Experimental investigation and parametric optimization of micro holes on inconel 718 using developed µ-AJM set-up

Vinod V Vanmore[1*] and Uday A Dabade[2]

Department of Mechanical Engineering, Walchand College of Engineering, Sangli, Maharashtra

ABSTRACT

Keywords:
Micro-abrasive Jet Machining (MAJM),
Inconel 718,
Material Removal Rate (MRR);
Taguchi Method;
Analysis of Variance (ANOVA)

Nowadays, trends in the manufacturing industry, micromachining on difficult to machine materials such as ceramics, silicon, glass, alloys of titanium and nickel, etc. is a challenging task. Difficult to machine materials are widely used for MEMS, electronic devices, medical and aerospace industries. The higher cost is associated with the machining of these materials. Mostly µEDM, µECM and µLBM process is used to create micro features. In this paper, an attempt is made to machine a micro-hole on Inconel 718 using developed in house Micro Abrasive jet machining set-up (µ-AJM). This process has several notable advantages such as minor heat-affected zones (HAZ) and cutting forces, high machining versatility and flexibility. The experiments are planned with the proper array. The experimentally measured values of different quality characteristics have been taken as hole diameter, MRR, and machining Time. It can be noticed that Standoff Distance (SOD) is an important factor and other factors Air pressure and abrasive mesh size does not show sufficient significance. The parametric effect of different most significant input process parameters on quality characteristics has been discussed. ANOVA results showed that the Stand of Distance was the most effective parameter. The optimal condition where Abrasive size (50,100) Mix standoff distance 1 mm and inlet pressure (P1) 9 bar for minimizing the hole Diameter and lesser machining time and higher MRR on Inconel 718 material.

1. Introduction

In the manufacturing industry current scenario is machining on difficult to cut materials such as Inconel alloy, Titanium alloy, Glass, Stainless steel alloys, etc. Have bigger challenges to researches because of high energy consumption, poor machinability, and low productivity. Micro AJM is one of the prominent machining technology for machining of hard & brittle material this method having different advantages over other Nontraditional machining processes are lack of heat affected zone, high flexibility, & very small cutting forces. Sharp irregular shapes of an abrasive particle are acting as a tool that is mixing during the process with air in the mixing chamber. The pressure of air is between 5 to 9 bar and the size of micro-abrasive particles are 10 to 25 µm are employed. The erosion mechanism during the process is different for brittle and ductile materials. Most of the researcher's experimental work is carried out following materials. Glass [1-7], polymethylmethacrylate [PMMA] [8], Quartz, [9] Nickel 233 [10], S. Ally et.al [11] investigated the erosion rate of materials Ti-6Al-4V alloy, aluminum 6061-T6, and 316L stainless steel using the velocity of jet 106 m/s and abrasive powder (Al2O3) 50 µm. With various inclination angles N. Shafiei et.al [12] predicted computer simulation of eroded profiles of an abrasive jet with time on the work surface. Vanmore V.V. et.al [13, 21] Developed and experimented with Laval nozzle for machining difficult-to-machine materials with the jet concentration on the ANSI SS304. Kumar Abhishekh et.al [14] presents machining of holes on quartz with in house developed AJM setup. Some investigation on machining methods. T. Burzynski et.al. [15] Studied masked erosive surface with the second strike and predicted effect of particles on the sidewalls of machined features & masked edges on glass creates microchannels using micro AJM. H. Get

*Corresponding author,
E-mail: vinodvanmore@gmail.com

et.al [16] observed that erosion rate depends on that angle of the jet while studying masked and unmasked microchannels were machined on polymethylmethacrylate [PMMA] at angle 550 the MRR is more. Also studied on cryogenic abrasive jet machining (AJM) on polymers is a cost-effective method. The finite element method & analytical method is used to optimize the CAJM of holes & micro-channels. M. Achtsnick et.al [17] developed a Laval nozzle with an increasing velocity of 30% compared to conversing nozzle & its verification has done using particle image velocimetry (PIV) experimentally. A. Ghobeity et.al. [18] Has invented a mixing device & studied factors affecting erosion repeatability. Lei Zhang et.al. [19] Proposed micro-abrasive intermitted jet machining (MAIJM). It has a time interval for impingement of the jet empirical model has been developed for prediction of the effects of the MAIJM process. A lot of research carried out on the optimization of various process parameters of MAJM machined. Features, holes, microchannel on glass, polymers PMMA but the very little study is carried out difficult to machine materials such as Inconel 718. Balasubramaniam et al. [20] examined the effects of jet particle size, standoff distance, centerline, and peripheral velocity on the generated work surface geometry and derived equations to obtain the surface shape produced by the abrasive jet machining process.

After literature reviewing come to know that so much research is carried on Glass, not for metals so, in this research work, an attempt was made to use MAJM for difficult mechanical materials such as the Inconel 718. Variable parameters such as the design of the Laval nozzle and Air pressure, abrasive types and size and standoff distance have an impact on MRR, micro hole diameter and machining time. It has been discussed with experimental research. This article is about experimental investigation of optimum processing parameters such as Taguchi methodology, L9 Orthogonal Array in DoE.

2. Experimental Conditions and Process Parameters

2.1 Material

In the present study, Inconel 718 used as the work piece materials. Because of better corrosion resistance. High-Strength-Temperature-Resistant (HSTR) material, has wide applications in the field of aerospace, automobile, mould making and medical industries. The plate thickness taken as 1.5 mm for experimentation. Chemical composition is shown in table 1. The Inconel 718 sheet cut into Rectangle of 50mm×25mm ×1.5mm and with better surface finish. Before the test weight of sample is measured with digital weighting machine.

After the test, the samples were cleaned with air and final weight was measured. The least count of machine is 0.001mg. Three measurements were taken for each sample and the average was the final reading. The weight loss per unit time of each specimen is calculated and considered as the material removal rate.

2.2 Machining parameters and outcome responses

The precision and standard of the products developed depend entirely on the processing parameters, as well as on the degree of significance. The following responses are measured experimentally. Here, Considering abrasive mesh size (Sic) µm, inlet air pressure (Bar) and stand-of-distance (mm) Predict different output results, ie material removal rate (gram / min), hole diameter Measure (µm) And processing time (min.) guiding pressure 1.4 bar taken as constant.

2.3 MAJM developed setup

The fabricated MAJM setup developed in house to carry out various experiments on different materials along with the effect of process parameters on the response variables. Fig. 1 shows the schematic diagram of the micro AJM experimental setup. The main components are a compressor, fluidized mixing chamber, Laval nozzle, and numerically controlled XYZ positioner along with working chamber along with an Air filter regulator (FRL) to remove moisture from compressed air. Two P1&P2 high pressurized pneumatic lines is required for working P1 shows compressed air pressure fed to the mixing chamber. P2 indicates guiding pressure fed to the nozzle for guiding the (air + abrasive) mixture stream [13] like a mixture of air abrasive papers through the nozzle. It is convert pressure energy into kinetic energy as result high pressure jet with guiding pressure cause convergent of jet some extent & divergent take place with the principal of the Coanda effect. This jet energy accelerates and impinging on workpiece, resulting in the formation of cracks along with material removals taken place.

After machining samples get cleaned with pressurized air and using a Dino-Lite Premier Digital Microscope (AM3713TB) measures micro hole dimensions. A stopwatch is used for measuring the time of single hole machining. Slip gauges are used for keeping Stand of Distance (SOD) in mm accurately and MRR is calculated by initial weight of work piece, minus after machining weight with respect time taken for machining (gm/min). The weight of the work piece is measured with a digital weighting machine with LC 0.001.

2.4 Design of experiment using taguchi method

Design of experiments (DOE) is described as a methodology for applying statistics systematically to experiments. DOE is designed to be a series of tests that deliberately change the input parameters (factors) of a product or process to see why the output response changes, fast and cost effective. Barrado et al. [22] Extending the next steps to implement the Taguchi experimental design:

Step 1. Select output or target parameters.

Step 2. Definition of input parameters & their levels.

Step 3. Determining the proper orthogonal array (OA).

Step 4. Assign factors and interactions to the columns of the array.

Step 5. Run the experiments.

Step 6. Statistical analysis and S / N ratio, as well as determining optimal settings for factor levels.

DOE describes some design tasks for the purpose of analyzing or explaining fluctuations in information under supervised conditions that are supposed to reflect Outer variation. Experimental statistical planning with basic ideas underlying DOE. Using MINITAB 16 statistical software package three factors with three level, L9

Table 1
Work piece material composition.

Element	Ni+C0	Cr	Fe	Nb + Ta	Mo	Ti	Al
Content (%)	50-55	17-21	Bal	4.75-5.5	2.8-3.3	0.65-1.15	0.2-0.8

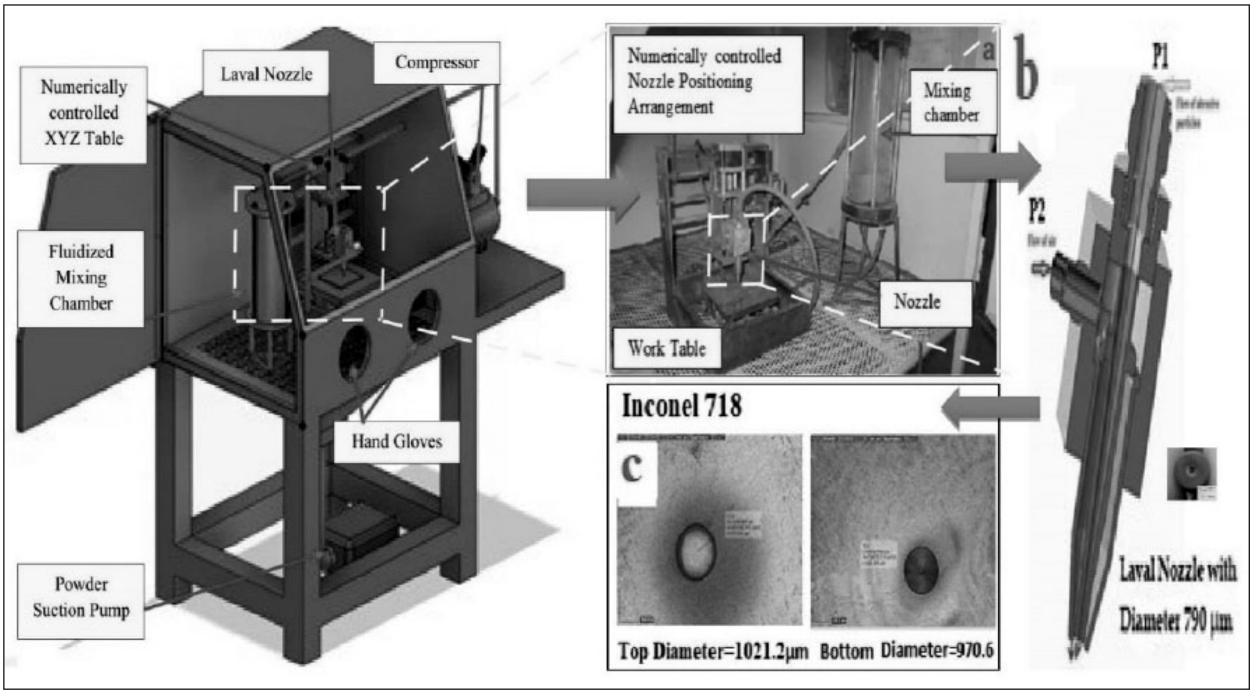


Fig. 1. Shows 3D image of Micro Abrasive jet Machine set up with its Components (a) Shows Numerically controlled XYZ positioner for Nozzle (b) Shows Cross Sectional View of Laval Nozzle (C) Micrographic Images of Top Hole diameter and bottom hole diameter on Inconel 718.

Orthogonal Array is selected. Table 2 shows factors and their working level. Taking into account the above conditions, the achievable limits of the parameters are chosen to ensure flawless machining of the Inconel 718. The entire experiment was performed in a newly developed setup under specific conditions. The experimental schematic diagram of MAJM shown in figure 2.

3. Result and Discussions

In this study Experiments were conducted to study effects of MRR, hole diameter and machining time. Here Taguchi's single factor at a time approach is considered and nine experiments based on Taguchi (L9) experimental design methodology were consider. We choose the S/N ratio for the smaller is better characteristic setting for the minimum hole diameter and machining time and Larger-the-Best for MRR Results from all experiments were statistically analyzed using analysis of variance (ANOVA) and the effects of the selected variable were evaluated as shown in Table 3 for material removal rate (MRR), Hole diameter (µm) and Machining Time (min).

3.1 Main effect of plot and ANOVA for MRR

In this study the optimal machining condition is maximum value S/N ratio, according to Taguchi method. Thus optimal condition was found as -0.2647,-59.4069 and -131793S/N ratio for MRR, Hole diameter, and Machining Time respectively in L9 orthogonal array Table 3. The optimal condition where Abrasive size (50,100) Mix standoff distance 1 mm and inlet pressure 9 bar for better machining of hole on Inconel 718 material. Table 4 shows ANOVA for larger MRR according to P valve 0.336 it does not produce significant level within 95% confidence level for all intervals gives maximum 44.80% contribution of Standoff distance parameter.

Hence standoff distance is most significant factor as compare to other two factors for maximum MRR. Figure 3 shows main effect plot for MRR. According to Taguchi Design Maximum value of main effect plot shows optimal condition for particular parameter. in this fig. for maximum material remove rate (MRR) can be predicted at 50 micron mesh size of abrasive particle, 3 mm standoff distance and Air pressure of 9 bar

Table 2
Factors and their working level.

Input Process Parameters	Unit	Notation	Level 1	Level 2	Level 3
Air Pressure	bar	P1	6	7	8
Stand of Distance	mm	SOD	1	2	3
Abrasive Mesh Size	µm	AMS	50	100	Mix (50, 100)

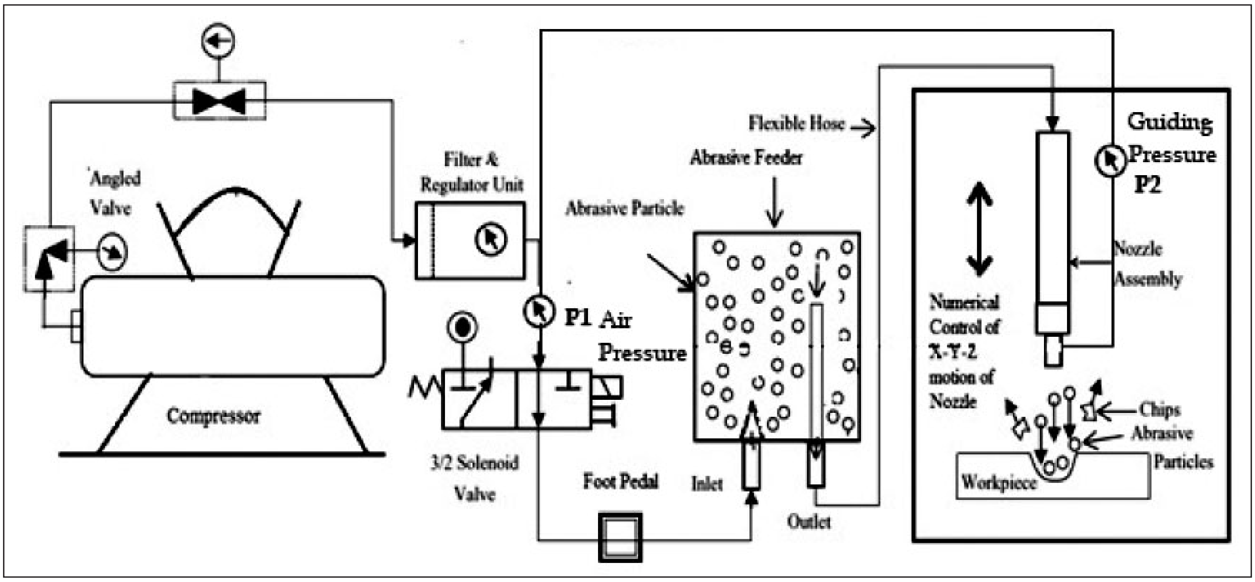


Fig. 2. Experimental schematic diagram of MAJM Developed setup.

Table 3
Design matrix with experimental result.

Trail No.	Abrasive mesh size (Sic) µm	SOD (mm)	Inlet Pressure (Bar) P1	MRR (gram)	Hole diameter (µm)	Machining Time (Min)	SNRA MRR	SNRA Hole diameter	SNRA Machining Time
1	50	1	7	1.21	1178	5.90	1.65571	-61.4229	-15.4170
2	50	2	8	1.34	998	4.21	2.54210	-59.9826	-12.4856
3	50	3	9	1.67	1340	4.37	4.45433	-62.5421	-12.8096
4	100	1	8	0.88	1145	5.10	-1.11035	-61.1761	-14.1514
5	100	2	9	1.79	1004	3.45	5.05706	-60.0347	-10.7564
6	100	3	7	1.26	1223	3.45	2.00741	-61.7485	-10.7564
7	mix	1	9	0.97	1021	4.56	-0.26457	-59.4069	-13.1793
8	mix	2	7	1.02	956	3.67	0.17200	-59.6092	-11.2933
9	mix	3	8	1.45	1290	3.20	3.22736	-62.2118	-10.1030

Table 4
Analysis of variance for MRR.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Abrasive mesh size	2	0.02065	13.85%	0.02065	0.01032	0.61	0.621
SOD	2	0.06676	44.80%	0.06676	0.03338	1.98	0.336
P1	2	0.02781	18.66%	0.02781	0.01391	0.82	0.549
Error	2	0.03380	22.68%	0.03380	0.01690		
Total	8	0.14902	100.00%				
Model Summary			R-sq=77.32%	R-sq(adj)= 9.27%			

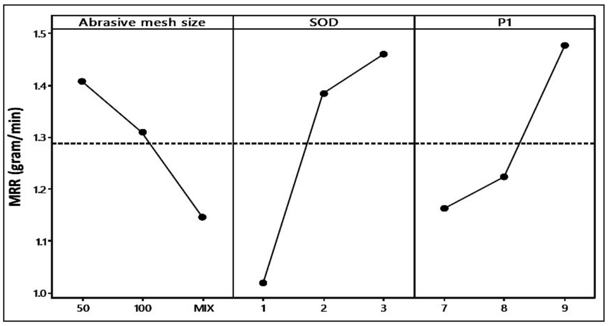


Fig. 3. Main Effect of plot for MRR

3.2 Main effect of plot and ANOVA for hole diameter

Consequently Table 5 shows ANOVA for smaller hole diameter with 95% confidence level for all intervals gives maximum 76.17% contribution of Standoff distance parameter as compare to other parameters. Hence standoff distance is most significant factor for smaller hole diameter. The sequence of importance of process parameters are SoD >abrasive mesh size > Air Pressure P1. Figure 4 shows main effect plot for hole diameter. According to Taguchi Design Maximum value of main effect plot shows optimal condition for particular parameter. in this fig. for smaller hole diameter can be predicted at 50 micron mesh size of abrasive particle, 3 mm standoff distance and Air pressure of 8 bar.

3.3 Main effect of plot and ANOVA for machining time

Consequently Table 6 shows ANOVA for Lesser Machining Time with 95% confidence level for

Table 5
Analysis of variance for hole diameter.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Abrasive mesh size	2	18944	10.43%	18944	9472	0.93	0.518
SOD	2	138405	76.17%	138405	69202	6.80	0.128
P1	2	4005	2.20%	4005	2002	0.20	0.836
Error	2	20361	11.20%	20361	10180		
Total	8	181714	100.00%				
Model Summary			R-sq=88.80%	R-sq(adj)= 55.18%			

Table 6
Analysis of variance for machining time.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Abrasive mesh size	2	1.75309	27.99%	1.75309	0.87654	12.11	0.076
SOD	2	4.28896	68.48%	4.28896	2.14448	29.62	0.033
P1	2	0.07629	1.22%	0.07629	0.03814	0.53	0.655
Error	2	0.14482	2.31%	0.14482	0.07241		
Total	8	6.26316	100.00%				
Model Summary			R-sq=97.69%	R-sq(adj)= 90.75%			

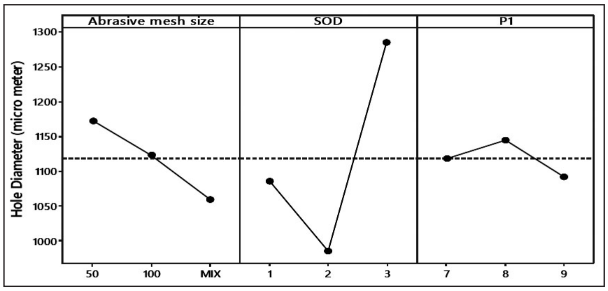


Fig. 4. Main effect of plot for hole diameter.

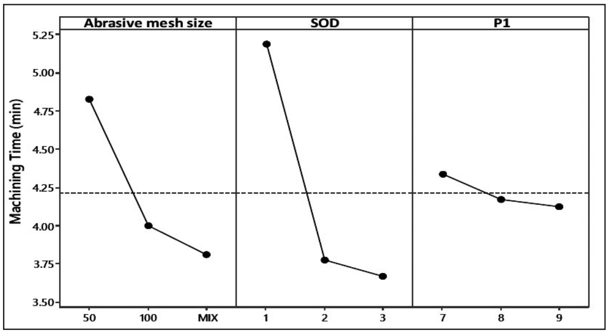


Fig. 5. Main effect of plot for machining time.

all intervals gives maximum 68.48% contribution of Standoff distance parameter as compare to other process parameters. Hence standoff distance is most significant factor for Lesser Machining Time. The sequence of importance of process parameters are SoD >abrasive mesh size > Air Pressure P1.

Figure 5 shows the main effect plot for Machining Time. According to Taguchi Design Maximum value of main effect plot shows optimal condition for particular parameter. in this fig. for smaller Lesser Machining Time can be predicted at 50 microns mesh size of abrasive particle, 1 mm standoff distance and Air pressure of 7 bar.

4. Conclusions

In this investigation we observed the experimental results of micro-hole machining on Inconel 718 using the Taguchi Experimental Design approach measures the diameter of top holes 1021.2µm and bottom hole 970.6µm (see fig.1c) generated in 1.5 mm thick Inconel 718 produced by MAJM. Based on analysis, following conclusions are made.

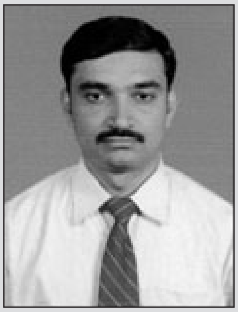
- The improved MAJM experimental setup investigates that Laval nozzles reduce the lateral variation of machined holes & increase the continuous flow of abrasive grains.
- The optimal parametric setting for maximum value S/N ratio, according to Taguchi method. Thus optimal condition was found as -0.2647,-59.4069 and -131793 S/N ratio for MRR, Hole diameter, and Machining Time respectively in L9 orthogonal array.
- The optimal condition where Abrasive size (50,100) Mix standoff distance 1 mm and inlet pressure (P1) 9 bar for better machining of hole on Inconel 718 material.
- Standoff Distance (SOD) is an important factor in minimizing the hole Diameter and lesser machining time in MAJM and other factors Air pressure and abrasive mesh size does not shows sufficient significance.
- Changes in the roundness of the machined holes are observed almost by accident, since they can be due to the characteristics of the abrasive jet stream.

References

1. EI-Domiaty, A; Abd EI –Hafez, HM and Shaker, MA: Drilling of glass sheets by abrasive jet machining, 'World Academy of Science, Engineering and Technology', 56, 2009.
2. Yamahata, C; Lacharme, F; Burri, Y and Gijs, MAM: A ball valve micropump in glass fabricated by powder blasting, Sensors Actuators, 'B Chem.', vol. 110, no. 1, 2005, 1–7.
3. Ghobeity; Papini, M and Spelt, JK: Abrasive jet micro-machining of planar areas and transitional slopes in glass using target oscillation, 'J. Mater. Process. Technol.', vol. 209, no. 11, 2009, 5123–5132.
4. Abhishek, K; Hiremath, SS: Machining of micro-holes on sodalime glass using developed micro-abrasive jet machine (μ-AJM), 'Proc. Technol.', 25, 2016, 1234–1241.
5. Suresh, R; Sohit, RK; Shapur, K: Abrasive jet machining for micro-hole drilling on glass and GFRP composites, 'Mater. Today Proc'., 5, 2018, 5757–5761.
6. Jagannatha, N; Hiremath, SS; Sadashivappa, K: Analysis and parametric optimization of abrasive hot air jet machining for glass using Taguchi method and utility concept, 'Int. J. Mech. Mater. Eng.', vol. 7, no. 1, 2012, 9–15.
7. Jagannatha, N; Somashekhar, SH; Sadashivappa, K; Arun, KV: Machining of soda lime glass using abrasive hot air jet: an experimental study, 'Mach. Sci. Technol.', vol. 16, 2012, 459–472.
8. Getu, H; Ghobeity, A; Spelt, JK and Papini, M: Abrasive jet micromachining of polymethylmethacrylate, 'Wear', vol. 263, no. 7-12 SPEC. ISS., 2007, 1008–1015.
9. Tomy and Hiremath, SS: Machinability and characterisation of machined hole on quartz using developed μ-AJM set-up, 'Adv Mater Process Technol'., vol. 5, no. 2, 2019, 242–257.
10. Prasad, SR; Ravindranath, K and Devakumar, MLS: Experimental investigation and parametric optimization in abrasive jet machining on nickel 233 alloy using WASPAS and MOORA, 'Cogent Eng'., vol. 5, no. 1, 2018, 1–12.
11. Ally, S; Spelt, JK and Papini, M: Prediction of machined surface evolution in the abrasive jet micro-machining of metals, 'Wear', vol. 292–293, 89–99, 2012.
12. Shafiei, N; Getu, H; Sadeghian, A and Papini, M: Computer simulation of developing abrasive jet machined profiles including particle interference, 'J Mater Process Technol'., vol. 209, no. 9, 2009, 4366–4378.
13. Vanmore, V.V; and Dabade, UA: Development of Laval Nozzle for Micro Abrasive Jet Machining [MAJM] Processes, 'Procedia Manuf'., vol. 20, 2018, 181–186.
14. Abhishek, K; Hiremath, SS; Kumar, A and Hiremath, SS: Improvement of Geometrical Accuracy of Micro Holes Machined Through Micro Abrasive Jet Machining, 'Procedia CIRP', vol. 46, 2016, 47–50.
15. Burzynski, T and Papini, M: Modelling of surface evolution in abrasive jet micro-machining including particle second strikes: A level set methodology, 'J Mater Process Technol'., vol. 212, no. 5, 2012, 1177–1190.
16. Getu, H; Ghobeity, A; Spelt, JK and Papini, M: Abrasive jet micromachining of polymethylmethacrylate, 'Wear', vol. 263, no. 7-12 SPEC. ISS., 2007, 1008–1015.
17. Achtsnick, M; Hoogstrate, M and Karpuschewski, B: Advances in High

Performance Micro Abrasive Blasting, 'CIRP Ann - Manuf Technol'., vol. 54, no. 1, 2005, 281–284.

18. Ghobeity, Getu, H; Krajac, T; Spelt, JK and Papini, M: Process repeatability in abrasive jet micro-machining, 'J Mater Process Technol'., vol. 190, no. 1–3, 2007, 51–60.
19. Zhang, L; Kuriyagawa, T; Yasutomi, Y and Zhao, J: Investigation into micro abrasive intermittent jet machining, 'Int J Mach Tools Manuf'., vol. 45, no. 7–8, 2005, 873–879.
20. Balasubramaniam, R; Krishnan, J and Ramakrishnan, N: Experimental study on the abrasive jet deburring of cross-drilled holes, 'J Mater Process Technol'., vol. 91, no. 1, 1999, 178–182.
21. Vanmore, VV and Dabade, UA: Experimental and Parametric Optimization of Micro Holes on ANSI 304 Using Micro Abrasive Jet Machining (MAJM), 'Procedia Comput Sci'., vol. 133, 2018, 620–626.
22. Barrado, E; Vega, M; Pardo, R; Grande, P and Del Valle, JL: Optimisation of a purification method for metal-containing wastewater by use of a Taguchi experimental design, 'Water Res'., vol. 30, no. 10, 1996, 2309–2314 ▪



Vinod Vasantrao Vanmore is working as Research scholar in Mechanical Engineering Department, Walchand College of Engineering Sangli. He completed his Masters (Mechanical-Production) from Walchand College of Engineering Sangli. He Currently Pursuing his Ph.D in Mechanical Engineering from Shivaji University Kolhapur. From 2008 to 2010, he was associated with Dembla valves Ltd Thane, as an Application Engineer. Since 2010, he has been an Assistant Professor with the Mechanical Engineering Department, Sanjeevan Engineering and Technology Institute Panhala, Kolhapur, Maharashtra. His research interest in Non-conventional machining and Micromachining for Difficult to cut materials, fluidics and optimisation techniques. He had published 6 research papers in national international conferences and journals.

Prof. Dr. Uday A Dabade completed his M.Tech and Ph.D from IIT Bombay, Received DST India Young Scientist award and AICTE-RPS projects. He had received international travel grants to attend and present research papers at Singapore, China (twice), Australia, Hongkong, Macau, USA (twice), Malasiya, Portugal, France and Thailand from DST, AICTE, UGC and TEQIP India. He had received grants from AICTE India to organize FDPin conventional, non-conventional and micro-machining area. He had organized / coordinated about 30 workshops, seminar and delivered about 35 expert lectures at various institutes in India. He had published more than 140 research papers in national, international conferences and journals. He had more than 840 citations with i12 and h-index of 12 (June 2020). Till now he had guided 71 PG students. Three students had successfully completed their PhD thesis and four are registered under his guidance. His research interest is in Micro and non-conventional machining, Precision engineering, Machining of difficult to cut materials, etc. Presently he has been deputed by NPIU, MHRD (GoI) as State Project Administrator (SPA) at Jaipur, Rajasthan State for TEQIP-III project (April 2019 onwards). (E-mail: udabade@gmail.com.)