PARAMETRIC OPTIMIZATION OF MICRO-DRILLING OF PMMA (POLY METHYL METH-ACRYLATE)*

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Abstract: *Micro-holes are the inherent feature of micro-products. Conventional micro-drilling has certain advantages over other non-conventional techniques because of better stability of the process. Further electrically non-conducting material can also be micro-drilled. In the present investigation, micro-drilling of PMMA, an aero-space material, has been carried out using CNC-milling machine. The circularity error, machining time, torque and thrust are optimised using grey based Taguchi method.*

Keywords: *Micro-drilling, PMMA, Grey based Taguchi method*

1. INTRODUCTION

Micro-holes are the inherent features in micro-products. Conventional micro-drilling is a stable process for the fabrication of micro-holes. Micro-EDM is another suitable process. But demerit of the process is that it can be applied to only electrically conducting material. Conventional micro-drilling can be applied to any type of material and the quality of hole is better compared to other process. But the disadvantage is the frequent failure of micro-drill bit because of low mechanical strength. So the optimisation of the process parameters is highly essential to reduce the failure of micro-drill bits for different materials. A number of investigations have carried out research in conventional micro-drilling for optimising the process parameters under different working conditions. W. S. Chen [1] has investigated on the wear and performance of micro-drills taking drilling force, torque and drilling wear as judging criteria. Hyon-ko-Sin [2] conducted a study on condition monitoring process on glass by using micro-drilling machine. The drill bits made of diamond and carbide of 0.3 mm diameter are used. A 3D machine vision measurement was used to measure the hole quality and the drill wear was inspected. It was found that positional errors of the fine holes, shapes of cracks and quality of hole surfaces are influenced by drilling conditions. R. Vimal, et al [3] has modelled and analyzed the thrust force and torque in drilling GRPF composites by multifaceted drill-bits using fuzzy logic. In the present investigation, the micro-drilling of PMMA has been carried out in a CNC milling machine. The drilling torque and thrust are measured using a Piezo-electric dynamometer. The circularity error has been measured using Scanning Electron Microscope. Taguchi Method has been used to optimise the process. L_9 orthogonal array has been used to carry out the experiment and the optimisation has been carried out. The feed and cutting speeds are taken as the process parameters. Torque, thrust and circularity error are taken as response criteria. Since, it is a multi-response criteria, Taguchi Method cannot be used alone to optimise the process. Grey-Taguchi Method has been used to optimise the multi-objective criteria. It is observed that the feed is having the most predominant factor.

2. TAGUCHI METHOD

Firstly in the 1950s, Genichi Taguchi, a Tokamachi engineer and statistician developed a methodology for applying statistics for improvement of the quality of manufactured goods. His methodology uses orthogonal arrays from DOE for studying a large number of variables to a small number of experiments. The conclusions which are obtained from experiments are applicable over the entire experimental set crossed by control factors and their conditions of levels. A loss function has to be defined by calculating deviation between experimental value and the value which is required. Then the loss function is to be converted into S/N ratio. Generally, there are three categories for the characteristics of responses in the S/N ratio analysis such as smaller-the-better, nominal-the-best and higher-the-better.

(1) For smaller-the-better

$$\frac{S}{N}\ ratio = -10\log(\frac{1}{n}\sum_{k=1}^{1} X_{ijk}^{2}) \quad (1)$$

Where X_{ijk} is the experimental value of i^{th} performance characteristics in the j^{th} experiment at the k^{th} number of test and n is the total number of runs.

(2) For nominal-the-best

$$\frac{S}{N}\ ratio = 10\log(\frac{X_{ijk}^{2}}{\sigma}) \quad (2)$$

Where $\bar{X}$ and σ are the mean and standard deviation of performance characteristics.

(3) For larger-the-better

$$\frac{S}{N}\ ratio = -10\log(\frac{1}{n}\sum_{k=1}^{1}\frac{1}{X_{ijk}^{2}}) \quad (3)$$

The S/N ratio for each level of process parameters is calculated based on the S/N ratio analysis. This S/N ratio corresponds to the single response optimization and this cannot be applied for multi-response parameters. Hence, to conquer this type of limitation of Taguchi method another modified form of it is considered i.e. Grey based Taguchi method.

3. GREY BASED RALATIONAL ANALYSIS

The grey relational analysis is based on the grey system theory which is used for solving complex interrelationships among the multiple responses very nicely. In this method first normalize all the responses according to three conditions such as

(1)For smaller-the-best

$$N_{ij} = \frac{(X_{ij})max - X_{ij}}{(X_{ij})max - (X_{ij})min} \quad (4)$$

Where N_{ij} = Normalized value after grey relational generation

$(X_{ij})_{max}$ = Maximum value of response parameter

$(X_{ij})_{min}$ = Minimum value of response parameter and

X_{ij} = Value of response in i^{th} column and j^{th} raw of design

(2)For nominal-the-best

$$N_{ij} = \frac{(X_{ij}-X_T)-(X_{ij}-X_T)_{min}}{(X_{ij}-X_T)_{max}-(X_{ij}-X_T)_{min}} \quad (5)$$

Where X_T is the target value of response

(3)For larger-the-better

$$N_{ij} = \frac{X_{ij} - (X_{ij})max}{(X_{ij})max - (X_{ij})min} \quad (6)$$

The calculated value of N_{ij} is in the domain of < 0, 1 > in each case. After this grey relational coefficients value are to be obtained for expressing the relationship between ideal value and the experimented actual value. The grey relational co-efficient can be formulated as

$$\gamma(x_{0j}, X_{ij}) = \frac{\Delta\min + \xi\Delta\max}{\Delta ij + \xi\Delta\max} \quad (7)$$

Where $\Delta ij = |x0j - Xij|$ (8)

= Absolute value of the difference of X_{0j} and X_{ij}, and ξ = Distinguishing coefficient varies from 0 to 1. Here we are taking ξ as 0.5. After determining the grey relational coefficient, we have to take average value of grey coefficients and this average value is called Grey Relational Grade.

$$\Gamma = \frac{1}{n}\sum_{k=1}^{n}\gamma(x_i(k), x_j(k)) \quad (9)$$

Where k= Number of tests

4. INVESTIGATION

In the present investigation, 5mm thicker PMMA sheet was taken into account as a work-piece, having length of 80 mm and breadth of 50 mm. The drill-bit which is applied in this experiment is solid carbide drill-bit which is a type of straight shank twisted drill of 1mm diameter. The point angle and flute length are 118° and 23 mm respectively. The output parameter of torque and thrust force was measured by the arrangement of 9272A type Kistler Co. prepared quartz 4 component dynamometer and 5070A type multi-channelled charge amplifier. And the local circularity error and time are measured by means of JEOL SEM-6480LV machine and stop watch respectively.

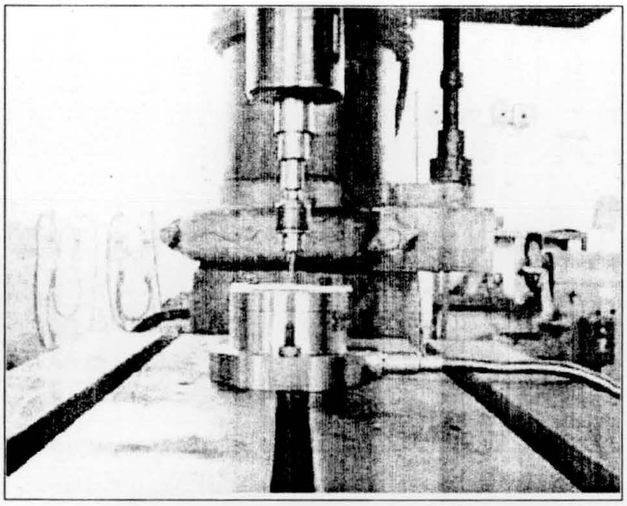

Fig 1. Experimental set up for Drill Bit, Work-piece and Dynamometer

The output parameters of thrust force and torque are measured simultaneously by using the piezoelectric dynamometer. The machining time was recorded by using a stop watch.

5. RESULTS AND DISCUSSION

Table 1: Value of Input Process Parameters

Process parameters	Code	Level (1)	Level (2)	Level (3)
Feed rate (mm/min)	A	20	25	30
Spindle speed (RPM)	B	2000	2500	3000

Table 2: Design.Table

Experimental Run	Standard Run	Feed Rate	Spindle Speed
1	2	25	3000
2	1	25	2500
3	9	20	3000
4	3	30	2000
5	7	25	2000
6	5	20	2000
7	4	30	2500
8	8	20	2500
9	6	30	3000

Table 3: Value of Output Responses

Run order	Torque (Nm)	Minimum	Maximum	Mean (N)	Local Circularity error(μm)	Machining Time (s)
1	0.1	1	4	2.5	50	7.31
2	0.1	1	6	3.5	20	18.50
3	0.1	1	19	10	30	20.30
4	0.1	4	12	8	10	17.16
5	0.1	0	24	12	20	19.17
6	0.1	1	6	3.5	48	23.34
7	0.1	1	6	3.5	30	16.03
8	0.1	1	6	3.5	30	23.52
9	0.1	1	17	9	40	16.52

Table 4: Grey Relational Generations

Run order	Standard order	Torque (Nm)	Mean thrust (N)	Local circularity error (μm)	Machining time (s)
Ideal sequence	Ideal sequence	1	1	1	1
1	2	0	1.0000	0.00	1.0000
2	1	0	0.8947	0.75	0.3097
3	9	0	0.2105	0.50	0.1986
4	3	0	0.4210	1.00	0.3923
5	7	0	0.0000	0.75	0.2683
6	5	0	0.8947	0.05	0.0111
7	4	0	0.8947	0.50	0.4621
8	8	0	0.8947	0.50	0.0000
9	6	0	0.3158	0.25	0.4318

Table 5: Value of Δij (Equation no. 8)

Run order	Torque (Nm)	Mean thrust (N)	Local circularity error (μm)	Machining time (s)
Ideal sequence	1	1	1	1
1	1	0.0000	1.00	0.0000
2	1	0.1053	0.25	0.6903
3	1	0.7895	0.50	0.8014
4	1	0.5790	0.00	0.6077
5	1	1.0000	0.25	0.7317
6	1	0.1053	0.95	0.9889
7	1	0.1053	0.50	0.5379
8	1	0.1053	0.50	1.0000
9	1	0.6842	0.75	0.5682

Table 6: Grey Relational Coefficients

Run order	Standard order	Torque (Nm)	Mean thrust (N)	circularity error (μm)	Machining time (s)
Ideal sequence	Ideal sequence	1	1	1	1
1	2	0.3333	1.0000	0.3333	1.0000
2	1	0.3333	0.8360	0.6667	0.4200
3	9	0.3333	0.3877	0.5000	0.3842
4	3	0.3333	0.4634	1.0000	0.4514
5	7	0.3333	0.3333	0.6667	0.4059
6	5	0.3333	0.8260	0.3448	0.3358
7	4	0.3333	0.8260	0.5000	0.4817
8	8	0.3333	0.8260	0.5000	0.3333
9	6	0.3333	0.4220	0.4000	0.4681

Table 7: Grey Relational Grades

Standard order	Experimental run order	Feed rate (Levels)	Spindle Speed (Levels)	Gray grades
1	6	1	1	0.46997
2	8	1	2	0.49815
3	3	1	3	0.40130
4	5	2	1	0.43480
5	2	2	2	0.56150
6	1	2	3	0.66665
7	4	3	1	0.56202
8	7	3	2	0.53525
9	9	3	3	0.40585

Overall gray relational grade is **0.50394.**

Table 8: Value of S/N ratio and mean

Standard order	Experimental run	S/N ratio	Mean
1	6	6.55860	0.46997
2	8	6.05280	0.49815
3	3	**7.93062**	**0.40130**
4	5	7.23421	0.43480
5	2	5.01300	0.56150
6	1	3.52204	0.66665
7	4	5.00496	0.56202
8	7	5.42887	0.53525
9	9	7.83269	0.40585

Table 9: Prediction Value

Factor levels for Prediction		Predicted S/N value	Predicted Mean value
Feed rate: 20	Spindle speed: 3000	7.21159	0.443797

Table 10: S/N Ratio ANOVA

Source	DOF	Seq. SS	Adj. SS	Adj. MS	F	P
Feed rate	2	3.799	3.799	1.8996	0.63	0.578
Speed	2	1.481	1.481	0.7406	0.25	0.793
Resi-dual Error	4	12.037	12.037	3.0093		
Total	8	17.318				

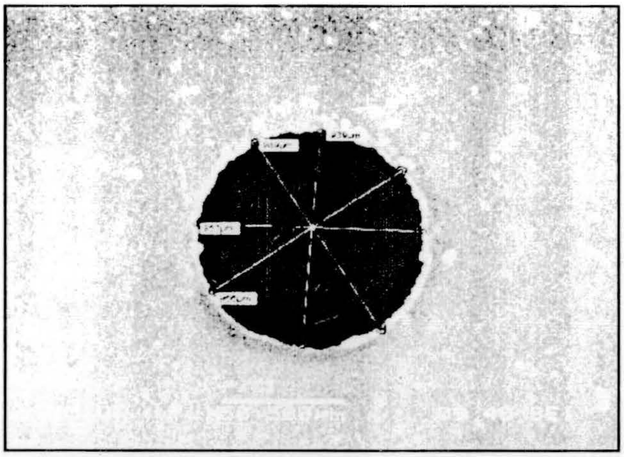

Fig 2. Micro Hole at 25 mm/min and 3000 rpm

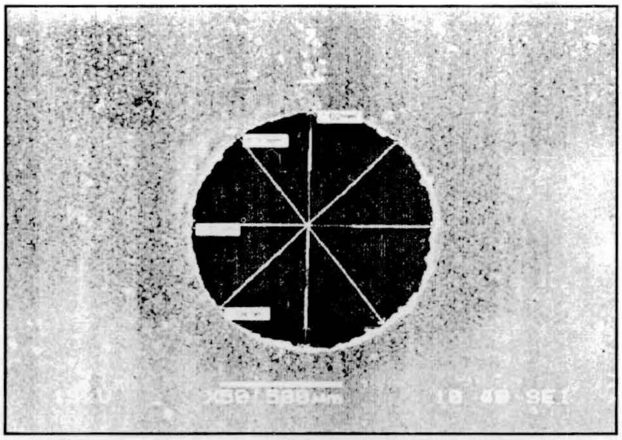

Fig 3. Micro Hole at 25 mm/min and 2500 rpm

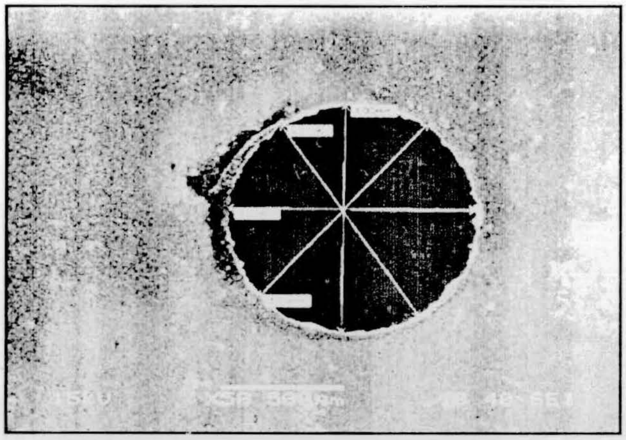

Fig 4. Micro Hole at 20 mm/min and 3000 rpm

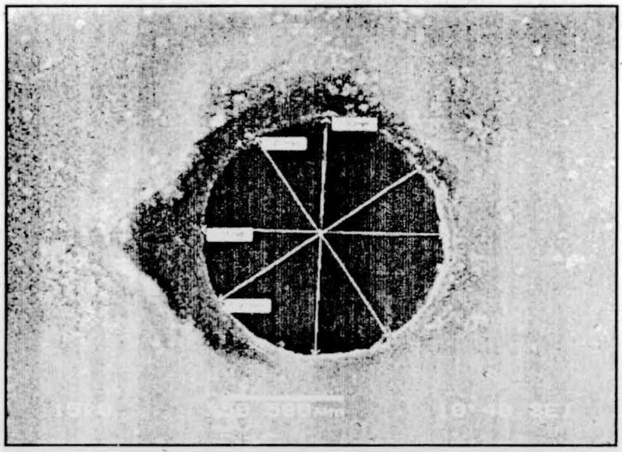

Fig 5. Micro Hole at 30 mm/min and 2000 rpm

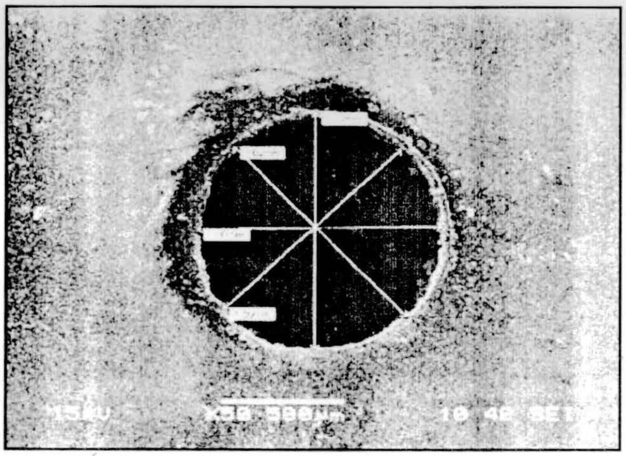

Fig 6. Micro Hole at 25 mm/min and 2000 rpm

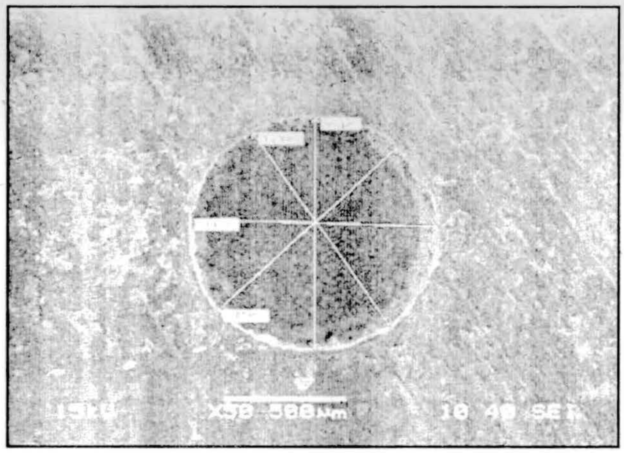

Fig 7. Micro Hole at 20 mm/min and 2000 rpm

From fig. 2 to fig. 11 shows the photographs of micro holes as obtained from scanning electron microscope. The process parameters in micro-drilling are the feed and cutting speed. The step-feed is maintained at a particular value. The process input parameters are given in Table 1. The process parameters are varied in three levels as per L9 Orthogonal array of Taguchi Method (Table 2). Torque, thrust, circularity error and machining time are taken as the response criteria (Table 3). It is indicated in Table 3 that torque value remains constant at 0.1Nm. This is because of low sensitivity of Piezo-electric dynamometer which is meant for conventional machining operation.

The present problem is a multi-objective problem. The optimization cannot be done

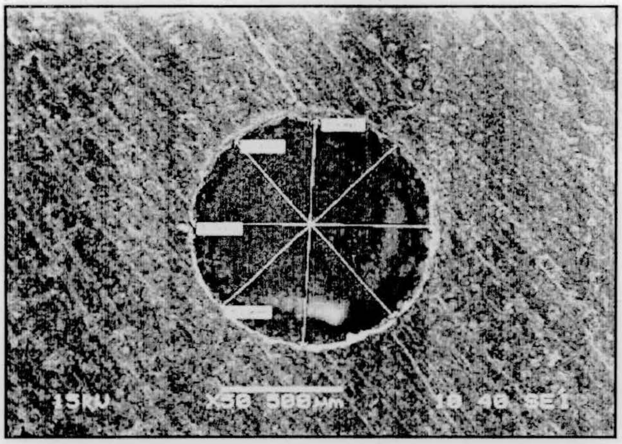

Fig 8. Micro Hole at 30 mm/rev and 2500 rpm

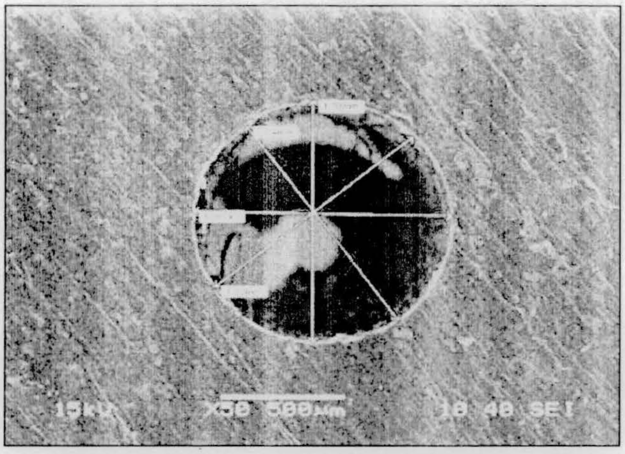

Fig 9. Micro Hole at 20 mm/rev and 2500 rpm

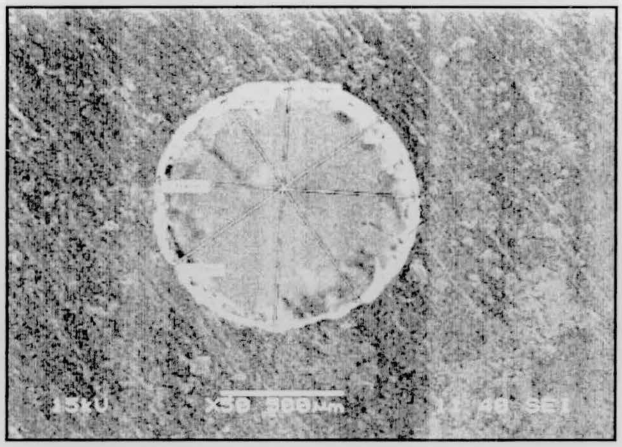

Fig 10. Micro Hole at 30 mm/rev and 3000 rpm

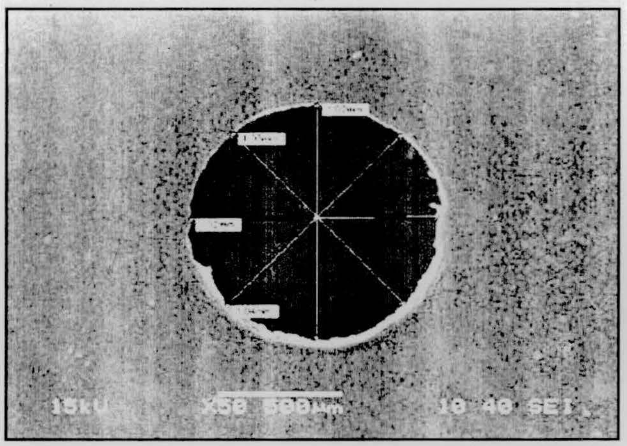

Fig 11. Micro Hole at 18 mm/rev and 2900 rpm

Table 11: Response for S/N Ratio

Level	Feed rate	Spindle speed
1	6.847	6.266
2	5.256	5.498
3	6.089	6.428
Delta	1.591	0.930
Rank	1	2

only by Taguchi Method. In order to optimize multi-objective criteria, Grey Taguchi Method has been used. The Grey relational generation is given in Table 4 as per equation (4). The value of Δ_{ij} is given in equation (8) are tabulated in Table 5. The grey relational co-efficient values are given in Table 6. The grey relational co-efficients are calculated by using equation no. 7. The grey relational grade is given in Table 7. The S/N ratio has been given in Table 8. The predicted values are shown in Table 9 corresponding to spindle revolving

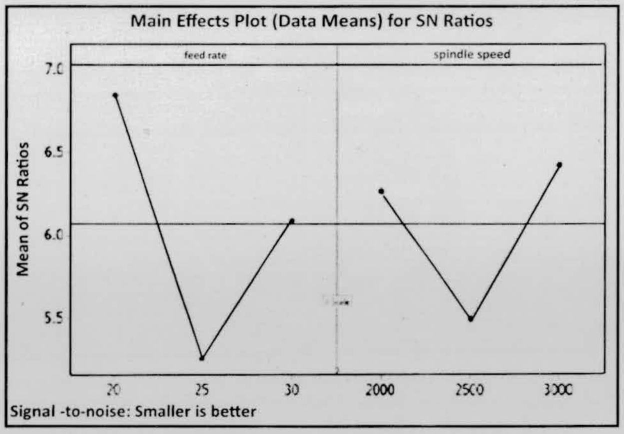

Fig 12. S/N Ratio Plot

300 RPM and feed rate 20 mm/min. Here the response criteria is the smaller the better, since low torque, low thrust, low circularity error and low machining time are desirable. S/N ratio for ANOVA table is given in Table 11. It is evident that the feed is more significant referring to Fig. 12 and Table 11. From the histogram plot of residuals in Fig 13, the values of S/N ratio are forming a parabolic shape and also visible in the range

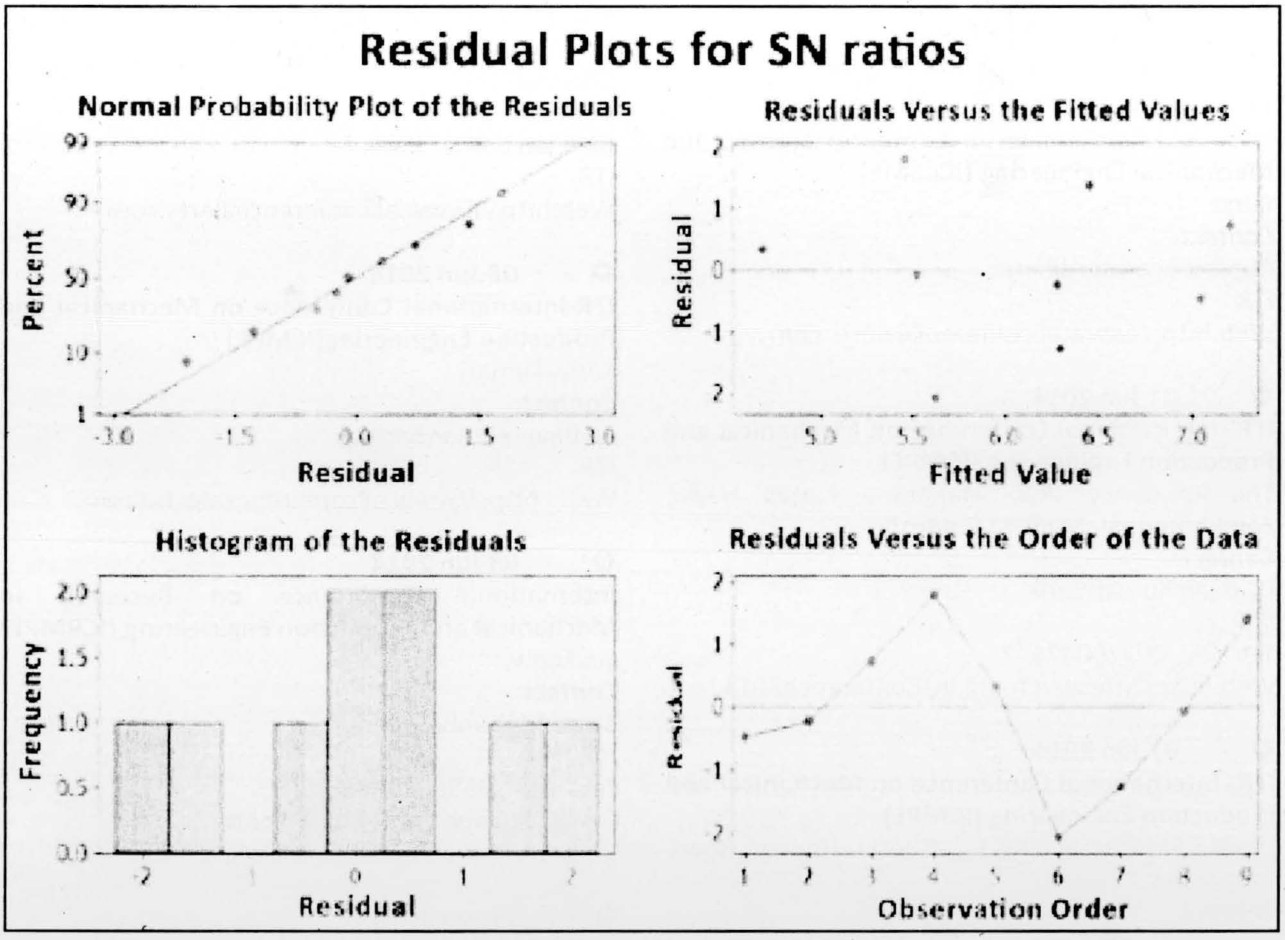

Fig 13. Residual plot for S/N ratio value

of [-2, 2]. Residual plot for S/N ratio are given in Fig 13. Referring to the Fig. 13, it is evident that the experiment is correct and the run no. six is the most significant.

6. CONCLUSION

1) Micro-drilling of PMMA has been carried out by using 1mm carbide drill bit.
2) Grey Taguchi Method has been used to minimize torque, thrust force, circularity error and machining time.
3) Spindle RPM 300 and feed rate 20 mm/min is found to be optimum values.

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