

(A High Impact Factor, Monthly, Peer Reviewed Journal) Visit: <u>www.ijirset.com</u> Vol. 8, Issue 5, May 2019

High Resolution Electrohydrodynamic Printing of PCL

Dr. Dajing Gao¹, Kishan Patel², Muharrem Tunel³, Yifan Fei⁴, Dr. Jack G. Zhou⁵

PhD, Department of Mechanical Engineering, Xi'an University of Technology, Xi'an, China¹

M.S, Department of Mechanical Engineering, Drexel University, Philadelphia, Pennsylvania, USA^{2,3,4}

Professor, Department of Mechanical Engineering, Drexel University, Philadelphia, Pennsylvania, USA⁵

ABSTRACT: With rapid growth of demand in microelectronic industry and biotechnology, traditional manufacturing methods cannot satisfy the developing needs of these industries. This paper introduces the development and testing ofprinting as well as a rapid-prototyping technology, called Electrohydrodynamic (EHD) inkjet printing. The process involved, known as "Electrospray in the cone-jet printing", can produce a thin and intact jet without the need to reduce the size of the nozzle. The aim of this paper is to investigate essential science and physics of cone-jet formation, material properties (surface tension, electric conductivity and viscosity) and study effects of operating parameters (Electric potential, Heating temperature and velocity of moving platform). An experimental modelis developed, to apply this printing technology and to show the results obtained from the experiments performed. Polycaprolactone (PCL) is selected as a printing material due to its low melting point, high viscosity and ease of biodegradability. Continuous printed lines of up to 13µm were obtained and complex shapes are printed in multiple layers.

KEYWORDS: Rapid Prototyping, Inkjet-Printing, Electro-spinning, Electrohydrodynamic, Cone-jet transformation.

I. INTRODUCTION

Conventional lithographic-based method is not cost effective and it lacks flexibility in fabrication as well as the required speed for processing large area is not enough. SLA process is also expensive and can only be applied to a certain range of materials. The resolutions in SLA and SLS are limited by the size of the laser spot. Ink jet print provides a cost effective method for fabrication of small features but the major issue with it is that of clogging by small nozzle size and extremely high driving pressure because of viscosity of ink. To overcome these restrictions, Electrohydrodynamic (EHD) inkjet (also called "EHD jet printing") has been proposed as a solution to the limited resolution of the conventional inkjet printer system, because EHD printing can generate small droplets without the need to miniaturize the nozzle. The process involved, called "electrospray in the cone-jet mode," uses electrical ("Maxwell") forces to pull the liquids from the nozzle tip, rather than apply thermal or acoustic energy to push liquid from a fine capillary. The EHD inkjet printing can be a high resolution inkjet printing technology because there is alarge "neck-down ratio" between the diameters of the nozzle and the jet: the jet diameter is about two orders of magnitude smaller than the nozzle diameter. Thus, in EHD jet printing the nozzle diameter (>100µm) can be much larger than that used in TIJ and PIJ printing (about 20µm): this may reduce blockages and make it easier to print a highly viscous liquid. The main objective of this paper is to investigate the basic science and physics governing electrohydrodynamic (EHD) 3D printing system using electric field to pull out high viscosity inks to achieve high resolution additive manufacturing. We propose a new experimental model developed at the 'Bio-Nano-Micro Design and manufacturing Laboratory' facility in Drexel University which potentially printed PCL strands of as small as 13µm. We also discuss the parameters such as Voltage applied between the electrodes, Temperature supplied to the syringe and the velocity of the moving platform which affect the thickness of the strands obtained.



(A High Impact Factor, Monthly, Peer Reviewed Journal) Visit: <u>www.ijirset.com</u> Vol. 8, Issue 5, May 2019

II. RELATED WORK

Yiwei Han, Chuang Wei, Jingyan Dong at el (2015) in their paper 'Droplet formation and settlement of Phasechange ink in high resolution electrohydrodynamic (EHD) 3D printing' presented a modelling frame work to model the droplet formation and settlement on substrate They used Finite element analysis to develop the model for droplet formation and droplet settlement and determined that the two competitive forces in EHD printing are electrostatic force and surface tension of the pending droplet at the tip of the meniscus under different printing conditions. They compared the resulted FEA models with the experimental measured droplet dimensions at different process conditions to validate the developed model, which demonstrated very good agreement between the experimental results and model prediction. They also demonstrated the capability of using phase change ink (wax) to print 3D structure by using EHD printing approach. The printing method that they employed gave a high resolution of up to 10µm.

Hong Kyoon Choi, Jang-Ung Park, (2008) presents simple scaling laws that describe the intrinsic pulsation of a liquid jet that forms at the tips of fine nozzles under electrohydrodynamically induced flows in their paper 'Scaling laws for jet propulsion associated with high-resolution electrohydrodynamic printing'. Their study concluded that the diameter of the formed jet is directly proportional to the square root of the nozzle size and inversely proportional to the electric field intensity. Also, the fundamental pulsation frequency is directly proportional to electric field intensity raised to 1.5 times. The equations and other aspects described in their study can be important in the design of systems for high-resolution EHD 3D printer.

Jiankang He et al (2016) Biofabrication in his paper 'Development of melt electrohydrodynamic 3Dprinting for complex microscale poly (ε -caprolactone) scaffolds' describes a melt Electrohydrodynamic printing technique for direct cell growth and tissue regeneration. The printing platform developed was verified for its feasibility to fabricate 3D tissue engineered scaffolds with complex geometries and microscale filament structures. The melting temperature was found to be stable for PCL printing, with the filament size of about 10µm. Biological experiments were performed to verify that the printed microscale scaffolds had good biocompatibility and facilitated cellular proliferation and alignment in vitro.

III. JET FORMATION MECHANISM

Cone formation:

To obtain a high resolution and uniform printing, it is important to understand the mechanism of cone formation and observe the parameters that affect it. Sir Geoffrey Ingram Taylor studied the phenomenon of a cone formation in 1964 by deriving a theory on hydrodynamic force, electrostatic force and surface tension. The equilibrium equation is given as follows: (1)

$$F + \Delta p \pi r^2 = 2 \pi r \gamma cos \theta + W$$

The value of force F exerted on a cylinder of length L is given by: (2)

$$F = \frac{V^2 L^2}{4 H^2} \frac{1}{\ln\left(\frac{2L}{R}\right) - \frac{3}{2}}$$

If pressure (ΔP) at top of the fluid equal to zero, the cone semi vertical angle (θ) is 49.3° and the weight of top of the liquid is neglected, the critical voltage (static equilibrium could no longer be maintained) for the appearance of cone with a straight generatrix (M Cloupeau, 1990) before the jet forms can be predicted by equation (3) which is derived by substituting the equation (2) into equation (1)



(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: <u>www.ijirset.com</u>

Vol. 8, Issue 5, May 2019

$$V = \frac{2H}{L} \sqrt{\left(ln \frac{2L}{R} - \frac{3}{2} \right) (2\pi r \gamma cos 49.3)}$$

Above the critical voltage, the static equilibrium value could no longer be maintained (Taylor, 1969). For a liquid meniscus formed at the exit of a conducting needle, like electrodes of needle to plate setup in Figure 13, the critical voltage can be approximately calculated as: (4)

$$W_{critical} \approx \sqrt{\frac{2\gamma R \cos\theta}{\varepsilon_0}} \ln\left(\frac{4l}{R}\right)$$

The l is distance between electrode of nozzle and electrode of substrate and this expression is valid when the electrode separation l is much larger than the radius of nozzle R (Chen, 2011). This formula only gives an approximation to the required starting voltage (experimentally verified within 10%) for each simulation.

Cone to Jet transformation:

The transformation of a cone into a jet is another important factor to understand the formation of a straight uniform jet. Electric field (E) and flow rate (Q) are the important parameters that affect the jet formation. 'Dripping' occurs at low value of Q and E with the help of gravitational forces i.e. droplet formation. A slight increase in the flow rate and/or electric field leads to the formation of a pulsating jet which are a result of repeated Taylor cone formation and relaxation. A 'pulsating jet' is formed at a lower value of 'Q' than the minimum value of Flow rate (Q_m) when the electric field intensity (E) is lower than the critical Electric field. When the Electric field reaches or increases beyond the critical electric field, a continuous stream of jet is formed. The voltage at which a 'pulsating jet' is transformed into a continuous jet stream is called as Taylor voltage. The characteristics of the jet stream goes on changing with increasing values of E. The equations for E and Q are as follows: (5) and (6)

$$E = \frac{4V}{d_N \ln\left(\frac{8H}{d_N}\right)}$$
$$Q \approx \frac{\pi d_N^4}{128\mu I} \left(\Delta P + \frac{1}{2}\varepsilon_0 E^2 - \frac{4\gamma}{d_N}\right)$$

Cone jet also known as the Taylor cone is the fundamental aspect of the EHD 3DP system. The phenomena of the method comes from the formation of this cone with the applied high voltage allowing for high resolutions to be achieved. The printing diameters are mostly smaller than the nozzle diameters. The Jet diameter(d) is calculated approximately by the following equation provided by Choi et al.,(2008): (7)

$$d \propto \sqrt{\frac{\gamma}{\varepsilon_0} \frac{\sqrt{d_N}}{E}}$$

The jetting modes occur at the end of the nozzle and can be observed using a high speed camera. At E/H value of 3.5 V μ m⁻¹ where H is the distance between the nozzle and the substrate, a pulsating jet is observed. A stable jet can be obtained at E/H value of 9 V μ m⁻¹. The following image (a) shows the phase diagram of different modes of jetting as result of increasing values of Q and E.



(A High Impact Factor, Monthly, Peer Reviewed Journal) Visit: <u>www.ijirset.com</u>

Vol. 8, Issue 5, May 2019



Fig 1: The figure on the left (a) show a schematic representation of a cone-jet formation The figure on the right (a,b,c,d,e,f) show the cone-jet transformation captured by a high speed camera

In order to obtain optimization, the modes of jetting for a given ink and printer are to be obtained using a systematic and quantitative approach. Dr. Lee presented an approach based on dimensionless analysis and parametric maps of the jetting process. A mixture of pure organic solvents such as ethanol and terpineol were printed using steel capillary tubes with inner diameter of 180 μ m. A high-speed camera was used to capture the images at different dimensionless numbers as shown in the following figure:



Fig 2: The figure on the left (b) shows cone-jet transformation at different values of α and β The figure on the right (c) shows different phases of the liquid jet at different values of α and β



(A High Impact Factor, Monthly, Peer Reviewed Journal) Visit: <u>www.ijirset.com</u> Vol. 8, Issue 5, May 2019

IV. EXPERIMENTAL SET-UP



Fig 3: Figure (a) shows the mechanism for movement in the Z-direction, Figure (b) shows the mechanism for movement in the X and Y direction. Figure (c) represents a Whale3 DC servomotor drive. Figure (d) is a High definition breakout board (HDBB) with connection for X, Y and Z direction and DC power supply

The experimental set-up consists of a High-Precision moving platform which produced a travel of 120mm, 90mm and 35mm in the X, Y and Z directions respectively. All the 3 Axes are controlled by a High definition breakout board micro controller (HDBB) and Whale3 servo drives. The high definition breakout board (HDBB) in the Figure 7. is an external microcontroller to process control signals and facilitate communication between the DC servo drives and the software being run from the personal computer, which output through the primary motherboard peripheral component interconnect (PCI) and USB slot. The HDBB breakout board is able to send signals to four separate axes: three for spatial motion and one for nozzle extrusion. Whale3 servo drives connects to both the HDBB and an individual servo motor. Signals from the HDBB will be sent to three Whale3 DC servomotor drives, and each of servomotor driveseparately attached to the three axes. The Whale3 drives have inbuilt PID control systems which process positionalinformation sent by the control software through the HDBB board. The Whale3 drives thus have a pivotal role in the overall performance of the device through the tuning of this PID control system. This connection is where the position feedback will be sent from so that it can be configured properly. The drive needs two power supplies for operation, one to feed the digital circuit and one to feed the motor.



(A High Impact Factor, Monthly, Peer Reviewed Journal) Visit: <u>www.ijirset.com</u> Vol. 8, Issue 5, May 2019



Fig 4: The figure on the left represents the final assembly of the components. The figure on the right (a) is the syringe used for the injection and (b) is the assembly of the heating elements with the syringe

In order to maintain the temperature of the both printing nozzles and piping path, a digital temperature controller in Figure 9 and two heating elements from OMEGA Incorporated are applied to printing application. The controller was embedded with PID control which could provide resolution up to 0.1 degree centigrade and monitor the temperature. To produce the required strength, we used a Trek model 677B high-voltage power supply and amplifier shown in. The output voltage range is 0 to ± 2 kV DC or peak AC that can also be modified manually. The current range is 0 to ± 5 mA DC or peak AC. The instrument is accurate in terms of voltage gain with better than 0.1% accuracy because it has a close loop control system. Additionally, the current can be limited to better than 1% error of setting value. The software used to control the entire set up is Mach3 which can control the moving platform in order to control axial movements. G-codes can be run by this software as well as basic axial movement comments. Coordinate commending codes are used to print basic shaped models.



Fig 5: The image of the left is Omega CSI32K Benchtop Heating Controller and the image on the right is Trek model 677B high-voltage power supply/amplifier



(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: <u>www.ijirset.com</u>

Vol. 8, Issue 5, May 2019

Material Properties:

Polycaprolactone (PCL) was used as the printing material for the printing experiments because it is a biodegradable material, it is a suitable material for the EHD 3DP method and its melting temperature is low compared to other printable materials which simplifies and hastens experiments. The reported printing temperature of the material was in the range of 70-100 °C. In our experimental setup, the material tube is heated to around 150-200 °C because to heat the glass material tube heating ropes surrounding the glass syringe is used which suffers from loss of heat to the surroundings.

Properties	Range of Value
Molecular Weight (M _n) (g mol ⁻¹)	530 - 630000
Density (م)(g cm ⁻³)	1.071-1.200
Glass Transition Temperature (T _g)(^o C)	(-65) - (-60)
Melting Temperature (T _m)(°C)	56-65
Decomposition Temperature (°C)	350
Inherent Viscosity (η _{inh})(cm ³ g ⁻¹)	100-130
Intrinsic Viscosity (η)(cm ³ g ⁻¹)	0.9
Tensile Strength (σ)(MPa)	4-785
Young Modulus (E)(GPa)	0.21-0.44
Elongation at Break (ε)(%)	20-1000

Table 1: Material Properties

V. RESULTS

For the first test, the PCL material was printed in the vertical (Z) direction in order to find the range of the electric field. It was found that after we reach the distance of 7mm between the nozzle and substrate, we loose the continuous jet stream as the electric field intensity between the nozzle and the substrate goes on decreasing as we increase the distance. It was also observed that the diameter of the droplet decreases with the increase in distance.



Fig 6: PCL Pillar printed by a 4mm diameter nozzle (Average height of pillar is 7mm)



(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: <u>www.ijirset.com</u>

Vol. 8, Issue 5, May 2019

For the second test, solid shapes were created instead of single lines by printing lines next to the each other as single and multiple layers. Printing takes place with the following printing parameters; velocity: 150(mm/min), acceleration: 0.625(mm/s2), temperature: $180(^{\circ}\text{C})$, applied voltage: 1.9(kV) and standoff height: 0.8(mm). The platform is moved $100\mu\text{m}$ in the x direction for each line allowing for 100 printed lines to be printed. The next test is done with the following parameters: velocity: 75(mm/min), acceleration: 0.5(mm/s2), temperature: $180(^{\circ}\text{C})$, applied voltage: 1.9(kV) and standoff height: 0.8(mm). The platform is moved a standoff height: 0.7(mm). Acceleration and standoff height are increased in order to stabilize the pattern and obtain a uniform structure.



Fig 7 : (a) 10X10mm single layer square including 100 printed lines. (b) View of the printed lines under microscope.



Fig 8 : (a) 10X10mm Single layer square including 100 printed lines, next to a penny for scale. (b) View of the grill shape under the microscope



(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: <u>www.ijirset.com</u> Vol. 8, Issue 5, May 2019

VI. EFFECT OF PARAMETERS

I. Effect of Electric Field:

The effect of changing the high voltage on the printed line width was examined under the following parameters: velocity: 100(mm/min), acceleration: $0.417(\text{mm/s}^2)$,temperature: $180(^{\circ}\text{C})$ and standoff height: 0.7(mm). All other parameters were kept constant while the high voltage was increased from 1kV up to 2 kV with a step size of 0.1 kV. It was observed that the material started to deposit from the nozzle at 1.4 kV at which this stage the printing and measuring was started. Each test was repeated 3 times with the same constant conditions and results obtained are presented in the table 2.

Applied	Printed line width (Micron)				50
High Voltage (Volt)	First test	Second test	Third test	Mean value	€ 40 E 30 F 30
1400	19	22	17	19.3	2nd test
1500	22	23	26	23.67	≥ 20 × 3rd test
1600	25	26	28	26.3	T Mean
1700	29	35	33	32.3	
1800	33	36	36	35	
1900	38	37	33	36	1400 1500 1600 1700 1800 1900 2000
2000	36	39	38	37.67	Applied High Voltage (Volt)

Fig 9: The table on the left shows Change in measured printed line widths andtheir mean value with respect to applied voltage. The Graph on the right shows change in printed line width vs applied Voltage

According to observed data, the following graph is plotted and given in Fig 14. As can be seen from the graph, the printed line width follows a gradual increasing trend with an increase of applied high voltage. This decrease in resolution and increase in line width can be explained by the increased amount of material deposited. The higher voltage applied causes a higher electric field force which in turn causes more material to be deposited from the nozzle onto the printing substrate resulting in wider printing patterns. An almost linear relationship between applied high voltage and printed line width is observed.

II. Effect of Heating Temperature:

The effect of temperature change printed line width was examined under the following constant conditions: velocity: 75(mm/min), acceleration: $0.3125(\text{mm/s}^2)$, applied high voltage: 1.9(kV) and standoff height: 0.5(mm) was. The other printing parameters were kept constant while the heating temperature was increased using the settings on the heater starting at $100(^{\circ}\text{C})$ to $200(^{\circ}\text{C})$ with a step size of $10(^{\circ}\text{C})$. It was observed that the material starts depositing from the nozzle at $140(^{\circ}\text{C})$ according to the digital readout on the heater. The temperature of the nozzle was also measured which showed that the nozzle was at about $110(^{\circ}\text{C})$ when initial material deposition began. Therefore, although the temperature was adjusted using the heater settings, the nozzle temperatures were taken as the measured temperatures to identify the precise temperature and the effect on the resolution during printing. Although the heater transmits heat to the syringe, the material cools down after passing through the nozzle, so it is the nozzle temperature that impacts the resolution rather than the medium in which the material is melted. The temperature tests were repeated 3 times with the same constant conditions and the observed data is shown in Table 3. The measured minimum value is $25\mu\text{m}$ at $110(^{\circ}\text{C})$ in 1^{st} test.



(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: <u>www.ijirset.com</u>

Vol. 8, Issue 5, May 2019

	Printed line width (Micron)				55
Temperature at the Nozzle Tip(<u>°C</u>)	First test	Secon d test	Third test	Mean value	SU SU SU SU SU SU SU SU SU SU
110	29	26	25	26.67	
116	31	28	27	28.67	
124	37	35	33	35	€ 30 • Mesu
130	41	36	37	38	25
137	42	45	46	44.3	20
143	51	46	46	47.67	110 114 118 122 126 130 134 138 142 146 150
150	53	49	51	51	Temperature at the Nazzle Tip (°C)

Fig 10: The table on the left shows the Change in printed line width for 3 tests and Mean value with respected to the nozzle tip and the graph on the right shows Change in printed line widths vs temperature at the nozzle tip

According to the observed data, a graph was plotted as shown in Fig 15. As observed from the graph, the printed line width shows a dramatic increase with increasing heating temperature. Increasing the temperature results in a decrease of the material viscosity which allows for more material to pass through the nozzle and more material is thus deposited on the printing substrate. More material results in a wider printed line which decreases the resolution of the printed material. Similar to increasing the voltage, increasing the temperature results in a linear relationship with the line width.

III. Effect of Velocity of the Platform

The effect of velocity of the moving platform on the printed line width was examined under the following constant printing parameters: temperature: $180(^{\circ}C)$, applied high voltage: 1.9(kV) and standoff height: 0.5(mm). The minimum acceleration value was selected for each velocity value as changes in velocity will cause changes in the acceleration values. All other printing parameters were kept constant while the printing velocity was increased starting from 10mm/min to 1500mm/min which was the maximum possible velocity that can be selected. For all velocities the material passed through the nozzle without any interruptions. All tests were repeated 3 times with the same constant conditions and the data obtained is presented in Table 4. The measured minimum value was $13\mu m$ at 1500mm/min in the 2^{nd} test while the maximum value was $111\mu m$ at 10mm/min in the 3^{rd} test.

Velocity of Moving	Printed line width (Micron)						
(mm/min)	First test	Second test	Third test	Mean value			
10	108	109	111	109.3			
50	54	56	54	54.67			
100	39	38	38	38.3			
150	27	29	30	28.67			
200	25	24	25	24.67			
250	22	22	23	22.3			
300	20	19	19	19.3			
350	17	18	18	17.67			
400	17	18	17	17.3			
450	17	17	16	16.67			
500	16	15	15	15.3			
1000	15	15	15	15			
1500	14	13	14	13.6			

 Table 4 : Change in measured printed line width for three tests and mean value with respect to the velocity of moving platform



(A High Impact Factor, Monthly, Peer Reviewed Journal) Visit: <u>www.ijirset.com</u>

Vol. 8, Issue 5, May 2019



Fig 11 : Change in printed line width vs velocity of moving platform

The graph shows that there is a sharp decrease in line width until a velocity of 200mm/min is reached. After the 500mm/min velocity value, there is no significant change as mentioned above. This result is important as higher operating speeds are not required for high resolution printing of thin lines. Furthermore, the velocity can be used as a characteristic printing parameter where by changing the velocity of the moving platform the resolution of printing during an operation can be modified according to the needed line width. The effect on which velocity has on the width in a short amount of time is also a key factor as an immediate change in resolution can be made in real time without a void time seen in changing the voltage or temperature. The difference between the line width for a velocity of 10mm/min and 1500mm/min is quite obvious and can be seen in Fig 17. We observed that the difference between the two printed lines is quite remarkable as the width was decreased approximately 9-fold just by changing the velocity of the moving platform.



Fig 12 : Comparison of line width from 1st test (a) Printed line view under the microscope for 10mm/min velocity(108µm). (b) printed line under the microscope for 1500mm/min Velocity(14µm)



(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: <u>www.ijirset.com</u>

Vol. 8, Issue 5, May 2019

IV. PRINTING COMPLEX SHAPES

The dragon shape was chosen because it represents the mascot of Drexel University. Firstly, a one-layer dragon shape was printed as a test before moving on to print a five-layer dragon shape. The printed shape was very small and detailed with approximately 350 lines g-code per layer. The following printing parameters were used to print a one-layer dragon shape: velocity: 150(mm/min), temperature: 180(°C), acceleration: 0.75(mm/s²), applied high voltage: 1.7(kV) and standoff height: 0.5(mm). The printed dragon and its view under the microscope are shown in Fig 18 where the printed line width was measured as 59µm. In some parts of the printed shape, the line width may vary because movement occurs across very short distances and the velocity changes during acceleration can cause wider or thinner patterns.



Fig 13 : The Figure on the left shows (a) One-layer Dragon logo print. (b) One-layer Dragon logo print next to a penny for scale.(c) Part marked by black circle to be viewed under the microscope. (d) View of printed line under microscope. The figure on the right shows (a) A Five-layer Dragon logo print next to a penny for scale. (b) View of foot part of the Five-layer Dragon logo print under the microscope

To print a five-layer dragon which is shown in Fig 19, the following printing parameters were set: velocity: 150(mm/min), temperature: $180(^{\circ}\text{C})$, acceleration: $1(\text{mm/s}^2)$, applied high voltage: 1.9(kV) and standoff height: 0.7(mm). The z axis was raised 75µm between layers after each layer was printed. The acceleration throughout printing was kept constant but the value was higher in comparison to the one-layer printed shape in order to avoid variations in line width in each layer. A higher voltage was also used in comparison to the one-layer printed shape in order to have enough electric field strength during the height change in going from layer to layer. However, some nonuniform line widths were observed when viewed under the microscope. This can be attributed to the sudden decreases and increases in velocity when making sharp turns due to the small size and complex nature of the desired dragon shape.

A one-layer and five-layer snowflake shaped print was completed to demonstrate a more homogenous printing construction which is shown in Fig 20. The snowflake model was designed to be 40mm in length and 40mm width overall. The printing parameters were selected to be as follows: velocity: 75(mm/min), acceleration: $0.5(\text{mm/s}^2)$, temperature: $180(^{\circ}\text{C})$, applied high voltage: 1.9(kV) and standoff height: 0.7(mm) for one-layer printing. In regards to the five-layer printing, the parameters were modified as follows velocity: 100(mm/min), acceleration: $0.75(\text{mm/s}^2)$, temperature: $180(^{\circ}\text{C})$, applied high voltage: 1.9(kV), standoff height: 0.7(mm), and the z axis was raised $75\mu\text{m}$ between layers after each layer deposition was complete. The printed line width was measured to be $41\mu\text{m}$ for the one-layer printing experiment while it was found to be less than $40\mu\text{m}$ for the five-layer model. This resulted in homogeneous printing for the five-layer model shown below in Fig 20c.



(A High Impact Factor, Monthly, Peer Reviewed Journal) Visit: <u>www.ijirset.com</u> Vol. 8, Issue 5, May 2019



Fig 20 : (a) One layer snowflake print. (b) View of one layer snowflake print under the microscope. (c) Five layer snowflake print. (d) View of five layer snowflake print under the microscope.

V. CONCLUSION

Electrohydrodynamic printing was found to be one of the most efficient methods for manufacturing micro-structures. With the described activation we were able to design and implement an automated 3D printing system. The proposed model has the capability of printing multiple layers with high resolution (less than 15µm) and uniform layer height. This set-up can print layer up to 30mm in height which is the maximum possible travel in the Z direction by the moving platform. However, the jet stream looses its continuity as we increase the height because the electric field intensity goes on decreasing as we increase the distance between the substrate and the nozzle. With the current setup, the maximum printing height varied between 3-7mm for our existing high voltage supply which had a limitation of 2kV. Hence, Theoretically, if one was to install a moving stage with a higher range and an efficient high voltage power supply this system would have the potential to print even more layers.Further tests are being carried on using different thermoplastic materials such as Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS). These materials have very high melting temperatures so the available heater band and material tube should be selected accordingly for conducting these experiments.We observed heat looses while supplying heat to the syringe i.e. the applied heat from the Omega CSI32K was higher than the actual temperature at the syringe observed by the thermostat. More efficient ways are to be employed so as to reduce the heat losses and obtain the optimum temperature at a lower value.

REFERENCES

- [1] Kyoon Choi, Jang-Ung Park, O Ok Park, Placid M. Ferreira, John G. Georgiadis, and John A. Rogers, "Scaling laws for jet pulsations associated with high-resolution electrohydrodynamicprinting", Appl. Phys. Lett. 92, 123109
- [2] Lifton, V., Lifton, G., & Simon, S, "Options for additive rapid prototyping methods (3D printing) in MEMS technology", Rapid Prototyping Journal, Vol 20 Issue: 5, pp.403-412



(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: www.ijirset.com

Vol. 8, Issue 5, May 2019

- [3] Alafaghani, A., &Qattawi, A, "Investigating the effect of fused deposition modeling processing parameters using taguchi design of experiment method". Journal of Manufacturing Processes, 36, 164-174.
- [4] Onses, M. S., Sutanto, E., Ferreira, P. M., Alleyne, A. G., & Rogers, J. A, "Printing: Mechanisms, capabilities, and applications of High-Resolution electrohydrodynamic jet printing (small 34/2015). Small, 11(34), 4412-4412.
- [5] Qin, H. (2016), "Development of high-resolution rapid prototyping method for flexible electronic devices based on electrohydrodynamic inkjet printing", Dissertation, NC State University, 2016-07-14
- [6] Masood, S. H., & Song, W. Q, "Development of new metal/polymer materials for rapid tooling using fused deposition modelling" Materials & Design, Vol 25, Issue 7, 587-594.
- [7] Han, Y., & Dong, J, "High-resolution direct printing of molten-metal using electrohydrodynamic jet plotting" Manufacturing Letters, Vol 12, 6-9.
- [8] Han, Y"High-resolution electrohydrodynamic (EHD) 3D printing of function materials", Dissertation, NC State University, 2018-07-01
- [9] Yao, T., Deng, Z., Zhang, K., & Li, S, "A method to predict the ultimate tensile strength of 3D printing polylactic acid (PLA) materials with different printing orientations" Composite Materials, Vol 163, 393-402.
- [10] Kocovic, P. "History of Additive ManufacturingIn 3D Printing and Its Impact on the Production of Fully Functional Components": Emerging Research and Opportunities (pp. 1-24). Hershey, PA: IGI Global, 2017
- [11] Noorani, R, "Rapid prototyping: Principles and applications". Hoboken, N.J: Wiley, 2006
- [12] Barton, K., Mishra, S., Alleyne, A., Ferreira, P., & Rogers, J, "Control of high-resolution electrohydrodynamic jet printing" Control Engineering Practice, 19(11), 1266-1273.
- [13] Hwang, T. H., Kim, Y. J., Chung, H., & Ryu, W, "Motionless electrohydrodynamic (EHD) printing of biodegradable polymer micro patterns", Microelectronic Engineering, 161, 43-51, 2014
- [14] Tse, L. Y. L, "Physics-based printhead designs for enhanced electrohydrodynamic jet printing", 2017
- [15] Liu, F., & Chen, C, "Electrohydrodynamic cone-jet bridges: Stability diagram and operating modes", Journal of Electrostatics, 72(4), 330-335, 2014
- [16] Vijayavenkataraman, S., Zhang, S., Lu, W., &Fuh, J, "Electrohydrodynamic-jetting (EHD-jet) 3D-printed functionally graded scaffolds for tissue engineering applications", Journal of Materials Research, 33(14), 1999-201, 2018