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Optimization of E-jet Based Micro Manufacturing Process Using Grey Relation Analysis*

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Abstract

Electrohydrodynamic (EHD) printing is a micro/nano manufacturing process to deposit the functional materials for fabrication of microelectromechanical systems (MEMS), microelectronic devices etc. The performance of the EHD system is greatly depends on process parameters like applied voltage between the ejection aperture and the substrate, standoff height, applied pressure, and nozzle size. In this paper, an attempt has been made to optimize the process parameters to attain better printing performance. Grey relation grade (GRG) analysis has been employed as a multi objective optimization method to find out the optimal process parameters. In this study, applied back pressure, nozzle standoff height, and applied voltage have taken as control parameters and printed droplet diameter and frequency have considered as printing performance characteristics which are to be optimized.

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Keywords: Electrohydrodynamic printing (EHD);Grey Relation Analysis;Optimization

1. Introduction

In order to meet new challenges to fabricate micro- nano level devices, much effort has been made to come up with new micro level fabrication techniques. In order to achieve these compact design and also proper functioning of the smaller devices high accuracy high resolution pattering as well as printing of the functional material itself required. Traditionally ink-jet based technologies have been employed to serve these purposes. Thermal inkjet (TIJ)

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or bubble jet and Piezoelectric inkjet (PIJ) are the most commonly used ink-jet technology [1]. The main limitation with the TIJ and PIJ is their printing resolution. The printing resolution is limited to about 20-30 μm. Use of smaller nozzle diameter during printing presents the problem of nozzle clogging for highly viscous fluid as well as the application of higher pressure. Not only that, the placement accuracy of the droplet is compromised due the presence of vibrations caused by the piezoelectric actuators [2].

Nomenclature

$A_i(k)$	normalized data sequence
$A_i(k)$	actual response data sequence
a	desired target value of the response
$\xi_i(k)$	grey relation coefficient
Δ_i	deviation sequence
ξ	distinguishing factor
B_i	grey relation grade

In E-jet printing electric field is applied to pull the ink and deposit the droplets in the substrate (surface on which printing is done). The printing resolution (<10 μm) [3] by this technique is very high than that of in case of TIJ and PIJ. Because of its ability to print micro/nano level droplets with high placement accuracy EHD printing finds its application not only in the area of nano/micro fabrication in electronics [4], microelectromechanical systems (MEMS) but also in photovoltaic [5], biotechnology [6], and combinatorial chemistry. In Electrohyrodynamic printing first with the help of applied pressure the ink material is supplied at the tip of the conducting nozzle to form a meniscus. Then a potential difference is applied between the conducting nozzle and substrate. Due to the applied electric field ions of the ink material get mobilized and accumulated at the tip of the nozzle, thus deforming the meniscus into a conical shape known as Taylor's cone [7]. At the sufficient electric voltage, electrostatic stress overcomes the surface tension force at the tip of the Taylor cone and eventually droplets get ejected. In this technology ink droplets gets ejected from the tip of the cone not from the tip of the nozzle, that's why it is possible to generate droplets which are smaller in size than the nozzle.

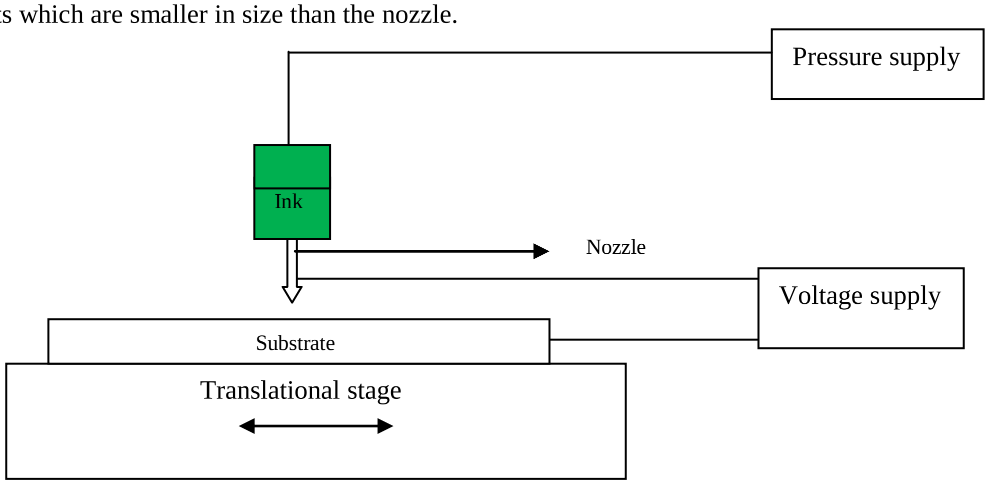

Fig 1. Schematic diagram of the EHD printing system

Although EHD printing is a relatively new technique but principle behind it was established long ago [8]. After that several researchers have studied that principle to print high resolution functional material droplets.H. Chen et al [9] printed particles which are much smaller than the nozzle diameter using EHD DOD technique, thus eliminating the difficulty to manufacture micro size nozzle. Many researchers have shown the capabilities of E-jet printing applied to different applications [10-13]. JANG-UNG PARK et al [3] describes high resolution electrohydrodynamically printed pattern and functional devices with submicron resolution. They also discussed about some key aspects of this approach. They have used direct high-speed imaging of the droplet formation processes. They have produced droplets with both pulsating jet mode and stable jet mode. Chen et al [14] & Choi et al [15] have proposed scaling laws for EHD printing. They showed that the jet diameter is proportional to the square root of the nozzle size and inversely proportional to the electric field strength. But there is a persistent issue with EHD printing is the printing speed. Its speed is somewhat less than the conventional inkjet technologies. Kim et al [16] proposed a hybrid printing scenario. They employed piezoelectric actuator to supply the ink at the nozzle tip and then applied electric field for printing. Previously DC source of current have been employed to apply the electric field between the nozzle and the substrate, pulsing of AC has been demonstrated for E-jet by Nyugen et al. [17]. Modulation of ac showed advantages over dc voltage in terms of fabrication of nozzles, droplet repulsion and drop-on-demand capabilities based on the frequency of sinusoidal voltage applied. S Mishra et al. [18] used pulsed DC voltage for printing. They demonstrated high speed high accuracy drop on demand printing mode. Kira Barton et al [19] of University of Illinois, developed a compact E-jet printing module aiming to provide compact, affordable, and user friendly E-jet printing system. Many researchers also take up the issue of heterogeneous printing of functional material with the help of multi nozzle print head [20].

In the literature cited above, no work has been attempted to optimize the process parameters of EHD printing system. Further, to best of our knowledge, any statistical analysis has also not been carried out yet. This paper presents Grey relation grade analysis (GRG) approach to find out optimal setting of the control variables so as to attain better printing performance.

The context is organized in the following manner: brief description about Grey analysis followed by experimental data collection and its analysis. Then, results and discussion about the conducted analysis presented. Finally, the paper is concluded with the findings of this study.

2. Grey relation grade analysis

The grey system theory is a new technique for performing prediction, relation analysis, and decision making in many areas. It was established in 1982 [21], also finds its application in area of multi objective optimization. In grey relation analysis, black represents having no information and white represents having all information. A grey system has a level of information between black and white. In other words, in a grey system, some information is known and some information is unknown. In a white system, the relationships among factors in the system is certain; in a grey system, the relationships among factors in the system are uncertain [22, 23].

Grey relational analysis is actually a measurement of the absolute value of the data difference between sequences, and it could be used to measure the approximate correlation between sequences. Since Taguchi S/N ratio analysis is unable to optimize multi objective function, grey relation grade analysis can be used to solve the multi objective problem. In this method multi objective function converted into a single performance criterion (grey relation grade) which is then optimized. The maximum value of GRG (grey relation grade) lead to simultaneous optimization of chosen several objective functions.

Since the grey relation grade represents the level of correlation between the reference sequence and the comparability sequence, the greater value of GRG (Grey Relation Grade) means that the comparability sequence has a stronger correlation to the reference sequence. In the other words, regardless of category of the performance characteristics, a greater GRG value corresponds to better performance. Therefore, the optimal level of control parameters is the level with the greatest GRG value.

2.1. Steps involved in Grey relation grade analysis

- Data pre-processing- Normalization. (Since the range and unit in one data sequence may differ from the others. The experimental results are normalized in the range between zero and one)

- Perform analysis – To find out the grey relation co efficient for each response variable on normalized data.

- Calculate the GRG- Find out the grey relation grade by averaging th grey relation co- efficient for each individual test runs.

- Select the optimal levels of process parameters.

The expected goal for each response factor is determined by Wu [24, 25] based on the principles of data processing. They are described in the following

- If the expected goal from the response variable is larger-the-better (ex- the benefit), then it can be expressed by

$A_i(k)=(a_i(k)\text{-}\min a_i(k))/(\max a_i(k)\text{-}\min a_i(k))$ (1)

- If the expectancy is smaller-the-better (ex- the cost and defects), then it can be expressed by

$A_i(k)=(\max a_i(k)\text{-} a_i(k))/(\max a_i(k)\text{-}\min a_i(k))$ (2)

- If the purpose to attain a predefined target value then nominal-the-best (ex- tolerance value), is used. It can be expressed by

$A_i(k)=1\text{-}|a_i(k)\text{-}a|/(\max a_i(k)\text{-}a)$ (3)

Where i= 1, 2, 3……m; k=1, 2….n. m is the number of experimental data (test numbers) and n is the number of parameters (response variable).$a_i(k)$ denotes original data sequence, $A_i(k)$ denotes data sequence after pre-processing (normalized data), max $a_i(k)$ represents maximum of $a_i(k)$, min $a_i(k)$ represents minimum of $a_i(k)$ values and a represents the desired target value. Data pre-processing is carried out with the help of above mentioned equations. The employability of specific normalization equation depends on the type of response variables involved in the problem. After normalization operation grey relational coefficient can be calculated with the help of post-processed sequence. It expresses the relationship between the ideal and actual normalized experimental results.

The grey relational coefficient $\xi_i(k)$ for the k^{th} performance characteristics in the i^{th} experiment can be expressed as follows-

$\xi_i(k)= (\Delta_{min}+ \xi\, \Delta_{max})/(\Delta_i(k)+ \xi\, \Delta_{max})$ (4)

Where, Δ_i is the deviation sequence of the reference sequence and the comparability sequence.
Deviation sequence Δ_i can be calculated as follows-

$\Delta_i=| A_o(k)\text{-} A_i(k)|$ (5)

$\Delta_{min}=\min| A_o(k)\text{-} A_i(k)|$ (6)

$\Delta_{max}=\max| A_o(k)\text{-} A_i(k)|$ (7)

Where $A_o(k)$ denotes the reference sequence and $A_i(k)$ denotes the comparability sequence, ξ is distinguishing or identification coefficient. ζ = 0.5 is generally used.

After the grey relational coefficient is derived, it is usual to take the average value of the grey relational coefficients to find out the grey relational grade [26, 27]. The grey relational grade is defined as follows-

$$B_{i=}\ \frac{(\sum_{k=1}^{n} \xi i(\mathrm{k}))}{n} \quad (8)$$

Where i= no of experiments and k= number of response parameters. The overall evaluation of the multiple performance characteristics is based on the grey relational grade value. The higher grey relational grade represents that the corresponding experimental result is closer to the ideally normalized value. Basically, the larger the grey relation grade value, closer will be the product quality to the ideal value. Thus, larger grey relational grade is desired for optimum performance. Based on the higher grey relation grade optimum level of each controllable factor is determined [28].

3. Data collection and analysis

In this work, the experimental data have been taken from the previous studies conducted by the Graf P.G [29] .In his work, he studies the effect of different control parameters on three printing performance namely droplet diameter, droplet frequency, and droplet volume for two different micro size nozzle diameter. The control parameters ware taken as- nozzle size, ink type, applied pressure, stand-off height, and applied voltage. Two values of each of these variables were used by him to conduct his studies.

The temperature maintained between 68° and 72° F and a relative humidity of around 30% while conducting the experiment. All the nozzles were coated with 20 nm of Au/Pd using a sputter coater Air was blown through the nozzles to ensure no fluid was in the nozzles. The ink was then placed into the syringe and testing began. The substrate that was printed on was a glass microscope slide with about 100 nm of gold evaporated onto it. A series of 5 lines were printed at a speed guaranteeing spacing between droplets.

In this study, we have taken applied pressure, stand-off height, and applied voltage as control parameters and droplet diameter and droplet frequency as response variable. The desired droplet volume should be as small as possible therefore equation (2) has been used for data pre-processing. As for droplet frequency equation (1) has been employed for normalization purpose.

4. Results and Discussion

The experimental data that have been used for this analysis is presented in table 1. Data pre-processing operation has been done on the data presented in the Table 1. This is done to make the response variable data consistent with each other. The normalized values of the response variables can be seen from Table-2. With the help of normalized response data, the next step is to calculate the deviation sequence which is basically the absolute difference between reference sequence and comparability sequence. For the calculation of the deviation sequence, the comparability sequence value taken as the normalized response data. After using equations (5-7) the deviation sequence values are calculated.

Table 1. Control variables & response variables

Experiment no	Pres. (psi)	Gap (μm)	Volt. (V)	Ave. Drop Freq. (Hz)	Ave. Drop D. (μm)
1	1	30	245	50.88	1.63
2	1	30	260	383.6	2.07
3	1	50	275	74.08	1.32
4	1	50	300	326.6	2.16
5	0.25	30	267	83.38	1.79
6	0.25	30	285	285.1	1.47
7	0.25	50	297	39.77	2.19
8	0.25	50	315	253.1	1.33

Table 2 Normalized response variable

Experiment no	Ave. Drop Freq. (Hz)	Ave. Drop D. (µm)
1	0.032309	0.643678
2	1	0.137931
3	0.099776	1
4	0.834385	0.034483
5	0.126821	0.45977
6	0.713555	0.827586
7	0	0
8	0.620467	0.988506

Table 3 indicates the values of deviation sequence for average droplet frequency and average droplet diameter.

Table 3 Deviation Sequence

Experiment no	Δ of Ave. Drop Freq. (Hz)	Δ Ave. Drop D. (µm)
1	0.967691279	0.356322
2	0	0.862069
3	0.900223922	0
4	0.165614913	0.965517
5	0.873178818	0.54023
6	0.286445459	0.172414
7	1	1
8	0.379532963	0.011494

The last step is to find the out the GRG value for each individual test runs. This is the performance index of the whole analysis. Taguchi S/N ratio analysis is capable of optimizing a single response variable or performance characteristics but fails to do so in case of multi objective or multi response system. And this is the relative advantage of GRG analysis over Taguchi S/N ratio analysis. It converts the multi objective function into a single objective problem which is the performance index i.e. GRG value. Optimizing of this index ultimately leads to the simultaneous optimization of the different objective function or response variables which are considered during analysis. The Grey Relation Grade (GRG) values are shown in Table 4.

Table 4 Response table for Grey Relational Grade

Experiment no	GRG	RANK
1	0.462282	6
2	0.683544	3
3	0.678543	4
4	0.546181	5
5	0.422391	7
6	0.689681	2
7	0.333333	8
8	0.773006	1

Since the grey relational grade represents the level of correlation between the reference sequence and the comparability sequence, the greater value of the grey relational grade means that the comparability sequence has a stronger correlation to the reference sequence .In other words, regardless of category of the performance characteristics, a greater grey relational grade value corresponds to better performance [30]. Therefore, the optimal set of the control parameters are the ones with the greatest grey relational grade value. From Table 4 it can be shown that the parameters values in the experiment no 8 give the best printing performance, which is shown by rank1 in the Rank column of the Table 4.

5. Conclusion

In the present study, the GRA approach has been proposed as a way of studying the optimization of EHD inkjet based micro manufacturing process control parameters. The relative advantage of GRA analysis over S/N ratio calculation has also been discussed. The GRA approach easily converts the optimization of the multiple performance characteristics into the GRG, thus simplifying the complicated analysis of multivariable multiple performance characteristics. The optimal EHD control parameters were determined for the multi-performance characteristics for minimum droplet diameter and maximum droplet frequency based on GRG value.

From the response table (Table 4) of the grey relational grade, the largest value of grey relational grade was selected for optimization. The corresponding optimal setting of control parameter combinations are at applied pressure-.25 psi, the standoff height between the nozzle and the substrate - 50 µm, and the applied voltage during printing– 315 volt.

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