ENHANCED LIQUID METAL MICRO DROPLET GENERATION BY PNEUMATIC ACTUATION BASED ON THE STARJET METHOD

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SUMMARY

We present a **novel pneumatic actuation system for generation of liquid metal droplets** according to the so-called StarJet method. In contrast to our previous work [1, 2], the performance of the device has been significantly improved: The **maximum droplet generation frequency** in continuous-mode has been **increased** to f_{max} **= 11 kHz** (formerly f_{max} = 4 kHz). In addition, the **droplet diameter** has been **reduced to 60 µm** by a **new design** of the **star shaped nozzle** made from silicon by MEMS technology. The size of the metal reservoir has been increased to hold up to 22 mL liquid metal and the performance and durability of the **actuator has been improved by using stainless steel and a second pneumatic connection.** Experimental results are presented regarding the characterization of the droplet generation as well as printed metal structures.

KEYWORDS

StarJet, Molten Metal Droplets, 3D-Printing, Rapid Prototyping, Droplet Generator

INTRODUCTION

The generation of micro droplets of liquid metals is a challenging area in the field of MEMS technologies. It is applicable in a large field of applications such as the generation of electrical 2D / 3D connections or metal layers in the field of microelectronics or MEMS [3][4], rapid prototyping of electric circuits [5] or 3D prototyping of small metal structures [6,7]. However, the generation of single micro droplets from molten metal at high temperatures is a highly complex task for several reasons: First of all, the dispenser must operate at temperatures above the melting point of the metal. Therefore, all parts of the device must be either fabricated of temperature stable materials or have to be thermally insulated from the hot parts of the system. Especially piezo actuators must be isolated [3] or actively cooled to prevent their destruction. The operation temperature of these materials is limited by the Curie temperature, typically ranging between 150°C and 300°C [8]. Also, the mechanical stress induced by heating up or cooling down the dispensing device requires certain design rules to be considered e.g. material combinations with suitable modulus of elasticity and appropriate coefficients of thermal expansion. Furthermore, the molten metal inside the device as well as the ejected droplets have to be shielded from oxidation by e.g. the application of protective gas.

The StarJet technology used for the dispensing of liquid metals droplets in the presented work is based on a pneumatic actuation principle. The gas flow which works as actuation mechanism avoids the oxidation of the liquid metal inside the reservoir of the device as well as the dispensed metal droplets in flight. The entire device consists of a pneumatic actuator module made from brass and a star shaped micro nozzle fabricated by silicon micromachining. All connections are sealed by high temperature stable materials e.g. Nova Mica. Thus, the limitation for the maximum operating temperature is the melting point of only the actuator material itself. In consequence, the StarJet technology should be suitable for generating liquid metal droplets of all kinds of metals with high melting points without suffering from the aforementioned problems.

EXPERIMENTAL SETUP

In contrast to the first StarJet droplet generator [1,2,9], the new actuator is made of stainless steel (Fig. 1) providing enhanced durability and higher working temperatures.

Figure 1: Enhanced StarJet actuator made from stainless steel.

The reservoir has been enlarged from 127mm³ to 22000 mm³ enabling the printing of extensive structures without refill. Through a drilling hole (D = 400 µm) at the bottom of the reservoir, the molten metal is transferred to the nozzle chips. The alignment of these chips is done by a laser fabricated positioning spring and fittings. In contrast to our previous work, the connection to apply nitrogen for driving the droplet ejection and the connection for rinsing the bypass channels are now separated (see Fig. 2). The pressure pulses can hence be applied faster and with a more precise timing improving the drop-on-demand functionality (DoD) significantly.

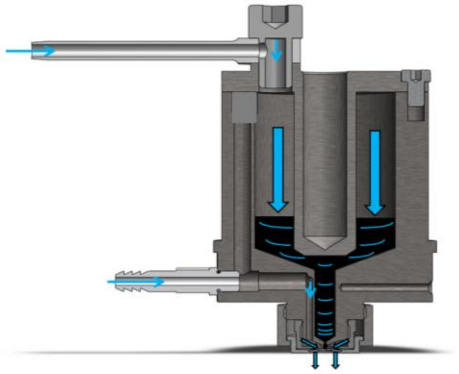

Figure 2: Model cross-section of the StarJet actuator. Blue arrows indicate the pneumatic actuation.

Therefore, an external solenoid valve (Festo GmbH) regulates the gas flow of the inert gas for pneumatic actuation by switching between a low pressure (10 hPa to 30 hPa) to prevent oxidation of the molten metal inside the reservoir and a higher actuation pressure (150 hPa to 1000 hPa) initiating the droplet ejection. The rinse pressure can be adjusted separately to match to the actuation pressure. The reservoir is covered by band heating element (Tueerk-Hillinger GmbH) and in addition a cartridge heater (Hotset GmbH) is placed inside the reservoir. The temperature is monitored by a NiCr-Ni thermopile sensor placed close to the reservoir outlet. The measured temperature is used for a closed-loop temperature regulation. The temperature control as well as the valve control is realised by a self-developed electronic control unit which is connected to a PC via USB port. This unit allows for precise, time defined actuation of the valve in combination with autonomous control of the reservoir temperature.

The fabrication of the StarJet nozzle chips is conducted using the established manufacturing process (see [9]). However, the nozzle size has been reduced by half to 50 µm utilizing a novel chip design via redesigning the photolithography masks. The experimental setup presented in this paper consists of the described StarJet actuator mounted above an x-/y-z-stage. In addition, a spinning axis can be mounted on this stage. Hence in contrast to earlier experiments, the distance between the nozzle and the substrate can be adjusted during the experiments.

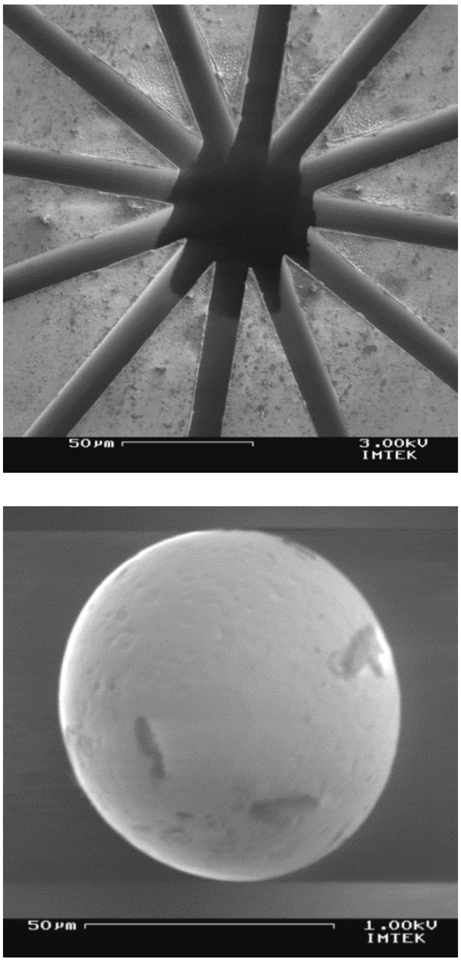

Figure 3a) REM picture of the silicon nozzle chip 3b) REM picture of a metal droplet generated with a 50 µm nozzle chip.

EXPERIMENTAL RESULTS

The StarJet technology features two different dispensing modes, the DropOnDemand-mode and the Continuous-mode (for details see [1]). Experiments presented in this paper were performed using both operation modes. In Continuous-mode, droplets are issued from the nozzle continuously at a certain “natural” frequency. This frequency depends on the nozzle geometry, the applied actuation pressure in combination with the rinse pressure and other parameters. Thus, each nozzle chip features an individual frequency range depending on the specific nozzle geometry. Since the new actuator exhibits two pneumatic connections (cf. Fig 2), the rinse pressure can now be adjusted independently of the driving pressure. This enables droplet frequency adjustment at fixed driving pressure (cf. two channel setup blue frames in Fig.4). Thereby, the lowest value is given by P_{rinse_min} which is the minimum rinsing pressure required to prevent a continuous jetting. The upper boundary P_{rinse_max} is the smallest value that inhibits droplet ejection (at fixed driving pressure). In contrast, the red markers show the frequency/pressure relation of the earlier single channel setup.

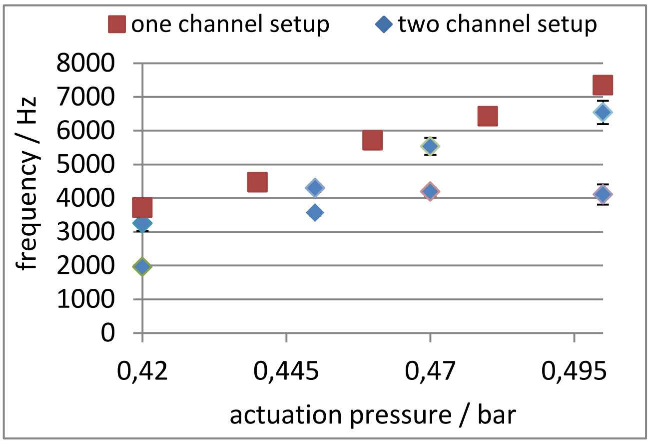

Figure 4: Measurement of droplet generation frequency as function of actuation pressure for 80 µm nozzle-chip.

Actuation pressures beyond $P_{actuation\_max}$ led to uncontrolled spraying of metal droplets. In several experiments, frequencies in the range from f_{min} = 200 Hz to f_{max} = 11 kHz where evaluated. With the redesigned nozzle (Fig. 3a), a minimum droplet diameter of D_{min} = 60 µm (Fig. 3b) has been achieved using a 50 µm nozzle chip. We also observed that droplet trajectory and the occurrence of satellites can be optimized by the rinse pressure. The droplet diameter is primarily defined by the nozzle size (D = 50 µm to 360 µm available). By dispensing single droplets at 350°C with a frequency of 5.5 kHz onto a spinning axis, coils can be fabricated using continuous operation. The adaptation of the dispensing frequencies and the rotation velocity of the axis allowed for printing homogeneous structures. Here, the single droplets merge after impact resulting in a solid structure (see Fig.5).The samples have been created at room temperature without any additional heat conditioning or post treatment.

Figure 5: Coil like structures printed at 350°C metal temperature.

By dispensing multiple layers of single droplets onto a moving substrate, walls can be created. Here, the distance between two droplets has to be set to double the value of the droplet diameter. Thus, the droplets don`t merge together resulting in a porous structure (See Fig. 6).

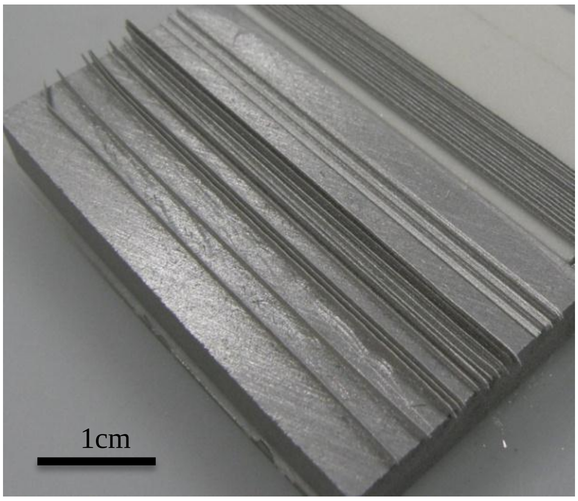

Figure 6: Walls printed at 350°C metal temperature on aluminum substrate.

The close-up view reveals that the droplets loose their spherical shape and solidify in a reformed state while impinging on the solid (See Fig. 7). This leads to a high surface roughness as well as to an enhanced wall thickness of 250 µm compared to the droplet diameter of D = 80µm. The surface of the printed structure has been measured with a profiler (Tencor, P11) to characterise the roughness of the walls. The structure exhibits an average surface roughness of R_t = 94 µm.

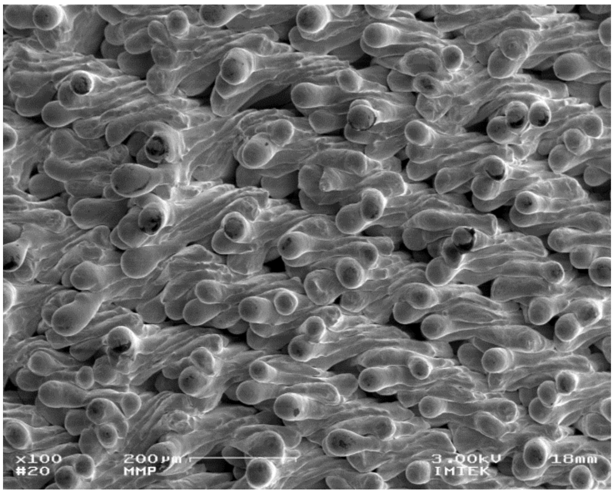

Figure 7: SEM image of a surface of printed solder wall.

Remarkably, only minor oxidization occurs on the surface of the printed structures, which is attributed to the pneumatic actuation by Nitrogen as described above. This example demonstrates that it is possible to influence the properties of the printed structures (morphology, porosity, wall thickness, roughness etc.) by variation of the process parameters. When operating in Drop on Demand mode, the actuation pressure is applied only in short pulses each leading to the ejection of one single droplet. This is done by opening a solenoid valve periodically for 3-8 ms. The rinse pressure is kept constant all the time to prevent oxidation at the nozzle outlet. A suitable valve opening time in combination with the matching actuation pressure leading to the ejection of single droplets has been experimentally determined for each nozzle chip. However, multiple combinations of valve opening time and actuation pressure are feasible for each chip. The printhead was successfully tested for 5 hours for continuously ejecting droplets in drop-on-demand mode without interruption at frequencies up to 25 Hz. A nozzle chip, generating droplets of D_{drop} = 80 µm, was used to print our affiliation logo on an aluminum substrate (see Fig. 8).

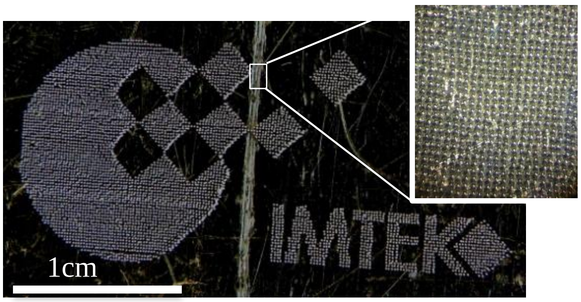

Figure 8: Printed IMTEK Logo, droplet diameter approximately 80 µm.

CONCLUSION & OUTLOOK

The described improved StarJet metal dispenser was successfully tested experimentally in continuous and DoD-operation mode. The miniaturized nozzle chip in combination with the V2 actuator with two pneumatic connections allows for higher frequencies (f_{max} = 11 kHz) and generation of smaller droplets (D_{min} = 60 µm) than before. By adjustment of the rinse pressure, the dispensing frequency can be adjusted. Furthermore, the occurrence of satellites is highly unlikely. The presented results show that the StarJet technology can be successfully applied for the 3D-prototyping of porous and non-porous metal structures. The presented structures demonstrate that depending on droplet temperature as well as other printing parameters, the porosity and wall thickness of the printed structures are controllable. The presented results are of course only a first step towards the controlled prototyping of metal micro-structures by direct printing of liquid metal. More work has to be dedicated to study the solidification and the resulting morphology of the metal surface as a function of materials and process parameters before more complex shapes can be generated. In the next step, the StarJet method will be applied at even higher temperatures to enable a wider choice of materials to be used for direct metal printing.

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