Research Article

Shahbaz Juneja[#], Jasgurpreet Singh Chohan, Raman Kumar, Shubham Sharma*[#], Ahmed Hussien Alawadi, Saurabh Aggarwal, Abhinav Kumar, Fuad A. Awwad*, Muhammad Ijaz Khan, and Emad A. A. Ismail

Multiresponse optimisation and process capability analysis of chemical vapour jet machining for the acrylonitrile butadiene styrene polymer: Unveiling the morphology

https://doi.org/10.1515/phys-2023-0203
received October 08, 2023; accepted February 01, 2024

Abstract: The implementation of three-dimensional (3D) printing technology has culminated in a notable rise in productivity and operational effectiveness for manufacturers. Additive manufacturing (AM) is a manufacturing technology that implies an alteration from the conventional approach of material removal. The fundamental idea underlying the AM technique is the gradual buildup of layers (layer-on-layer accumulation). In conventional approaches, every component can have detrimental implications due to the direct interaction between the tool and the workpiece, leading to the loss of heat through friction. The utilisation of 3D printing as a way to surpass conventional processing methods signifies a novel development in several sectors. This method involves the utilisation of unconventional techniques for the fabrication of components. The primary objective of this research is to investigate the chemical vapour jet drilling technique specifically applied to acrylonitrile butadiene styrene (ABS) materials. The intent is to enhance the surface characteristics, or surface finish (SF), and the dimensional accuracy (DA) of ABS workpieces. An evaluation regarding the reliability, repeatability, as well as preciseness of the vapour jet drilling (VJD) process is conducted *via* the utilisation of experiment and data analysis. The study employed a Taguchi L9 design of experiments to carry out a series of tests aimed at analysing the implications of three independent variables: pressure, flow rate, and standoff distance. The researchers employed a multiresponse optimisation approach to attain an optimal combination of parameters that resulted in a superior SF with DA. Consequently, the overall appeal of

# These authors contributed equally to this work and should be considered first co-authors.

*** Corresponding author: Shubham Sharma,** Centre for Research Impact and Outcome, Chitkara University Institute of Engineering and Technology, Chitkara University, Rajpura-140401, Punjab, India; Department of Mechanical Engineering, Lebanese American University, Kraytem, 1102-2801, Beirut, Lebanon, e-mail: shubhamsharmacsirclri@gmail.com, shubham543sharma@gmail.com
*** Corresponding author: Fuad A. Awwad,** Department of Quantitative Analysis, College of Business Administration, King Saud University, P.O. Box 71115, Riyadh, 11587, Saudi Arabia, e-mail: fawwad@ksu.edu.sa
Shahbaz Juneja: Mechanical Engineering Department, University Center for Research & Development, Chandigarh University, Mohali, Punjab, 140413, India, e-mail: juneja_shehbaz@yahoo.com
Jasgurpreet Singh Chohan: Mechanical Engineering Department, University Center for Research & Development, Chandigarh University, Mohali, Punjab, 140413, India, e-mail: jasgurpreet.me@cumail.in
Raman Kumar: Mechanical Engineering Department, University Center for Research & Development, Chandigarh University, Mohali, Punjab, 140413, India, e-mail: ramankakkar@gmail.com
Ahmed Hussien Alawadi: College of Technical Engineering, The Islamic University, Najaf, Iraq, e-mail: ahmedalawadi1985@iunaja.edu.iq
Saurabh Aggarwal: Department of Mechanical Engineering, Uttaranchal Institute of Technology, Uttaranchal University, Dehradun, 248007, India, e-mail: sonu86dit@gmail.com
Abhinav Kumar: Department of Nuclear and Renewable Energy, Ural Federal University Named After the First President of Russia, Boris Yeltsin, 19 Mira Street, 620002, Ekaterinburg, Russia, e-mail: drabhinav@ieee.org
Muhammad Ijaz Khan: Department of Mechanical Engineering, Lebanese American University, Kraytem, 1102-2801, Beirut, Lebanon; Department of Mechanics and Engineering Science, Peking University, Beijing, 100871, China, e-mail: scientificresearchglobe@gmail.com
Emad A. A. Ismail: Department of Quantitative Analysis, College of Business Administration, King Saud University, P.O. Box 71115, Riyadh, 11587, Saudi Arabia, e-mail: emadali@ksu.edu.sa

the outcome was reached. The process's capabilities and dependability were assessed by conducting tests on the substrates at their optimal settings. Surface roughness and circularity were measured at numerous locations on the substrates. The study determined that the process capability indices (C_p and C_{pk}) had values over 1.33 for each of the response parameters, with C_{pk} values also exceeding 1. The analysis of histograms and capability indices demonstrates that the VJD method, when conducted under optimised conditions, may be categorised as statistically controlled for the processing of ABS materials.

Keywords: 3D printing, chemical vapour jet drilling, ABS, Taguchi L9 DOE, surface roughness, circularity

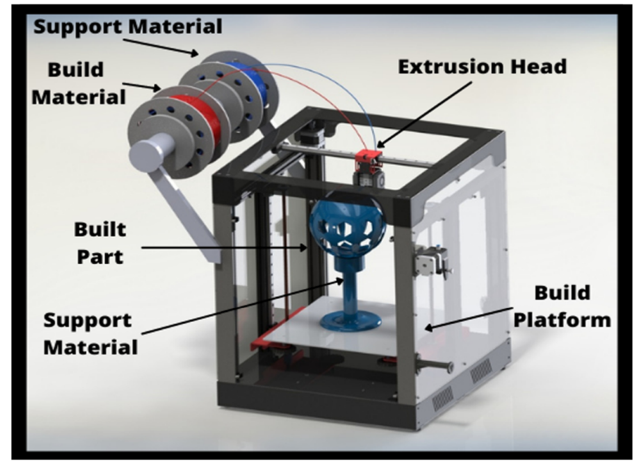


Figure 1: FDM apparatus setup [6].

1 Introduction

In today's world, additive manufacturing (AM), also known as rapid prototyping, is widely employed in various technical applications. AM produces a wide range of complex objects from numerous materials using the layer-by-layer manufacturing technology, which may also be produced using other processes such as fused deposition modelling (FDM), an extensively used process for creating 3D products [1]. Layers are formed in the FDM process by extruding a thermoplastic material *via* a nozzle to produce a single cross-section of a component, which is subsequently repeated as layers until the component creation is finished [2]. Nowadays, the FDM technology, when paired with specialised 3D printers, enables the manufacturing of exact components with complicated forms and voids. Small production machines based on the FDM technique are now relatively inexpensive and are being used in academic institutions, enterprises, and even residences [3]. The FDM method is a quick, low-cost, clean, and safe technique for producing a product through layer-by-layer deposition [4]. In FDM, the material of choice is softened and inserted into a liquefier, which melts it and then drives the molten material out of the nozzle resulting in the end product (Figure 1). The machine moves, and the extruded material is deposited to achieve the desired shape [5].

With the enormous increase of interest in the last few decades for mass manufacturing and the necessity to produce high-quality goods in a shorter time and at a cheaper cost, FDM utilisation has also increased [7]. The most common FDM materials are polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polyethylene terephthalate, nylon, thermoplastic polyurethane, and polycarbonates. Due to its exceptional characteristics, such as resistance to corrosion, superior strength, resistance to thermal and corrosive moisture, and high recommendation for machining operations, ABS is among the most commonly used materials in the market at present [8].

Post-production activities for FDM products involve the use of a few non-traditional machining techniques. Less waste and materials wear and tear result from non-traditional processing since it avoids point-to-point interaction among tools and components. These procedures signify the commencement of the machining of intricate shapes with excellent surface finish (SF) at a reasonable price, satisfying the needs of efficient and enhanced manufacturing in material deformation [9]. ABS parts' surface and finish can be damaged by conventional tools when they are handled *via* conventional techniques, including milling, turning, boring, drilling, and grinding. ABS is subject to point-to-point interactions in traditional methods, due to the friction between the instrument and the workpiece, causing the material to melt further [10].

The cost of tool changing and production has increased many folds as a result of traditional processes, raising the production cost. The examination of chips reveals that the material has been deformed plastically [11]. Recently, a study has been carried out to create a better machining method in the context of such imperfections. Among all the feasible machining techniques, the unconventional procedure is one of the more effective ones.

Parts made from 3D printing typically go wasted during standard machining due to the wasting and unmanageability of plastic components; this entails the need of an unconventional method to reuse the components. Recycling processes can be handled chemically or mechanically [12]. In non-conventional-type machining, innovative machining procedures, including electrodischarge machining, laser cutting, abrasive water jet, and vapour finishing, are employed [13]. In machining, chemical vapour processes are used. SF is improved by processes, which employ methods such as chemical treatment and coating [14]. Drilling operations and other machining processes are performed on 3D-printed materials. These processes are performed utilising unconventional techniques, including abrasive jet machining, and so on. To employ parts as jigs, fixtures, and tools, acetone vapour jet drilling (AVJD) is carried out on the components. Acetone facilitates SF during drilling and resulting in more circular drill holes [15]. Recycled plastic is a better way to use ABS material for a better environmental impact because ABS material is non-biodegradable, which increases the plastic waste and leads to advancements in recycling [16,17].

Moreover, to enhance the surface, chemical dipping is one such technique [15] that employs chemical treatments and coatings. SF and machining of components are enhanced by acetone solvents [16]. Surgical instruments, bone implants, tissue implants, and prosthetics are among the medical devices and implants that FDM can produce. One significant issue that necessitates attention is the considerable amount of ABS material that is wasted throughout the manufacturing as well as post-processing stages, pertaining to both traditional and non-traditional methods. Due to the non-biodegradability of ABS/PLA materials, the primary challenge is the disposal of waste ABS material [17]. In an attempt to address this matter, multiple studies have been initiated in the recycling of materials. Further study as well as utilisation of recycled ABS within numerous areas of contemporary life is crucial to mitigating environmental consequences [18]. In addition, recycling is necessary to avert environmental and human health risks [19] owing to the non-biodegradable characteristics of the material.

In addition, drilling along with water-jet machining, abrasive jet, and laser machining constituted a significant proportion of prior attempts. The aforementioned techniques had replaced the conventional machining process. ABS material recycling is the aim of the current investigation, which has focused on non-traditional machining and drilling techniques. The implications of drilling 3D-printed components with acetone vapour were examined in this research. Vapour jet drilling (VJD) employing acetone has been employed to perform the process on ABS.

Within machining, chemical vapour processes were additionally employed. These methods contributed to the enhancement of SF, employing methods, including chemical processing as well as coating [16]. Materials that have been 3D-printed were subject to machining processes including drilling. Abrasive jet machining is one of the non-conventional techniques employed for completing these drilling processes. The components undergo AVJD in order to prepare them for subsequent applications such as fixtures, tools, moulds, and so forth. Enhanced circularity of the drill holes is accomplished with the aid of acetone throughout the SF phase of drilling [17].

Acetone exhibits superior performance as a liquid solvent for treating ABS components, including vapour smoothing, polishing, and adhering, when compared with methyl ethyl ketone as well as tetrahydrofuran. Tetrahydrofuran melts at a higher temperature and evaporates at a slower rate [18,19], despite the fact that its solvent characteristics are identical to those of acetone.

The "non-biodegradable" character of ABS material contributes to a rise in plastic waste, which in turn resulted in developments in ABS material recycling. Consequently, recycling this material is a more efficient technique in terms of the environment's impact [20–22].

To analyse the data, the response surface methodology and genetic algorithm (GA) were utilised, and finally process capability indices were utilised to validate the results. The Pareto front was concluded to supply adequate optimum combinations of input parameters to achieve the best output outcomes that satisfy the demands. In practice, the method may be applied to various multilevel, multifactor design problems. The model was developed to determine the most optimum input parameters or the best combination of input parameters to acquire the nominal output parameters in 3D-printed items.

2 Experimental methodology

For this research, an optimal control study is carried out in order to determine the utmost appropriate factors for the outcomes. This study complies with the GA, and the results are validated using Process capability indices. Acetone is used as a surface enhancer, increasing the efficiency and smoothness. Acetone drilling demands a parametric analysis of the end output. The results of the present study shed light on the impact of AVJD on the circularity and surface quality of 3D-printed materials. The major concern behind the selection of AVJD for the ABS substrate is the recycling of the ABS material to reduce the wastage of material and improve the efficiency of the manufacturing or finishing process. The methodology adopted for the present research work is presented in Figure 2.

2.1 Experimental setup

Experiments are carried out on a CVJ machine setup designed in-house for this study for the current research work. Parts used in the investigation are described in Table 1.

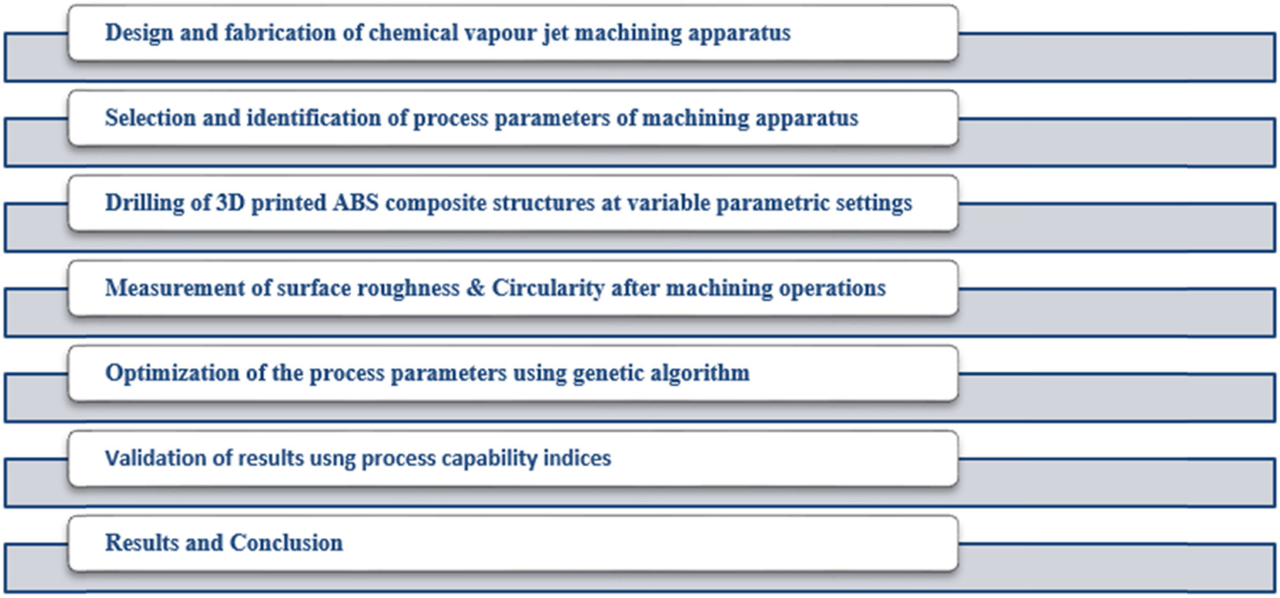


Figure 2: Flow chart representing the methodology of research work.

The machine is partitioned into two primary segments, as depicted in Figure 3(a–c). The first portion is the control flow subsection, which contains the compressor, mixing chamber, and gauges. The workstation part, which is the second component, consists of a reservoir, a nozzle, as well as control valves. A high-pressured vapour of air and acetone are ejected through the assistance of a flow control valve, and the amount that is expelled depends on the operating circumstances of the specific experiment. An adjustable worktable allows for the standoff distance adjustment, and a pressure valve allows for the compressed air pressure adjustment. Three parametric groups are employed as input parameters for chemical vapour jet machining, including the compressed air pressure, acetone vapour flow rate, and the gap between the workpiece and the nozzle, in addition to cutting at three distinct levels. Although the screws are used to regulate the standoff distance, or the gap between the nozzle and the workpiece, a nozzle holding setup is provided directly above the workpiece holding fixtures. Utilising the flow regulating valves, the compressed air pressure and acetone vapour flow rate are maintained.

2.2 Work material

ABS is a thermoplastic polymer commonly employed in the fabrication of lightweight and structurally durable components. The superior character of the ABS material enhances its utilisation and optimal performance. The practicality and long-term viability of the material have been enhanced by its resistance to corrosion, superior strength, excellent machinability, resistance to heat and chemical moisture, as well as the accessibility of a broader colour spectrum. Impact resistance and toughness have been regarded as the key criterion for assessing ABS

Table 1: Comprehensive overview of the components utilised in the setup for the experiment

S.No.	Materials	Summary/analysis
1	Compressor	To achieve a maximal optimum pressure up to 12 bar
2	Pressure gauge	This component efficiently regulates and manages the pressure
3	Inlet pipe and outlet pipe	Pipes meant for compressed air routes/pathways/passages
4	T-joint	For joining pipes, inlet-channel pathways, and outlet passageways
5	Mixing chamber	For blending the gaseous vapour and the acetone solvent to produce a homogenous solution
6	Flow-control valve	Regulates the fluid's flow rate
7	Nozzle	The term "outlet" refers to the point of discharge and usually associated with the release comprising a high-pressure stream flow of liquids
8	Workpiece holder	The workpiece serves as a fixture for holding the sample throughout the experimental process
9	Reservoir	A storage facility designed for collecting and recycling excessive gaseous vapour wastes

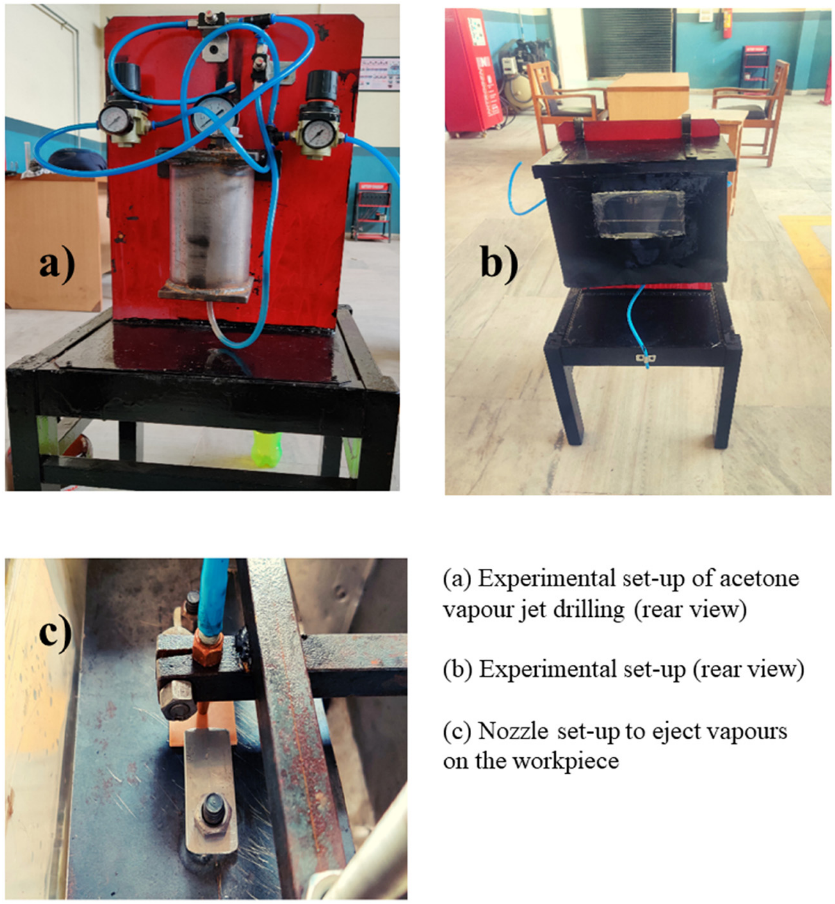


Figure 3: (a–c) Components of the experimental setup.

material. The temperature of ABS materials ranges from −40 to 100°C, rendering them favourable for a diverse array of methods and applications. ABS materials discover applications in an extensive variety of industries, encompassing automotive, aerospace, toy manufacturing, electrical housing, household appliances, and several other areas.

2.3 Experimentation

In this investigation, an optimisation analysis is conducted to ascertain the optimal parameters for the desired outcomes. This study employs the Taguchi approach for designing or formulating the experimental layout plan. Acetone serves as a surface enhancer, enhancing the effectiveness, texture, and polish of the material. Utilisation of acetone during drilling operations requires a comprehensive assessment of eventual outcomes through parametric analysis. The outcomes acquired from this experimental study offer valuable insights into the implications of AVJD on the circularity and SF for 3D-printed materials.

Analysis of the AVJD process is done following the investigation into the efficacy of the chemical vapour jet drilling (CVJD) method in enhancing the surface properties and dimensional precision of ABS workpieces. This investigation assesses the impacts of three independent variables – standoff distance, flow rate, and pressure – using a Taguchi L9 design of experiments (DOE). Furthermore, optimisation is made utilising a GA.

2.3.1 Rationale behind the usage of Taguchi and GA for the current study

The rationale behind the usage of L9 Taguchi, GA, and process capability is presented as follows with suitable literary source support.

2.3.1.1 Taguchi L9 design

The Taguchi L9 experimental design is selected due to its effectiveness in carrying out a series of experiments requiring a minimum number of trials. This arrangement has facilitated the analysis of the implications that independent variables have on the response factors, namely, surface roughness and circularity [19–21]. By employing the L9 design, the investigators are able to identify optimal parameter combinations while employing fewer resources through the application of a systematic, methodical, and organised approach to testing [19–21].

2.3.1.2 GA

Now, in the context of GA optimisation, the technique has evolved in response to the processes of natural selection. This algorithm is well-suited for obtaining optimal solutions for multivariate complex problems [19–21]. To attain the highest level of surface roughness and circularity in the AVJD process, an optimal combination of input variables (pressure, flow rate, and standoff distance) is determined employing the GA in this investigation [19–21].

Suitable for the multiresponse optimisation technique utilised in this investigation, GA is efficient in identifying optimal solutions as well as examining an extensive solution space when multiple objectives have been available.

2.3.1.3 Process capability evaluation

In accordance with the process capability evaluation, in order to assess the dependability and replicable nature of the AVJD process under ideal conditions, process capability indices (C_p and C_{pk}) are utilised. The components could be produced within the defined tolerance limits when C_p and C_{pk} values exceed 1.33 [20–22]. This indicates that the method is statistically controlled. Hence, the evaluation divulges knowledge regarding the potential of the process to be utilised in industries as well as for additional scholarly investigation [19–21].

3 Results and discussion

3.1 Surface roughness and circularity

The results obtained for surface roughness and circularity studies after successful experimentation on the ABS substrate using the AVJD operation employing a predefined set of input variables are shown in Table 2. The maximum and minimum surface roughness values obtained are 2.664 and 1.598 µm, respectively. The maximum value of surface roughness has been achieved at 5 bar pressure, 19 ml/min flow rate, and 2.5 mm standoff distance, whereas the minimum value of surface roughness is obtained at 3 bar pressure, 16 ml/min flow rate, and 2.5 mm standoff distance. Similarly, maximum and minimum circularity obtained are 0.5210 and 0.3320 µm, respectively. The maximum value of circularity has been achieved at 5 bar pressure, 16 ml/min flow rate, and 1.5 mm standoff distance, whereas the minimum value of circularity is obtained at 3 bar pressure, 13 ml/min flow rate, and 1.5 mm standoff distance. Additionally, the circularity denotes the degree to which the geometry of an object approaches that of a perfect circle, whereas surface roughness quantifies the presence of irregularities on a surface. The effectiveness of AVJD can be influenced by the pressure, rate of flow, and standoff distance. Increased material removal may take place as a consequence of increased pressure and flow rates, thus impacting surface characteristics. Circularity is affected by the standoff distance, which in turn impacts the concentration as well as focus of the acetone vapour.

3.2 GA optimisation results

It is challenging to select the best input parameters to produce the best outputs depending on the specification. Numerous results may be poor not because the database is disruptive or the algorithm is inefficient but simply

Table 2: L9 input parameters and output results obtained

S. no.	Pressure *X*1	Flow rate *X*2	Standoff distance *X*3	Surface roughness (smaller is better)	Circularity (smaller is better)
1	3	13	1.5	2.664	0.3320
2	3	16	2.5	1.598	0.4951
3	3	19	3.5	2.528	0.3855
4	4	13	2.5	2.560	0.3629
5	4	16	3.5	2.461	0.4960
6	4	19	1.5	4.056	0.3598
7	5	13	3.5	3.663	0.4119
8	5	16	1.5	4.095	0.5210
9	5	19	2.5	4.205	0.4631

because the control variables are selected inaccurately. In the current study, along with several other basic random-based evolutionary algorithms, GA is used to discover the ideal set of input variables for effective output results. In this optimisation, the term $X1$ is ascertained to be Pressure, $X2$ to be Flow Rate, and $X3$ to be standoff distance. Hence, by utilising the GA method, the following two equations are generated to evaluate the optimal combination of "input parameters."

$$\begin{aligned}\text{Surface roughness} = {} & 18.33 - 0.07128\,X1 - 1.809\,X2 \\ & - 2.832\,X3 + 0.09983\,X1 \times X1 \\ & + 0.05989\,X2 \times X2 \\ & + 0.4590\,X3 \times X3 \\ & + 0.001444\,X1 \times X2 \\ & + 0.04467\,X1 \times X3.\end{aligned} \tag{1}$$

$$\begin{aligned}\text{Circularity} = {} & -2.601 - 0.2387\,X1 + 0.4133\,X2 \\ & + 0.1140\,X3 + 0.02853\,X1 \times X1 \\ & - 0.01308\,X2 \times X2 - 0.01862\,X3 \times X3 \\ & + 0.002700\,X1 \times X2 - 0.000867\,X1 \times X3.\end{aligned} \tag{2}$$

Using Eqs. (1) and (2), it is determined that the maximum surface roughness is achieved at 3 bar pressure, 15.0665 ml/min flow rate, and 2.9390 mm standoff distance. Second, the maximum circularity is obtained at 3.5909 bar pressure, 13 ml/min flow rate, and 1.5 mm standoff distance.

As demonstrated by the equation, an increase in the rate of flow and pressure is conducive to a corresponding increase in roughness, whereas an increase in standoff distance yields a corresponding reduction in roughness.

The equation suggests that in order to attain optimal circularity, specific purposes must be accomplished by pressure, rate of flow, and standoff distance; this emphasises the significance of attaining an optimal balance among these factors.

This research has employed numerous combinations of input variables to attain the maximal output outcomes for each individual case. However, an evolutionary GA method has been used as a multiobjective optimisation approach to identify the unique combination of input variables that yields the maximal output. The weight set formula is employed for determining the multiobjective optimisation utilising the equation presented as follows.

$$\begin{aligned}Z_{\min} = {} & 0.5(18.33 - 0.07128\,X1 - 1.809\,X2 - 2.832\,X3 \\ & + 0.09983\,X1 \times X1 + 0.05989\,X2 \times X2 \\ & + 0.4590\,X3 \times X3 + 0.001444\,X1 \times X2 \\ & + 0.04467\,X1 \times X3 + 0.5(-2.601 - 0.2387\,X1 \\ & + 0.4133\,X2 + 0.1140\,X3 + 0.02853\,X1 \times X1 \\ & - 0.01308\,X2 \times X2 - 0.01862\,X3 \times X3 \\ & + 0.002700\,X1 \times X2 - 0.000867\,X1 \times X3).\end{aligned} \tag{3}$$

Employing the input parameter combinations as a foundation, the maximum output results are obtained from Eq. (3), under the conditions of "3 bar pressure," "14.7405 ml/min flow rate," and "1.5 mm standoff distance." The optimisation results are presented in Table 3.

The best and mean fitness values are 2.07191 and 2.07192, respectively, and the best worst and mean scores subsequent to optimisation and function selection are depicted in Figure 4.

3.3 Process capability assessment

Confirmatory tests are necessary to validate the multi-response optimisation tool's efficacy. Twenty ABS substrates were subject to processing under optimal conditions. Table 4 shows the final results of 20 operations performed on workpieces under optimal processing conditions. Under optimal conditions, particularly at 3 bar pressure, 15 ml/min flow rate, 3 mm standoff distance or gap between the workpiece and the nozzle for surface roughness and under conditions of 3.5 bar pressure, 13 ml/min flow rate, and 1.5 mm standoff distance or gap between the workpiece and the nozzle for circularity, considerable enhancement in surface roughness and circularity is realised. However, by ensuring reliability as well as repeatability, histograms confirm the normal distribution of data points.

The AVJD process has been conducted for evaluating the process capability which will aid in establishing the process capability to fabricate components under tolerance limits. In order to determine the process capability

Table 3: Optimisation results

	Pressure (bar)	Flow rate (ml/min)	Standoff distance (mm)	Objective function value
Single objective	3.0000	15.0665	2.9390	1.4550
Single objective	3.5909	13.0000	1.5000	0.3226
Multiobjective	3.0000	14.7405	1.5000	2.0719

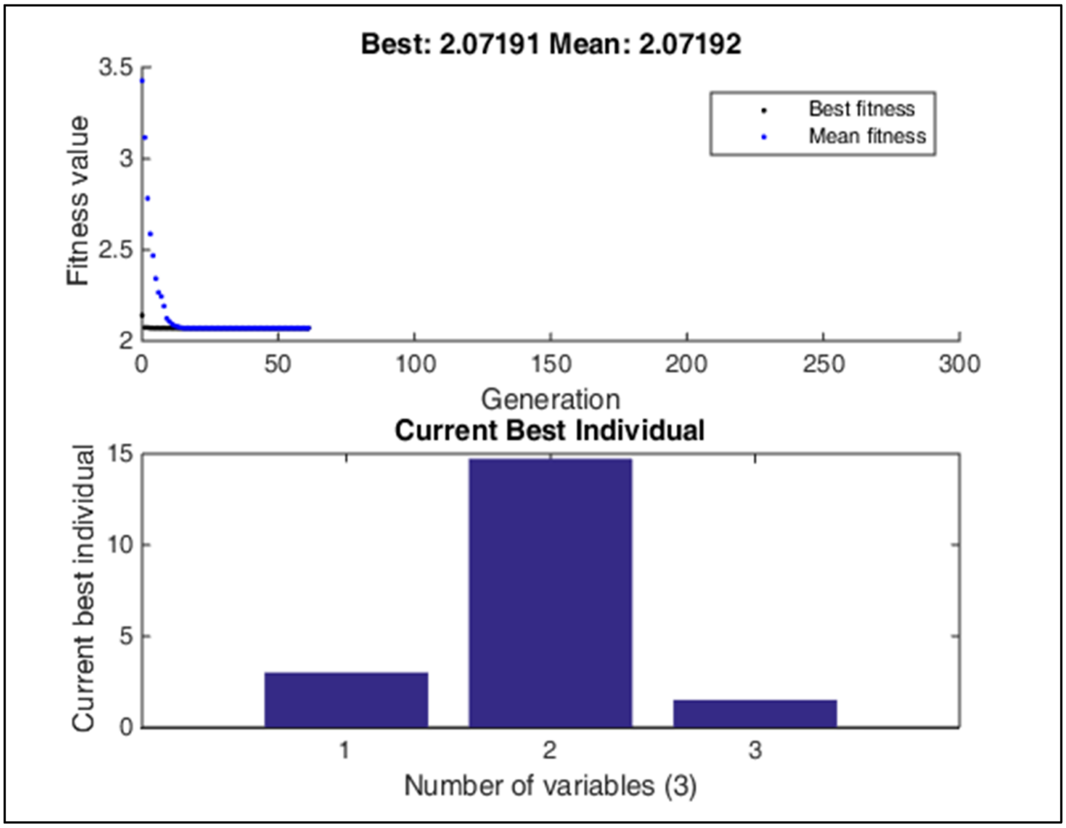


Figure 4: Optimisation graphs.

Table 4: Confirmatory results

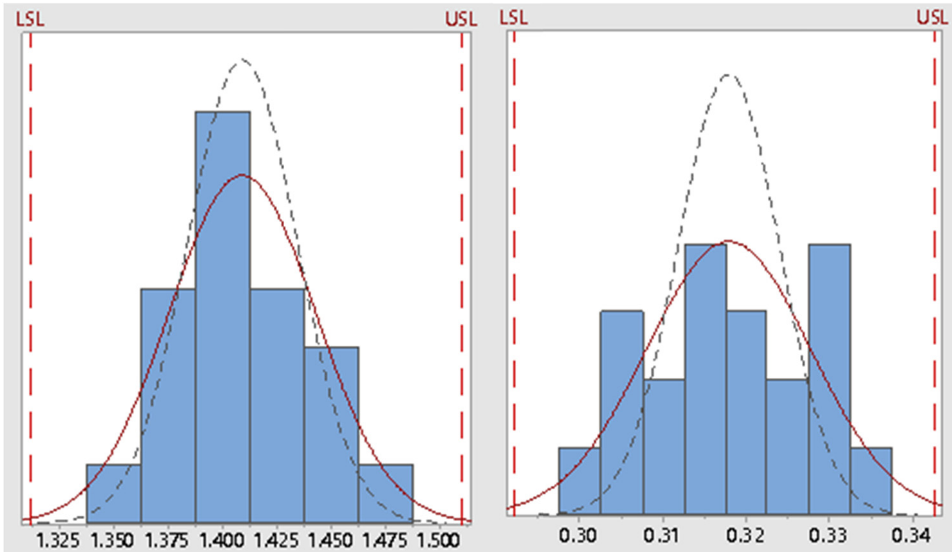
S. no.	Surface roughness	Circularity
1	1.342	0.3108
2	1.369	0.3151
3	1.48	0.3022
4	1.454	0.3032
5	1.406	0.3313
6	1.395	0.3296
7	1.394	0.3265
8	1.396	0.3325
9	1.422	0.328
10	1.432	0.3304
11	1.381	0.3246
12	1.373	0.3196
13	1.425	0.3123
14	1.447	0.3151
15	1.412	0.3201
16	1.386	0.3133
17	1.399	0.3058
18	1.388	0.3156
19	1.432	0.3183
20	1.45	0.3031

indices (C_p, C_{pk}), the response data from confirmatory experimental studies are employed [18,19]. The two process capability indices, C_p and C_{pk}, are determined as follows:

$$C_p = \frac{\text{USL} - \text{LSL}}{6\sigma},$$

Table 5: Evaluation of process capabilities for distinct responses

	Surface roughness	Circularity
Observations	20	20
USL	1.51	0.3425
Target (mean value)	1.41	0.318
LSL	1.312	0.2922
Maximum value	1.48	0.3325
Average	1.40915	0.31787
Minimum value	1.342	0.3022
Range	0.02552893	0.0061544
Standard deviation	0.0033655	0.0099115
C_p	1.35	1.36
C_{pk}	1.28	1.31



(a) (b)

Figure 5: Histograms: (a) surface roughness and (b) circularity.

$$C_{pk} = \text{Minimum of}\left[\frac{x - \text{LSL}}{3\sigma}, \frac{\text{USL} - x}{3\sigma}\right],$$

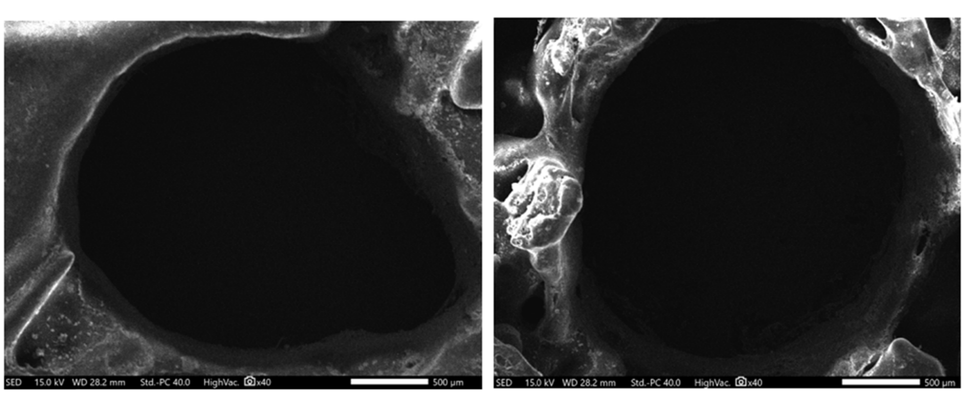
where USL is the upper specification limit, LSL is the lower specification limit, x is the process mean, and σ is the process standard deviation.

For each of the two responses, Table 5 shows the findings of the process capability analysis. C_p levels across each response variable are higher than 1.33, whereas C_{pk} values are more than 1. These process capability indices are commonly used as industry benchmarks.

Histograms for two-response parameters are developed in order to affirm or validate the "normal distribution" hypothesis. Figure 5 shows the histograms for surface roughness and circularity. According to histogram analysis, the data are normally distributed and appear in both the upper and lower levels. The data points for surface roughness and circularity lie exactly between lower and upper limits. Surface roughness and circularity are achieved by generating the sharp and tall bell-shaped curves. The maximal accuracy and repeatability are apparent in the circularity of the drilling surface of substrates after VJD, whereas the surface roughness varies in a very small range.

3.4 Surface morphology

It is convenient to examine the modifications, surface roughness, and circularity of the investigated findings from SEM



(a) **(b)**

Figure 6: SEM micrographs of AVJ treatment under different conditions: (a) under condition A and (b) under condition B [20].

micrographs, which depict the image of the substance in a highly magnified scale (40×) . The micrographs from SEM analysis during AVJD and our current study are shown in Figure 6(a and b). Moreover, the surface morphology analysis shows the characteristics and structure of the surface of a material. The mechanisms underlying the impacts of AVJD on surface roughness and circularity are visually depicted in SEM micrographs. The surface morphology is impacted by factors, including pressure, flow rate, and standoff distance variations. SEM images reveal a discernible reduction in surface roughness and an increase in circularity.

Additionally, Figure 6a displays the substrate SEM picture obtained at 3 bar pressure, 15 ml/min flow rate, and 3 mm gap between the workpiece and the nozzle, showing a noticeable reduction in surface roughness. Figure 6b shows the SEM image of the substrate treated at 3 bar pressure, 15 ml/min flow, and 1.5 mm gap between the workpiece and the nozzle, exhibiting a slight enhancement in circularity. To recapitulate, it is evident and obvious that the circularity and SF have been enhanced.

All in all, a localised environment produced by the high-pressure vapour induces material removal from the ABS surface *via* chemical means. Influencing the SF and dimensional accuracy (DA), the intensity and emphasis of the chemical reactions are controlled by the tunable parameters (pressure, rate of flow, and standoff distance) [19–21].

Furthermore, acetone, functioning as a surface enhancer, is engaged in interaction with the ABS material, which has the potential to modify as well as soften its surface. The parameters determines the optimum combination of rate of flow, standoff distance, and pressure that yields superior surface roughness and circularity [19–21].

4 Conclusions

This research employed AVJD for conducting experiments on ABS substrates. The investigation assessed the implications of three autonomous factors – pressure, flow rate, and standoff distance – on the surface characteristics and dimensional precision of ABS materials generated through CVJD by employing a Taguchi L9 DOE. Systematically analysing the process parameters was made possible by the experimental design. With the objective of determining a particularly favourable parameter combination that would yield an exceptional SF while retaining DA, the research employed a multiresponse optimising method. Validating the reliability, repeatability, and accuracy of the VJD method, the researchers employed the process capability indices (C_p and C_{pk}). Maximising surface irregularity as well as circularity was considered a goal when optimising the input variables employing the GA. In order to ascertain the optimum parameter combination that yields maximal outcomes, equations were formulated. Optimal input parameters were determined through the implementation of multiobjective optimisation.

Circularity was exhibited in a range of 0.3320–0.5210, whereas surface roughness varied from 1.598 to 2.664 µm. The implications of pressure, rate of flow, and standoff distance on the surface characteristics were demonstrated in order to ascertain the optimum AVJD conditions. The research affirms the effectiveness of the process under optimal circumstances. By computing C_p and C_{pk} values, the capability of a process for producing components within the limits of tolerance can be determined. Statistical control as well as adherence to industry benchmarks are evidence of C_p levels exceeding 1.33 and C_{pk} values exceeding 1. A normal distribution of data is validated by histograms depicting surface irregularity and circularity. A discernible reduction in surface irregularity and an enhancement in circularity have been noticed in microscope images at the optimum setting of parameters. The research findings illustrated how circularity and SF could be effectively enhanced through optimised AVJD conditions.

By utilising acetone as a surface enhancer, AVJD was developed with the intention of further enhancing the drilling process efficacy and fluidity. Concerning the recycling of the ABS material to mitigate waste while strengthening the manufacturing efficiency, this study underlined the implications of AVJD on the surface quality as well as circularity of 3D-printed ABS materials.

At optimum process parameters, the process capability of ABS substrates processed with the AVJD method has been successfully investigated. For industrial purposes, the process of drilling ABS workpieces under optimised conditions can be defined as statistically controlled. The optimal parameter configurations could be useful for future research into the possibilities of VJD for FDM parts.

5 Societal benefits from the research

The research findings have contributed to the following societal benefits:

a) **Increased efficiency and productivity:** AVJD has the potential to substantially strengthen the efficacy and productivity of the 3D-printing technique, according to the research findings. Enhanced surface characteristics are the outcomes of optimised conditions, which greatly contribute towards the aesthetic appeal of finished products manufactured through 3D printing.

b) **Reduced material waste and material recycling for sustainability:** The choice of AVJD for ABS substrates corresponds with the goals of recycling ABS materials, thereby minimising the waste of materials during the production phase.

   This initiative promotes responsibility for the environment within the realm of 3D printing, thereby supporting sustainable practices.

c) **Applications across industries:** ABS materials possessing enhanced characteristics have been utilised in an array of sectors, including automobile, aviation, electric housing, and household appliances, among others.

   This study demonstrates the versatility of the technology by offering opportunities for the application of AVJD across various industries.

d) **Optimised manufacturing processes:** The controlled and accurate drilling of ABS workpieces is made possible through the implementation of optimised factors determined by the study.

   A thorough comprehension of process capabilities can be favourable to industries as it ensures the manufacturing of components of superior quality.

e) **Prospects for future research:** The settings of optimal parameters delineated in this investigation establish a fundamental basis for subsequent scholarly inquiries concerning the potential of VJD in the context of FDM components.

This phenomenon presents opportunities for ongoing enhancement and novel approaches in the realm of AM.

To summarise, this research not only enhances the comprehension of AVJD on ABS materials but also makes a contribution to the wider domain of 3D printing by highlighting the significance of sustainability, efficiency, and the potential for AM technology advancements.

Acknowledgments: Researchers Supporting Project number (RSPD2024R576), King Saud University, Riyadh, Saudi Arabia.

Funding information: Researchers Supporting Project number (RSPD2024R576), King Saud University, Riyadh, Saudi Arabia.

Author contributions: Conceptualisation: SJ, JSC, RK; methodology: SJ, JSC, RK; formal analysis: SJ, JSC, RK; investigation: SJ, JSC, RK; writing – original draft preparation: SJ, JSC, RK; writing – review and editing: SJ, JSC, RK; supervision: SS, AHA, SA, AK, FAA, MIK, EAAI; project administration: SS, AHA, SA, AK, FAA, MIK, EAAI; funding acquisition: SS, AHA, SA, AK, FAA, MIK, EAAI. All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Conflict of interest: The authors state no conflict of interest.

Data availability statement: All data generated or analysed during this study are included in this published article.

References

[1] Parandoush P, Lin D. A review on additive manufacturing of polymer-fiber composites. Compos Struct. 2017;182:36–53.

[2] Mazzanti V, Malagutti L, Mollica F. FDM 3D printing of polymers containing natural fillers: A review of their mechanical properties. Polymers (Basel). 2019;11(7):1–22.

[3] Yasa E, Ersoy K. A review on the additive manufacturing of fiber reinforced polymer matrix composite. Solid Free form Fabrication 2018: Proceedings of the 29th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference; 2018. p. 1024–33.

[4] Yadav D, Chhabra D, Kumar Garg R, Ahlawat A, Phogat A. Optimization of FDM 3D printing process parameters for multi-material using artificial neural network. Mater Today: Proc. 2020;21:1583–91. doi: 10.1016/j.matpr.2019.11.225.

[5] Peng X, Kong L, Fuh JYH, Wang H. A review of post-processing technologies in additive manufacturing. J Manuf Mater Process. 2021;5(2):1–23. doi: 10.3390/jmmp5020038.

[6] Juneja S, Chohan JS, Kumar R, Sharma S, Ilyas RA, Asyraf MR, et al. Impact of process variables of acetone vapor jet drilling on surface roughness and circularity of 3D-printed ABS parts: fabrication and studies on thermal, morphological, and chemical characterizations. Polymers (Basel). 2022;14(7):1367. doi: 10.3390/polym14071367.

[7] Jaisingh Sheoran A, Kumar H. Fused deposition modeling process parameters optimization and effect on mechanical properties and part quality: Review and reflection on present research. Mater Today: Proc. 2020;21:1659–72. doi: 10.1016/j.matpr.2019.11.296.

[8] Singh S, Ramakrishna S, Singh R. Material issues in additive manufacturing: A review. J Manuf Process. 2017;25:185–200.

[9] Paul L, Babu J, Paulo Davim J. Non-conventional micro-machining processes. In: Gupta K, editor. Materials Forming, Machining and Post Processing. Materials Forming, Machining and Tribology. Cham: Springer; 2020. p. 109–39. doi: 10.1007/978-3-030-18854-2_5.

[10] Teti R. Machining of composite materials. CIRP Ann. 2002;51(2):611–34.

[11] Hocheng H, Puw HY. Machinability of fiber-reinforced thermoplastics in drilling. J Eng Mater Technol. 1993;115(1):146–9.

[12] Thakur S, Verma A, Sharma B, Chaudhary J, Tamulevicius S, Thakur VK. Recent developments in recycling of polystyrene based plastics. Curr Opin Green Sustain Chem. 2018;13:32–8. doi: 10.1016/j.cogsc.2018.03.011.

[13] Müller F, Monaghan J. Non-conventional machining of particle reinforced metal matrix composite. Int J Mach Tools Manuf. 2000;40:1351–66.

[14] Galantucci LM, Lavecchia F, Percoco G. Quantitative analysis of a chemical treatment to reduce roughness of parts fabricated using fused deposition modeling. CIRP Ann – Manuf Technol. 2010;59(1):247–50. doi: 10.1016/j.cirp.2010.03.074.

[15] Colpani A, Fiorentino A, Ceretti E. Characterization of chemical surface finishing with cold acetone vapours on ABS parts fabricated by FDM. Prod Eng. 2019;13:437–47. doi: 10.1007/s11740-019-00894-3.

[16] Kim JK, Kang CK. Basic studies on recycling of ABS resin. Polym Plast Technol Eng. 1995;34(6):875–90. doi: 10.1080/03602559508012182.

[17] Pakkanen J, Manfredi D, Minetola P, Iuliano L. About the use of recycled or biodegradable filaments for sustainability of 3D printing: State of the art and research opportunities. Smart Innov Syst Technol. 2017;68:776–85. doi: 10.1007/978-3-319-57078-5_73.

[18] Perakis M, Xekalaki E. A process capability index that is based on the proportion of conformance. J Stat Comput Simul. 2002;72(9):707–18. doi: 10.1080/00949650214270.

[19] Singh R. Process capability analysis of fused deposition modelling for plastic components. Rapid Prototyp J. 2014;20(1):69–76. doi: 10.1108/RPJ-02-2012-0018.

[20] Juneja S, Chohan JS, Kumar R. Preliminary investigations on performance of acetone vapour jet drilling operations on 3d printed abs parts. Mater Today: Proc. 2022;68:749–55.

[21] Chaudhari AA, Godase AM, Ravindra J, Abhijit N. Acetone vapor smoothing: A postprocessing method for 3D printed ABS parts. Int J Res Sci Innov. 2017;4:123–7.

[22] Puerta APV, Fernandez-Vidal S, Batista M, Girot F. Fused deposition modelling interfacial and interlayer bonding in PLA post-processed parts. Rapid Prototyp J. 2019;26:585–92.