euspen's 16th International Conference & Exhibition, Nottingham, UK, May 2016
www.euspen.eu

Design of a multi-metal printer for jetting droplets directly from the melt

Ralph Pohl[1], Bas Lemmen[1], Peter van den Oever[1]

[1]*Demcon Advanced Mechatronics, Institutenweg 25, 7521 PH Enschede, The Netherlands*

Ralph.Pohl@demcon.nl

Abstract

In the last years stable and reliable jetting of metals (Ag, Au, Sn) directly from the melt at temperatures up to 1600 °C has been demonstrated by Océ-Technologies. In this paper we describe the challenges in upscaling this technology from process research to additive manufacturing research capable of making multi-metal 3D objects.
To enable high quality metal printing, chemical reactions of the ambient atmosphere with the molten metal must be prevented, and an inert environment close to the heated cartridges is required. To this end, the process chamber of the printer is filled with high purity argon from the bottom of the chamber, exploiting a laminar flow driven by the density difference between the argon and the atmospheric gases. The substrate holder of the printer can be heated to 500 °C while maintaining a high dynamic stability during stage movement. The heated part of the substrate holder is made of tungsten-copper to ensure high thermal conductivity and high mechanical stiffness (eigenfrequencies > 500 Hz). Inconel flexures are employed to achieve a thermal decoupling of the substrate holder, while providing high mechanical stiffness at the specified working temperatures. To eliminate alignment errors, errors in jetting angle and speed, and time of flight errors, the printer is calibrated a priori using a vision system based on dark field illumination of the droplets. A bi-telecentric lens is used to minimize distortions resulting in a single drop reproducibility error of 1 µm. It is shown that the sophisticated thermal design of the substrate holder, a state-of-the-art stage and a highly accurate vision system enable a droplet to droplet accuracy of less than 7 µm.

Additive manufacturing, jetting of metals, high precision stage, thermal engineering

1. Introduction

Due to continuous progress in additive manufacturing technologies the fabrication of complex 3D structures is routinely achieved. In particular the printing concept has gained momentum since it provides for fast, low-cost, and contact-free deposition at room conditions and poses minimal disturbances to the receiver substrate, on which the material is deposited. However, printing of metals has been limited to low-melting point metals [1, 2], pastes [3, 4], and metal-containing inks [5-7]. These materials are generally not optimized in terms of material properties, e.g. mechanical strength, electrical conductivity, corrosion rate, and material cost, or suffer from limited resolution.
In the last years, Océ-Technologies demonstrated a printing concept, which was successfully employed to achieve stable and reliable jetting of pure metals - directly from the melt at temperatures up to 1600 °C [8]. Based on this concept, a first metal printing machine was developed (see Figure 1), that allows for in-depth research on additive manufacturing principles, such as the printing of multi-material 3D objects.
In this article, three major aspects of the prototype - namely: the realization of an inert processing chamber, the innovative design of a dedicated substrate holder, and the development of an optical calibration system are discussed.

2. Processing chamber

The current design of the prototype consists of four individual print-heads, which are placed in a shared processing chamber with an estimated volume of 1 m^3. In order to prevent chemical

Figure 1. Overview of the metal printing prototype.

reaction with the molten metal during the printing process, an inert process environment is realized. To minimize the time and the argon consumption of the filling process, two scenarios based on turbulent and laminar flows were assessed.
To this end, a simple model of the turbulent filling process was employed. It can be shown that the turbulent mixing process leads to a logarithmic decay of the concentration of atmospheric gases and inert conditions are achieved after approximately 2 hrs. Consequently, a relatively high amount of argon (>13m^3) is required to flush the process chamber.
Next, CFD simulations were performed to compute the time needed for a filling process, which exploits the density gradient between argon and air, see Figure 2 (a). The resulting laminar argon flow is computed to decrease the filling time significantly and inert conditions are achieved after less than 10 min. Consequently, also a decreased amount of argon (1.3 m^3) is needed to fully flush the process chamber and to achieve inert conditions. However, validation experiments indicated a less

(a) (b)

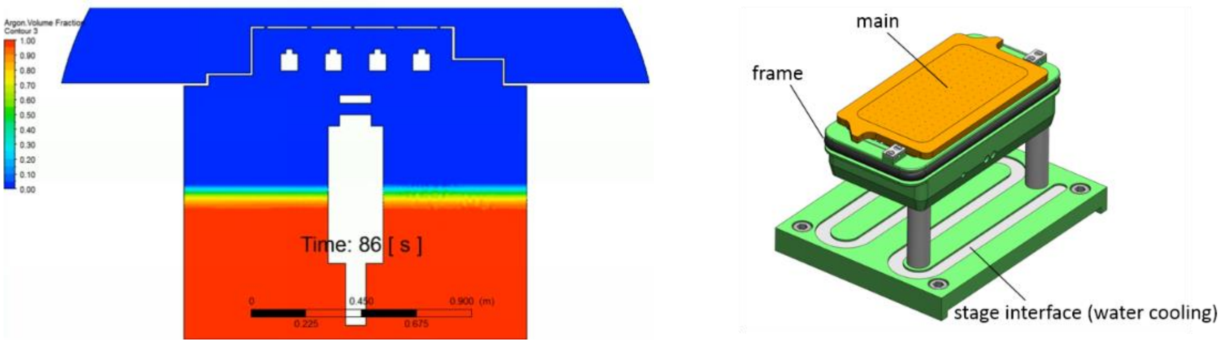

Figure 2. (a) CFD simulation of the argon (red) filling, using the laminar flow. The air (blue) is pushed outwards via small openings, located at the top of the process chamber. The white shapes refer to the four printheads (top), the substrate (center) and the z-stage (bottom) . (b) A CAD of the substrate holder indicating the main body, the frame, and the water cooled stage interface.

efficient and therefore significantly slower filling process. The time needed to fully flush the process chamber increased by a factor of four, which is assumed to be related to imperfections in the laminar flow, and the outgassing of micro-cavities in the process chamber during the filling process.

3. Substrate holder

In order to achieve high quality printing results at high printing speeds, a custom made substrate holder is required. This holder needs to ensure accurate positioning of the substrate and must allow for a feedback controlled substrate temperature of up to 500 °C. Moreover, the temperature gradient across the surface of the substrate holder is minimized to less than 10 °C. Based on these requirements a thermally decoupled substrate holder was developed. Figure 2 (b) shows the design of the substrate holder. The main body consists of a tungsten-copper alloy (50/50), which provides high mechanical stiffness (eigenfrequencies > 500 Hz) at high temperatures, while providing a sufficient thermal conductivity to minimize the temperature gradient across the substrate area. The temperature of the main body is controlled using ceramic heat emitters and two thermocouples, which are embedded in the main body of the substrate holder.

Inconel flexures were employed to achieve a thermal decoupling of the main body from the frame, while providing high mechanical stiffness at the specified working temperatures of 500 °C. In addition, the temperature of the stage interface of the substrate holder is cooled using water. The temperature at the interface to the high precision stage was simulated to vary less than 1 °C, and is therefore assumed to be not affected by the heating of the substrate. Finally, mechanical and vacuum clamping are available to fix the substrates on the heated surface.

4. Optical vision system

Droplet velocity and jetting angle, as well as the actual positions between the individual printheads and the varying velocity of the translation stages have an impact on the final position of a printed droplet on the substrate. To calibrate the system in order to compensate for potential positional errors of the droplets on the substrate, an optical measurement system is employed.

To minimize distortions, the system uses a bi-telecentric lens that provides a constant magnification independent of the object location. Dark field illumination using a low-angle ring light ensures a maximum contrast between substrate and droplet, and thus allows for an accurate determination of the circumference of each printed droplet. Finally, the central position of each droplet is determined and further processed to optimize the process parameters, with respect to a uniform printing process, i.e. equidistant spacing between the individual droplets. Using calibrated test samples, the accuracy of the measurement system was verified to be less than 1 µm. The overall droplet to droplet accuracy of the printing machine was derived from tolerance measurements of the individual components involved. To this end, several methods have been employed and the total positioning error was calculated to be less than 7 µm.

5. Conclusions

This article provides a brief overview about the design and development of a prototype high resolution metal printing machine, which allows for the jetting of metals directly from the melt. To this end, design considerations of the inert processing chamber, the design of a dedicated substrate holder, and the development of an optical calibration system were discussed. It was shown that the sophisticated thermal design of the substrate holder and a highly accurate vision system enable an overall droplet to droplet accuracy of 7 µm. The presented printing machine is understood as an important step towards the industrialization of high resolution printing of metals, and future work therefore aims on the improvement and modification of the existing setup with respect to specific applications.

References

[1] K. Yamaguchi 2003 Microsystem Technologies **9**(3) 215–219
[2] Collin Ladd, Ju-Hee So, John Muth and Michael D Dickey 2013 Advanced Materials **25**(36) 5081 – 5
[3] M. Feinaeugle, A.P. Alloncle, Ph. Delaporte, C.L. Sones and R.W. Eason 2012 Applied Surface Science **258** 8475 – 8483
[4] S. A. Mathews, R. C. Y. Auyeung, H. Kim, N. a. Charipar, and A. Piqué 2013 Journal of Applied Physics **114**(6) 064910
[5] Jolke Perelaer, Patrick J. Smith, Dario Mager, Daniel Soltman, Steven K. Volkman, Vivek Subramanian, Jan G. Korvink and Ulrich S. Schubert 2010 Journal of Materials Chemistry **20**(39) 8446
[6] Bong Kyun Park, Dongjo Kim, Sunho Jeong, Jooho Moon and Jang Sub Kim 2007 Thin Solid Films **515**(19) 7706–7711
[7] Seung Hwan Ko, Jaewon Chung, Nico Hotz, Koo Hyun Nam and Costas P. Grigoropoulos 2010 Journal of Micromechanics and Micro-engineering **20**(12) 125010
[8] Océ Innovate Magazine Spring 2015 40 - 46