Parametric optimization in Rotary Ultrasonic Drilling of BK7 through RSM based PSO

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Abstract. This paper aims to establish the rotary ultrasonic machining as a pragmatic solution to tackle the machinability issues with brittle materials. In the present article, drilling variant of rotary ultrasonic has been used to machine the optical glass BK7 owing to its numerous applications in manufacturing sector. Experimental matrix has been designed by utilizing the response surface methodology after scrutinizing the machining variables (feed rate, spindle speed and ultrasonic power) through single variable at a time approach. Material removal rate (MRR) and surface roughness (SR) have been chosen as responses for assessing drilling performance. Thereafter ANOVA analysis was done at 95 % confidence level for figuring out the significant model terms (linear, interaction and square) that affect the responses of interest. Feed rate was found to have profound impact over the machining performance. Thereafter, desirability approach and particle swarm optimization (PSO) were used for yielding the right combination of input factors for concurrent optimization of responses. In comparison to desirability, particle swarm optimization (PSO) provided the instant optimal solutions to meet the industrial requirements. Further, confirmation experiments validated the accuracy of desirability and PSO to predict the optimal solution with little errors.

1. Introduction
With superior properties such as high hardness, high chemical resistance and wider transmission range with low thermal expansion co-efficient, BK-7 has numerous applications [1]. Conventional machining processes end up with many limitations like higher cutting forces, rapid tool wear, chipping and geometrical inaccuracies in machining BK-7 due to its high hardness and brittle nature, thus restricting its widespread applications. Even non-traditional machining processes including abrasive jet machining, chemical etching, electrochemical machining, laser beam machining, electric discharge machining, find it hard to become the pragmatic solution due to their inherent limitations like taper cutting, low material removal rate, surface defects, low aspect ratio, generation of heat affected zone and recast layer etc. Ultrasonic machining (USM) which is closest to rotary ultrasonic machining (RUM) in material removal mechanism suffers from low machining rate and higher cutting forces. So, need arises to explore the RUM to seek a fruitful solution to tackle all the problems mentioned above. RUM is an advanced machining process that involves direct contact of abrasive particles that are directly coated over the core drill. This arrangement results in hybridization of the conventional grinding and ultrasonic machining. This special arrangement also leads to achieve 6-10 times more material removal that cannot be matched by either conventional grinding or USM individually. Abrasive particles have light and intermittent contact with the workpiece surface and follow a spiral sinusoidal trajectory during the grinding variant of RUM [2].
1.1. Motivation for research work

Literature was extensively reviewed for identifying the following research gaps that led the authors to carry out the experimental investigation:

- Narrow range of ultrasonic power (20-40 %) in past research
- Scarcity of literature related to drilling of BK7 using RUM; rather researchers focused only on grinding variant of RUM for processing BK-7.
- Lack of use of techniques of design of experiments
- Almost no attempt on optimization of rotary ultrasonic drilling (RUD) performance using particle swarm optimization

To address the above-mentioned gaps, BK-7 has been drilled using the RUM with a broad range of ultrasonic power (30-80%). Further, response surface methodology (RSM) was coupled with desirability approach and particle swarm optimization for finding the right parametric setting of machining variables (ultrasonic power, spindle rotational speed and feed rate) for achieving concurrent optimization of responses of interest — material removal rate (MRR) and surface roughness (SR).

2. Materials and methods

2.1. Experimental set-up

Through holes of depth 5 mm were drilled through the square workpiece (50mm×50mm) using standard set-up of RUM (knee series 10, sonic mill), with a power rating of 1 kW. Enlarged view of machining zone and core drill are shown in Fig. 1. Core drills with 220 mesh sized diamond abrasives, 100% concentration and metal binder were used as constant tool variables for the machining. The outer diameter of core drill was 8 mm with thickness of 0.75 mm.

![Figure 1. Machining zone and tool nomenclature](image)

2.2. Experimental Procedure and data collection

The present experimental work involves the machining variables namely feed rate (FR), spindle speed (SS), and ultrasonic power (UP). Another machining variable “coolant pressure” was omitted from the final experimentation, as it did not show any remarkable influence over the responses of interest “MRR” and “SR” as revealed from screening/pilot experimentation. Design expert software (version 9) was used for statistical analysis and planning experimental matrix. Response surface methodology based central composite rotatable design (CCRD) was incorporated for framing the experiment settings as it best fits the second order response surfaces to estimate the regression coefficients accurately [3,4]. Table 1 gives the details of machining variables and their levels, which were finalized based on pilot experimentation and literature review.
Table 1. Machining variables and their levels

| Machining Variables | Levels |
|---------------------|--------|
| SS- spindle speed (rpm) | L-1 2318 | L-2 3000 | L-3 4000 | L-4 5000 | L-5 5682 |
| FR- Feed rate (mm/min) | 0.095 | 0.30 | 0.60 | 0.90 | 1.105 |
| UP- ultrasonic power (%) | 30 | 40 | 55 | 70 | 80 |

3. Results and discussion

Experimentation was replicated twice and average of all the observations corresponding to each experimental setting is recorded in Table 2. Thereafter these observations were fed to design expert software to perform ANOVA analysis. The confidence level was kept 95% so as to apply the outcome of this research work on industrial scale. Consequently, model terms in Table 3 having P value less than or equal to 0.05 were significant and insignificant terms were removed by adopting the backward elimination method for improving the models. The results of ANOVA tests for both the responses are summarized in Table 3.

Table 2. Experimental observations for MRR and SR

| Exp. No. | Spindle Speed (RPM) | Feed Rate (mm/min) | Ultrasonic Power (%) | MRR (mm³/s) | SR (µm) |
|----------|---------------------|--------------------|----------------------|-------------|---------|
| 1        | 3000                | 0.3                | 40                   | 0.1412      | 0.636   |
| 2        | 5000                | 0.3                | 40                   | 0.1523      | 0.548   |
| 3        | 3000                | 0.9                | 40                   | 0.2821      | 0.855   |
| 4        | 5000                | 0.9                | 40                   | 0.3256      | 0.683   |
| 5        | 3000                | 0.3                | 70                   | 0.165       | 0.398   |
| 6        | 5000                | 0.3                | 70                   | 0.1936      | 0.385   |
| 7        | 3000                | 0.9                | 70                   | 0.3926      | 0.808   |
| 8        | 5000                | 0.9                | 70                   | 0.4869      | 0.779   |
| 9        | 2318                | 0.6                | 55                   | 0.2093      | 0.714   |
| 10       | 5682                | 0.6                | 55                   | 0.2906      | 0.559   |
| 11       | 4000                | 0.095              | 55                   | 0.0891      | 0.368   |
| 12       | 4000                | 1.105              | 55                   | 0.5003      | 0.914   |
| 13       | 4000                | 0.6                | 30                   | 0.2011      | 0.735   |
| 14       | 4000                | 0.6                | 80                   | 0.3563      | 0.524   |
| 15       | 4000                | 0.6                | 55                   | 0.2283      | 0.593   |
| 16       | 4000                | 0.6                | 55                   | 0.2426      | 0.590   |
| 17       | 4000                | 0.6                | 55                   | 0.2381      | 0.577   |
| 18       | 4000                | 0.6                | 55                   | 0.2463      | 0.583   |
| 19       | 4000                | 0.6                | 55                   | 0.2253      | 0.550   |
| 20       | 4000                | 0.6                | 55                   | 0.2548      | 0.609   |

3.1. Optimization through desirability and PSO

Desirability approach helps to attain the right parametric conditions when responses of interests are of conflicting nature as in present study where MRR increases with feed but at the cost of increase in SR [5]. It does so by transforming the Multi-objective function into a single objective function and then maximizing it. Although desirability gives the best possible optimal settings of input parameters to yield the better machining performance but finds it hard to give the optimal setting of one of the output parameters with desired values of other parameters. Such situation can be easily taken care of by PSO that is a stochastic intelligent technique [6,7].
Table 3. ANOVA for MRR and SR

| Source          | MRR P value | % contribution | SR P value | % contribution |
|-----------------|-------------|----------------|------------|----------------|
| Model           | 0.22        | < 0.0001       | ---        | 0.42           | < 0.0001       |
| SS              | 0.00723     | 0.0001         | 3.29       | 0.023          | < 0.0001       |
| FR              | 0.17        | < 0.0001       | 77.27      | 0.32           | < 0.0001       |
| UP              | 0.026       | < 0.0001       | 11.82      | 0.037          | < 0.0001       |
| SS×FR           | 0.00120     | 0.0419         | 0.55       | Insignificant  |
| FR×UP           | 0.00534     | 0.0004         | 2.43       | 0.025          | < 0.0001       |
| SS×UP           | Insignificant |              | 0.00594    | 0.0078         | 1.42           |
| (SS)^2          | Insignificant |              | 0.00477    | 0.0143         | 1.14           |
| (FR)^2          | 0.004453    | 0.0009         | 2.02       | 0.00564        | 0.0091         |
| (UP)^2          | 0.002038    | 0.0118         | 0.93       | 0.00356        | 0.0289         |

SS: spindle speed; FR: feed rate; UP: ultrasonic power; SOS: sum of squares; confidence level: 95 %

For current investigation, first a PSO program was formulated using MATLAB (Version 8.0.1.604). MRR and SR models developed by RSM were fed to the program to look for optimal solutions. The optimization problem with objective function and all the constraints can be summarized as:

**Maximize:** MRR

\[0.368 \leq SR (\mu m) \leq 0.914; \quad 2318 \leq \text{Spindle speed (rpm)} \leq 5682; \quad 0.095 \leq \text{Feed rate (mm/min)} \leq 1.105; \quad 30 \leq \text{Ultrasonic power (%)} \leq 80\]

Using these constraints and objective function, optimal conditions were predicted by PSO program for MRR by varying the SR from its minimum to maximum value. A graph as shown in Fig. 2 was plotted between MRR and SR for all the possible optimal solutions corresponding to a specific value of SR. Graph depicts the variation of the MRR with respect to SR. MRR was found to upsurge with increment in surface roughness, highlighting their conflicting nature. It happens due to increase in feed rate in the predicted solutions that reduced the machining time enhancing MRR but significantly deteriorating the surface finish. Optimal setting predicted by desirability was also validated using the PSO algorithm by putting constraint on SR as 0.531µm, which predicted the MRR value as 0.3483 mm³/sec as shown in Fig. 2. Corresponding parametric condition predicted by PSO, logged in Table 4, was also validated experimentally at 95 % confidence level. This demonstrates the capability of PSO to predict almost similar value of MRR as predicted through RSM with the advantage of faster prediction as well.
Table 4. Confirmatory results and optimized conditions for responses

| Approach | Response(s) | FR (mm/min) | SS (rpm) | UP (%) | Predicted | Experimental | %Error |
|----------|-------------|-------------|----------|--------|------------|--------------|--------|
| Desirability | MRR (mm³/s) | 0.57 | 4777 | 80 | 0.3485 | 0.3603 | -3.38 |
|          | SR (µm)     | 0.531 | 0.546 | -2.82 |
| PSO      | MRR (mm³/s) | 0.57 | 4831 | 80 | 0.3483 | 0.3641 | -4.54 |
|          | SR (µm)     | 0.531 | 0.517 | 2.63 |

4. Conclusions
1. Selected machining variables (feed rate, spindle speed and ultrasonic power) have substantial impact on MRR at 95% confidence level. The feed rate has maximum % contribution of 77.27 followed by ultrasonic power (11.82%) and spindle speed (3.29%) on MRR.
2. The feed rate had monotonic impact over surface roughness with maximum percentage contribution of 76.19%. Ultrasonic power substantially affected the surface roughness with moderate contribution of 8.81%.
3. The desirability approach provided optimal setting as spindle speed 4777 rpm, feed rate 0.57 mm/min and power 80%.
4. PSO technique was equally viable for optimization as that of desirability with the advantage of faster prediction.
5. Current work was focused on machining variables only. In future work, some other input factors like abrasive size, type of abrasive bonding, tool diameter, tool thickness, tool profile can also be included to further improve the performance of RUM.

5. References
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