MHD printhead for additive manufacturing of metals

Author(s):
Suter, Martin; Weingärtner, Eduardo; Wegener, Konrad

Publication date:
2012

Permanent link:
https://doi.org/https://doi.org/10.3929/ethz-b-000058255

Originally published in:
Procedia CIRP 2, https://doi.org/10.1016/j.procir.2012.05.049

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia CIRP 2 (2012) 102 – 106

www.elsevier.com/locate/procedia

1st CIRP Global Web Conference: Interdisciplinary Research in Production Engineering

MHD printhead for additive manufacturing of metals

M. Suter[a,b] *, E. Weingärtner[a], K. Wegener[a,b]

[a]*Institute of Machine Tools and Manufacturing, ETH, Tannenstrasse 3, Zurich 8092, Switzerland*
[b]*inspire AG, Tannenstrasse 3, Zurich 8092, Switzerland*
*Corresponding author. Tel.: +41 44 632 4526; fax: +41 44 632 1159; *E-mail address*: suter@iwf.mavt.ethz.ch.

Abstract

Within the scope of additive manufacturing of metal parts, a droplet generator for metal melts is proposed. Its magnetohydrodynamic (MHD) working principle is shown and the actuation force available for droplet generation is calculated. The design of such a printhead is shown to consist only of very few, non-moving parts and therefore it is of great simplicity. First results gained with a prototype printhead show that successful droplet generation is possible, but that pollution of the melt with oxides and sparks developing during the droplet generation process have to be overcome to fully exploit the potential of the proposed print head.

Keywords: print head; MHD; additive manufacturing; metal droplets

1. Introduction

In additive manufacturing, the demand for producing metal parts is ever increasing since many years. The commercially available processes for the manufacturing of metal parts are based on metal powders as raw materials and laser irradiation as tool. The laser is either used to locally fuse the particles of a powder bed (as in Selective Laser Melting or Selective Laser Sintering) or to create a melt pool on the workpiece into which powder is injected to increase its volume (as in Laser Engineered Net Shaping)[1].

Since lasers are still expensive, the parallel operation of multiple systems to increase productivity is often hindered by high costs. One possible approach to overcome this dilemma is the application of droplet generators and drops of molten metal as manufacturing tool. These have the potential to establish an additive manufacturing process at lower costs. Droplet generators suitable for such a process have already been proposed [2-5] and good mechanical properties of parts built with droplets have been found [6], but, by today, none of them is commercially available for manufacturing purposes. The reasons for this are not fully clear and it can only be speculated about. One reason might be the cumbersome systems needed to turn a continuous droplet generator [2, 3] into a much easier to control drop-on-demand generator.

Based on this consideration, a simple to use drop-on-demand droplet generator has been designed and tested. The operation principle of the print head is magnetohydrodynamics (MHD), which is the application of the Lorenz force, acting on currents passing through a magnetic field. This operating principle allows the design of a print head with no moving parts and, thus, reduced complexity. In principle it can be built with only two different materials (one an electrical conductor, one an insulator), which can be selected to withstand very high temperatures.

2. Magnetohydrodynamic (MHD) working principle

MHD is the science of the behavior of electrical conducting fluids in the presence of magnetic fields. It has been intensely studied in the middle of the last century either for its application in astronomy or for the creation and control of metal blankets, proposed for the cooling of fusion reactors [7]. Also for energy

 http://dx.doi.org/10.1016/j.procir.2012.05.049

conversion MHD has been proposed, especially for MHD generators and MHD pumps.

The print head presented in this paper can be seen as a MHD micro-pump providing a drop-on-demand droplet generation by short impulses of a MHD pumping force. For a MHD pump a rectangular channel geometry is often applied with two opposite channel walls as electrodes and the two other walls as insulators (see Fig. 1).

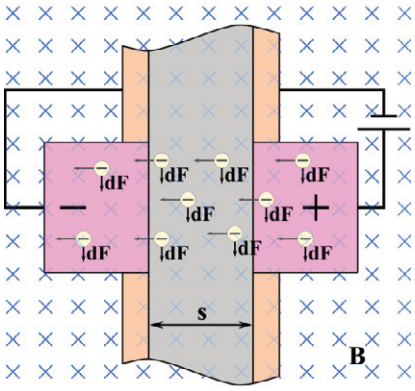

Fig. 1. Schematic illustration of a MHD pump

When a voltage is applied across the electrodes, current flows through the conducting fluid in the channel. If a magnetic field, perpendicular to the current direction and to the channel, is present, the Lorenz force acting on the moving electrons results in a volume force acting on the fluid along the channel direction.

The force acting on a single electron is given by the formula for the Lorenz force:

$$dF = e(\boldsymbol{v} \times \boldsymbol{B}) = evB \qquad (1)$$

Here e stands for the electron charge, $\boldsymbol{v}$ for the electron speed and $\boldsymbol{B}$ for the magnetic flux density of the magnetic field. Since $\boldsymbol{v}$ and $\boldsymbol{B}$ are assumed to be perpendicular, the cross product can be replaced by the product of the absolute values. The total force acting on the fluid is the force on a single electron multiplied by the number of electrons (the total charge Q) in the channel.

$$F = \int_V dF = QvB \qquad (2)$$

The total charge is linked to the current I running through the electrodes by

$$Q = It = I\frac{s}{v}\,, \qquad (3)$$

and thus the total MHD force becomes

$$F_{mhd} = IBs\ . \qquad (4)$$

A more thorough deduction of the equation (4), starting with the full set of MHD equations, can be found in [8].

3. Print head design

Fig. 2 depicts a simplified version of the print head proposed in this work. It consists of two functional units. The first unit forming the fluid channel incorporates two stainless steel electrodes (1) and two microscope glass slides (2). These four elements form the rectangular channel as described in the previous section. The cross section of the channel is a square with a side length of 4 mm. One end of the channel is close by a ceramic cube containing a nozzle (3). The other end of the channel is left open for refilling with print material from a crucible.

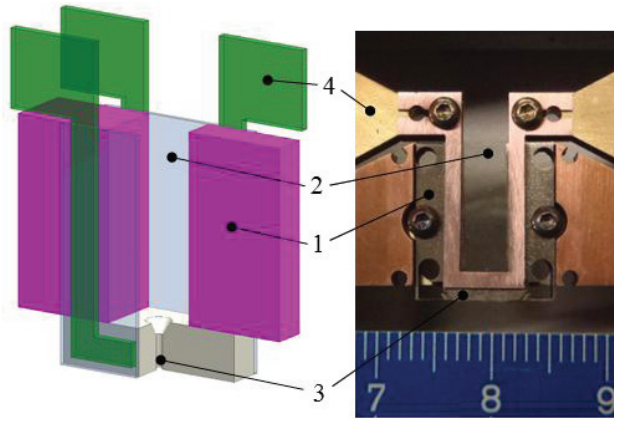

Fig. 2. Simplified CAD model of the printhead with one quarter-section cut out

The second unit includes two U-shaped sheets (4) forming a coil with two semi-windings. By running a DC current through this coil the magnetic field is created. At the same time, the resistive heat generated in the coil is the heat source for maintaining the whole print head at a temperature above the melting point of the printing material.

4. Experimental setup

Fig. 3 shows a picture of the experimental setup. To create the droplet ejection force, two current sources have to provide power to the printhead system (1). The first one feeds the coil and generates the magnetic flux density in the printhead channel. This current source (4) is designed to deliver DC current and, therefore, the magnitude of the current is limited by the total ohmic losses in the current loop. Big effort has been performed

to keep low all ohmic losses, except for the losses of the coil which is designed to a specific value to set the temperature level. A ribbon cable with a large cross section and copper clamps (3) are used to connect the source to the experimental chamber (2). In this way, the full output of a 300A Agilent power supply (4) can be used.

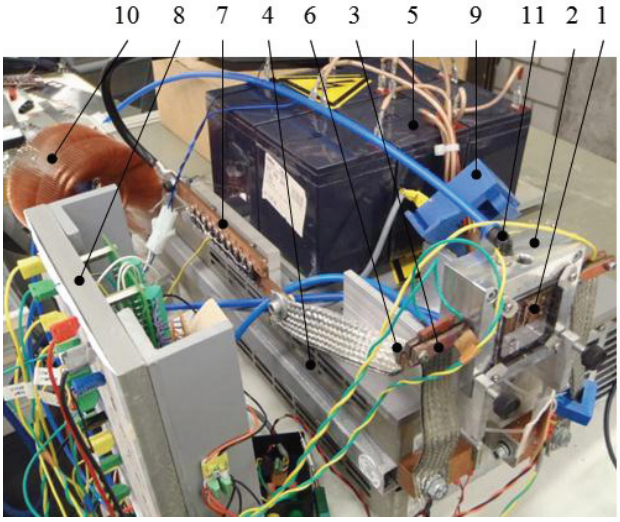

Fig. 3. Experimental setup: (1) printhead assembly, (2) experimental chamber, (3) bus bars, (4) DC power supply, (5) battery stack, (6) ribbon cable, (7) mosfet module, (8) signals connector block, (9) LEM current transducer, (10) cooling fan, (11) nitrogen inlet

The second current source has to provide short current pulses to the electrodes to initiate the ejection of a droplet. Although ohmic losses do not limit the magnitude of the current pulse in a similar way as for the coil current, low losses mean low voltages and therefore a safer experimental setup. With these considerations in mind, a parallel stack of lead acid batteries (5) with a nominal voltage of 12V is employed with the parallel arrangement of the batteries resulting in a low internal resistance. The batteries are connected (6) directly to the print head electrodes with a mosfet module (7) acting as an electronic switch in between. A DAQ board, mounted in a computer, controls the mosfet module and collects various sensor data (only the connector block (8) is visible). The setup is able to generate square current pulses of amplitude up to 1200A and duration in the range of 1-20 ms. The pulses are measured with a LEM current transducer (9).A closed circuit water cooling system limits the temperature of the experimental chamber and cools the mosfet module with a fan (10). The experimental chamber is flooded with nitrogen (11) at a flow rate of ~2 l/min.

As printing material for these first experiments, tin was selected because of the low melting point and high evaporation point. In this way, the temperature of the coil does not have to exceed ~600° C for heating the melt to roughly 300° C. This means that glass slides can be used as insulating channel walls, which otherwise would have to be replaced, e.g. by sapphire windows (which are much more expensive), or by a non-transparent material, but then losing the opportunity to observe the melt in the printhead.

For the observation of the droplet ejection process, a high speed camera is taking pictures at a rate of 11'000 frames per second. The camera is synchronized to the current pulse generation through a common trigger signal. This trigger signal is processed by the camera in at the most one time frame, so the synchronism is guaranteed to be better than 91µs.

5. Results

Fig. 4 shows a sequence of images illustrating the ejection of a droplet. The duration of the current pulse is 4 ms, hence the image sequence just starts after the pulse is over. Up to then, the melt is still completely inside the printhead and the energy for the further movement is drawn from the inertia of the fluid. Soon after the melt has protruded out of the nozzle, it starts to neck under the influence of surface tension and produces a droplet roughly 5.6 ms after the current pulse. The diameter of the produced droplet is ca. 0.9 mm with the nominal nozzle diameter being 0.5 mm.

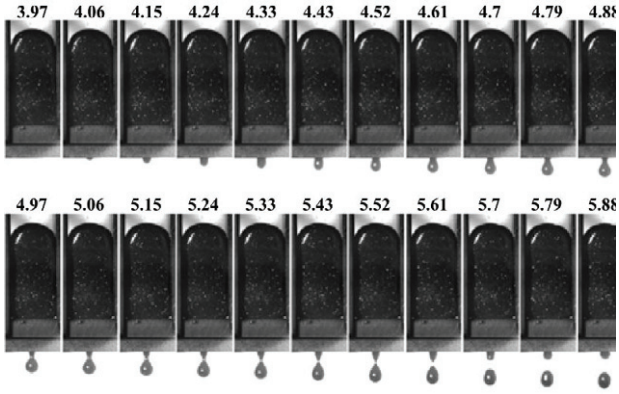

Fig. 4. Image sequence of drop ejection with a 0.5mm diameter nozzle

The experiments were conducted in nitrogen atmosphere and the refill procedure consisted of melting the raw material in a syringe-like crucible, letting the oxides collect on the surface and filling the print head with clean tin from the bottom of the syringe. Although these measures have been taken, the melt in the print head degenerates in quality over time. A skin of tin oxide is formed on the surface of the melt, changing its look and altering its wetting behaviour against the electrodes and windows.

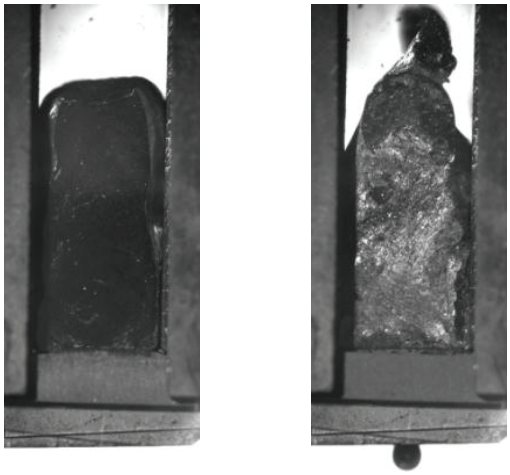

Fig. 5. (left) Fresh print head with first charge of tin (right) same print head after ejection of about 90 drops and two refill's

In Fig. 5 the aging of the melt inside the printhead can be seen. On the left, a fresh printhead with its first charge of tin is shown. The surface is shiny and only little light is scattered into the camera. The same printhead after forty minutes of experiments and the ejection of about 90 drops, is shown on the right. This printhead has been refilled twice. The melt is covered with a skin sticking to the glass windows and forming unpredictable contact angles to the electrodes.

By this aging behavior of the melt, the ejection process is influenced dramatically, leading to a rather chaotic performance of the droplet generation. Because of this lack of repeatability the influence of the printhead parameters, such as nozzle diameter and pulse amplitude and length, could not be studied.

A second phenomenon hindering the application of such a printhead in further experiments is the occurrence of sparks between the melt and the electrodes. Especially at low fill levels, sparks have been recorded, with the risk to damage the mosfet switch or the glass windows.

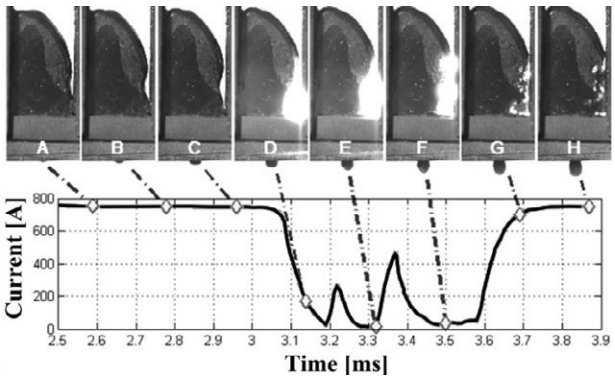

Fig. 6. Ignition of a spark between melt and electrode as one electrode as completely dewetted

Fig. 6 shows sequential images of a droplet ejection process which involves the ignition of a spark (images D-F). Below the images, the recorded current flowing through the melt is plotted. A dash-dot line connects each image with its corresponding marker in the current signal. In image A, taken at 2.6 ms after the trigger, it can be seen that under the influence of the current pulse, the melt has already dewetted most of the right electrode leaving a small gap between the two. This dewetting progresses in images B-C and culminates in the ignition of a spark in image D. It is believed, that by the time the spark ignites, the electrode is completely dewettet and the spark starts as if a mechanical switch were opened. After some time, where almost no current flows, the melt is touching the electrode again, the current rises and the spark extinguishes (images G-H).

Although the droplet generation cannot be controlled in a fine enough manner, it is already possible to generate solid structures with the ejected droplets. In Fig. 7 the simplest structure – a pillar made of droplets printed on top of each other – is shown. The bonding between the solidified drops seems to be strong after the first findings and will be further investigated in future studies. In a preliminary analysis, the deviation of the droplets flight path from the nominal direction has been investigated and the standard deviation has been found to be 0.3°. With an operating distance of 20 mm this would lead to a deposition error of ~ 0.1 mm.

Fig. 7. String of solidified drops (rotated by 90 degrees)

6. Conclusions

For the proposed printhead for high melting point metal melts the feasibility and the potential has been shown. Further improvements to the print head are needed to attain stable operating conditions. These improvements should include a better inert atmosphere, possibly with a different inert gas or under vacuum conditions. Further investigations should clarify the reasons for the dewetting of the melt from the electrodes, which is causing the sparks.

7. Outlook

With the right measures taken for stable operating conditions, the research should extend to high melting

metals. If the print head can successfully master these, a new manufacturing method could be established.

It is believed that with the high volume output of the print head, a promising field of application would be 5-axis additive manufacturing of near net shape blanks. With droplet sizes in the range of one millimeter, the parts to build need to be relatively large, matching the resolution of the droplets. For example the blades of impellers could be printed onto a turned blank part, followed by a milling operation to produce the required surface finish.

References

[1] Levy, G.N., R. Schindel, and J.P. Kruth, RAPID Manufacturing and rapid tooling with layer manufacuturing (LM) technologies, state of the art and future perspectives. CIRP Annals - Manufacturing Technology, 2003. **52**(2): p. 589-609.

[2] Orme, M., A Novel Technique of Rapid Solidification Net-Form Materials Synthesis. Journal of Materials Engineering and Performance, 1993. **2**(3): p. 399-407.

[3] Tseng, A.A., M.H. Lee, and B. Zhao, Design and operation of a droplet deposition system for freeform fabrication of metal parts. Journal of Engineering Materials and Technology-Transactions of the Asme, 2001. **123**(1): p. 74-84.

[4] Harnisch, J.W., Aufbau und Untersuchung eines Drop-on-Demand-Systems für den Hochtemperatureinsatz. Fortschritt-Berichte VDI. Reihe 9, Elektronik/Mikro- und Nanotechnik Nr. 384 384 38962812009: VDI.

[5] Metz, T., et al. StarJet: Pneumatic Dispensing of Nano- to Picoliter Droplets of Liquid Metal. in Micro Electro Mechanical Systems, 2009. MEMS 2009. IEEE 22nd International Conference on. 2009.

[6] Orme, M. and R.F. Smith, Enhanced aluminum properties by means of precise droplet deposition. Journal of Manufacturing Science and Engineering-Transactions of the Asme, 2000. **122**(3): p. 484-493.

[7] Tillack, M.S. and N.B. Morley, Magnetohydrodynamics. 14th Edition ed. Standard Handbook for Electricl Engineers1998: McGraw Hill.

[8] Jang, J. and S.S. Lee, *Theoretical and experimental study of MHD (magnetohydrodynamic) micropump.* Sensors and Actuators A: Physical, 2000. **80**(1): p. 84-89.