STARJET-BASED, PNEUMATICALLY ACTUATED LIQUID METAL DROPLET PRINTING AT UP TO 500 °C

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SUMMARY

In this work, we present a novel generation of pneumatically actuated printheads based on the StarJet technology which have been successfully applied for the direct non-contact printing of droplets from molten metal [1, 2]. This paper reports the technological advances of the newly designed printhead V3 which for the first time has been fabricated by selective laser melting (SLM). The StarJet technology features an inert rinse gas that surrounds the droplets inside the nozzle. V3 features an integrated heating for rinse gas which prevents the droplets from fast solidification and oxidation after ejection, as they are surrounded by hot nitrogen gas. The feasibility of the StarJet technology is demonstrated for printing at temperatures up to 500 °C. Moreover, the angular deviation of the droplets' flight path has been investigated. A maximum angular deviation of 0.89° has been evaluated. The droplets' velocity after ejection and the influence of the different pressures on this parameter have been investigated.

KEYWORDS

StarJet, Molten Metal Droplets, 3D Printing, Rapid Prototyping

INTRODUCTION

The direct non-contact printing of liquid metal droplets offers a large number of possible industrial applications, and has the potential to replace currently established processes. This includes direct metallization of solar cells, formation of electrical contacts on printed circuit boards (PCBs), 3D integration of microelectronics in hybrid packages as well as the fabrication of micro structured metal layers on polymers for molded interconnect devices (MIDs) [3]. Especially the direct placement of solder balls on PCBs is of high interest in this field [4].

It is however still challenging to generate droplets from molten metals in the micrometer scale. The StarJet technology utilizes a star-shaped nozzle which forms and centers the droplet of molten metal inside the orifice before it is ejected [1]. Figure 1 depicts an SEM view of a StarJet nozzle chip with the star-shaped orifice and the rinse gas channels surrounding it.

The chip is attached to the printhead which is pneumatically actuated and features two gas inlets for e.g. nitrogen. For the generation of droplets, two individual gas pressures are used: The actuation pressure is used to apply a short pressure pulse on top of the molten metal reservoir to push metal in the nozzle.

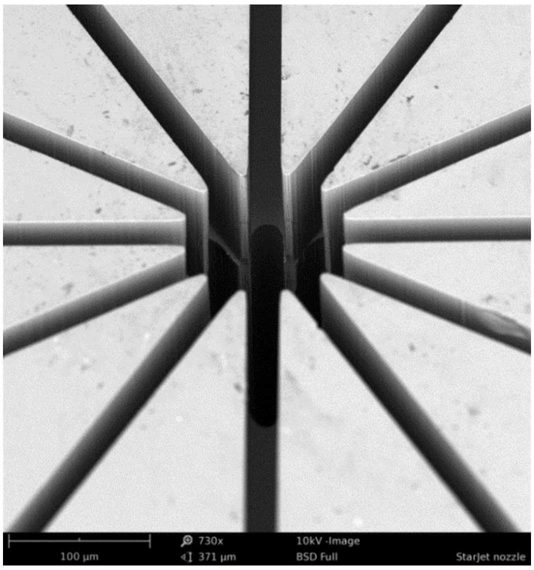

Figure 1: SEM view of a StarJet nozzle chip made from Si with star-shaped nozzle orifice (center) and surrounding rinse gas channels.

The rinse gas pressure results in an even flow through the bypass channels of the chip, surrounds the droplets in the nozzle and directs its path after ejection. It also prevents oxidation of the droplets. This technology currently enables the direct printing of metal droplets with diameters down to 60 µm.

The pneumatic actuation principle has several advantages over other actuation principles such as piezoelectrically driven devices, which are limited in their maximum operating temperature due to depolarization of the actuator above their Curie temperature. This usually limits the operating temperatures to below 350 °C or requires complex thermal shielding above this temperature for the actuator [5, 6, 7]. The maximum operating temperature of the StarJet technology is however only limited by the melting temperatures of the printhead material. The technology is therefore not inherently limited but in principle feasible for the direct printing of higher melting metals.

In this work, the pneumatic actuation principle has been further improved over the previously developed printhead V2 to allow for higher printing temperatures.

For industrial applications a high repeatability and low deviation of the droplets' flight paths are of importance as these enable precise placement of droplets on substrates. Therefore, the angular deviation of the droplets after ejection, depending on rinse and actuation gas pressures, has been investigated.

FABRICATION AND EXPERIMENTAL SETUP

Like the previous version V2 of the actuator [2], the novel version V3 is made of stainless steel to ensure high temperature stability. However, for V3, the fabrication technology selective laser melting (SLM) is used. Figure *2* depicts an exploded view of printhead V3.

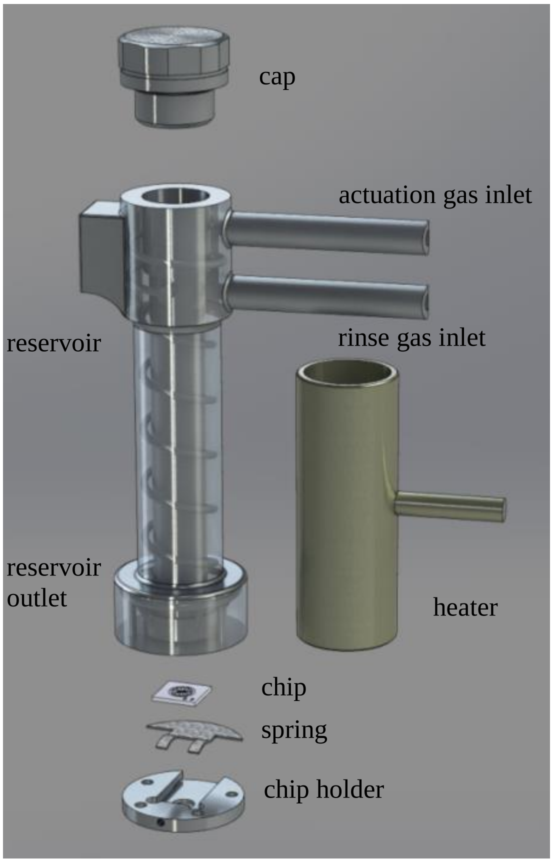

Figure 2: Exploded view of StarJet V3 actuator with integrated heating channels for rinse gas surrounding the reservoir.

The SLM process enables the fabrication of gas channels in the side-walls of the printhead (Figure 2), which allows for pre-heating of the rinse gas before it comes in contact with the molten metal. This not only reduces the risk of oxidation but also effectively prevents an undesired cooling of the metal droplets, which is especially important for high printing temperatures.

The StarJet nozzle chips are fabricated from silicone by deep reactive ion etching (DRIE) processes and are attached below the outlet of the main reservoir which has a small reservoir outlet tube with a diameter of 400 µm. The droplet diameter primarily depends on the chip orifice diameter and can thus be tuned by exchanging the nozzle chip. For the desired droplet diameter, a chip with a suitable orifice diameter can be chosen. Typical orifice diameters of chips in operation range from 50 - 200 µm. The newly developed chip holder for printhead V3 features a spring which presses the chip under the reservoir outlet. The chip can be slid into the chip holder from the side. This allows for nozzle chip exchange without dismounting the chip holder. The printhead has been miniaturized in comparison to the previously developed V2, to allow for easier system integration. The reservoir features a volume of 1500 mm^3. To melt the metal inside the reservoir, the complete printhead assembly is heated up to the necessary temperature by a heater which surrounds the printhead as depicted in the explosion view (Figure 2).

Like the previous version, V3 can be used in two different operation modes. In the Continuous Mode, a constant rinse gas pressure and a constant actuation pressure are applied to the chip and reservoir. This leads to a continuous formation of droplets at high frequencies of up to 11 kHz. The second operation mode is the Drop-on-Demand mode, where a constant rinse gas pressure is applied and short actuation pressure pulses on top of the reservoir lead to the formation of individual droplets. For the pressure pulses a pneumatic high speed valve was used (Type*: MHE2MS1H-3/2G-M7-K, Festo, Germany*) which is opened for 5 ms for each individual droplet. Presented results were created using Drop-on-Demand mode. For printhead V3, low pressures in the range of some 10 mbar for the actuation pressure and some 100 mbar for the rinse gas pressure have to be applied.

The droplet ejection and flight path are investigated with a high speed camera (*MotionBlitz, Mikrotron, Germany*), by visualizing the nozzle outlet and the first millimeters of flight path. For this, the deviation from the straight path is evaluated after 1 mm distance from the nozzle, which is a typical distance between nozzle and substrate when printing structures.

EXPERIMENTS

Printing at 500 °C

The maximum operating temperature of the StarJet technology has been extended from previously 350 °C to up to 500 °C. At 350 °C the technology is limited to the direct printing of solder balls. Based on the technology, it was possible to produce droplets of molten metal from the alloy Zamak (Zn96Al4) in Drop-on-Demand mode (Figure 3). To achieve this, the printhead had to be heated up to 500 °C. The depicted droplets were printed with a nozzle chip orifice diameter of $d_{\mathrm{orifice}} = 140\ \mu\mathrm{m}$, leading to droplet diameters of $d_{\mathrm{droplet}} = 180\ \mu\mathrm{m}$.

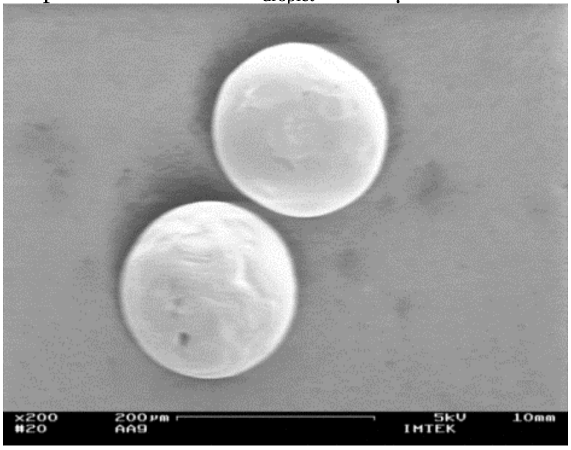

Figure 3: Droplets from Zamak (d = 180 µm), printed using the StarJet technology.

Velocity and angular deviation analysis

Moreover, the deviation in flight path for printed solder droplets in Drop-on-Demand mode was further investigated, as the precision of droplet placing is crucial for industrial applications. In the same series of experiments, the velocity of the droplets after ejection and the correlation with adjusting the rinse gas pressure for a constant actuation pressure was also investigated. A chip with nozzle diameter $d_{\mathrm{nozzle}} = 183\ \mu\mathrm{m}$ was used for these experiments.

The rinse gas pressure can be adjusted independently from the actuation gas pressure. The droplet generation is possible in a certain parameter range for actuation pressure and rinse pressure and possible combinations mainly depend on the diameter of the nozzle orifice. For the experiments, a variable rinse gas pressure and a constant actuation pressure of $p_{\mathrm{actuation}} = 0.02$ bar were applied in order to investigate the impact of a variable rinse gas pressure on droplet ejection. For a given actuation pressure, the rinse pressure can be varied in the range of some 10 mbar and has a direct influence on the velocity of the droplets. Figure 4 shows the ejection of one single solder droplet from a chip with $d_{\mathrm{orifice}} = 183\ \mu\mathrm{m}$ ($p_{\mathrm{rinse}} = 0.11$ bar, $p_{\mathrm{actuation}} = 0.02$ bar).

For the actuation pressure $p_{\mathrm{actuation}} = 0.02$ bar, the rinse gas pressures 0.11 bar, 0.12 bar and 0.13 bar were each applied to create 10 individual droplets. Figure 5 displays the results from these measurements. The droplet velocity for a constant actuation pressure rises for an increasing rinse pressure. This indicates that the droplet velocity can be directly influenced by adjusting the rinse gas pressure in a certain parameter range.

Moreover, it was investigated in this context if different rinse gas pressures for constant actuation pressures have an impact on the flight path of the droplets. Table 1 shows the mean deviation in flight path for three different rinse pressures 1 mm after ejection. For each run, ten droplets were generated.

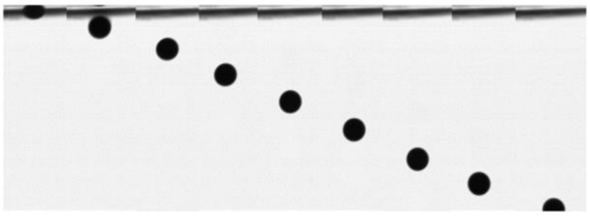

Figure 4: Image series of an ejected solder droplet from the StarJet printhead V3.

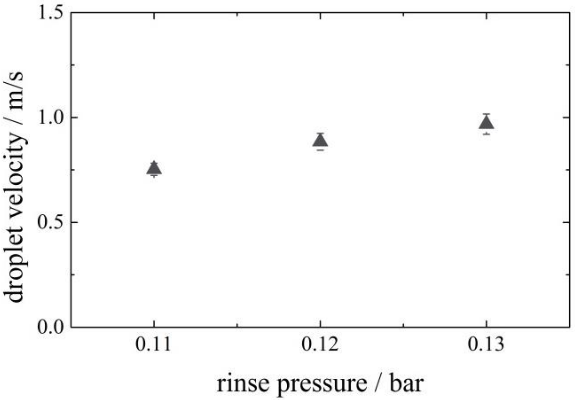

Figure 5: The droplet velocity for increasing rinse pressure and constant actuation pressure of $p_{\mathrm{actuation}} = 0.02$ bar.

The angular deviation slightly decreases for higher rinse gas pressures in this series of measurements. This indicates that a higher rinse gas pressure can lead to a better guiding of the droplet after ejection. Comparing the deviation of the droplets with the droplet diameters, it can be stated that the deviation is relatively small. The mean value is in the range of 10 µm, whereas the droplet diameter is around 200 µm. There are however some outliers and the maximum deviation in flight path for $p_{\text{actuation}} = 0.02$ bar amounts to 26 µm, which explains the standard deviations for the measurement (Table 1). Moreover, in this measurement, for higher rinse gas pressures (0.13 bar), the number of outliners decreases significantly, as the lower standard deviation indicates.

Table 1: Standard deviation of droplets' flight path after ejection depending on different rinse gas pressures for $p_{\text{actuation}} = 0.02$ bar.

Actuation pressure / bar	**Mean deviation / µm**	**Standard deviation / µm**
0.11	13.2	9.8
0.12	11.1	6.7
0.13	7.3	4.4

The experiments have been extended to a series with different actuation pressures and the deviations have been investigated. A maximum angular deviation of 0.89° was found over a series of experiments with different rinse and actuation gas pressures. The mean angular deviation was found to be even smaller at 0.26°.

CONCLUSION

The StarJet technology currently allows for the drop-wise printing of molten metals at up to 500 °C while in general exhibiting a very low angular deviation in droplet flight path. The droplets are pneumatically generated with the two independent gas pressures, rinse gas and actuation gas. These two gas pressures allow for a direct control of droplet generation and have an influence on the droplets’ velocity after ejection. It is indicated that for a given actuation pressure, the rinse gas pressure can be used to control the droplets’ velocity after ejection from the nozzle. The mean angular deviation of the droplets’ flight path has been found to be only 0.26° and the maximum angular deviation is only 0.89° for a given series of experiments. This high accuracy and repeatability show that the StarJet technology has the potential to be used in industrial applications, where the precise placement of metal droplets is required.

Further research is carried out in order to enable droplet printing at even higher temperatures than shown here, targeting aluminum or silver at up to 1000 °C. This ultimately may pave the way for new approaches for the fabrication of 3D interconnects.

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