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Comparison and Evaluation of Various Material Jetting Technologies in Terms of Additive Manufacturing

V. Korkut[1], H. Yavuz[2]*

[1]Department of Mechanical Engineering, Adana Science and Technology University, Adana, Turkey
[2]Department of Mechanical Engineering, Çukurova University, Adana, Turkey

Material Jetting (MJ) is an emerging technique categorised as a part of Additive Manufacturing (AM) technology. This technique is based on manufacturing a part by depositing base material in the form of tiny droplets over a substrate point by point, then layer upon layer in a controlled manner. Various base materials such as polymers, metals and even biological types can be used depending on the operation to be accomplished. Although material jetting has been widely used in the fields of conventional inkjet printing and micro-dispensing for many decades, it has started to play an important role in the additive manufacturing industry since late 90's. Material jetting is getting more and more popular day by day due to the advantages provided. Such advantages like high deposition rates at high resolutions without sacrificing the final density and the strength cannot be achieved simultaneously in other additive manufacturing techniques. Practically, material jetting has the same operational principles as the 2D ink-jet process. It can also be categorized according to the liquid injection mechanism based on mechanical impact, thermal, pneumatic or electromagnetic effects. These mechanisms are mostly responsible from the droplet formation which is strongly related to the process time and final part quality. "It is necessary to precisely control the material jetting systems. For this, it is necessary to overcome the image processing, inspection and expensive equipment cost problems. It is only then additive manufacturing technology can be carried a step further.

Keywords: Material jetting, Drop on demand, Droplet jetting, Jetting mechanisms

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Corresponding author: dr.hakanyavuz@gmail.com

1. Introduction

Material Jetting (MJ) is a process of generating droplets repetitively. It has a similar operational principle to that of the inkjet printing technique. In the material jetting process, the liquid phase material is first collected in a chamber. This material is then jetted into the desired coordinates in small droplets. In this process, the volume, velocity and frequency of the droplets are important [1]**.** In other words, the base material is directly deposited droplet by droplet to generate 3D physical object. It is rather different than any other types of additive manufacturing (AM) techniques such as fused deposition modelling (FDM), powder bed fusion (PBF) and direct energy deposition (DED) [2]. Even though other AM methods are still attractive for specific tasks in crucial industries such as automotive, aircraft and biomedical; there are several limitations considering the final product properties such as low strength, density, resolution and coarse surface finish. In fact, those undesired properties could be minimized by selecting the suitable AM method. However it is still not possible to eliminate all technical problems with a single operation currently. For instance, PBF presents highly accurate 3D objects in geometry, but the loss of density and strength may not be tolerated in many functional operations [3]. Another one, DED stands for again high precision in layering process. Furthermore, DED has already taken a place in the space and the automotive industry for manufacturing durable parts with high complexity. However, this technology is not feasible or practical for every case due to several reasons: Astronomical equipment costs, the necessity of fully controlled atmosphere and a qualified operator considering the dangers of high power consumption and hazardous gas emissions [4]. At this point, MJ could change the future of manufacturing industry with its promising features such as high density, high strength, reduced costs, shorter leading times and being eco-friendly [5]. Moreover, low power consumption and wide material options make MJ method more applicable to the broader working fields. It could be used in laboratories for experimental research as desktop devices or directly to manufacture in the factories. In this method, polymers, medical contents or metals even the high melting point ones could be processed [6]. Although the total setup cost for MJ system is lower than other that of AM methods, the price of control system is still high for some research and development activities due to several reasons. The mechanical structure of the nozzle requires micro-scale manufacturing. In addition, control system for power, heat and pressure supply must be operated precisely. In some cases, image processing techniques may be necessary in order to monitor the droplet motion and condition. Therefore, the most suitable jetting technique must be chosen according to the operation requirements not to waste extra time and effort.

Hereby, the main types of MJ processes are discussed mainly focusing on ejection methods and related mechanisms used. In addition, presented study is concluded discussion on selection of the most suitable ejection method for the best final product specifications.

2. Jetting Types

There are several jetting types available since its invention dating back to beginning of the century. The main types can be categorised with respect to the liquid ejection mechanism [8]. Firstly, deposition rate (the frequency of droplet ejection) should be considered for as an important feature of the technique. There are two main types of flow namely as continuous jetting and drop-on-demand jetting (DoDJet) [9].

If the droplets are ejected with high frequency, they cannot have enough time to form individual drops. This results in continuous flow that consists of partially combined but heterogeneous droplets. In this flow, droplets cannot be fully controlled, thus application fields are limited. On the other hand, if droplets are generated one by one then every single droplet can be controlled in size, velocity and other crucial droplet parameters. This phenomena allows homogeneity between all droplets, thus more consistent deposition characteristics. Therefore, drop-on-demand technique becomes more reliable in precise operations such as electronic packaging, 3d micro manufacturing, development of MEMs and medical products [10].

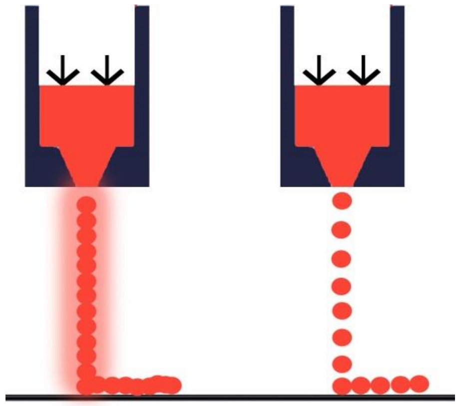

Figure 1: Continuous Jetting (left), Drop on Demand Jetting (right)

Table 1: Comparison of DoDJet with Continuous Jetting[11]

	Drop on Demand	Continuous
Deposition Rate	<1 kHz	>=1 kHz
Droplet controllability	High	Low
Material Usage	Low	High
Finish Quality	High	Poor

In the following sections, different types of mechanisms of DoDJet have been presented. The details provided cover the advantages and disadvantages of the reviewed techniques.

2.1. Thermal Jetting

This type of jetting is based on creating gas bubble inside the liquid reservoir. This is done by heating the liquid locally to vaporize. Heat supplement can be made in two ways. One is to use a resistive wire to heat up and the other one to use a couple of probe for electrical spark generation. When the pulsatile current pass through the wire or the probes, electrical energy is converted into the heat energy and maintains local (and pulsatile) heating. The local heat generated inside reservoir causes the liquid to vaporize and form a gas bubble. Basically, every single bubble pushes the same volume of liquid to come out of the orifice in form of droplets. In the literature, this type of droplet ejection technique is also named as Bubble Jet [12].

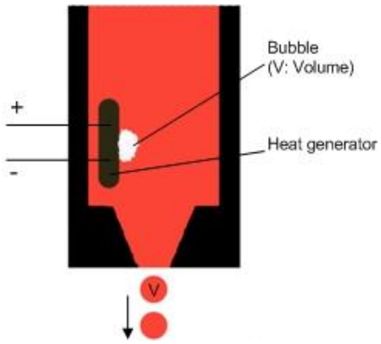

Figure 2: Representative image of Thermal Jetting

Although the thermal jetting was one the first techniques based on DoDJet, it has several limitations. During the bubble generation by the local heater, the electrical inputs for the heater play a major role that requires precise control. Since the heating source needs to be in direct contact with the liquid, the chemical composition of the liquid may change due to the heat supplied. Also, the volume of ejected droplet and generated bubble may not be equal in every cycle. This factor affects the homogeneity of the flow negatively. For the reasons mentioned above, the usage of thermal jetting is limited in options for both material and precise deposition size.

2.2. Pneumatic Jetting

Droplets are generated by pushing the liquid out of the orifice via pneumatic pressure supplied in the liquid chamber. Every pressure pulse tends to squeeze a certain amount of liquid, then supply is cut (or pressure is balanced). Each of this cycle produces a droplet formed on demand. With the advantage of the high-tech sensors and control devices, this pressure based ejection system could be controlled precisely. Since there is no direct contact between the liquid and the ejection source [13], the ejection of liquids with high temperatures become possible with this method. Hence, the base material options are so wide, including the high melting point metals.

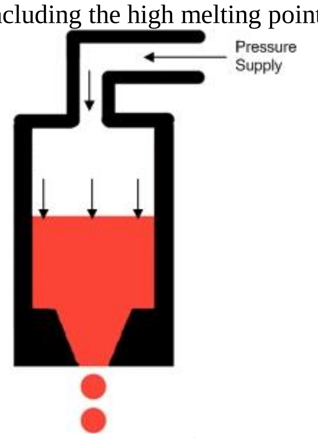

Figure 3: Representative image of Pneumatic Jetting

However, considering the compressibility of gases, fluctuations may occur in pressure level during operation. Decreasing the level of liquid in vacuumed reservoir may also complicate the pressure control problem. Moreover, low ejection frequencies may result in low deposition rates too.

2.3. Magnetohydrodynamic Jetting

In this type of jetting, the liquid is driven without any mechanical contact. Lorentz forces are generated on conductive liquid by the combination of electric and magnetic fields. Conductivity is a key property of this method. Electromagnetic fields need an electrically conductive material to be able to exert a quantitative force over the material itself. Having no direct contact (unlike pneumatic jetting) with the molten metal, the technique enables high melting point metals to be used as metals are good conductors even when in liquid form [14].

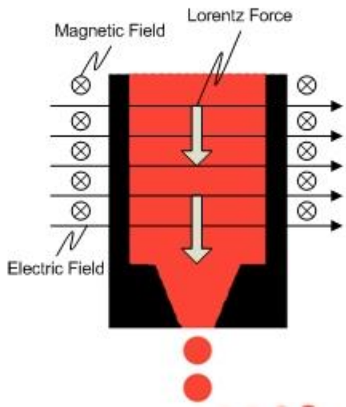

Figure 4: Representative image of MHD Jetting

Although this technique has numerous advantages, available materials are limited apart from a few metals. In addition, both the magnetic and the electric field generators need to be positioned accurately in order to maintain sufficient driving force on the liquid. Besides, these generators generally consume high energy and occupy large working areas. Also, it is difficult to control the droplets are in this method. Therefore intensive simulations are needed to be performed before the successful practical implementation of the technique [15].

2.4. Push-Mode Jetting

This method is a promising type of jetting technique in many fields due to its wide range of material options and also high deposition rates. The principle of push-mode jetting is to create mechanical impact on the liquid by an actuator with a certain amount of displacement. Every impact pushes the liquid out of the orifice on demand in the form of droplets. Firstly, an actuator is mounted for the creation of vibration impact. In this technique, the actuator selection depends on to the operation to be accomplished. There are two main actuators available in the push-mode jetting namely as piezoelectric transducers and solenoid coils. Both of these actuators can provide high deposition rates as they vibrate at high frequencies very precisely. The main difference is mostly related to the desired layer resolution. While piezoelectric actuators can exhibit very small displacements like few microns, solenoid coils can vibrate up to a millimetre in scale. Since the amount of displacement determines the droplet volume, the selection of actuator should be made in accordance with the operation specifications.

It should also be noted that the parameters of a droplet strongly depends both on the orifice properties and the reservoir geometry. As these actuators can operate at higher precision resolutions than other MJ methods, higher deposition rates could be obtained by using push-mode method. [16].

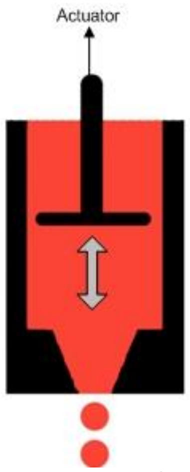

Figure 5: Representative image of Push-Mode Jetting

Push-mode systems generally consist of an actuator (as a vibration source), a mechanical type of piston (as an impact transmitter) and a custom reservoir with an orifice. Dimensional correlation between impact transmitter and inner reservoir must be considered carefully in order to generate consistent droplets. Precisely ejected homogeneous droplets result in high resolution and surface quality of the final product. On the other hand, push-mode jetting requires advanced control engineering skills. There are many process parameters that must be controlled simultaneously. Such a task requires precisely driving the actuator, generating precise pressure variations and precise temperature control. In most cases an image processing techniques for such precise control may be necessary. Due to precision needed for the technique, all parts of the mechanical system including reservoir and transmitter structure requires high precision micro-manufacturing. If the compatibility between all the components are maintained in harmony; high resolution, high deposition rates with more material options could be achieved in a single process comparing to the other jetting methods [17]. Since the ejection source is in a direct contact with the liquid, operational temperature range becomes small. But if the correct insulation method and material is applied to the transmitter, this limitation disappears and high temperature operations become possible.

3. Results

In the Table 2, the presented jetting types and some critical information is provided. In a typical application, firstly the material type to be used should be chosen. Considering the properties of the selected material type, operating temperatures, expected leading times and final resolution can be seen from the table. The information given in the table summarizes the details provided in the study.

Table 2: Comparative chart of four different methods

		Thermal	MHD	Pneu-matic	Push-Mode
Capabilities	Material Option	Limited	Limited	Wide	Wide
	Temperature Range	Small	Large	Very Large	Very Large
	Deposition Rate	Medium	Medium	Low	High*
	Layer Resolution	Low	Low	High	High
	Droplet Controllability	Medium	Low	Low	High
Requirements	Engineering Mastery	High	High	High	Very High
	Setup Space	Medium	Large	Large	Small
	Power Amount	Medium	High	Low	Low

*Deposition rate could be multiplied by increasing orifice and transmitter number proportionally.

Main drawbacks related to the demanded method can also be seen from the table. Before deciding on a suitable method, it is important to define the expectations from the final product. The expected final product features could only be achieved with the suitable control system and affordable labour cost. By considering these issues together, time and material waste could be minimized for the selected operation.

Conclusion

According to the table, push-mode type jetting provides wider variety of material options with a wide temperature range. Although there are the difficulties in application of the technique, the final product may have better properties than the other MJ methods. In addition, the features of high deposition rates and short processing times without sacrificing the strength and the density, can be achieved via push-mode technique only in a single process. In conclusion, push-mode jetting technique may carry the manufacturing industry further in many crucial fields.

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