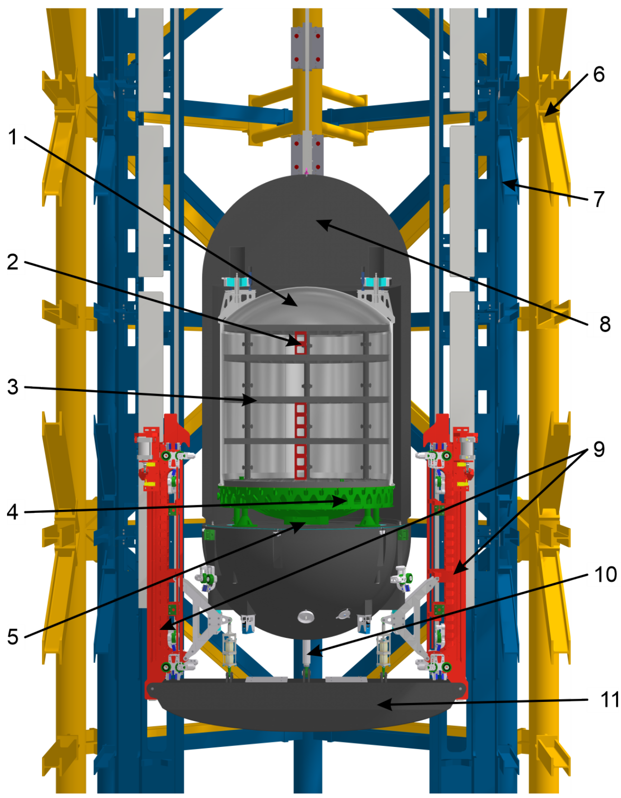

FIG 2. Experiment carrier inside the gondola of the *Einstein-Elevator*; 1: pressure tight shell, 2: stiffening elements, 3: payload level, 4: carrier base, 5: cooling systems, 6: outer supporting structure, 7: inner supporting structure, 8: gondola, 9: drive carts, 10: coupling rod, 11: traverse

The carrier consists of a base that holds all the hardware used for operating the carrier. This includes a variety of sensors that collect the following data:
- triaxial acceleration data measured with four separate sensors
- triaxial rotation rate of the carrier
- magnetic field strength inside the carrier

- temperature at the inlet and outlet of the cooling circuit, at the carrier and at the experiment
- pressure of the surrounding gondola vacuum as well as the pressure inside the payload volume

The base can provide a 24 V DC power supply with 400 W. During the idle time a 230 V AC power supply can automatically be connected to the experiment hardware. Additionally, a network connection for the experiment hardware is available. The connection is routed to the outside of the gondola using two optical data couplers. That way the experiment can be accessed and controlled remotely from the outside. Furthermore, the experiment hardware can be connected to a cooling circuit with a cooling capacity of 1 kW. This system is centered under the base and connects to a second cooling circuit of the *Einstein-Elevator* during idle time. The cooling circuit could theoretically be operated during experiment time, however, the vibrations caused by the pump would increase the residual acceleration and therefore reduce the quality of the microgravity. Experiments that require a vacuum can utilize a pipe that connects the vacuum outside the carrier with the payload volume. This connection can be closed if required.
On top of the base, an optional pressure-tight shell can be placed. When the gondola is evacuated the shell separates the payload volume and the gondola vacuum. A normal atmosphere remains inside the carrier and reduces restrictions to the experiment setup, while still utilizing the acoustic decoupling provided by the vacuum.
The payload is placed on payload levels inside the pressure tight shell and on top of the base. The basic version of those levels allows spaces of 240 mm, 360 mm, or 480 mm between individual levels. Each level has cutouts to pass cables or other connections through the level. One payload level is shown in figure 3.

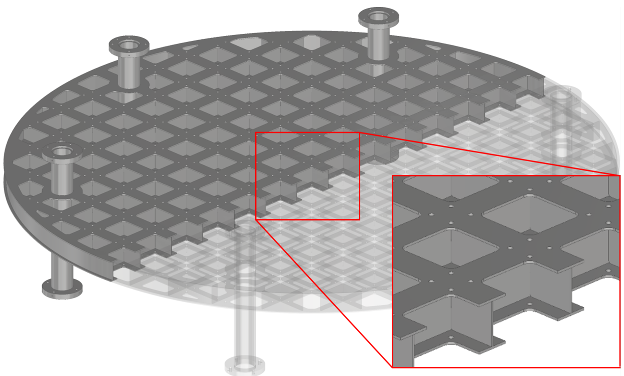

FIG 3. Payload level

4. MANUFACTURING OF THE SEED STICKS

The Laser Metal Deposition process is carried out within a process chamber in the experiment carrier of the *Einstein-Elevator* during the vertical parabolic flight. For a high quality of weightlessness, the experiment carrier is also acoustically decoupled by creating a vacuum between the gondola and the pressure tight shell. Of the four seconds available, about three seconds are used to set up the seed sticks. The manufacturing process is then deactivated. In the remaining time, the molten pool has to cool down before the gondola starts to decelerate with 5 *g*, so that the manufacturing of a seed stick took place exclusively under microgravity. After about four minutes, the *Einstein-Elevator* is operational again and the next vertical parabolic flight can begin. This process is repeated until the seed stick has reached a height of 100 mm. Especially the material transitions have to be considered critically and have to be examined more closely afterwards.
With the Laser Metal Deposition process, the material application is generated either by a movement of the component or by the nozzle. In this test setup, the processing optic is fixed on top of the process chamber. This determines the focal length of the laser beam. A linear axis is provided for the vertical feed to set up the seed sticks. A sample plate is mounted at the end of the linear axis. During production, the sample plate moves from top to bottom at a defined feed rate. It is important to note what residual accelerations occur in the experiment carrier when the linear axis drive is active during free fall. If the drive has a significant effect on the quality of the weightlessness, the sample plate is only moved vertically between flights. In addition, a stepper motor is integrated on the sample plate, so that several seed sticks can be produced one after the other through the rotation without having to open the gondola, the pressure tight shell and the process chamber.

4.1. Component setup in the experiment carrier

Since the gondola of the *Einstein-Elevator* is a closed system, all of the components required to carry out the experiments have to fly with it. In figure 4 the essential components for the manufacturing of the seed sticks and their arrangement in the experiment carrier of the *Einstein-Elevator* are shown (network and venting lines are not shown for a better overview).
In order to reduce the residual accelerations that occur in the system as far as possible, the experiment setup in the carrier must be constructed vibration resistant and rigidity. This is made possible by using few levels and placing all heavy components as far down in the experiment carrier as possible. In addition, the components in the carrier must be arranged in such a way that the center of mass is in the center of the carrier. Otherwise, the carrier would perform rotations after the acceleration phase of the gondola and falsify the test results.
In this experimental setup, the components are placed on a total of two levels. In the first level, the diode laser and the associated energy source are mounted due to the size and weight. The drive of the linear axis is fixed in the center. The linear axis leads vertically upwards to the bottom of the second level, so that the piston of the axis can perform the feed movement of the sample plate via a corresponding seal on the bottom of the process chamber. The control computer for the experimental system is also based on the first level. In the second level, the powder conveyor and all components of the pneumatic system are located next to the centrally located process chamber. These components are relatively small and light, except for the shield gas tanks. Due to the direct connection to the process chamber, the pneumatic lines only have short lengths. The laser beam is guided via a fiber from the diode laser to the processing optics, whereupon the beam is processed by a collimator and a focusing lens. This results in a focus diameter of 2.9 mm and the seed sticks can be manufactured. The heat energy generated during the buildup of the beam in the diode laser can be dissipated with the aid of the cooling system on the bottom of the experiment carrier. Various viewing windows are integrated on the process chamber to observe and subsequently evaluate the manufacturing process. These include a thermal imaging camera and a high-speed camera.

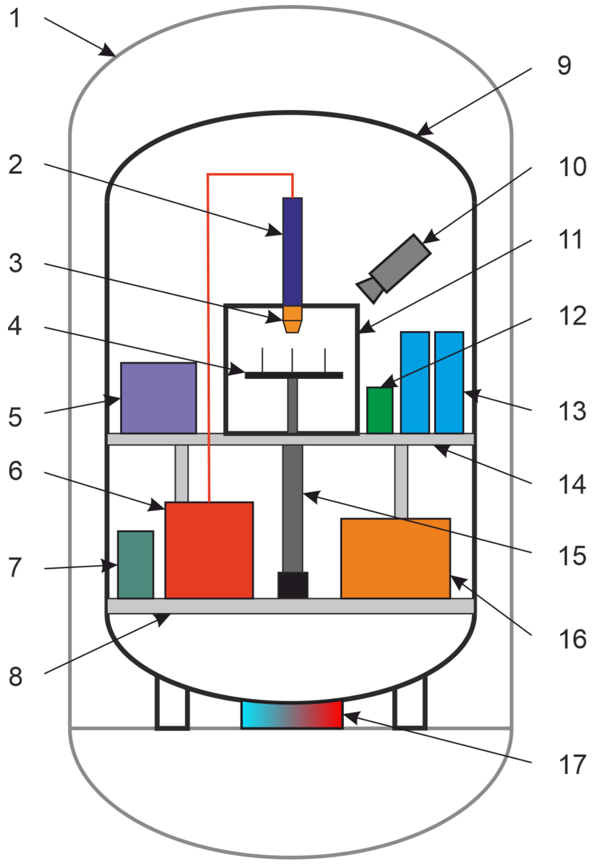

FIG 4. Component setup in the experiment carrier; 1: gondola, 2: processing optic, 3: nozzle, 4: rotary table, 5: pneumatic circuit, 6: laser, 7: control computer, 8: first payload level, 9: pressure tight shell, 10: observation tools, 11: process chamber, 12: powder feeder, 13: shield gas tank, 14: second payload level, 15: linear axis, 16: battery, 17: cooling system

4.2. Pneumatic circuit

For optimal manufacturing with the Laser Metal Deposition process, various parameters must be adjusted to the environmental and production conditions before and during the process. This includes the laser power, the powder mass flow, the shielding gas flow, the laser spot diameter, the focus diameter of the powder, the vertical feed rate and the material properties of the powder. This chapter describes the movement and the control of the shielding gas in the system. Due to the properties of the used materials (nickel and titanium alloys), the inert gas argon is used as the shielding gas.

In Laser Metal Deposition, the shielding gas has three main tasks: With the help of the shielding gas, the metal powder is picked up in the powder feeder and ultimately transported to the melt pool via the coaxial nozzle. In addition, the shielding gas flows through the nozzle from the protective glass of the process chamber to the central outlet of the coaxial nozzle. This flow prevents damage to the protective glass, since the particles cannot collide with the glass surface. Since metal powder is used in this experiment, there is a risk of a dust explosion. In order to prevent this, the entire system while starting up is evacuated and then flooded with argon immediately until the required residual oxygen content has been reached. This eliminates a mandatory condition for a dust explosion to occur. The entire experimental setup is in a closed system, the gondola of the *Einstein-Elevator*. A constant pressure of 1 bar should remain within the pressure tight shell and the process chamber. The pneumatic circuit diagram of this research project is shown in figure 5.

The circuit starts with an argon reservoir with an initial default pressure of 200 bar. Since the pressure will decrease over time and the process should be reproducible, a pressure regulator is used, which constantly reduces the outlet pressure to 2 bar, regardless of the inlet pressure. The line then splits into two paths. The first line leads into the process chamber and flows through the coaxial nozzle during the manufacturing process. In order to be able to set a regulated volume flow at this point or to completely deactivate the shielding gas supply, a mass flow controller is installed. The second path transport the argon to the powder feeder. The volume flow must also be able to be precisely set and readjusted at this position, so that a mass flow controller is also used here. Inside the powder feeder, the metal powder is picked up and transported further by the volume flow of the shielding gas. From this position, the components are designed for a gas-powder mixture.

It will take a few seconds for the powder feeder to build up the required mass flow. During this time, the supply line of the powder to the process chamber is closed by using a powder switch. Otherwise, particles could limit the visibility inside the chamber and increase the risk that the manipulator's moving components will wear out faster. Instead of this, the mass flow is directed to a specially designed cyclone that separates most of the particles contained in the shielding gas. A collection container located at the bottom of the cyclone catches the particles. Since the material has not yet been contaminated or altered, it can be reused. In order to remove the remaining part of the particles from the mixture, a separator is used, in which the particles are distributed in a large volume and sink down by gravity, followed by a filter system. After that part, pure gas is conveyed again.

The pumped gas must be stored under pressure in a container at the end of the pneumatic circuit to maintain the pressure of one bar inside the pressure tight shell. The volume flow required for this can only be built up with the help of a compressor. Concerning the best possible quality of weightlessness in the experiments, all residual accelerations occurring in the system should be reduced as far as possible. This means that during the free fall the compressor must not be activated. An additional air tank and a compressor are also integrated into the system, so that a vacuum is built up resulting in a volume flow before the next free fall time. A mass flow controller between the filter system and the vacuum reservoir can be regulated based on the prevailing pressure difference in such a way that the volume flow corresponds exactly to the sum of the two volume flows set at the beginning. As soon as the negative pressure in the chamber is no longer sufficient to set the required volume flow, the compressor must be activated again. This principle means that exactly as much gas is stored as is initially released.

When the correct mass flow through the powder feeder and the volume flow are set and the *Einstein-Elevator* and the other components of the manufacturing process are ready for operation, the powder switch toggles. In this circuit, the powder-gas mixture leaving the powder feeder flows first into the powder distributor and is then divided into several lines, which are then routed directly to the coaxial nozzle via the flange of the process chamber. At this time, the vertical parabolic flight of the *Einstein-Elevator* can be started and the seed sticks can be manufactured under microgravity. Depending on the efficiency, a small part of the metal powder will not be used and will be distributed within the process chamber.

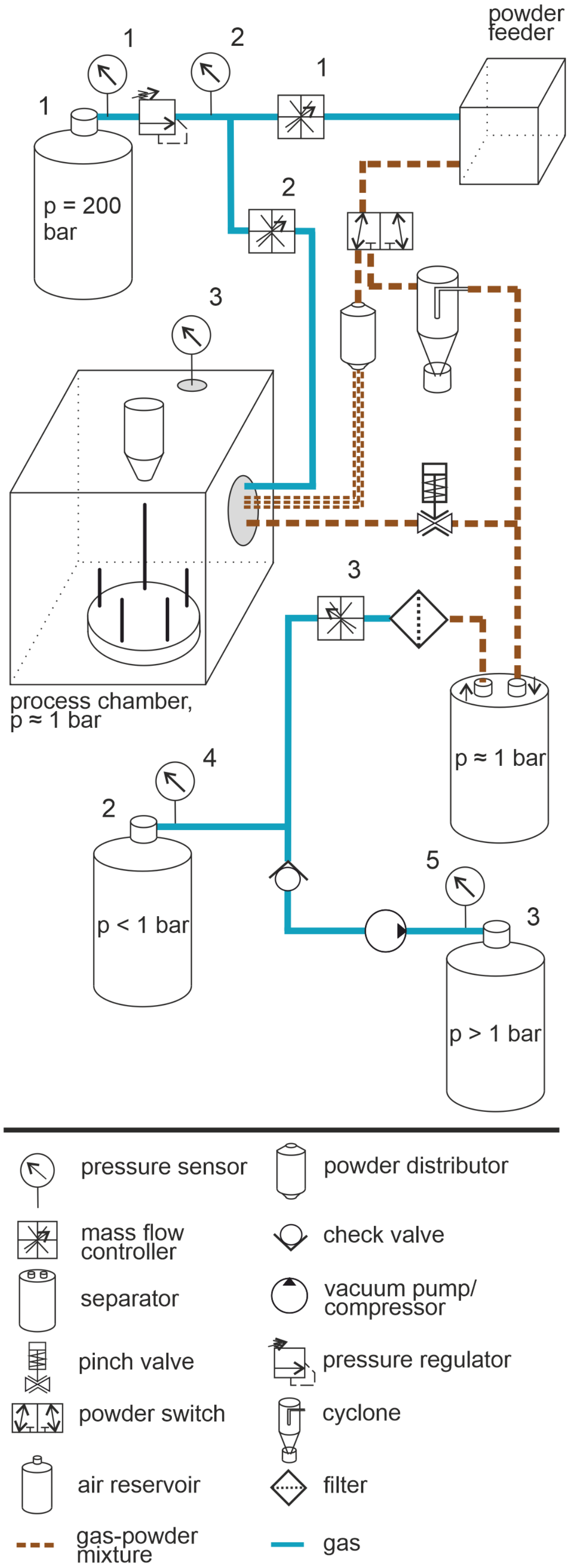

FIG 5. Pneumatic circuit diagram

In addition to the inlet lines, there is also an outlet line on the flange. The line leads to the filter system and is placed in the chamber so that as many unused particles as possible are drawn out of the chamber. The pinch valve is open during this operating phase. When closed, the valve ensures that the powder-gas mixture cannot flow backwards into the process chamber during the start-up phase. Additional pressure sensors are planned for monitoring at key positions so that the process can be better monitored and the entire system can be shut down in the event of a fault.

5. REQUIREMENTS FOR A POWDER FEEDER

The usual powder feeders in industry only work under gravity conditions. Often, they have a bottle like bin as a reservoir for the 3D printable powder. From this bin the powder has to flow down into a notch on a rotating disc. The notch is emptied by a stream of conveying gas in a second step. This principle will not work under non-gravity conditions. Hence, one main aim of the research project is the development of a new powder feeder system for non-gravity conditions and the testing via the *Einstein-Elevator*.
The requirements for the powder feeder are defined by the conditions of the experiments inside the *Einstein-Elevator* and by the equipment for the Laser Metal Deposition process. Some of the main requirements are:

- The feeding system has to work under normal earth gravity (1 *g*), under five times earth gravity (5 *g*) and under no gravity (0 *g*) too. This requirement is related to the different gravity conditions inside the *Einstein-Elevator* during one flight. It is useful to start with the conveying process before entering the 0 *g*-phase, because the 0 *g*-time should be used completely for Laser Metal Deposition process. Hence, an almost stationary gas-powder-flow at the laser melting point has to be established at the beginning of the free fall time. This means that the feeding process as well as the pneumatic conveying process has to work independent form the gravity conditions in all phases of the work cycle of the *Einstein-Elevator*.
- The feeding system has to work with different powders. It is planned to use two different powders for additive manufacturing.
  - The first powder is Inconel 625, which is an alloy on nickel base with 22 % of chromium, around 9 % of molybdenum, around 4 % of niobium and tantalum and several other elements of less than 0.5 % each. The powder has a mean particle size d(50) = 36 µm. Its bulk density is 4.16 kg/l.
  - The second powder to use is Ti64-G23-E, also known as Ti-6Al-4V. It is an alloy on titanium base (89 %) with around 6 % of aluminium and around 4 % of vanadium. Other elements are only present in traces. The Ti64-powder is a little bit coarser with a mean particle size d(50) = 70 µm. Its bulk density is around 2.38 kg/l.
- The shielding gas is argon, which is the carrier gas for the powder too. The volumetric flow rate of the shielding gas is at minimum 8 l/min, better around 15 l/min. Into the stream of gas the powder has to be uniformly feed. Higher gas velocities may contribute to an undisturbed conveying process of the powder.
- In the first trials of the Laser Metal Deposition process two powder mass flow rates were successfully tested: 13.3 g/min for Inconel 625 and 7.4 g/min for Ti64. Because of their different bulk density, it is around the same volumetric flow rate of 3.2 ml/min. The mass flow rate of the

powder and hence the mixture rate of powder in the carrier gas stream has to be easily and precisely adjusted.
- A blocking or jamming of the powder inside the powder feeding system has to be avoided at all times. The generation of a stable constant material flow rate is an important requirement.

6. VIRTUAL PROTOTYPING WITH DISCRETE ELEMENT METHOD (DEM)

The main problem in designing a machine for the use under zero gravity conditions is to consider all effects and reactions which happens in the lack of gravity. Specially the behaviour of the moving bulk material under zero gravity is hard to predict by classical analytical or continuum theory. Therefore, numerical simulations based on the Discrete Element Method (DEM) are used in the research project.
The DEM was introduced by Cundall and Strack in the late 1970s [13]. At first it was used for simulating the behaviour of rocks and soil in geomechanics. With increasing computational power, the DEM is today a method for simulation bulk material in mechanical, process and agricultural engineering as well as mining [14]. At the University of Magdeburg it was especially used for the analysis and optimisation of conveying technology like bucket elevators and scraper conveyors [15] or screw and shaftless screw conveyors [16] and their bulk transfer stations [17].

The DEM is a numerical method for simulating the motion of many particles. It is a mesh free method and considers the discrete nature of bulk materials much better than FEM or CFD. When the position of all particles is known, the solver checks for contact or overlap of every particle with other particles or walls. Using the so-called soft sphere approach the particle itself cannot deform but they can overlap. Out of the overlap the contact force depending on the chosen contact laws is calculated. Based on the knowledge of the resulting forces and torques on each particle as well as with the knowledge of the particle mass, the new positions and orientations of the particles can be calculated based on Newtons second law of motion. The described calculation cycle is repeated to simulate a certain simulation time. Geometric boundary conditions can be considered as well as globally force fields such as gravity. Hence, it is very simple to consider a user defined gravity vector in DEM.
Often spherical particles or conglomerate of spheres (“multispheres”) are used for simulation due to the low computational effort during the contact detection. The DEM is a very calculation intensive method. Typically, real particle systems need to be idealised regarding shape, particle size distribution and particle stiffness. For getting a realistic behaviour of the simulated bulk material, a calibration of the DEM parameters is necessary. The calibration process requires the undertaking of relatively simple experiments like an angle of repose or draw down test and a series of analogous simulations to determine the set of DEM parameter which fits best to the material behaviour seen in the experiments [18] [19] [20] [21].
For the following DEM simulations, the open-source software LIGGGHTS® [22] is used in its version 3.8.0. The post-processing was made with Paraview [23].

7. DIFFERENT POSSIBILITIES OF CONVEYING BULK MATERIAL UNDER ZERO GRAVITY

7.1. Creating artificial gravity

One possibility to get bulk material conveyed under low or zero gravity conditions is to create artificial gravity. The easiest way to have a gravity-similar effect is to set a system into rotation. Then the centrifugal forces in radial direction have a gravity-like behaviour. Walton and Vollmer described a possible design with two cones. The bottoms of the cones are facing each other. Between the cones lateral surface is a small gap. They are rotating around their central axis and so the infilled bulk material has to move to the furthest surface region of the two cones because of centrifugal forces [24]. A comparable idea was created as DEM-simulation and is shown in figure 6. The whole system is reminiscent of a rotary valve with a vertical rotation axis. A conical housing was designed. Inside this housing a shaft with cellular blades is located. The shape of the blades is nearly the inside shape of the conical housing. The housing is fixed and has a little opening at its largest diameter. The shaft with its blades is rotating around its symmetry axis.

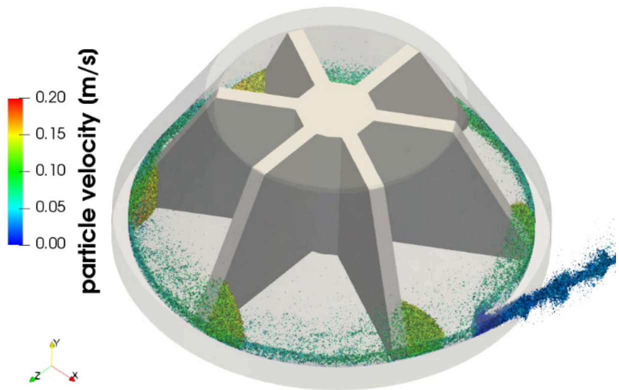

FIG 6. DEM simulation of a blade wheel for conveying powder under 0 *g*

The idea is to fill powder inside the free space between the blades. By rotating the shaft with its blades, the powder is forced to get in circular movement and hence getting a centrifugal force on every particle. This centrifugal force effects a radial movement of the powder. The conical shape of the housing forces the powder to move to the largest diameter position of the cone. There the powder is concentrated and can left the feeder through a little gap in the housing. The powder outlet is connected with the carrier gas stream to mix it in. The feeding process will work until nearly the whole powder has left the blade wheel feeder because the powder is forced to gather at the outlet diameter.
The DEM-simulation shows that the principle conveying is working. Challenging is the design of the outlet. Here jamming of particles occurs which results in a fluctuation of the mass flow rate. The powder mass flow rate could be adjusted by the rotational speed of the blade wheel.

7.2. Dispersion of powder

Another possibility of getting a mixed powder and carrier gas flow is to create a fluidised bed or better a diluted gas particle mixture first and then convey it. Such systems are called blow tanks in pneumatic conveying. However, there is an additional mixing element required to keep the mix diluted in the bin. The idea is to have a bin with swirl stirrers inside where the powder is filled. By rotating the stirrers, the powder will compose a dilute dispersion with the gas inside the bin. When the carrier gas stream is floating through this bin, it will carry this dispersion and convey it (see figure 7).

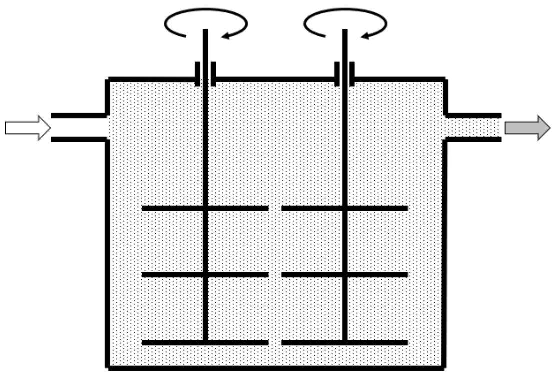

FIG 7. Sketch of a powder feeder by creating a diluted dispersion

Without gravity, the dispersion should be more stable as under earth gravity conditions. But the change of gravitational forces in the *Einstein-Elevator* will have an effect on the powder. Than the stirrers have to keep the powder in dispersion. Another disadvantage is that the system will work not continuously but in a batch process. The longer the feeder is working, the fraction of the powder in the carrier gas will decline.
A second possibility to create an aerosol is to push the powder into a stream of the carrier gas. Therefore, a line is filled with powder and one end of the line is closed with a piston. The other end of the line is connected with a mixing chamber, where the carrier gas is floating through. When the piston is moving it pushes the powder into the mixing chamber and the carrier gas flow is taking the powder with (see figure 8).

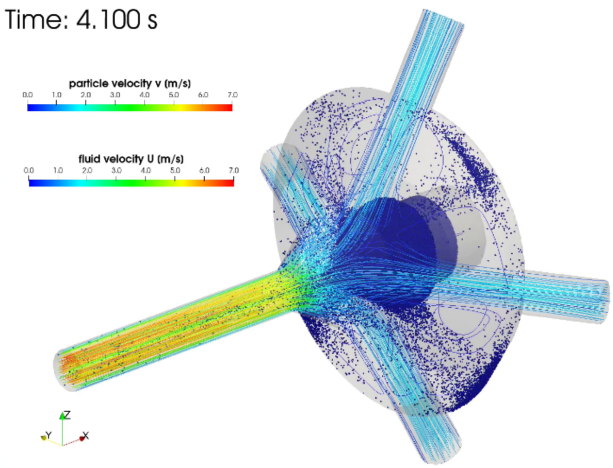

FIG 8. Coupled CFD-DEM-simulation of a powder feeder with piston drive and mixing chamber

For low powder mass flow rates a very slow-moving piston is needed or the line has to be of a low diameter. When the line is very thin, the piston has to be of very low dimensions too, so the design of the driving system is challenging. Furthermore, the powder could jam inside the line so the process can have fluctuations in the mass flow rate. If several pistons are used a continuous feeding could be realised. If only one piston is used, the system could only work batch-wise.

7.3. Screw conveyor

The third possibility of getting a mix of carrier gas and powder is to move the powder by a screw conveyor. By simulating simple screw conveyors under 0 g conditions it is detected that screw conveyors will work under 0 g conditions under two different circumstances. Either the screw conveyor has to have a high filling or the screw has to rotate very fast. To get a low mass flow rate of the powder by having high rotational speeds the design of the screw has to be adapted in comparison to classical screw designs. The pitch of the screw, the height of the blades and the diameter of the screw has to be very low. So, it is hard to achieve the required mass flow rates.

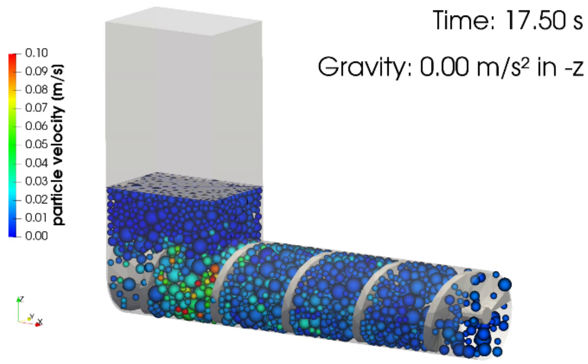

FIG 9. DEM-simulation of a classical screw conveyor under 0 g. The material feeding is realised by a piston which vertically moves in the down.

When it is possible to vary the rotational speed of the screw it is much easier to get the right mass flow rate and to adjust it in a fine range. During operation it has to be ensured that the screw is filled in a high ratio. One possibility to ensure this is to force the feeding of the screw by moving a piston in the storage bin in relation to the volume the screw is conveying (see figure 9). The piston should not push the powder inside the screw but has to close the opening space which is created by conveying the powder out of the hopper. The moving piston will prevent that the powder is losing its bulk density or could move in wrong directions.
It is also possible to use a dosing screw feeder with the former described higher speed and fine design of the screw and pitch. Feeding this screw conveyor can be realised by a more classical screw installed vertically (see figure 10). This vertical screw conveyor acts as the storage bin. This screw has to rotate very slow to get a mass flow rate nearby the mass flow rate of the dosing screw. To get a constant movement of the powder in the direction to the dosing screw the storage screw has to rotate steady and perhaps with a higher volumetric flow rate as the theoretical needed volumetric flow rate to force the feeding of the dosing screw feeder. At the end of the dosing screw there is only the shaft left where the carrier gas is floating around. The carrier gas is taking the powder and the mixing is done. To change the powder ratio in the mixture, the rotational speed of the dosing screw can be changed or the volumetric flow rate of the carrier gas can be adjusted.

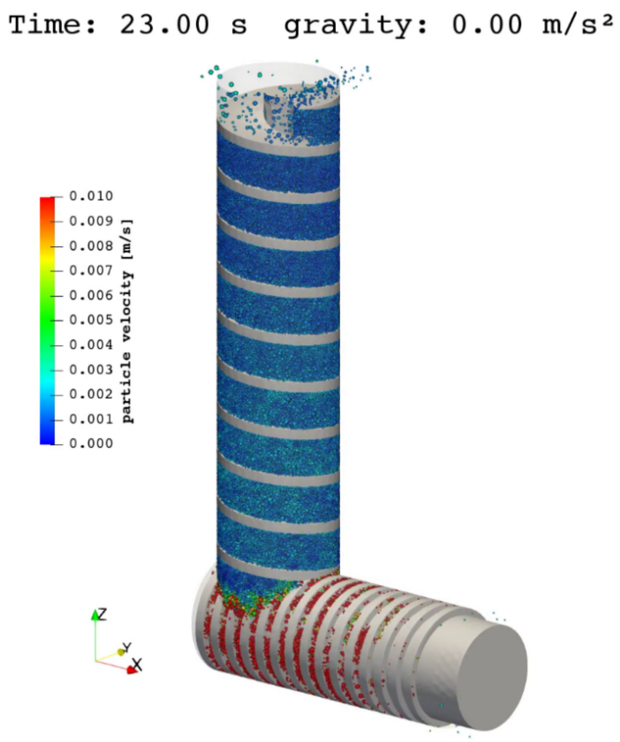

FIG 10. DEM-simulation of a dosing screw feeder with forced feeding by a larger vertical storage screw conveyor.

8. SUMMARY AND OUTLOOK

After the construction of the experimental setup, seed sticks are first produced under earth gravity. The process parameters must be adjusted for having optimum material and geometric properties. Seed sticks will then be fabricated in the *Einstein-Elevator* under microgravity using the exact same process parameters. A comparison of the samples will show the influence of gravity on the Laser Metal Deposition process and which parameters need to be adjusted to obtain identical results. In order to realize the research aim, it is necessary to develop a reliable powder handling technology for the metal powders under microgravity, which allows a precisely controlled feeding of a powder mass flow rate to the melting zone.
Analysis of the fabricated seed sticks will initially be performed geometrically, measuring the width of the samples along their length. In addition, metallographic analysis and determination of the mechanical properties of the titanium (Ti-6Al-4V) and nickel alloys (Inconel 625) are planned. The cylindrical shape of the seed sticks, 3 mm in diameter and 100 mm in height, is selected so that the geometry meets the conditions of the uniaxial tensile strength test according to DIN EN ISO 6892-1:2017-2 [9]. The mechanical properties are also verified by an indentation hardness test (Vickers hardness test).
Metallographic analysis also includes measurement by computed tomography. Figure 11 shows a computed tomography (CT) scan with pore analysis of a seed stick (nickel alloy) from the preliminary tests, which has been produced under 1 *g*. In the left part of the figure, shown in blue, the individual air inclusions (pores) can be seen in the cross-section of the sample. The more pores are contained in the material, the greater the ratio of the void volume to the total volume. The porosity for the samples from the preliminary tests is 0.28 % for Inconel 625 and 0.001 % for Ti-6Al-4V. With the samples produced under microgravity, it is necessary to find out how the porosity ratio and the pore size distribution changes. In the right part of the figure, the surface of the sample can be observed. Three neckdowns can be seen along the length, which result due to the changes in laser performance during manufacturing.

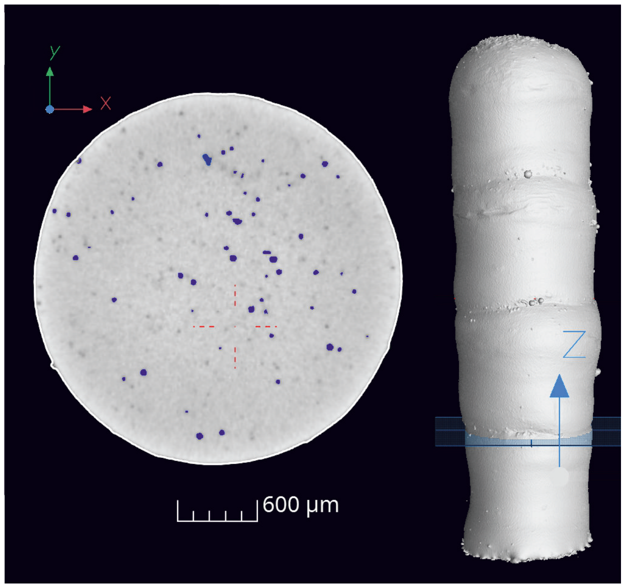

FIG 11. Computed tomography (CT) scan with pore analysis of a seed stick (nickel alloy) manufactured under earth gravity

As soon as the manufacturing facility in the *Einstein-Elevator* can be put into operation, a study of the seed sticks will show the influence of microgravity on the laser metal deposition process. In addition, the results can be used to determine the influence of other gravity conditions, like the Moon or Mars, on the manufacturing process. Furthermore, the development of a powder conveyor for use in microgravity is also of great interest for other research areas.

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