Corrigendum

Corrigendum: Design and Experimental Study on Pneumatic Extruding Direct-writing Deposition for Multi-materials (J. Phys.: Conf. Ser. 1074 012145)

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In the original published article, an incorrect version of figures 6 was used, and the correct figure 6 is provided here.

Fig. 6. (1) 3D parts fabricated by PEDWD; (2) an image of the cross section of the 3D parts.

The correction of figures 6 does not affect any of the results discussed in the paper, and the rest of the main text remains unchanged.
We apologize to the editor and the readership.
Design and experimental study on pneumatic extruding direct-writing deposition for multi-materials

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Abstract. To develop a low-cost direct-writing-based additive manufacturing for multi-materials, a concept design of pneumatic extruding direct-writing deposition (PEDWD) was presented in this paper. Sn63Pb37 alloy and YH-W906 paraffin wax were used as raw materials in this study, they were heated to be molten in the chambers. Under the driving of compressed nitrogen, the molten materials were squeezed out from the nozzle and formed parts on an aluminium alloy substrate. By conducting the experiments and measuring the shape of deposited two-dimensional (2D) and three-dimensional (3D) parts, the influence induced by the structure design of nozzle and driving pressure on the mass flow rate of molten material was analysed both theoretically and experimentally. The stability and reliability of PEDWD were proved by the final successful fabrication of 2D and 3D parts. This paper shows that PEDWD provides a novel way to fabricate parts for multi-materials with low-cost and flexibility.

1. Introduction
The direct writing (DW) technology is a group of process technologies that achieves the deposition, dispersion or processing various materials onto different types of substrates driven by the pre-designed graphic data [1]. Based on their basic working principle, DW can be divided into three types, namely micro-droplet-based DW, high energy beam-based DW, micro-flow-based DW and tip-based DW [2]. The key of micro-droplet-based DW is the controlling of the precision of micro-droplet; high energy beam-based DW has a higher processing precision, but the processing equipment is expensive; micro-droplet-based DW and micro-flow-based DW both have a higher efficiency than beam-based DW. In a micro-droplet-based DW process, the liquid function material is discretized as individual droplets, but in a micro-flow-based DW process, the delivery of material is continuous, hence, the shape precision of the parts fabricated by micro-droplet-based DW is obviously lower than that of micro-flow-based DW. Because of material limits, the application scope of tip-based DW is narrow.

In a micro-flow-based DW process, the materials are deposited directly on a substrate and become the desired structure or patterns with no tooling or masks. Micro-flow-based DW mainly includes three categories: nozzle dispensing processes, quill-pen printing processes and aerosol DW [3]. Li et al. [4] presented the DW nozzle dispensing technique which employed a smart pump to provide driving force to deposit materials on different substrates. Using special functional ink, this nozzle dispensing technique produced lines with 75 μm line width, dots with 85 μm diameter, two-dimensional (2D) and three-dimensional (3D) structures such as scaffold, thin-wall cylinder. Based on the principle of quill-pen, Zheng et al. [5] designed a pinhead mounted a porous fur brush for ink printing of liquid alloys.
The porous fur brush was used to overcome the high surface tension and make the ink attach well to the different types of papers. Smay et al. [6] assembled 3D structures by adopting direct writing of colloidal gel-based inks. As raw material, the electro-ceramic and metal powder electrode compositions were mixed, dispersed in aqueous solutions, and then, gel solutions was added to the previous dispersion to obtain colloidal gel with appropriate rheology. Using the discrete nozzles and colloidal gel ink of ceramic and metal, 3D multilayer structure was printed out. The final sintering removed superfluous material and made ceramic and metal powder bond together. The above-mentioned DW technology all need inks, these inks solidify to bond together depends on post processing such as evaporation, gelation, solvent-driven reactions, to leave only the desired materials after deposition [3], the whole process is relatively complex. At present, a large number of academic researchers worldwide take efforts to develop new and improved printable inks for DW. But the research on micro-flow-based DW technology that deposit hot molten materials on to the substrate to forms 2D or 3D structures without post processing has seldom been reported.

This paper proposed a micro-flow-based DW technology named pneumatic extruding direct-writing deposition (PEDWD), which selected hot molten material as deposited material and employed compressed nitrogen as driving force. Under the driving action of compressed nitrogen, the material was squeezed out from the nozzles, and formed lines, surfaces or solids on the substrate. The influence of critical process parameters on the final quality of the part fabricated by PEDWD was investigated. Two structure designs of nozzles was proposed, and the change of inner flow field induced by the different structure design was analyzed both theoretically and experimentally. Finally, 2D and 3D parts were fabricated successfully.

2. Materials and methods
A PEDWD experimental apparatus was proposed as shown figure 1. The pressure & valve controller regulated the compressed gas coming from the nitrogen source to be an appropriate pressure value. When a DW deposition started, the piston rod was lifted by a cylinder, and the compressed nitrogen force the molten material flow out from the nozzle onto the moving substrate to form parts. When the deposition was completed, the piston rod moved down and its lower end moved into the hole on top of the nozzle (figure 2). Meanwhile, the valve between the chambers and the nitrogen source was closed, and the valve between the chambers and the vacuum tank (vacuum degree:-7000—9000 Pa) was open, the negative pressure in the chambers and the rod inserted into the hole jointly prevented the anymore molten material to flow out. The raw material was put into chamber A to be heated to be molten, a stainless steel filter screen was placed in Chamber A to avoid clogging the nozzle. In order to measure the low working pressure of the chamber precisely, A U-type water manometer was installed in the apparatus. The temperature of the chambers was controlled by the temperature controller that employed k-type thermocouple. 3D platform can moves at X, Y, Z direction respectively. All movements of the 3D platform, opening and closing of valves were controlled by a computer system.

![Figure 1. Schematic diagram of the experiment apparatus.](image-url)
Two materials were used in this study: Sn63Pb37 metal alloy, the other material was commercial YH-W906 paraffin wax that was usually as raw material of the investment casting. The two materials both had good fluidity and lower viscosity, which were applicable to the DW experimental study. The outflow channel of the nozzles was cylindrical shape. The DW experiment results of different materials are investigated respectively in next section.

3. Results and discussion

3.1. Sn63Pb37 metal alloy

The molten Sn63Pb37 was assumed to be incompressible, and the maximum predicted value of Reynolds number was 250, which is too small to induced turbulence, and the flow of molten Sn63Pb37 was set to be laminar in the nozzle[7]. The mass flow rate controlling of liquid plays a critical role in the shaping of the deposited parts, so, the study on the mass flow rate controlling is very important. Based previous assumption, the mass flow rate at the orifice of the nozzle \( Q_v \) can be presented by Hagen–Poiseuille equation[8]:

\[
Q_v = \frac{\pi d^4}{128 \mu h} \Delta p
\]

Where \( d \) and \( h \) were the diameter and height of the outflow channel of the nozzle, respectively; \( \mu \) was the viscosity of the molten material, and was constant; \( \Delta p \) was pressure difference between the upper end and lower end of the outflow channel of the nozzle. From (1), the mass flow rate was influenced by the fourth powder of \( d \). The diameter of the outflow channel had a more important role than other parameters in the mass flow rate controlling. Under \( d = 0.2 \text{ mm} \), the distance between the nozzle and substrate \( l_c = 1.0 \text{ mm} \), \( \Delta p = 5000-25000 \text{ Pa} \), the velocity of the substrate \( v_s = 20 \text{ mm/s} \) and the temperature of the chamber was kept at 263 \(^\circ\text{C} \), the deposited metal lines were continuous but not uniform, see figure 3. When \( d = 0.3 \text{ mm} \), the continuous and uniform metal lines were obtained.

![Figure 3. Metal line fabricated by nozzle with \( d = 0.2 \text{ mm} \).](image)

Due to the small diameter, using an increased height nozzle is difficult. In addition to \( d \) and \( \Delta p \), the design of nozzle also can adjust the mass flow rate directly. Thus, two different nozzle designs were introduced and shown by figure 4, in which \( d = 0.3 \text{ mm}, h = 1 \text{ mm} \), and the throttle channel had the same sizes with the outflow channel.

From conservation of mass:

\[
\rho A_w v_s = \rho A_o v_n
\]

Where \( \rho \) was the density of molten material; \( A_w \) was the cross-sectional area of the deposited lines; \( v_n \) was the flow velocity of molten material at the outlet surface of the nozzles; and \( A_o \) is
the cross-sectional area of the outlet of the nozzle. From above-mentioned, the metal lines fabricated with nozzle with \( d = 0.3 \text{ mm} \) were continuous and uniform, it was reasonable that \( A_w \) was used to characterize the influence of \( \Delta p \) and structure design of nozzles on mass flow rate.

![Throttle channel](image)

**Figure 4.** Two different nozzle designs.

![Cross-sectional area of the metal lines](image)

**Figure 5.** Cross-sectional area of the metal lines.

Under \( l_G = 1.0 \text{ mm} \), different \( \Delta p \) and \( v_r = 20 \text{ mm/s} \), the deposited metal lines were fabricated by nozzles (a), (b), respectively. The cross-sectional area of the metal lines was measured using a digital microscope (VHX-600, KEYENCE CO., LTD, Japan), and shown by figure 5. The cross-sectional area increased with rising pressure, namely the mass flow rate increased with rising pressure, this was agree with equation (1). The changing rate of the cross sectional area shown that in the range of lower pressure, the influence of the change of pressure on mass flow rate weakened. The results also indicated that nozzle (b) reduced the cross sectional area by approximately 28 percent, means that a thinner metal line can be fabricated by nozzle (b), what is more, a part fabricated by nozzle (b) had a higher precision. The cross-sectional area reduction induced by throttle channel was due to the fact that after the fluid flowed out from the throttle channel, the vortices that appeared in the area downstream of the throttle channel dissipated some of the fluid’s kinetic energy [9], which in turn reduces \( v_n \), as shown by equation (2), smaller \( v_n \) produced smaller \( A_w \). As a demonstration, under \( \Delta p = 9000 \text{ Pa} \) and other previous condition, 3D metal parts were fabricated using nozzle (b), shown by figure 6(1). The metal parts were fabricated via the stacking of layers from the bottom up. The image of the cross section of the 3D parts indicated the layers bonded together. The successful fabrication of 3D parts showed the stability and reliability of PEDWD.

![3D parts](image)

**Figure 6.** (1) 3D parts fabricated by PEDWD; (2) an image of the cross section of the 3D parts.

3.2. YH-W906 paraffin wax

Molten paraffin wax belongs to non-Newtonian fluid, its viscosity was not constant under different pressure, so Hagen–Poiseuille equation (1) was not suitable for analyzation of the influence of pressure on mass flow rate of the molten paraffin wax [10]. By conducting the experiments, how the pressure affected the mass flow rate of molten paraffin wax was investigated.
Adopting nozzle (a) with $d = 0.5 \text{ mm}$, under $l_C = 1.0 \text{ mm}$, different $\Delta p$ and $v_s = 15 \text{ mm/s}$, the deposited paraffin wax lines were fabricated. Unlike the molten Sn63Pb37 that solidified immediately after it was squeezed out from the nozzle, the Sn63Pb37 liquid had no enough time to spread fully, the molten paraffin wax solidified more slowly, and the paraffin wax liquid can spread fully on the substrate before it solidified completely. Hence, the central height of all the paraffin wax line (H), defined by figure 7(1), was the same. The Change of width ($W$) can be used to characterize the influence of pressure on the mass flow rate of molten paraffin wax. The width of the paraffin wax lines fabricated under different pressure was measured by the digital microscope, shown by figure 7(2), in which the line width increased with rising pressure. The experimental results showed that the relationship between the line width and the pressure was approximately linear, this indicated that the change of pressure had no significant influence on the viscosity of molten paraffin wax in this study. Finally, Adopting nozzle (a) with $d = 0.3 \text{ mm}$, under $l_C = 1.0 \text{ mm}$, $\Delta p = 25000 \text{ Pa}$ and $v_s = 20 \text{ mm/s}$, several paraffin wax 2D or 3D parts were fabricated by PEDWD, shown by figure 8. The images shown the paraffin wax lines were continuous and uniform, the layers also bonded together.

Figure 7. (1) Definition of the height (H) and width (W); (2) Width of the paraffin wax lines.

Figure 8. 2D and 3D paraffin wax parts fabricated by PEDWD.

4. Conclusions
A pneumatic extruding direct-writing deposition based additive manufacturing was developed to fabricate 2D or 3D parts for multi-materials. The hot-melt material was melted in the chambers that were clamped by the band heaters, Molten materials contained in the chambers was squeeze out by selecting the compressed nitrogen as a driving force. The steady, continuous molten material stream was delivered from the nozzle to the moving substrate, and formed 2D or 3D structures. An experimental apparatus was built to verify the feasibility of this additive manufacturing technology. The experimental results showed that structure design of the nozzle and the pressure both significantly influence on mass flow rate of the molten materials. The throttle channel added to the nozzle reduced the flow by approximately 28 percent. Mass flow rate of the molten materials increased with rising pressure, and the relationship between the mass flow rate and the pressure was approximately linear. Finally, several 2D and 3D parts were successfully fabricated by PEDWD, and the optical images obtained from the digital microscope proved that the good interlayer bonding was achieved. It can arrived at a conclusion that PEDWD provided an additive manufacturing technology with good stability and reliability for multi-materials.
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