Optimization of awj process using fuzzy taguchi method for improving surface characteristics of silicon wafer

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Abstract. This study investigates the slicing capabilities and surface characteristics of Silicon wafer by optimizing the operation parameters of the Abrasive water jet machining process. Slicing carried out on single crystal pure silicon ingot in AWJM by using an abrasive particle of size 80 mesh. To optimize the AWJ operation parameters L9 Taguchi orthogonal array is used and compare the superficial feature like surface roughness, topography, and slicing rate using different input parameters like SOD, water jet pressure, and flow rate of abrasives. To know the significant slicing parameter, which impact in the surface finish of silicon wafer by ANOVA analysis and the empirical model of the slicing process is find by using a regression model, Further Fuzzy logic analysis used to predict the abrasive water jet machining process parameters with Mamdani fuzzy rules and Triangular membership function. SEM analysis is portrayed by the surface morphology of different mesh size machined on pure Si wafer.

1. Introduction
In Abrasive water jet machining (AWJM) a stuff outing or cleaning activity used to dissolve openings and holes by the effect of grating particles blended with water of the on hard and weak materials. This procedure is non-warm, non-compound, and non-electrical along these lines, and it does not adjust the metallurgical and physical properties of the material. This procedure includes the utilization of a rapid stream of grating particles blended with pressurized water on the machined surface by a spout of little breadth, little distance across. Substance evacuation happens by the rubbing activity of grating particles with water. AWJM takes a shot at the basic rule of water disintegration. This procedure utilizes the motor vitality of the water alongside the rough to disintegrate the metal at the purpose of contact. The property of the abrasives used plays a imperative role in determining the facet finish and topography. A newly designed AWJ with auger system to control the abrasive flow rate was used and concluded the surface quality is better in moving jet rather than stationary [2]. To find the percentage of contribution and the more significant operational parameters for the surface roughness are identified by using the analysis of variance (ANOVA) [3].The influential process parameters are predicted, and suggested increment in pressure steer to the increase in MRR [4]. High abrasive flow rate reduces the surface roughness, also explained the different abrasives used in this process [5, 6]. The optimum particle size and reusable chances of garnet were described [9]. The highest quality with integrity properties and low surface roughness from abrasive erosion was evaluated [10]. The effect of the stylus tip had no significant influence on roughness parameters [11]. This work aims to optimize the AWJ process parameters by
different abrasive mesh size by machining single crystal silicon ingot using the L9 orthogonal array and compare the surface characteristics. Standoff distance (SOD) frolie a vita l character in AWJ slicing operation, damage crop up in the silicon substrate. [12, 13] In this experimental work, an effort made to analyse the slicing parameters at most favourable level by using Taguchi analysis and a fuzzy algorithm to conduct an in-depth study and the performance of garnet during the AWJM process.

2. Methodology
In this investigation, Taguchi based design of experiments is followed, and nine slices sliced using AWJM (OMAX 2626) (Figure 1) and their specifications are summarized in table 2. Experimental data of the above DOE based assessment are composed to review the consequence of various multi-criteria operation factors to determine the machinability in AWJM by using the abrasive material garnet of mesh size 80, which plays the most vital role in the machining process. Single crystal silicon is used as work material for this experimentation has 25 mm in diameter and 150mm in length, with an optical grade of resistivity being >10 Ohm-cm. Having vast application in solar and electronic industries are sliced using non-contact type machining. The intensive properties of Si ingot are summarized in Table 1.

| Property item          | Value          |
|------------------------|----------------|
| Crystal Structure      | Diamond Cubic |
| Electrical resistivity | >10 Ohm-cm    |
| Mohr’s hardness        | 7              |
| \( \rho \), g/cm\(^3\) | 2.329          |
| Liquefaction point, [°C] | 1412          |
| Boiling Point, [°C]    | 2878           |

Table 1. Specifications of the Si work piece (25°C).

| Table 2. AWJ machining specifications (OMAX 2626). |
|--------------------------------------------------|
| Table Size                                       | 1168 (787) mm |
| X-Y travel                                       | 737 (660) mm  |
| Z axis Travel                                    | 203 mm        |
| Foot Print (with controller), mm                 | 1829 x 2946   |
| Weight (Tank empty)                              | 1364 kg       |
| Height, mm                                       | 2340          |
| Operating Weight                                 | 2962 kg       |
| Speed                                            | 4572 mm/min   |
| Electrical Requirements                         | 3-Phase, 300-480 VAC 50-60 Hz |
These observations were done to explore the consequence of abrasive rate, feed rate, and water pressure was changed for each and every slice for better surface finish, more over an efficient material removal rate (MRR), performed with an influence of different level of energy. Water pressure, and the abrasive flow rate have a direct effect on metal removal rate, Standoff distance plays a key role in AWJ which influences more in MRR and the jet will gradually diverge leads to increase in width of cut, also it increase the diameter of the jet reducing its kinetic energy and proportionally increasing roughness also higher the SOD increase substrate damage [21, 22]. The ranges of the machining parameters are shown in Table 3. After slicing, to determine the surface topographies of the sliced silicon, wafers are measured by a Talysurf instrument to obtain surface roughness (Ra) and the material removal rate was calculated using the equation (1) are listed in table 4 which gives the irregularities and rugged space of the slice surface and the slicing rate of the process.

\[
MRR = \frac{(\text{Weight before machining} - \text{Weight before machining})}{\text{Time taken for machining}}
\]  

FESEM (EI Quanta FEG 200) analysis was performed to measure the cracks developed on the sliced surface and multi-response optimization has been done to enhance the slicing capability of AWJM activity, with lower surface roughness and higher MRR.

### Table 3. Slicing parameters of AWJ.

| Symbol | Slicing Parameters       | Different Levels |
|--------|--------------------------|------------------|
| \( P \) | Water Jet Pressure(Mpa)  | Level I | Level II | Level III |
|        |                          | 200     | 250      | 300       |
| \( SOD \) | Stand-off distance(mm)  | 2       | 3        | 4         |
| \( AFR \) | Abrasive flow rate(kg/min) | 0.34   | 0.44     | 0.54      |

Using Mat lab 2019 fuzzy logic sets was formulated to identify the optimized values of output for our prescribed input machining parameters. It consists of different conceptual components are fuzzification, degree of membership, rule-based systems, fuzzy inference system, fuzzified. Initially, membership functions are used to fuzzify the input and output operation parameters of AWJM and then developed the rule viewer using fuzzy logic investigation, which allows the actions by the Center of Gravity (CoG) a method of defuzzification for the proper selection of the control.
3. Results and discussions

3.1. Consequence of incompatible slicing control factors on Ra and MRR.

To review the superiority of slicing factors on the output response variables taguchi DOE is used to carry out the modelling. In this experimental study, water jet pressure (MPa), SOD (mm), abrasive flow rate (kg/min) are chosen as slicing parameters (design factors) and the other parameters are assumed to be constant in this experimental study. Based on work piece and machine operating condition the values of the slicing parameters with their levels are selected as shown in Table 3. In this study, three level design (L9) has been contributing for examination. The experimental results with slicing parameters and its responses are shown in Table4. To regulate the effect of the garnet in the facet arithmetical average value of the silicon wafer, the sliced surface profile were assessed by computerized non-contact tester. The assessed Ra and MRR revealed a rise in surface finish and slicing rate is due to the selection of garnet size also the influenced parameters like SOD and abrasive flow rate. To know the excellence of the characterization, Signal to noise ratios (S/N) for each slicing parameters were computed to minimize the discrepancy in surface waviness values.

The signals specify the consequence on the mean responses and noises are computed by the impact on the allowances from the average responses, which will reveal the sensitiveness of the evaluation output of surface roughness to the noise factors. To understand the AWJM process based on the prior experience, the suitable S/N ratio should be identified. In this experimental study, the S/N ratio is determined based on the criterion the smaller the better for Ra, to minimize the responses, the larger the better for MRR to maximize the responses and computed according to Eq. (2) and (2a).

\[
\frac{S}{N} \text{Ratio}(\eta) = -10 \log 10 \left( \frac{1}{n} \sum_{i=1}^{n} y^2 \right)
\]

(2)

Where, n is no. of iteration done in this study is equal to 2 and y is the facet roughness value for the i\(^{th}\) experiment.

\[
\frac{S}{N} \text{Ratio}(\eta) = -10 \log 10 \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y^2} \right)
\]

(2a)

Figure 2. shows the factor consequence diagram for the surface micro-irregularities and MRR with an abrasive Garnet (80 mesh) signify that the water pressure, SOD, abrasive flow rate are probed and best possible in level 3, level 3 and level 2 for ameliorate surface roughness. Based on results, the prime level position of parameters are A3B3C2 for abrasive water jet slicing.

| Exp. No | P (MPa) | SOD (mm) | AFR (kg/min) | MRR (g/min) | Ra (µm) | SN Ratios (Ra) | SN Ratios (MRR) |
|---------|---------|----------|--------------|-------------|---------|----------------|-----------------|
| 1       | 200     | 2        | 0.34         | 15.313      | 1.62    | -4.190         | 23.701          |
| 2       | 200     | 3        | 0.44         | 14.753      | 2.09    | -6.402         | 23.378          |
| 3       | 200     | 4        | 0.54         | 18.144      | 1.50    | -3.521         | 25.174          |
| 4       | 250     | 2        | 0.44         | 15.200      | 1.77    | -4.959         | 23.636          |
| 5       | 250     | 3        | 0.54         | 18.608      | 1.51    | -3.579         | 25.394          |
| 6       | 250     | 4        | 0.34         | 14.752      | 2.26    | -7.082         | 23.377          |
| 7       | 300     | 2        | 0.54         | 14.118      | 1.87    | -5.436         | 22.995          |
| 8       | 300     | 3        | 0.34         | 18.291      | 1.72    | -4.710         | 25.245          |
| 9       | 300     | 4        | 0.44         | 18.175      | 2.21    | -6.887         | 25.189          |
The most excellent intensity of the slicing factors were estimated by S/N ratio ($\eta$) can be computed as:

$$\eta = \eta_{Tm} + \sum_{m=1}^{p} \eta_{m} = \eta_{Tm}$$

(3)

During slicing single crystal silicon with garnet, the estimated surface roughness (Ra) is 2.16 µm, material removal rate (MRR) is 14.601 g/min and actual surface roughness (Ra) is 2.21µm, material removal rate (MRR) is 18.175 g/min for the level A3B3C2. In the surface roughness analysis, the main machining variables are water pressure and standoff distance and abrasive flow rate. Between these three slicing parameters, in the most effective technique, the AFR is ranked one, influences surface finish features of single-crystal silicon brittle materials. To validate the results obtained during analysis stage a confirmation test be executed by frame the slicing factors at most favourable level. The iteration results are encapsulated in Table 4, and the factor effect diagram is given out in Fig.2. The signal to noise ratios shows that abrasive flow rate had more influence in surface roughness than other factors, but in material removal rate, abrasive flow rate and water pressure frolic a vital role. The lowest surface waviness is successfully reached when water jet pressure, SOD and AFR are the best appropriate control factors according to the level of 3, 3, and 2, respectively, for 80 mesh garnet.

![Figure 2. (a, b) Factor effect diagram for the Ra and MRR with an abrasive Garnet (80 mesh).](image)

3.2. ANOVA analysis.

To point out the most efficacious operation parameters which influence the surface roughness of a single-crystal silicon wafer the analysis of variance (ANOVA) test was carry out to improve the surface characteristics. The ANOVA table for surface coarseness and Material removal rate are listed in Tables 5, and 6, respectively. From the ANOVA Table 5 and 6 for Ra and MRR with water jet pressure, SOD, AFR are remarkable within a specified range of 95%. The efficacy of R-Sq (Pred) = 34.15% for Ra is 0.3415, and 31.30% of the variability in MRR are explained by that model. The value of ordinary $R^2$, i.e. 0.3415 which is not close to the adjusted R squared ($R^2_{adj}$) for the model is 0.5997%. Degree of freedom (DOF) was used to identify the importance of machining parameters based on the information received on the number of independent samples. For calculation, it is equal to the number of iterations minus the number of auxiliary factors evaluated. The outcomes of ANOVA shows that abrasive flow rate operation parameter have remarkable contribution on the surface roughness values and Stand-off distance process parameters have significant contribution on MRR of the silicon slice by AWJM also numerical model and analysis of variance (ANOVA) was developed and presented by a design expert. The goodness of fit for the replica is indicated by the R2 coefficient. In this analysis for the surface roughness with 80 mesh abrasive, after considering the significant factors, the value of the coefficient ($R^2_\text{adj} = 0.5997$) specify that 59.97% of the total variableness is elucidate by the developed replica. The F-value of 0.89 hinted the model is exceptional. For the material removal rate, the significant factors the value of the coefficient
specify that 45.76% of the total variability is elucidated by the formulated model. The F-value of 0.89 hinted the model is exceptional. The consequence of water jet pressure, SOD, AFR shown in Fig. 4. It explains that the Ra and MRR gradually increase with increase in water jet pressure and AFR.

**Table 5.** The ANOVA for the surface roughness with 80 mesh abrasive.

| Slicing Factors | F  | SSA   | VA   | F-value | P-value | Contribution |
|-----------------|----|-------|------|---------|---------|--------------|
| P (Mpa)         | 2  | 0.05829 | 0.02914 | 0.22 | 0.821 | 8.71%        |
| SOD (mm)        | 2  | 0.10336 | 0.05168 | 0.39 | 0.721 | 15.45%       |
| AFR (kg/min)    | 2  | 0.23949 | 0.11974 | 0.89 | 0.528 | 35.80%       |
| Error           | 2  | 0.26776 | 0.13388 |       |        | 40.03%       |
| Total           | 8  | 0.66889 |       |       |        | 100%         |

Notes: *Significant; S = 0.365893; R-Sq (Pred) = 34.15% R-Sq (adj) = 59.97%.

**Table 6.** The ANOVA for the Material Removal Rate with abrasive Garnet 80 mesh.

| Slicing Factors | F  | SSA   | VA   | F-value | P-value | Contribution |
|-----------------|----|-------|------|---------|---------|--------------|
| P (Mpa)         | 2  | 1.095 | 0.5475 | 0.07 | 0.933 | 3.93%        |
| SOD (mm)        | 2  | 10.123 | 5.0614 | 0.67 | 0.599 | 36.29%       |
| AFR (kg/min)    | 2  | 1.543 | 0.7717 | 0.10 | 0.907 | 5.53%        |
| Error           | 2  | 15.133 | 7.5665 |       |        | 54.25%       |
| Total           | 8  | 27.894 |       |       |        | 100%         |

Notes: *Significant; S = 2.75072; R-Sq (Pred) = 31.30% R-Sq (adj) = 45.76%.
Figure 3. Residual Plots for Surface Roughness and MRR with abrasive Garnet 80 mesh.

With design expert software the eventual mathematical regression model in terms of actual factors are determined and written in Eq.4 and 5.

Surface Roughness $Ra (\mu m) = 1.679 + 0.0 P (Mpa)_{200} + 0.110 P (Mpa)_{250} + 0.197 P (Mpa)_{300} + 0.0 SOD (mm)_{2} + 0.020 SOD (mm)_{3} + 0.237 SOD (mm)_{4} + 0.0 AFR (kg/min)_{0.34} + 0.157 AFR (kg/min)_{0.44} - 0.240 AFR (kg/min)_{0.54}$ (4)

Material Removal Rate, MRR (g/m) = 9.33 + 0.0079 P (Mpa) + 1.073 SOD (mm) + 4.19 AFR (kg/min) (5)

Figure 4. Surface Plots of Material Removal Rate, MRR (g/m & Surface Roughness $Ra (\mu m)$.

3.3. Optimization of multi objective characteristics using fuzzy logics.

To predict the surface roughness and MRR the Fuzzy logic-based technique is used to develop the set of rules to be followed in calculations. The input variables water jet pressure, standoff distance, abrasive flow rate were identified as important factors to the output parameter $Ra$ and MRR to frame the fuzzy logic algorithm. The basic structure of the fuzzy prognosticator is shown in Fig.6. In the fuzzy prognosticator study, the Fuzzification and defuzzification use the input and output membership functions to get the precise output values by framing fuzzy rules based on logical decisions. In this investigation, the fuzzy control and response slicing factors are fractionate into three level of uncertain sets (Low, Medium, High), and the responses can be fractionate into five level of uncertain sets as {very low (mf1), low (mf2), medium (mf3), high (mf4) and very high (mf5)} [20] and the intensity of membership function of water jet pressure, SOD, abrasive flow rate is shown in Figure 7.
Figure 5. Structure of the Fuzzy predictor for the Ra and MRR analysis.

Figure 6. Fuzzy logic designer function for the Input and Output Variables.

Table 7. Range of Fuzzy subsets used for Ra and MRR for single crystal silicon.

| Conditions    | Range (SR) | Range(MRR) | Membership Functions |
|---------------|------------|------------|----------------------|
| Very low      | 0.5 – 1.5  | 12.5 – 15  |                      |
| Low           | 1.5 – 1.75 | 15 – 16    | Triangular           |
| Medium        | 1.75 – 2   | 16 – 17    |                      |
| High          | 2 – 2.5    | 17 – 18    |                      |
| Very High     | 2.5 – 3    | 18 – 20    |                      |

3.4. Fuzzy analysis.

Based on the L9 Taguchi orthogonal array, nine fuzzy rules were developed in this analysis. The interrelation among the identified control factors and the response factors are given by fuzzy rules, which allows the effort by the Center of Area (CoA) defuzzification technique for the proper selection of the control. The guidelines are formulated with reference to the revealed iteration results like Material Removal Rate (g/min) and Surface Roughness (µm) as shown in Table 4. To predict the precise output, a centroid technique is recommended in the de-Fuzzification process and was developed accompanied by the assistance of degrees of truth based controller with a collection of functions in matrix laboratory. The process of getting crisp output values is termed as defuzzification where it adopted as single point method to predict the responses as portrayed in the form a graph shown in Fig.7 performed with a collection of
functions in MATLAB. It helps to get the optimized MRR and Surface roughness for the given control factors by fuzzy rule and the optimum MRR values arrived by fuzzy logic analysis for single crystal silicon slicing by AWJM is 14.5 g/min and Ra 2.12 µm accompanied by the input of low medium high of water jet pressure, SOD, AFR against the experimental value of 14.75g/min,2.09 µm. It shows that medium level of SOD helps to increase the MRR and poor surface finish as high velocity of abrasive particles leads to increase the brittle action of the silicon material. Fig.8. Shows the Ra (µm), MRR (g/min) & rule surface viewer (3D) using fuzzy logic analysis.

![Figure 7.](image1)

**Figure 7.** Input Membership functions of a) P b) SOD c) AFR d) Output membership function of (i) Ra (µm) (ii) MRR (g/min).
3.5. Surface Morphology of single crystal silicon sliced by AWJM.

To understand the surface texture of sliced silicon, which is composed of an arbitrary array of convergence the impact of a meteorite or steps after slicing. The micro slicing action accompanied with fracture of a metal of the ingot are by the focused beam of high-velocity abrasive particles during the slicing of single crystal silicon. Among the machining parameters, the standoff distance take part an essential role in the surface topography and substrate damage due to the variation in SOD jet divergence increases, which will affect the penetration and the surface flatness [11-13]. To estimate the surface feature after slicing, a SEM analysis of the surface topography of the wafer surface is elucidated at distinct amplification. It is noticeable that the sliced surface has influenced by the control is not so even because of variations in SOD and the velocity of the focused beam and more influenced in surface finish also abrasive particle size and velocity is highly influenced in surface finish and MRR
4. Conclusions
The slicing characteristics of the single crystal silicon using non-traditional machining technique AWJM were analysed under different machining factors by using taguchi L9 orthogonal matrix method. All the nine observations were performed as per L9 orthogonal array and the results of the experiment are optimized the machining parameters on the slicing rate of single crystal silicon using fuzzy logic analysis. The meticulous consequence are encapsulated as follows:

1. While slicing single crystal silicon MRR increases even as the abrasive flow rate escalate if the standoff distance and water pressure is moderate. This is due to the rapid velocity of the abrasive particles with appropriate mixture which leads to removal of material with micro cutting also because of brittle fracture of single crystal silicon.

2. For slicing single crystal silicon with garnet, the estimated surface roughness (Ra) is 2.16 µm and experimental surface roughness (Ra) is 2.21µm. In the surface roughness examination, the dominant machining variables are P, SOD, and AFR. Between these three slicing parameters, in the most effective technique, the AFR is ranked one, specifically influences surface finish features of single-crystal silicon brittle materials.

3. When compare the computed MRR 14.601 g/min with the actual MRR 18.175 g/min shows AFR and P plays a vital role. Also it identifies high material removal rate was occurred with moderate slicing parameters like P, SOD, AFR.

4. In ANOVA analysis, the Contribution percentage influence of slicing parameters for surface roughness and material removal rate are 8.71%,15.45%,35.80% and 3.93%,36.29%,5.53% respectively and it shows abrasive flow rate have influenced more in quality of the surface and SOD have major contribution in Material Removal Rate. To measure the most influential independent variables in dependent variable also used to know how near the data are to the fitted retrogression line. The increased adjusted R-squared value shows that it improves the model than the expected.

5. The experimental data of Ra and MRR was compared with fuzzy logic analyzed value. The surface roughness value of the fuzzy model for AWJM is 2.12 µm and material removal rate of
14.5 g/min. To develop the most perfect prediction model, the leading proposed model is the fuzzy model which helps to find the fine predicted value.

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