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RESEARCH ARTICLE - MECHANICAL ENGINEERING

Experimental Modelling and Analysis in Abrasive Waterjet Cutting of Ceramic Tiles Using Grey-Based Response Surface Methodology

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Abstract The better machining capabilities of abrasive waterjet cutting (AWJC) characterized by the absence of thermal distortion make it highly competitive with other cutting processes employing plasma and lasers. The present report was oriented towards examining the effect of AWJC parameters like abrasive grain size, abrasive flow rate, nozzle–workpiece standoff, water pressure and jet traverse rate on the surface roughness and taper angle of cut produced with ceramic tiles. Taguchi's L_{27} orthogonal array was used for conducting the cutting trials, and a combined technique of grey-based response surface methodology (g-RSM) was disclosed for obtaining the optimal level of AWJC parameters. The g-RSM method was supplemented with analysis of variance to identify the vital parameters affecting the quality characteristics. The optimal parameter setting was validated by conducting a confirmation test. The cut surfaces were also examined using field emission scanning electron microscope images, P-profile plots and atomic force microscope images.

Keywords Abrasive waterjet cutting · Ceramic tiles · Grey Taguchi · Response surface methodology · P-profile plot · Field emission scanning electron microscopy · Atomic force microscopy

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1 Introduction

The waterjet in pure form or mixed with abrasives was employed to machine various materials. The process of abrasive waterjet cutting (AWJC) was eco-friendly with good machining capabilities to handle materials like steel, Inconel, granite, titanium. The success of the process depends on its instrumentation used to generate the kinetic energy from extremely high-pressure water. The waterjet mixed with abrasives was focussed at higher speeds on the workpiece to perform the required operation. The abrasive grit size and its hardness were found to affect the finish of the cut surface in single-pass cuts [1]. While machining ductile materials like aluminium, the effect of feed rate was observed to be significant in affecting the roughness of cut surface, while the kerf characteristics were affected by the traverse speed [2,3]. The taper on the cut surface was found to be affected by the ingredients of the abrasive slurry. Further, the presence of a polymer in the slurry could improve the metal removal rate [4]. While machining the fibre-reinforced plastics, jet traverse rate was observed to affect the quality of machined surface [5]. Three distinct regions (an initial damage region, a smooth cutting region and a rough cutting region) were visualized along the kerf wall produced by AWJC process [6]. Generally, garnet was used as abrasive in machining operations but colemanite powder could also be used for obtaining better cut characteristics [7]. The multiple process inputs in AWJC and factor interactions need a thorough study to enable complete quality control of the process.

The optimal input conditions could be identified by using the approaches of neural networks, genetic algorithm (GA), response surface methodology (RSM), principal component analysis (PCA) and fuzzy logic [8]. The modelling ability of fuzzy-based methods was found to be equally effective like the neural networks [9,10]. The regression model was used to effectively link the parameters in AWJC, and nozzle diameter was identified as an important parameter affecting the kerf width [11]. The neural network model integrated with GA was found to predict the responses accurately than the regression model [12]. The traverse speed and nozzle diameter were also identified as the influential parameters in AWJC [13]. A hybrid approach combining GRA and PCA was also observed to predict the optimal solution effectively [14]. The RSM was used to generate a mathematical model for linking the various parameters in machining. The central composite design was generally employed for experimentation before applying RSM [15]. However, Taguchi design could also be used for experimentation to form a response surface model [16,17]. The quadratic model formed using RSM was generally optimized using the desirability analysis using the larger-the-better desirability function [18,19]. The analysis of variance was used to find the adequacy of models generated using RSM [20,21].

The ceramic tile of size one square feet was chosen as the work material. It finds wide applications in floors, walls, exterior house trims, etc. The composition of ceramic tile used in the study is as follows: SiO_2—33.14%, Al_2O_3—

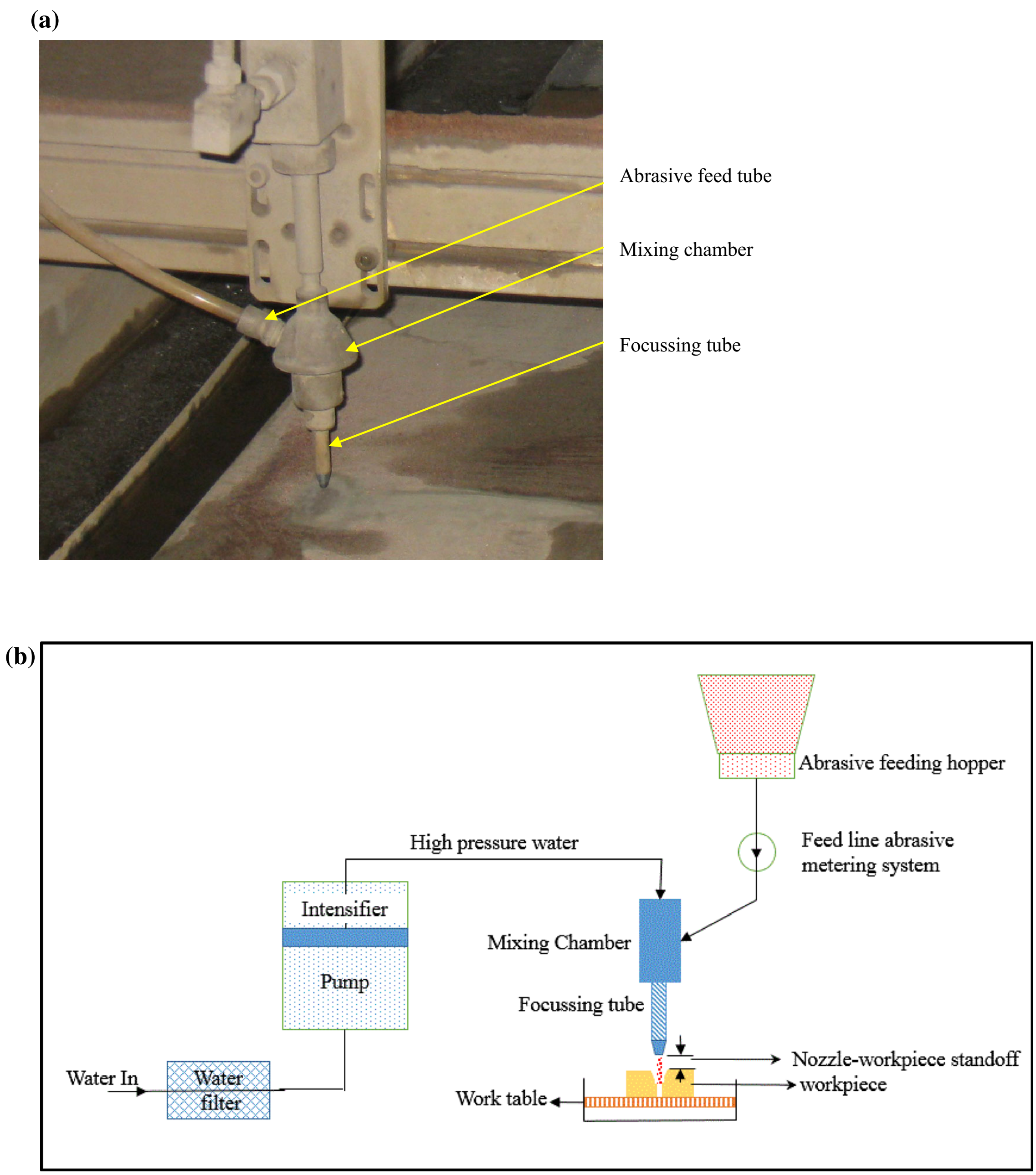

Fig. 1 **a** Abrasive waterjet cutter, **b** schematic layout of AWJC process

27.02%,CaO—0.22%, MgO—0.03%, Na_2O—0.46%, K_2O—0.05%, TiO_2—0.17%, Fe_2O_3(T)—0.27%, MnO—0.003%, P_2O_5—0.26% and L.O.I at 950°C—38.26% by weight. The ceramic tiles provide good resistance to various chemical elements and offer an easiness of cleaning. The cut surface of tiles should possess good finish to avoid further processing.

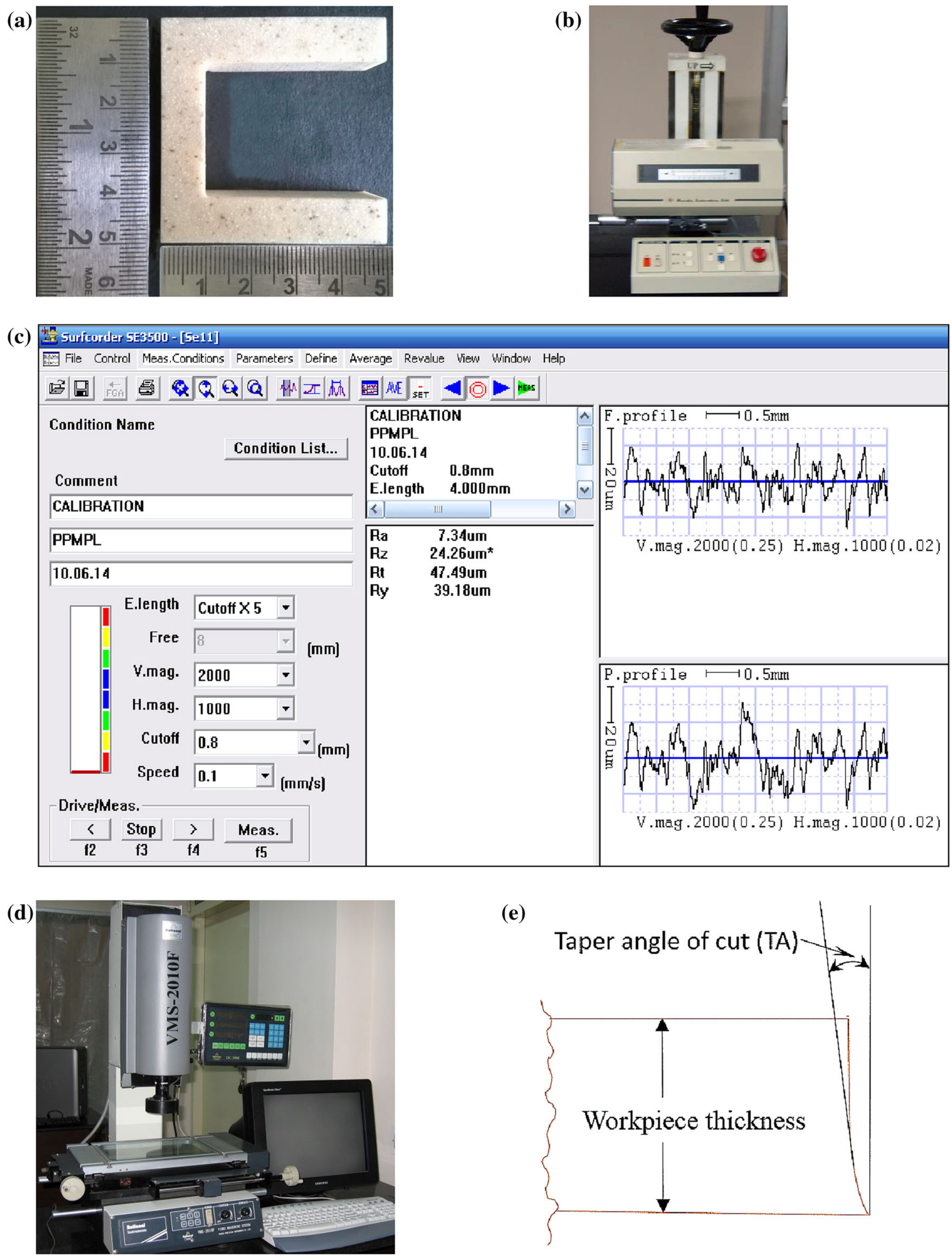

Fig. 2 **a** Profile of the machined work sample, **b** surface hardness tester, **c** measurement of surface roughness, **d** video measuring system and **e** measurement of taper angle of cut

From the review of the literature, it was observed that parameter design in AWJC of ceramic tiles was observed to be scarce though a considerable work was addressed in waterjet machining of different materials. The aim of the research was to investigate the surface roughness and taper angle of cut in AWJC of ceramic tiles. The motivation of the work is the fact that more engineers are using AWJC for handling non-ferrous materials and polymers. The quality of cut can still be improved to save the cost of secondary processing as well as time. The distinctive value of the paper lies in the disclosure of grey-based response surface methodology (g-RSM) for finding the optimal level of AWJC parameters for ceramic tiles.

2 Design of Machining Trials and Experimentation

The machining experiments were conducted using waterjet (Germany) cutter (model: S3015, SL-V 50 HP) which was inbuilt with an integral dual intensifier and pumping system to generate a maximum pressure of 4000 bar. The waterjet projected at the work material was directed through a sapphire nozzle of diameter 0.76 mm, suitably controlled by a microprocessor-based system. The waterjet cutter is shown in Fig. 1a. The impact angle of jet was maintained at right angles to the surface of the work material during all the machining trials. A schematic layout of the AWJC process is shown in Fig. 1b. The abrasives fed from the hopper were mixed with

Table 1 Responses obtained during various machining trials

Trial	Control parameters					Responses	
	A—abrasive grain size (mesh)	B—abrasive flow rate (g/min)	C—water pressure (bar)	D—nozzle–workpiece standoff (mm)	E—jet traverse speed (mm/min)	SR (µm)	TA (deg)
1	80	300	2000	1	200	5.552	2.101
2	80	300	2500	2	300	6.147	1.892
3	80	300	3000	3	400	5.742	1.201
4	80	400	2000	2	400	6.963	1.134
5	80	400	2500	3	200	5.184	2.013
6	80	400	3000	1	300	5.439	1.092
7	80	500	2000	3	300	7.364	1.243
8	80	500	2500	1	400	5.437	1.023
9	80	500	3000	2	200	5.353	0.982
10	100	300	2000	1	200	5.328	2.142
11	100	300	2500	2	300	6.422	1.823
12	100	300	3000	3	400	5.716	2.012
13	100	400	2000	2	400	4.936	1.622
14	100	400	2500	3	200	5.177	1.824
15	100	400	3000	1	300	5.187	1.631
16	100	500	2000	3	300	4.642	1.292
17	100	500	2500	1	400	5.056	0.882
18	100	500	3000	2	200	5.342	0.932
19	120	300	2000	1	200	4.233	2.131
20	120	300	2500	2	300	5.343	1.519
21	120	300	3000	3	400	4.823	1.243
22	120	400	2000	2	400	5.885	0.934
23	120	400	2500	3	200	4.172	1.342
24	120	400	3000	1	300	3.663	1.392
25	120	500	2000	3	300	4.866	0.981
26	120	500	2500	1	400	4.422	0.956
27	120	500	3000	2	200	4.042	0.749

the high-pressure water in a mixing chamber, and the abrasive waterjet was allowed to hit the workpiece after passing through a focussing tube.

The AWJC parameters chosen for experimentation were the abrasive grain (mesh) size (A), abrasive flow rate (B) in g/min, water pressure (C) in bar, nozzle–workpiece standoff (D) in mm and jet traverse speed (E) in mm/min. These dominant cutting parameters were selected based on the literature [1–7,13]. Preliminary cutting trials were also performed to ensure that the range of AWJC parameters chosen for experimentation could produce decent values of the responses. Unlike the traditional central composite design used along with RSM, the experimental trials were designed using Taguchi's L_{27} orthogonal array which permits the study of interactions among the various machining parameters. The number of trials in Taguchi's L_{27} orthogonal array design is lesser than the number of runs required in central composite design. The surface roughness (SR) and taper angle (TA) of cut were measured as the quality characteristics after various trials. The parameters were varied at three levels during the cutting trials. A channel section of overall depth 50 mm and width 50 mm was cut during each trial. The thickness of the ceramic tile employed in cutting trials was 12 mm, and the photograph of cut profile is shown in Fig. 2a. A channel section was chosen to include both the shorter and longer length of cuts with sharp corners as well.

The trials were conducted at random to reduce the effects of extraneous factors [8], and two replications were obtained during each trial. A contact stylus-type surface roughness tester (model: Surfcorder: SE3500) shown in Fig. 2b was used to measure the SR at the middle of depth along the direction of cut. A cut-off length of 0.8 mm and an evaluation length of 4 mm were employed to measure the SR at a probe speed of 0.1 mm/s (Fig. 2c). A video measuring system (model: VMS-2010F) displayed in the Fig. 2d was used to measure the TA as shown in Fig. 2e. It was inbuilt with a high-resolution CCD camera and a DC 3000 data processor with a maximum magnification capability of 190X. The qual-

Table 2 Normalization of responses and GRG values

Trial	S/N ratio		Normalized S/N ratio		Grey relational coefficient		GRG
	SR	TA	SR	TA	SR	TA	
1	−14.889	−6.449	0.404	0.018	0.456	0.337	0.3969
2	−15.773	−5.538	0.259	0.118	0.403	0.362	0.3823
3	−15.181	−1.591	0.356	0.550	0.437	0.527	0.4819
4	−16.856	−1.092	0.080	0.605	0.352	0.559	0.4554
5	−14.293	−6.077	0.503	0.059	0.501	0.347	0.4242
6	−14.710	−0.764	0.434	0.641	0.469	0.582	0.5255
7	−17.342	−1.889	0.000	0.518	0.333	0.509	0.4212
8	−14.707	−0.198	0.434	0.703	0.469	0.627	0.5483
9	−14.572	0.158	0.457	0.742	0.479	0.660	0.5695
10	−14.531	−6.616	0.463	0.000	0.482	0.333	0.4078
11	−16.153	−5.216	0.196	0.153	0.383	0.371	0.3774
12	−15.142	−6.073	0.363	0.060	0.440	0.347	0.3934
13	−13.868	−4.201	0.573	0.265	0.539	0.405	0.4720
14	−14.282	−5.220	0.505	0.153	0.502	0.371	0.4367
15	−14.298	−4.249	0.502	0.259	0.501	0.403	0.4520
16	−13.334	−2.225	0.661	0.481	0.596	0.491	0.5432
17	−14.076	1.091	0.538	0.844	0.520	0.762	0.6412
18	−14.554	0.612	0.460	0.792	0.481	0.706	0.5933
19	−12.533	−6.572	0.793	0.005	0.707	0.334	0.5208
20	−14.556	−3.631	0.459	0.327	0.480	0.426	0.4534
21	−13.666	−1.889	0.606	0.518	0.559	0.509	0.5342
22	−15.395	0.593	0.321	0.790	0.424	0.704	0.5640
23	−12.407	−2.555	0.814	0.445	0.729	0.474	0.6012
24	−11.277	−2.873	1.000	0.410	1.000	0.459	0.7294
25	−13.743	0.175	0.593	0.744	0.551	0.661	0.6064
26	−12.912	0.387	0.730	0.767	0.650	0.682	0.6659
27	−12.132	2.513	0.859	1.000	0.780	1.000	0.8900

ity characteristics observed for the various trials are shown in Table 1.

3 Grey-Based Response Surface Methodology (g-RSM)

Metal cutting in industries is always associated with stringent requirements related to surface finish. A good surface finish can avoid secondary processing saving both the cost and time. Taguchi approach uses signal-to-noise (S/N) ratio to measure the performance of a system [8]. The approach of g-RSM employs the grey relational grade (GRG) as a measure of performance. The calculation of GRG effectively reduces the multiresponse optimization problem into optimization of a single response.

Step 1: Calculate the S/N ratio (η_{ij}) for the quality characteristics and perform normalization as a part of data pre-processing. The S/N ratio and normalized S/N ratio (Z_{ij}) values were calculated using Eqs. 1 and 2, respectively [14].

$$S/N\text{Ration}(\eta_{ij}) = -10\log_{10}\left(\frac{1}{r}\cdot\sum_{i=1}^{n}(y_{ij})_k^2\right) \tag{1}$$

$$Z_{ij} = \frac{y_{ij} - \min(y_{ij},\quad i=1,2,\ldots,m)}{\max(y_{ij},\quad i=1,2,\ldots,m) - \min(y_{ij},\quad i=1,2,\ldots,m)} \tag{2}$$

where r is the number of replication, y_{ij} is the observed response value, n is the number of response, m is the number of observation, $k = 1, 2, \ldots, r$ and $j = 1, 2, \ldots, m$.

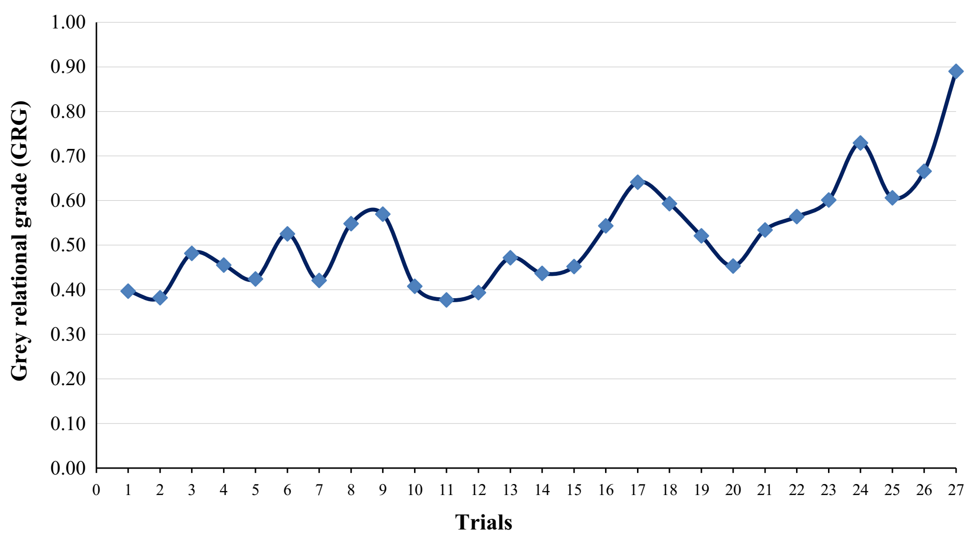

Fig. 3 Variation of GRG for different trials

Table 3 ANOVA on GRG values

Source	Sum of squares	DOF	Mean square	F value	p value Prob > F	
Model	0.3356	11	0.031	14.131	< 0.0001	Significant
A—abrasive grain size	0.0469	1	0.047	21.743	0.0003	
B—abrasive flow rate	0.0357	1	0.036	16.545	0.001	
C—water pressure	0.0226	1	0.023	10.488	0.0055	
D–nozzle–work piece standoff	0.0123	1	0.012	5.698	0.0306	
E—jet traverse speed	0.0024	1	0.002	1.090	0.3131	
AB	0.0118	1	0.012	5.462	0.0337	
AE	0.0098	1	0.010	4.539	0.0501	
BD	0.0045	1	0.005	2.107	0.1673	
CD	0.0114	1	0.011	5.293	0.0362	
A^2	0.0239	1	0.024	11.076	0.0046	
B^2	0.0025	1	0.002	1.154	0.2997	
Residual	0.0324	15	0.002			
Cor total	0.3680	26				

Step 2: Compute the grey relational coefficient (GRC-γ_{ij}) using Eq. 3 to study the link between the best and normalized experimental results [14].

$$\gamma_{ij} = \frac{\Delta \min + \xi \Delta \max}{\Delta_{oj}(i) + \xi \Delta \max} \quad (3)$$

ξ is the distinguishing coefficient whose value is taken between 0 and 1 to heighten the difference between the relational coefficients.
Step 3: Calculate the GRG values using Eq. 4. The GRG values represent both the responses in a particular trial [8].

$$\mathrm{GRG}_j = \frac{1}{n}\sum_{i=1}^{n} \gamma_{ij} \quad (4)$$

Step 4: Construct a second-order polynomial equation for GRG to study the behaviour of system within the experimental domain and perform analysis of variance (ANOVA) on GRG values to study the impact of cutting parameters on the responses [16].
Step 5: Generate the three-dimensional response surfaces to understand the effects of parameters in affecting the responses.
Step 6: Find the optimal combination of cutting parameters from desirability analysis and perform the confirmation test for validation [17].

4 Results and Discussion

4.1 Computation of GRG Values

The data pre-processing was done to bring the responses on a common scale, and the responses were normalized for further analysis [14]. The S/N ratio, normalized S/N ratio and the GRCs were calculated using the appropriate equations described in Sect. 3. The GRG values were indicative of the system performance [8]. The GRC and GRG values are shown in Table 2. The GRG values are single representatives of both the responses (SR and TA) observed during the machining trials. A larger value of GRG was desired for better responses. The peak value of GRG was observed as 0.8900 (trial number 27), displaying the proximity of the parameter combination to the near optimal operating condition. The GRG values for various trials are plotted in Fig. 3. The variations in the GRG values were due to the difference in the process parameter settings employed during experimentation. The considerable variations in GRG values for the different trials display the significant effect of different levels of AWJC parameters on the observed quality characteristics. Convergence in the plot indicates the lesser influence of parameter levels employed during adjacent trials. The absence of convergence in GRG values prove the noteworthy impact of the levels of process parameters chosen for study (Fig. 3).

Table 4 *R*-squared and adequate precision

SD	0.0465	*R*-squared	0.9120
Mean	0.5218	Adj *R*-squared	0.8474
C.V. %	8.9054	Pred *R*-squared	0.7202
PRESS	0.1030	Adeq precision	15.4476

4.2 Fitness and Adequacy of Quadratic Model

The computed GRG values were used as solitary representatives of both the responses. A mathematical model was formed using the technique of RSM to find the association between the AWJC parameters. Usage of Taguchi's L_{27} array for experimentation permits the study of interaction among the cutting parameters with lesser trials. A polynomial equation of second order (quadratic model) was established using Design Expert software (version 7.0.0) which generates the model coefficients using QR factorization method [16,17]. The mathematical model is depicted in Eq. 5.

$$\begin{aligned}\mathrm{GRG} = {} & 1.71611 - 0.029771 * A + 4.86765 * 10^{-}4 * B \\ & -1.04995 * 10^{-}4 * C - 0.55359 * D \\ & +1.65752 * 10^{-}3 * E + 1.56747 * 10^{-}5 * A * B \\ & -1.42887 * 10^{-}5 * A * E + 5.50655 * 10^{-}4 * B * D \\ & +1.23432 * 10^{-}4 * C * D + 1.57828 * 10^{-}4 * A^2 \\ & -2.49549 * 10^{-}6 * B^2 \end{aligned} \quad (5)$$

The model presented in Eq. 5 was devoid of insignificant terms. The analysis of variance (ANOVA) was performed on the GRG to sort out the fitness and model adequacy [16,19]. The model *F* value was observed to be 14.131, demonstrating its significance (Table 3). The influence of various AWJC parameters and their interactions was proved by the value of probability (p value less than 0.05). The model fitness was shown by the closeness of *R*-squared value (0.9120) to unity [16]. Further, there was a reasonable agreement between the predicted and the adjusted *R*-squared values. An adequate precision value of 15.4476, which was considerably greater than 4, ascertains the adequate model discrimination (Table 4).

4.3 Study of Three-Dimensional Response Surfaces

Three-dimensional response surface plots were generated to link the GRG with the AWJC parameters (Fig. 4). An increase in abrasive flow rate allows for participation of more abrasive particles in the process of machining. Hence, there is an effective increase in the number of cutting edges avail-

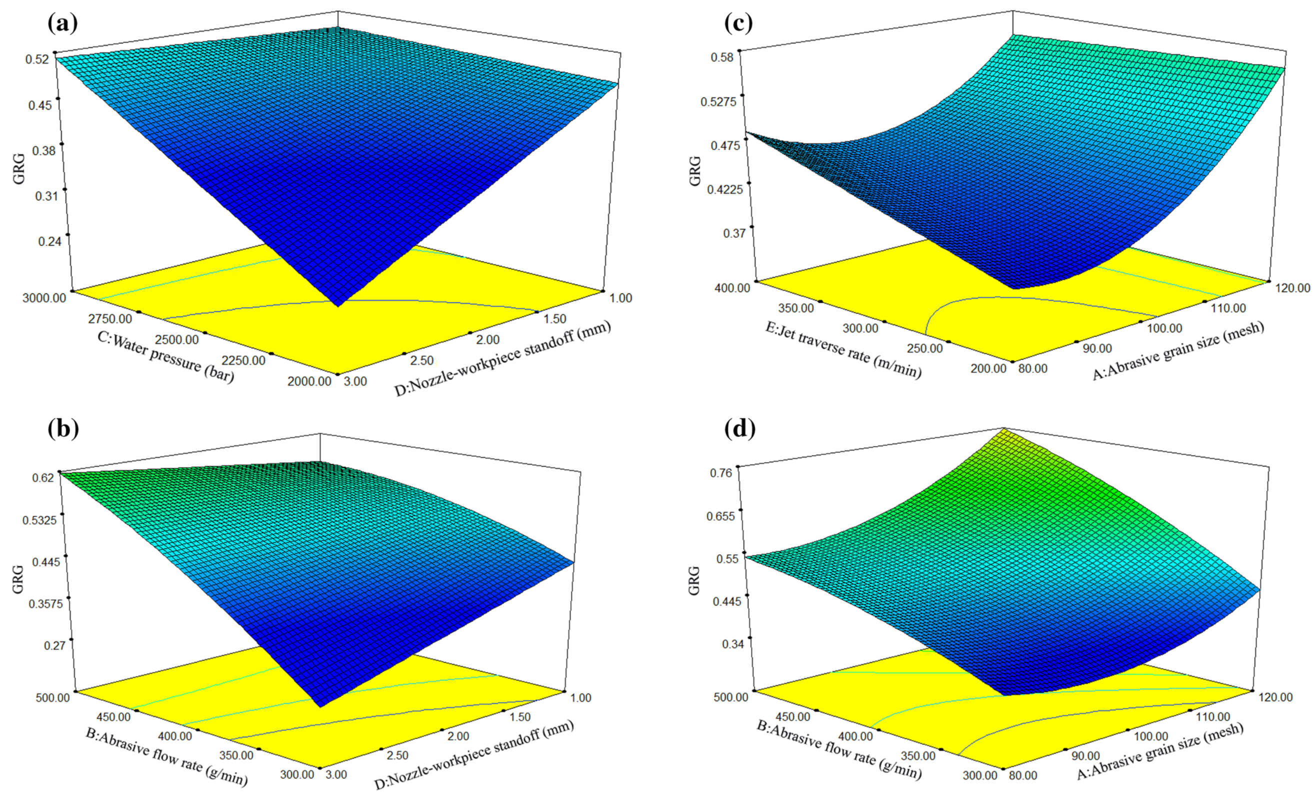

Fig. 4 Three-dimensional response surface plots

able per unit area of the jet. The momentum transfer from the waterjet to the abrasive becomes essential to improve the ability of penetration and surface finish [7]. Hence, a higher level of abrasive flow rate was preferred and it was shown by a larger value of GRG (Fig. 4b). The top portion of the kerf was observed to be wider than the bottom portion resulting in a tapered cut surface. The taper angle could be reduced by enhancing the cutting ability of jet [3]. An increased flow rate of abrasives would improve the cutting ability of the jet and hence an enhanced GRG value as visualized from Fig. 4d. An improvement in water pressure enhances the energy content of jet ensuring crack initiation and propagation, thereby offering an effective mode of material removal in case of brittle materials [1]. Hence, a higher value of water pressure was desired for better process responses as seen from a larger value of GRG (Fig. 4a). A larger value of nozzle–workpiece standoff was found to create divergence of the jet allowing it to lose its energy [5]. The reduced kinetic energy of jet was observed to spoil the surface finish and increase in the kerf as well. Hence, a lower level of nozzle–workpiece standoff was desired as indicated by an improved value of GRG in the plots (Fig. 4a, b). A moderate value of jet traverse rate (Fig. 4c) was preferred for ceramic tiles as an increased value was found to spoil the surface texture by creating more striations, while a lower value could increase the taper angle of cut. A larger abrasive grain size was desired (Fig. 4c, d), as larger grains can impart more kinetic energy on surface being cut producing good quality characteristics.

4.4 Effect of AWJC Parameters on Surface Roughness and Taper Angle of Cut

The effect graph displayed in Fig. 5 shows the impact of various AWJC process parameters on the responses (SR and TA). It was observed that finer grains of abrasives produce better surface finish. This is due to the fact that a smaller abrasive grain removes minimal material from the parent, improving the surface finish and reducing the taper angle of cut. A higher abrasive flow rate allows extra mechanical interactions as more cutting edges are involved in machining, improving the surface finish [7]. An increase in water pressure improves the energy content of the abrasive waterjet, and it plays an important role in improving both the responses. A lower level of nozzle–workpiece standoff and jet traverse rate were observed to improve the surface finish and kerf taper [1,5]. A minimal level of nozzle–workpiece standoff reduces the jet divergence producing a better finish and reduced taper angle of cut (Fig. 5).

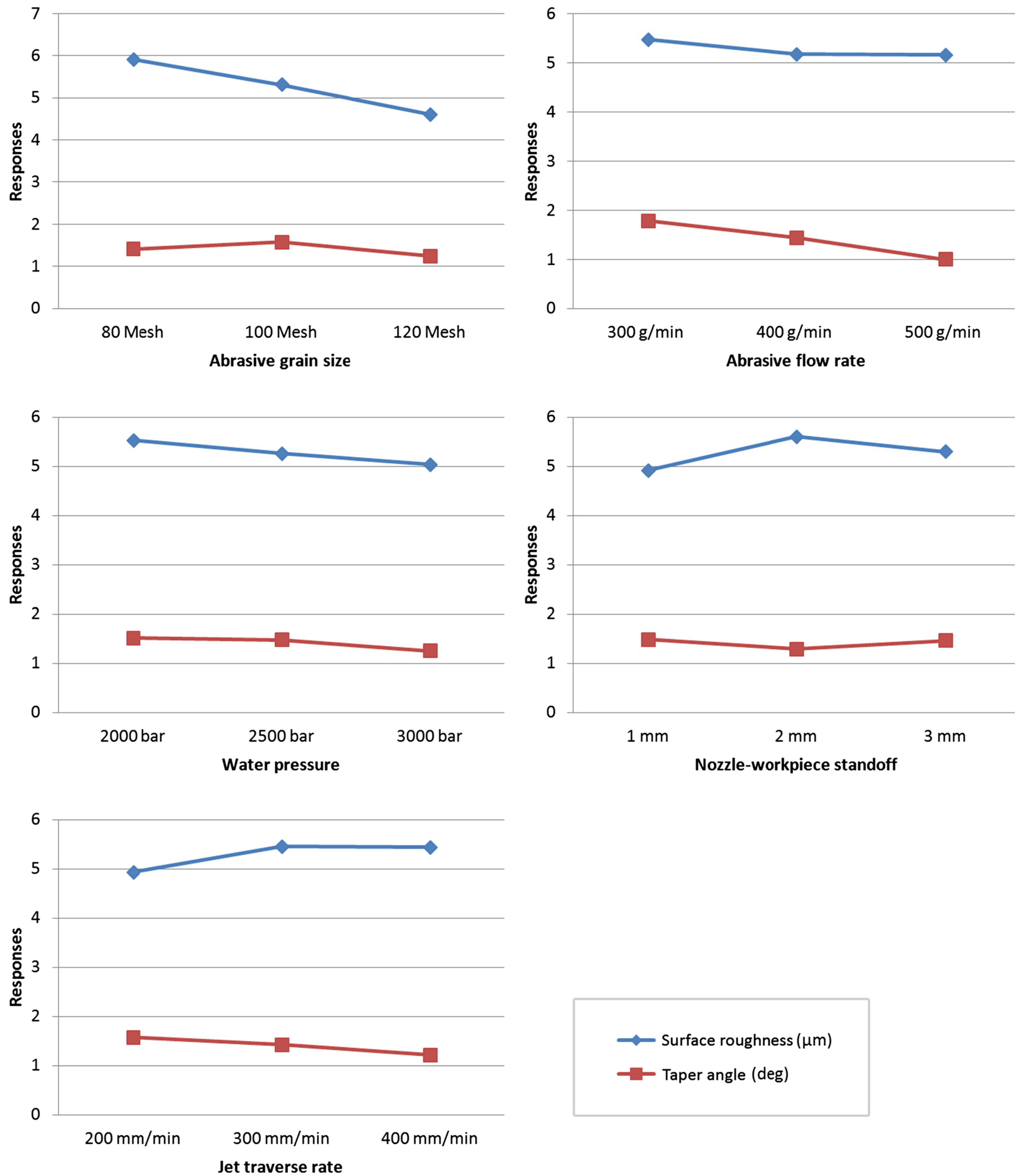

Fig. 5 Effect of AWJC parameters on the responses

4.5 Desirability Analysis

The Design Expert software (version 7.0.0) was used to perform the desirability analysis using the '*larger-the-better*' desirability function [16]. The results of desirability analysis are listed in Table 5. The AWJC condition revealing the highest desirability value was selected as the optimal condition [18, 19]. The optimal level of AWJC parameters were selected

Table 5 Desirability analysis

Parameter	Name	Level	Low level	High level
A	Abrasive grain size	120.00	80	120
B	Abrasive flow rate	500.00	300	500
C	Water pressure	2998.39	2000	3000
D	Nozzle–workpiece standoff	1.68	1	3
E	Jet traverse speed	311.70	200	400
Response	Prediction	SE mean	95 % CI low	95 % CI high
GRG	0.900764	0.075552	0.739728	1.061799

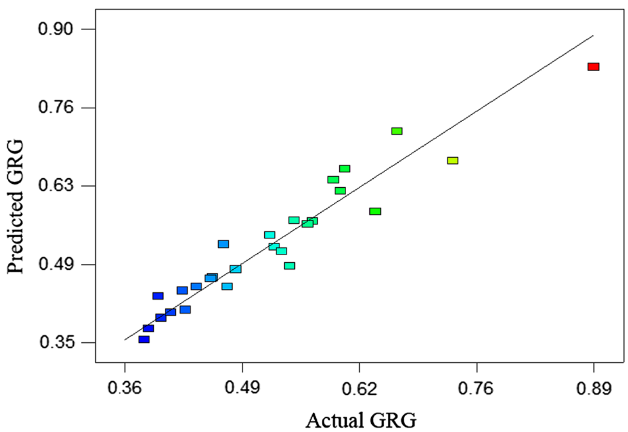

Fig. 6 Plot of the predicted versus actual values of GRG

as: abrasive grain size—120 mesh, abrasive flow rate—500 g/min, water pressure—2998.39 bar, nozzle–workpiece standoff—1.68 mm and jet traverse speed—311.70 mm/min. The plot of predicted versus the actual values of GRG (Fig. 6) did not show any unusual pattern. Most of the values were observed to fall close to a straight line, indicating the accuracy of prediction.

4.6 Confirmation Experiment

A confirmation test was important to validate and authorize the g-RSM approach. The responses obtained with the initial setting of AWJC parameters was compared with those attained with the optimal operating condition predicted by the g-RSM method (Table 6). The parameter setting corresponding to trial number 27 portraying the peak value of GRG within the experimental domain was chosen as the initial setting. The confirmation test had authorized the effectiveness of g-RSM approach. A significant improvement was observed in the GRG value and hence the responses.

The macroview of cut surface obtained using the initial parameter setting (abrasive grain size—120 mesh, abrasive flow rate—500 g/min, water pressure—3000 bar, nozzle–workpiece standoff—2 mm and jet traverse speed—200 mm/min) and g-RSM setting (abrasive grain size—120 mesh,

Table 6 Confirmation test

Parameter setting	GRG	Responses	
		SR (μm)	TA (deg)
Initial setting	0.89002	4.087	0.754
Optimal setting using g-RSM	0.90076	3.240	0.703
Improvement	0.01074	0.847	0.051
Percentage improvement	1.21 %	20.72 %	6.76 %

abrasive flow rate—500 g/min, water pressure—2998.39 bar, nozzle–workpiece standoff—1.68 mm and jet traverse speed—311.70 mm/min) is displayed in Figs. 7a and 8a, respectively. The reduction in the number of striation was clearly evident in the surface machined by using the optimal parameter setting (Fig. 8a) compared to the one produced with the initial parameter setting (Fig. 7a).

The P-profile plots generated using Surfcorder SE3500 for the surfaces machined using initial setting and g-RSM setting is shown in Figs. 7b and 8b, respectively. The plots were generated for a cut-off length of 0.8 mm and at a probe speed of 0.1 mm/s. The evaluation length was taken as 4 mm. The Ra value of surface roughness was measured as 4.087 μm for the initial setting of parameters (Fig. 7b) and 3.240 μm for the optimal setting of parameters (Fig. 8b). This validates the significant improvement in surface finish obtained with the g-RSM setting. The atomic force microscopy (AFM) images of cut surfaces were also studied to understand the surface texture characteristics. Surface texture is a function of roughness and waviness in the surface. An atomic force microscope (nodel: Park XE-100) inbuilt with XEP software was employed in tapping mode to observe the topography of the cut surface. The microscope uses an I-V spectroscopy with an XY scanner of superior resolution. The topographic feature of the tapping mode AFM image shown in Fig. 8c indicates a better surface texture in terms of the contrast induced due to peaks and valleys, when compared to the texture available in Fig. 7c. Hence, the optimal setting of parameters was observed to produce a surface with relatively lesser roughness and waviness. The reduction in peaks and valleys has contributed to a good surface texture. The

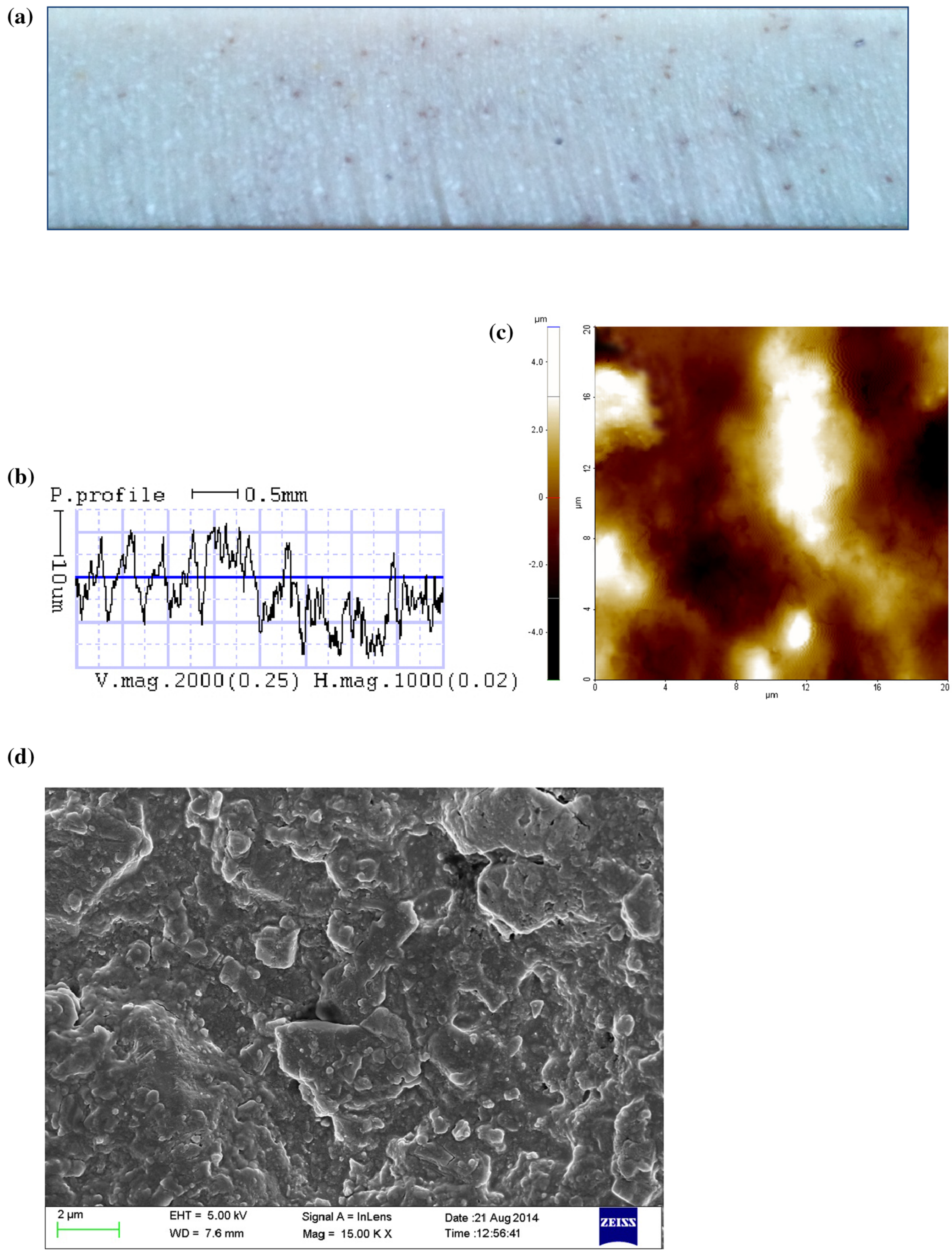

Fig. 7 Initial setting of AWJC parameters. **a** Macroview of cut surface, **b** P-profile plot, **c** tapping mode AFM topography, **d** FESEM image of cut surface

field emission scanning electron microscope (FESEM) image shown in Fig 8d (g-RSM setting) indicates a better cut surface in terms of roughness, compared to the image in Fig. 7d (initial setting). These images were taken using Carl Zeiss (MA15/EVO 18) scanning electron microscope, capable of attaining a resolution of 4.5 nm at 30 kV in low vacuum mode.

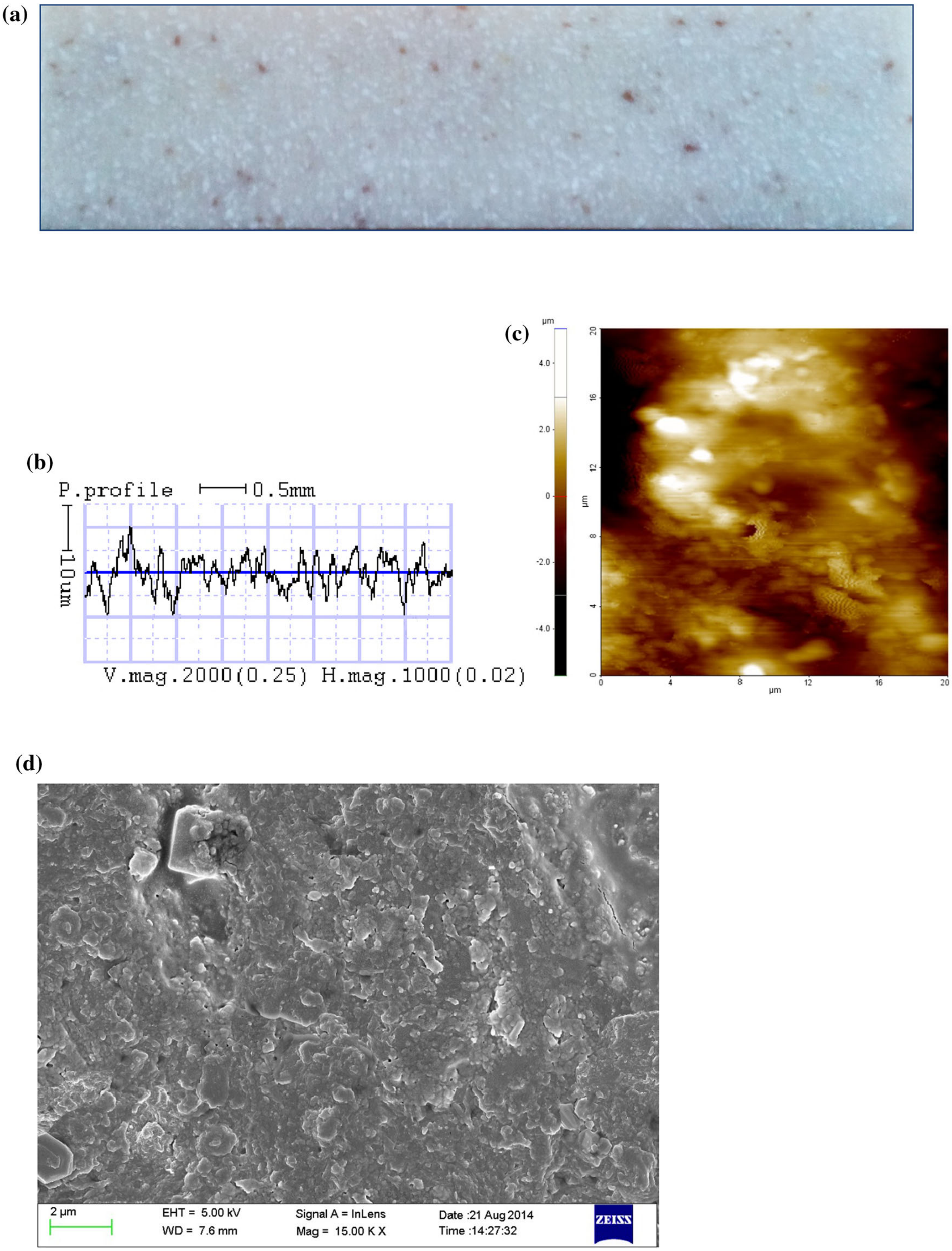

Fig. 8 g-RSM setting of AWJC parameters. **a** Macroview of cut surface, **b** P-profile plot, **c** tapping mode AFM topography, **d** FESEM image of cut surface

The impact of abrasive particles hitting the work piece and generating cracks was evident from all the FESEM images. The induced cracks further propagate to remove the material, and the brittle mode of fracture could be clearly visualized from the FESEM images.

5 Conclusions

The report had disclosed the effects of parameters in AWJC of ceramic tiles. A new approach of grey-based response surface methodology (g-RSM) was adopted to identify the best cutting condition for better quality characteristics. The following conclusions were drawn.

- The AWJC trials were designed using Taguchi's L_{27} orthogonal array which offers the scope to study the interaction among the parameters. The parameter effects were studied using lesser experimental runs compared to the central composite design used with RSM.
- The GRG values were used to represent the responses as a performance index, and RSM was used to create a model for GRG in terms of all the parameters and their interactions.
- The new methodology of g-RSM had proved its effectiveness in converting a multiresponse problem into a single-response problem. The optimal setting of AWJC parameters for ceramic tiles was obtained as: abrasive grain size—120 mesh, abrasive flow rate—500 g/min, water pressure—2998.39 bar, nozzle–workpiece standoff—1.68 mm and jet traverse speed—311.70 mm/min.
- The predicted values of GRG and the values from the experimental domain matched well with each other displaying a better fit. The input parameters (abrasive grain size, abrasive flow rate and water pressure) and the interaction between abrasive grain size and abrasive flow rate were found to significantly influence the responses (SR and TA). The second-order term of abrasive grain size was also found to be significant, and the mathematical model for GRG was found to be adequate.

The quadratic model along with the research findings will offer the required guidelines and necessary database for cutting ceramic tiles. It will also help the concerned industries in meeting the stern cutting requirements.

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