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Highly efficient microporous melt drop jet metal 3D printing

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Abstract

Metal additive manufacturing, also known as 3D metal printing, is a 3D printing technology based on the principle of uniform metal microdrop injection molding, which was proposed and developed by American scholar Orme in 1993.It is based on the "discrete-stacking" molding principle, through the droplet injector to produce uniform metal droplets, while controlling the movement of the three-dimensional substrate, so that the metal droplets are precisely deposited at a specific location and fused with each other, solidification, point by point and layer by layer stacking to achieve rapid printing of complex three-dimensional structures.It is a manufacturing technology that integrates computer-aided design, material processing and molding technology, digital model files as the basis, and special printing materials through software and numerical control system to create solid items by stacking layer by layer through different technologies.This technology has the advantages of wide range of injected materials, unconstrained free forming and no need for expensive special equipment, and has a wide range of applications in the fields of tiny and complex metal parts preparation, circuit printing and electronic packaging, and structural and functional integrated parts manufacturing.

Keywords

Additive Manufacturing, 3D Printing, Drop-on-Demand.

1. Introduction

In recent years, with the military and civilian areas of mechanical systems, device structures and other trends toward miniaturization, integration, lightweight development, metal parts to meet the application in such systems and devices, its size further reduced, while the structure is more complex, how to achieve functional integration, tiny size, complex shape of the metal parts of the manufacturing has become a hot spot for domestic and foreign research.Traditional microfabrication methods based on material removal principles such as, precision turning [1], precision milling [2], micro EDM [3], ion beam machining [4] and other technologies have been able to meet most of the production needs, but still have greater limitations for parts with complex cavities and thin-walled structures. In the face of this demand, the additive manufacturing principle-based additive manufacturing technology has emerged to provide a new way for the high-efficiency and low-cost manufacturing of complex tiny parts, structure-function integrated parts, etc.According to the different energy sources used by the forming equipment, additive manufacturing can be divided into laser rapid prototyping technology [5], electron beam rapid prototyping technology [6], three-dimensional micro-welding technology [7], and so on. From the principle of additive manufacturing, it is known that the molding material properties are related to the particle size of the additive, i.e., the finer the particle size of the additive and the more uniform the size, the better the mechanical properties of the molded workpiece, the more regular the surface quality, and the more accurate the molding

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dimensions, based on which scholars have proposed the uniform microdrop injection technology.

Homogeneous microdrop injection molding technology is a technique for digitally controlling the generation, distribution, and solidification deposition of micron-sized droplets, which can be classified as Continuous-ink-jet (CIJ) [8] and Drop-on-Demand (DOD) [9] depending on the metal microdrop generation principle and control method.As shown in Figure 1.1, continuous injection technology has the advantage of high droplet generation efficiency, but requires charging and deflecting devices for selective deposition, which makes the device complex and difficult to control precisely, and also requires a waste droplet recovery device to collect the waste liquid, which will inevitably lead to higher costs due to material loss.Figure 1.2 shows a typical piezoelectric on-demand microdrop injection device. Compared with continuous injection, on-demand injection does not require a droplet recovery device and a droplet deflection device, and has the advantages of relatively simple structure, low cost, and adjustable driving pressure waveform. Since this technology involves many aspects of microdrop injection, deposition and molding, and the control of process parameters is complicated, most of the current research is still in the laboratory research stage, and in-depth research on key technical issues such as stable metal microdrop injection, precise microdrop deposition, and molding quality control is still needed to make this technology widely used.

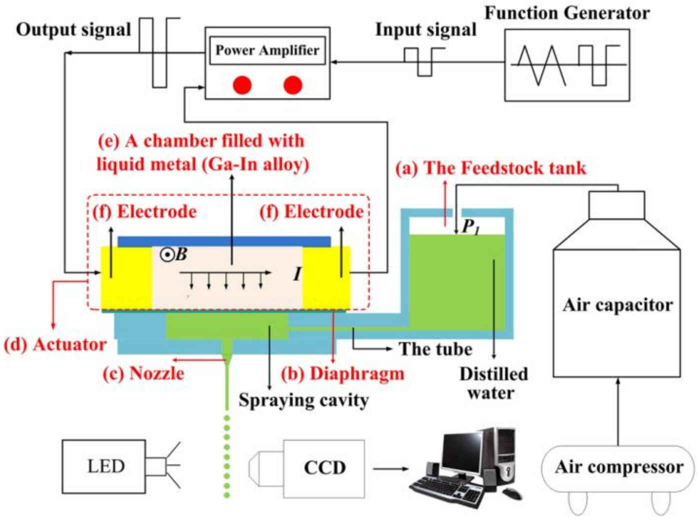

Figure 1.1: Schematic of droplet formation by CIJ technology

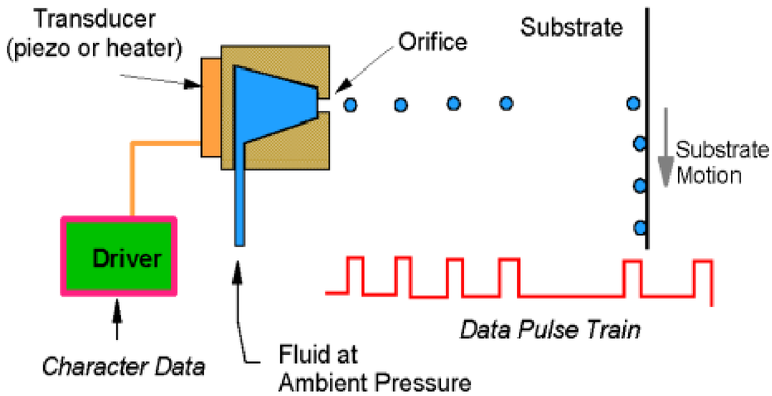

Figure 1.2: Schematic of droplet formation By DOD technology

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2. Stable injection method for homogeneous metal microdroplets

Stable injection of uniform metal droplets is a prerequisite for accurate printing of three-dimensional structures. Metal fusion injection can be divided into piezoelectric, pneumatic, mechanical vibration and ultrasonic injection according to the droplet driving method, however, this technology involves the generation, deposition and solidification of uniform metal droplets, lap forming and other processes, and the forming quality is affected by many factors such as the uniformity of droplet size, fusion state and lap morphology, etc. To apply it directly to the actual production of tiny metal parts, it is necessary to break through the key technologies such as stable injection of uniform metal droplets and optimal control of surface morphology of the parts.

2.1. Piezoelectric

Pulsed Orifice Injection Method (POME) is an advanced piezoelectric actuated on-demand injection technique developed by Kawasaki Research Laboratory, Tohoku University, Japan [10-14]. According to the different ways of acting on the molten metal, the pulsed microporous injection device can be divided into the piezoelectric and actuated rod type, the piezoelectric structure is designed for the injection of low melting point metals and alloys, and the actuated rod structure is designed to achieve the injection of high melting point metals and alloys, and the schematic device diagrams are shown in Figure 2.1 and 2.2.

In the development of pulsed microporous injection technology, the first to be born was the design of a pressurized sheet structure geared toward the injection of low melting point metals and alloys. The device was mainly used for the injection of droplets of low melting point metals such as tin, tin-lead alloys and various lead-free brazing materials.The principle device is shown in Figure 2.1. The metal is melted into liquid in the crucible and a certain gas pressure is applied to the crucible. Under the combined action of gravity and pressure, the dissolved metal enters the injection section through the replenishment channel at the bottom of the crucible and fills the whole space, and the piezoelectric ceramic drives the metal sheet to produce elastic deformation driven by the pulse signal, and the resulting volume force causes the liquid in the crucible to be ejected from the The resulting volumetric force causes the liquid in the crucible to be ejected through the micro-hole at the bottom of the injection section.This design enables consistent motion displacement so that the pressure applied to the liquid in the injection section remains stable each time, and can ensure uniform and controlled injection of the liquid. However, for high melting point materials, it is difficult to find suitable materials for pressure plates, for example, ceramic materials are high temperature resistant but brittle and cannot produce elastic deformation at the required scale, and this structure cannot meet the requirements of droplet injection.

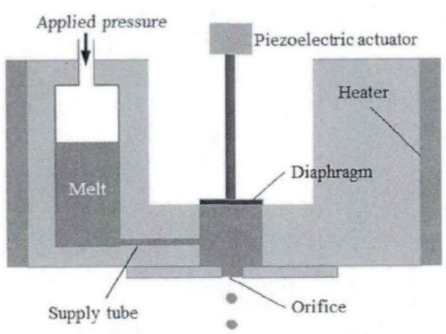

Figure 2.1: Pressed-panel pulsed microporous injection device

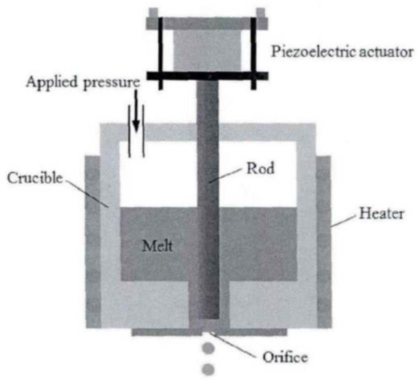

Figure 2.2: Drive rod type pulse micro-hole injection device

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With the development of pulse microporous injection technology and the need for droplet injection of high melting point metals and alloys, the pressure plate type structure has been modified and a drive rod type structure design has emerged, the schematic diagram of the device principle is shown in Figure 2.2.Compared with the piezoelectric structure design, the drive rod structure design is more complex, the heating method is changed from resistance heating to induction heating; the cooling efficiency of the piezoelectric ceramic cooling system requires higher cooling efficiency; the driving voltage of the piezoelectric ceramic requires more; the choice of crucible, micro-hole and drive rod materials is more meticulous, etc.The transmission rod type pulse microporous droplet injection device is mainly composed of pressure control system, piezoelectric actuation system, temperature control system and vacuum system. The working principle is that the piezoelectric ceramic displacement is directly transferred to the local melt near the injection hole of the crucible by the high temperature resistant transmission rod, which breaks the equilibrium formed by the internal and external surface tension and static pressure of the melt at the nozzle and causes a certain amount of liquid in the cavity to break away from the liquid surface at the nozzle to form droplets.Unlike the pneumatic pulse type or the perturbation method in which the elastic deformation of the metal pressure plate applies a volumetric force to the entire melt, the drive rod type, because it only perturbs the melt near the crucible injection hole in a pulsed manner, causes little disturbance to the entire system, makes it easy to maintain system balance, and makes it easier to achieve on-demand injection of uniform droplets.

2.2. Pneumatic

As shown in Figure 2.3, the mechanical vibration type injection device structure its principle is similar to the piezoelectric driven piston type, the biggest difference is the different drive source, the technology uses a modified solenoid valve as the drive source [15].Compared with the piezoelectric drive system, the solenoid valve drive control device is simpler, lower cost, and has a wider temperature range, but the injection frequency is low, the piston rod vibration response is poor, and the microdrop generation process is not easily controlled. The pneumatic driven injection technology uses pulsed air pressure as the driving force and the melt in the extrusion chamber flows out of the nozzle to form micro-droplets.The technique was first proposed by the University of Toronto, Canada, which developed a first-generation metal microdrop injection device with the structural schematic shown in Figure 3.4, which realized the injection of tin, lead, and zinc, etc. Metal particles with a diameter of about 170 μm were prepared using a nozzle with a minimum diameter of 76 μm, with a high deposition accuracy and an average deviation in position of about 0.095 times the microdrop diameter [16]. A silicon nozzle of 183 μm was used to produce solder particles of about 210 μm at Oak Ridge National Laboratory, USA [17].The group at Northwestern Polytechnic University also carried out preliminary basic research on the pneumatic on-demand injection process for different materials, and realized the injection of metals such as tin-lead and aluminum and their alloys [18-20]. Zeng Xianghui used pneumatic on-demand injection technology to achieve the injection of aluminum microdroplets with a diameter of about 1 mm using a 400 μm graphite nozzle, and studied the effects of supply pressure and oxygen content on the injection process [21].

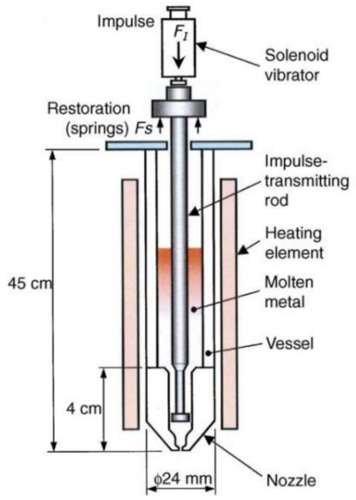

Figure 2.3: Schematic of the fabricated DOD generator of super heated metal droplets.

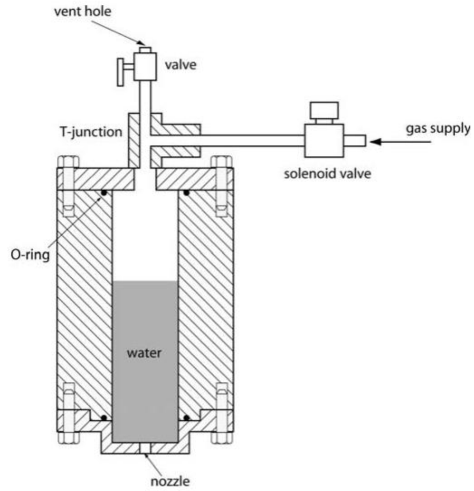

Figure 3.4 Schematic diagram of pneumatic DOD generator

This technique has been studied more systematically by Northwestern Polytechnic University and Huazhong University of Science and Technology in China [21,23], and the principle device is similar to Figure 3.4. When the pneumatic pulsed homogeneous droplet injection works on demand, the pulse signal is passed through an electromagnetic relay to control the opening and closing of the solenoid valve, and the high-pressure gas enters the crucible through the solenoid valve, which raises the pressure in the crucible and causes the liquid to be ejected from the micro-hole and broken into droplets by the instability of the liquid beam flow. The remaining gas in the crucible is rapidly discharged from the relief valve at the top of the crucible, leaving the crucible in a negative pressure, under which the remaining liquid after droplet breakage will be pulled back into the crucible.

The biggest advantage of pneumatic pulsed droplet injection deposition molding technology compared with continuous homogeneous droplet injection deposition molding technology is the realization of droplet injection on demand. During the deposition process, when droplets are needed, a certain pulse signal is applied to the solenoid valve, which causes the liquid in the crucible to produce droplets by the action of gas pulses; when droplets are not needed, the solenoid valve closes and droplets stop being ejected, Figure 2.5 shows the schematic diagram of the pneumatic pulsed droplet injection deposition molding system on demand.Compared with the continuous type, this system is simple in structure, does not require charging and deflection of the droplet, and achieves complete utilization of the material in the crucible. In a related field, Osaka University, Japan, developed droplet-based net forming (NDM) technology and studied the effect of droplet injection speed on forming aluminum fabricated parts [24]; C. Escure studied the impingement process of aluminum droplets on hot and cold substrates [25]; Luo analyzed the lateral instability of uniformly charged droplets during deposition [26]; Fang analyzed the effect of droplet solidification angle at different substrate temperatures and the effect of droplet injection frequency and substrate speed on the deposition quality of fabricated parts. Chandra proposed a heat conduction model and predicted the droplet and substrate temperatures to obtain good droplet metallurgical fusion [28]. The thin-walled metal devices were prepared by Yanpu Chao using the initiating pulse microdrop deposition technique, and the fabricated parts were prepared as shown in Figure 2.6 [29].

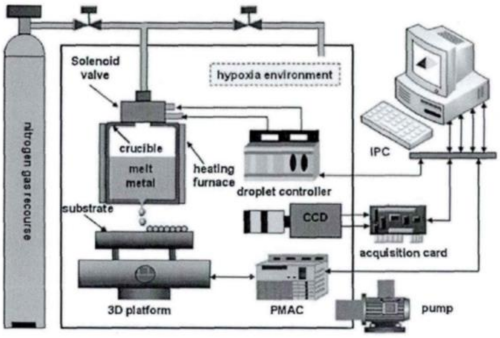

Figure 2.5: Pneumatic pulsed on-demand injection schematicFigure

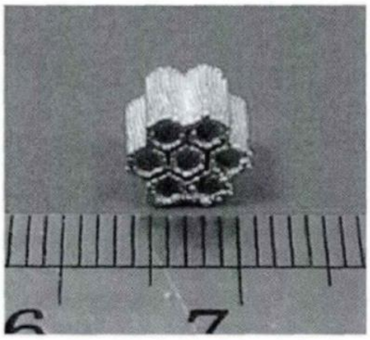

Figure 2.6: Pneumatic pulsed on-demand injection of thin-walled metal parts

2.3. Ultrasonic jet type

The piezoelectric-driven ultrasonic atomizer, developed from microelectro mechanical (MEMS) and inverse piezoelectric effect high-frequency drive technology, is a high-performance ultrasonic atomization device. Limited by the principle of injection, the traditional piezoelectric and pneumatic on-demand jet printing has the problem of low frequency, scholars based on ultrasonic atomization device proposed piezoelectric ultrasonic jet uniform metal microdrop deposition molding technology. At present, ultrasonic atomization technology has important applications in 3D printing technology and aerospace manufacturing. The piezoelectric ultrasonic jet device has the advantages of simple structure, uniform and fine size of the formed droplets and high productivity, but there is a complex coupling relationship between its nozzle structure, jet material, driving waveform and the characteristics of the sprayed droplets, and the influence law of these influencing factors on the characteristics of the droplets needs to be studied clearly, as briefly described below.

In order to understand the specific physical process of material injection by piezoelectric nozzle, Bogy [30] designed a nozzle structure with variable runner length as shown in Fig. 2.7, and studied the effect law of runner length on material injection delay time and meniscus vibration period by varying the runner length, the effect law of waveform width on microdrop velocity by varying the width of rectangular drive waveform, and the response law of drive waveform on microdrop velocity by varying the The response law of excitation frequency on microdrop velocity was studied by changing the excitation frequency. The experimental results showed that the material ejection time and meniscus vibration period increased with the increase of the flow channel length, the microdrop velocity showed periodic changes with the increase of the waveform width, and the microdrop velocity fluctuation increased with the increase of the excitation frequency.

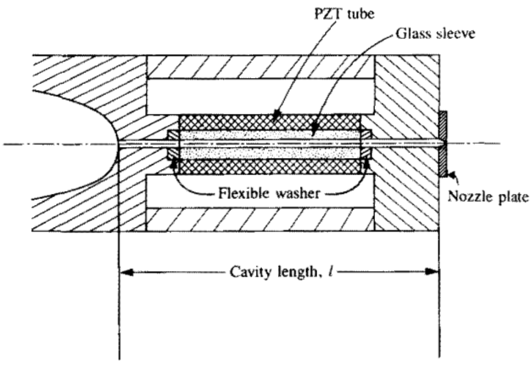

Figure 2.7: Schematic of ink jet nozzle assembly.

In response to these experimental results, Bogy treated the material in the flow channel as a compressible fluid and used the propagation of acoustic pressure waves to explain the experimental phenomena well. Although Bogy investigated in detail the influence laws of flow channel length, rectangular drive waveform width, and injection frequency on the material injection process, and also found that acoustic pressure wave propagation in the flow channel is the kinetic process of material injection, other influencing factors that affect the material injection process were not analyzed in depth.

To further investigate the laws of influence of drive waveform, material physical properties, and nozzle size on the microdrop injection process, Liou [31] investigated the laws of influence of drive waveform parameters (amplitude, width, and edge time), material physical properties (viscosity, surface tension coefficient), and nozzle size on microdrop volume and velocity using CFD simulation models for the nozzle structure and drive waveform shown in Figure 2.8. Tsai [32,33] investigated the effect law of drive waveform amplitude on the spraying performance of silver nanoparticle suspension, ethanol, and glycol materials for bipolar trapezoidal drive waveform and MJ-AL-01 piezoelectric nozzle.Wu [34,35] investigated the effect of unipolar trapezoidal drive waveform parameters (waveform width, amplitude) and injection frequency on the injection performance of deionized water and glycol materials for the coaxial extruded piezoelectric nozzle structure and unipolar trapezoidal drive waveform based on the acoustic-acoustic propagation principle of Bogy for the conical nozzle structure shown in Figure 2.9, and studied the pressure waveform at the nozzle using CFD simulation model The influence of the pressure waveform at the nozzle on the microdroplet injection performance was studied using CFD simulation model for the conical nozzle structure shown in Fig. 2.9. Kwon [36] analyzed the influence of the drive waveform on the satellite droplet and microdroplet ligament behavior by measuring the droplet formation and velocity profiles for the MJ-AT series piezoelectric nozzle and the unipolar trapezoidal drive waveform. kim [37] developed a double closed-end nozzle structure and demonstrated that the pressure waveform within the nozzle oscillates in the Helmholtz mode.

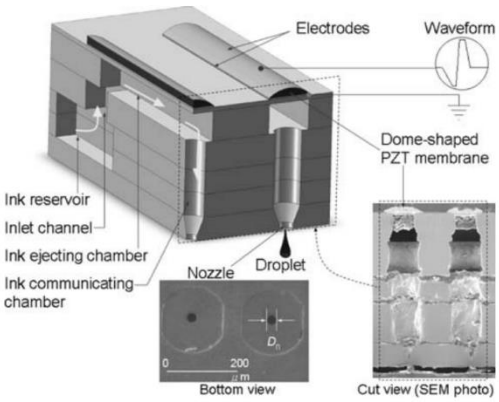

Figure 2.8: Structural, bottom and cut view of PIJ printhead

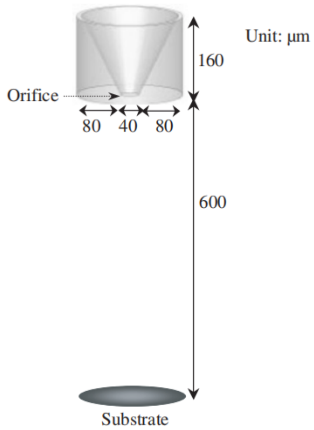

Figure 2.9: A schematic diagram of the inkjet printhead

3. Research Content and Methodology

(1) Ultrasonic microporous melt drop injection mechanism study

To study the microphysical processes of molten droplet ejection from micro-hole in inert gas environment, including droplet extrusion and neck fracture processes. To study the influence law of parameters such as ultrasonic vibration frequency, amplitude, geometric parameters of spray hole and physical properties of metal on molten droplet forming size and spraying speed. The specific method is to observe the melt droplet formation and injection state by high-speed camera, to obtain the size and flight speed of melt droplet by image analysis software, and to observe the melt droplet injection and forming state in real time, and finally to establish the mathematical model of melt droplet injection.

(2)Study of the mechanism of solidification crystallization of micron-sized molten droplets and fusion between adjacent droplets

The crystallization and solidification process of individual droplets in air is studied first; specifically, the surface morphology of the solidified individual droplets is directly observed by scanning electron microscopy, and the cross-sectional lattice distribution is observed by metallographic microscopy to reveal the crystallization and solidification mechanism of individual droplets in air.

The effects of droplet temperature, substrate temperature, and droplet size on the cooling and solidification pattern on the substrate and the fusion mechanism between the droplet and the neighboring droplets will be investigated. In addition, numerical simulation combined with experimental verification will be used to analyze the cooling and crystallization mechanism of microdroplets during the whole process of injection, flight, collision spreading deformation and fusion deposition, and to establish a mathematical model of heat and mass transfer for molten droplet deposition.

(3)Nozzle structure and control system design and optimization

Firstly, design and select the nozzle structure such as heating tube, ultrasonic vibration piece and spray hole according to the new spraying method and related parameters such as molten metal heating requirements and physical properties of metals. Research and development of continuous spraying and fixed-point on-demand spraying control systems.

Based on the experimental study of the molten droplet spraying mechanism and the influence of spray hole geometry parameters on molten droplet formation and spraying, the nozzle and spray hole are further optimized to make the printing accuracy and efficiency better.

(4)Metallographic organization and mechanical properties of printed parts

To analyze the metallographic and microstructure of 3D printed parts, and study the laws of influence of printing parameters such as melt droplet size, injection frequency and bottom plate temperature on their metallographic and microstructure characteristics; to study and test the mechanical and mechanical properties such as microhardness and friction wear of printed parts by using tensile test machine, hardness tester, friction wear tester and surface roughness meter. In order to accurately grasp the relationship between the printing process parameters on the organization and mechanical properties of the printed workpiece, and further improve the accuracy and quality of printing.

4. Conclusion

Piezo-ultrasonic melt-jet 3D printing of metals is an important future research area due to its efficient forming mechanism. The above findings show that nozzle structure, injection material, and drive waveform all significantly affect the characteristics of the injected microdroplets, and there are complex coupling relationships between them, which leads to the current single-hole and array ultrasonic injection technologies are not yet able to precisely control the melt deposition process of the injected microdroplets. To control the piezo-ultrasonic metal fusion jet 3D printing to achieve high speed and high precision material injection, it is necessary to fully study the micro-hole fusion droplet injection mechanism and fusion mechanism based on the material properties to reasonably design the nozzle structure and precisely control the driving process.

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