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Optimization of Al6061 Face Milling Process Parameters using Taguchi and Multiresponse Regression Analysis

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Abstract

Context: Now a day's Aluminum and its alloys are used for different modern applications due to its improved mechanical properties like low density, good structural rigidity, etc.

Purpose of the Paper: The purpose of this paper is to identify the optimal setting of machining parameters speed, feed rate and depth of cut on surface roughness (Ra) and material removal rate (MRR) in the face milling process.

Research Methodology: An L27 orthogonal array is used for Face Milling of Al 6061 T6 alloy. The surface roughness (Ra) and MRR are estimated and analyzed using the Taguchi design of experiment method for the identification of optimum controllable parameter combinations. ANOVA is utilized to explore the most significant parameter affecting the surface roughness and MRR. At long last, a Multiresponse regression investigation is performed to study the combined impact of the two responses.

Research Findings: Taguchi S/N ratio examination and ANOVA investigation conclude that feed rate is a significant parameter for surface finish followed by the speed & depth of cut respectively. Again feed rate & depth of cut have an equivalent impact on the S/N ratios of material removal rate and speed does not affect the material removal rate.

Impact on Technology, Industry & Environment: This research will add a new dimension to select the optimum values of parameters for surface finish & material removal rate which reduces the manufacturing time, manufacturing cost as well as increases the quality and productivity of the components. Taguchi method limits the measure of experimentation thus saves time and resources.

Keywords: Al6061; Milling; Surface Roughness; Material Removal Rate; Taguchi; Regression analysis

1. Introduction

1.1 Machining Science:

In present-day of machining industries, the fundamental center is to accomplish high-quality products, in terms of surface finish, dimensional accuracy, ideal cutting conditions, high production rate, less wear on the cutting devices and so forth [Rajesh N. et al. 2017]. There has been increased enthusiasm for observing all parts of the machining procedure. [Sukumar M. S., Venkata Ramaiah P., and Nagarjuna A. 2014].

Manufacturing processes can be optimized by choosing the appropriate composition of the material or process parameters for machining. Surface roughness and material removal rate assumes a significant job in numerous territories and has extraordinary significance in the assessment of machining accuracy in milling. Milling is a machining activity performed to expel the material from the workpiece by a rotating cutter. Generally, machine operators are using trial & error method to set machining conditions, but it is not an effective way to accomplish desirable performance. Milling operation is broadly utilized in numerous items, so it needs to set a systematic approach to obtaining desired surface quality and high material removal rate [Zhang et al. 2007]. Milling is a versatile and well-established manufacturing process for fabricating three-dimensional intricate components and can be classes in various kinds, such as horizontal milling, vertical milling, Slot milling, End milling, and Face milling, etc. Among all milling processes face milling is typically favored for fine machining of bigger surfaces.

1.2 Aluminum alloy Al6061

Aluminum and its alloys are utilized in an assortment of uses, for example, making vehicle and aviation segments, rocket parts, stockpiling compartments, marine applications, storage containers, etc., as a result of its low density, fantastic corrosion resistance, and better thermal and mechanical properties. These metals are easy to machine as compared to other metals. With the addition of various kinds of metals properties of pure aluminum can be enhanced. [Deepak D. and Rajendra B. 2016]. Now a day's Al6061 is one of the most significant and widely used materials in the industries from Al 6xxx series alloys. It is created in 1935 and contains Mg and Si as its major alloying parts [Robert and Sanders 2001]. It is an easily available metal and has good mechanical properties, exhibits good weldability, commonly extruded. It is mostly used in aircraft, automobiles, boats, packaging of food and beverage industries [Johnson J., Bibin K.T, and Sankar A. 2018].

1.3 Taguchi Design of Experiment

Taguchi is a systematic approach to deal with deciding the ideal settings of parameters considered to deliver results with the least variety, which assists with completing a predetermined number of examinations to accomplish exact outcomes [Bhuvanesh D. and Radhika N. 2017]. The excellence of Taguchi configuration is that multiple factors (both control as well as noise factors) can be considered at once. By the utilization of the Taguchi strategy, industries are capable to reduce product development cycle time, therefore reducing expenses and expanding profit. Taguchi configuration considers changeability brought about by noise factors, which are typically disregarded in the traditional DOE approach [Zhang et al. 2007]. Figure 1 shows Steps in Taguchi Methodology.

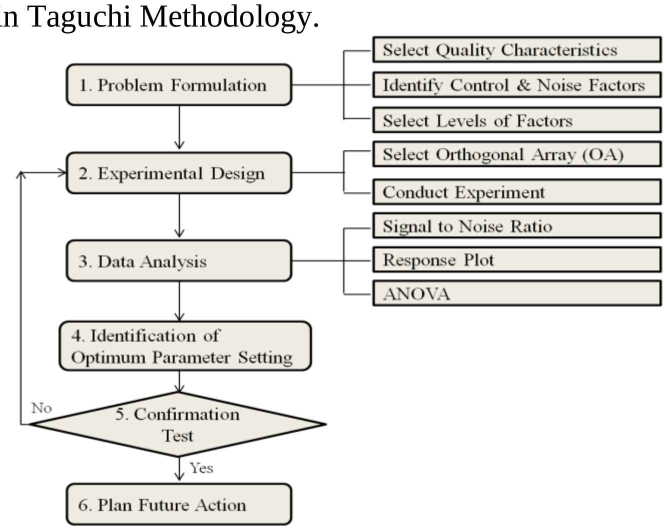

Fig.1. Taguchi Methodology Flowchart

2. Literature Survey

2.1 Optimization of processing parameters using Taguchi method

Nowadays due to industrials rivalry, the utilization of optimization strategies for the right choice of process parameters is amazingly important to stay away from non-esteem included costs. The optimum process parameter setting requires deliberate methodologies [Gaitonde, V. N et al., 2009]. As indicated in literature different conventional methods, for example, geometric programming, goal programming, and dynamic programming have been viably applied to optimize process parameters settings [Dhavamani, C. and Alwarsamy, T. 2011]. Amongst the different strategies, the Taguchi-based methodology has created exceptional and remarkable control that appears differently with customary practices. [Luo M., Liu G., and Chen, M. 2008].

Niranjan D. B. et al. (2017) and Rajendra B., Deepak D. (2016) streamlined Speed, feed rate, and depth of cut in the turning of Al 6061 for surface finish and material removal rate. Kishore et al. (2015) considered the impact of cutting parameters on cutting force and surface unpleasantness performing CNC turning on Al6061- 4 wt% TiC composite.

Wear conduct of hybrid composite was researched by Zakaulla Mohamed, Anwar khan A.R., and Mukunda P.G. (2015). M. Nourani M., Milani A. S. and Yannacopoulos S. (2015), completed the full factorial plan for improvement of the ultimate tensile strength (UTS) of friction stir welded Al 6061 plates. Ugrasen G. et al. (2018) determined the ideal process parameters concerning Ultimate Tensile Strength (UTS) and hardness of the weld joint utilizing the Taguchi technique.

Chandra Kandpal B., Kumar J. and Singh H. (2017) proposed a multi-response improvement strategy utilizing the Taguchi approach and utility idea for electrical discharge machining (EDM) of Al6061/10%Al_2O_3 MMC. Misbah Niamat et al., 2019 enhanced Electrical Discharge Machining parameters for electrode wear rate (EWR) and material ejection rate of Aluminum 6061 T6 Alloy utilizing Taguchi plan of assessment.

Adalarasan R., Santhanakumar M., and Thileepan S. (2016) enhanced lesser cutting parameters using the Taguchi-based response surface method. Thorat S.R. and Thakur A.G. (2018) utilized Grey Relational Analysis (GRA) and Taguchi strategy for the advancement of burnishing process parameters to limit surface roughness and to amplify surface hardness.

2.2 Optimization of processing parameters using other methods

Rajesh N. et al. (2017) created a regression model and solved by using a genetic algorithm to examine the impacts of cutting parameters on Machining responses for turning of Al6061. Priyadarshi D. and Sharma R. (2015) distinguished ideal parameter setting for turning of Al-6061-SiC-Gr Hybrid Nanocomposites by considering Cutting force and roughness as a response parameter utilizing response surface philosophy. Warsi S. S. et al. (2018) performed multiobjective optimization using gray relational analysis, response surface optimization, ANOVA for specific cutting energy, material removal rate, and surface roughness on turning of Al6061. Imhade P. O. et al. (2018) carried out the modeling and optimization of surface roughness using the least square approximation method and response surface methodology.

2.3 Optimization of processing parameters in Milling

Shaik J. H. & Srinivas J (2017); Kumar D., Chandna P., and Pal M. (2017), built up a coordinated framework to demonstrate and improve the processing parameters during end milling of Al 6061. Nghiep T.N., Sarhan A.A.D., and Aoyama H. (2018) examined the mechanism of deflection error, and Tomadi S.H. et al. (2017) introduced the forecast model in the end milling process. Kondayya D. and Gopala Krishna A. (2012) introduced a non-dominated sorting genetic algorithm-II for modeling and multi-objective optimization of the CNC end milling process.

Niknam S. A. and Songmene V. (2013) utilized Taguchi and ANOVA investigation to streamline burr size and surface finish parameters similarly Palanisamy P., Rajendran I., and Shanmugasundaram S. (2007) utilized Genetic Algorithm by considering machining time as a target for slot milling activity. Shinge A. R., and Dabade U. A. (2018), explored the impact of preparing factors in micro-milling of Al 6063 T6 utilizing Taguchi L16 symmetrical array. Lee Seoung Hwan and Lee Sang-Heon (2003) endeavored to obtain ideal cutting conditions for burr minimization in face-processing tasks. Response Surface Methodology (RSM) has been utilized by Premnath A. A. (2015) for finding the ideal machining parameters while milling Al6061/Al2O3/Gr.

Sayuti M., Sarhan A. A. D. and Hamdi M. (2013), upgraded SiO2 nanolubricating parameters in the processing of Al6061-T6 to accomplish right lubrication conditions. Baharudin B.T.H.T et al. (2012) utilized the Taguchi strategy to locate the ideal surface harshness for Al6061 face milling. Sukumar M. S., Venkata Ramaiah P., and Nagarjuna A. (2014) utilize artificial neural network (ANN) model & Taguchi S/N ratio examination for getting the ideal blend of parameters to accomplish a decent surface finish in face milling activity.

3. Research gaps

- Al 6061-T6 is a typical alloy that is utilized in different modern applications for some reason since it has prevalent mechanical properties.
- Very little research is carried out on Al6061 face milling process to optimize the processing parameter setting as well as impact of processing parameters on two responses at a time i.e. surface roughness and material removal rate are not analysed.
- At present, numerous endeavors are being attempted to optimize different processing parameters utilizing the Genetic algorithm, Response surface methodology, regression analysis, neural network, Grey Relational Analysis (GRA), Taguchi strategy, etc.
- In this research, the Taguchi technique and regression investigation are utilized to improve the processing parameter settings.

4. Industry Requirements

In the present date necessity of industry is to make items having high quality at low cost as well as high productivity, less machining, and production time. This paper will fulfill the industries need to deliver excellent items with minimal effort.

5. Problem Definition

Problem definition of under-lying paper is to improve the processing parameters setting, for example, speed, feed rate, and depth of cut on surface roughness (Ra) and material removal rate (MRR) in the face milling process by utilizing Taguchi plan of Experiment & Multiresponse regression analysis.

6. Research Objectives

This paper has the following objectives:

- To study the different machining processes on Al6061 and factors affecting that.
- To identify the factors responsible to achieve better surface finish and high material removal rate in face milling process.
- To optimize processing parameters setting by using the Taguchi design of an experiment & Multiresponse regression modelling.

7. Research Methodology

This research work investigated the optimum setting of machining parameters (speed, feed rate, and depth of cut) in face milling of Al6061-T6 alloy to accomplish the minimal surface roughness and high material removal rate utilizing Taguchi plan of an experiment. Experimentation is done according to the L27 orthogonal array with 03 control factors and 03 levels for each factor. Further examination is completed using signal-to-noise (S/N) ratio investigation and analysis of variance (ANOVA), to figure out which process parameters are significant. At long last, a confirmation test is done to examine the improvement in optimization. Finally, a Multiresponse regression examination is performed to study the combined impact of the two responses.

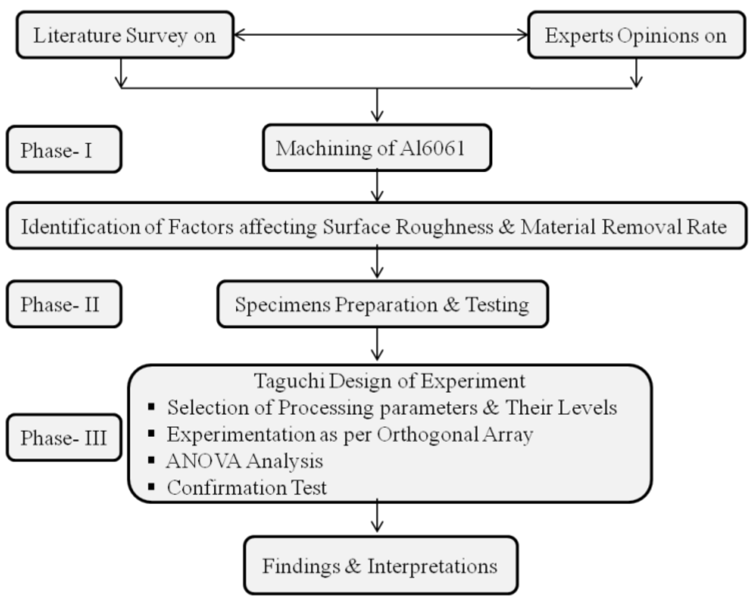

Fig.2. Research Methodology Flowchart

8. Experimental Work

8.1 Material

In this paper blocks of Al 6061 T6 alloy with size 50mm*60mm*50mm are used for experimentation. The chemical composition of the Al 6061 T6 alloy is given in Table 1.

Table 1. Chemical Composition of Al6061 T6 alloy

Elements	Cr	Fe	Si	Mg	Mn	Cu	Zn	Ti	Al
Percentages	0.1	0.35	0.5	0.08	0.04	0.28	0.02	0.01	Balance

8.2 Machining Parameters

Cutting Speed (v), Feed rate (f) & depth of cut (d) are chosen as input parameters similarly Surface roughness & Material removal rate are chosen as output factors for the examination. According to suggestions of the cutting instrument maker and the limit of the machine device the levels of these input parameters were chosen as appeared in Table 2.

Table 2. Levels of Input Parameters used in this study

Input Parameters	**Level 1**	**Level 2**	**Level 3**
Spindle speed (RPM)	1000	1500	2000
Feed rate (mm/min)	200	400	600
Depth of cut (mm)	0.4	0.8	1.2

8.3 Experimental Setup & Procedure

For performing face milling a Cosmos 05-axis vertical milling machine with a rotational speed of 8000 rpm and motor power of 11 kW was utilized as appeared in figure 3. A carbide face milling cutter having diameter 63mm, 05 inserts, sixteen cutting edges for each insert manufactured by Tungaloy have been used as cutting tools as shown in figure 4. The impact of the selected milling input parameters on output factors and ideal settings of the parameters have been practiced utilizingTaguchi's L27 orthogonal array. Table 3 shows the experimental plan and corresponding results.

Fig. 3. Setup of Vertical Milling Machine

Fig.4. Face Milling Cutter

8.4 Measurement of Output Factors

Surface roughness (Ra) is estimated by surface roughness analyzer SRT-6210 as shown in figure 5. Three readings for surface roughness were taken for every surface and its average is considered as a final value, to minimize the error. Material Removal Rate (MRR) is determined with the help of formula, [Material Removal Rate = Width of cut (mm) * Depth of cut (mm) * Feed Rate (mm/min)].

Fig.5: Surface Roughness Tester

Table 3. Experimental structure utilizing L27 orthogonal array and the values of the responses

Exp. No.	**Cutting Speed (RPM)**	**Feed Rate (mm/min)**	**Depth of cut (mm)**	**Ra (µm)**	**MRR (mm3/min) as per formula, MRR=D*W*Feed Rate**
1	1	1	1	0.7171	4800
2	1	1	2	0.1467	9600
3	1	1	3	1.4914	14400
4	1	2	1	0.4986	9600
5	1	2	2	1.1361	19200
6	1	2	3	1.4067	28800
7	1	3	1	0.1732	14400
8	1	3	2	0.9563	28800
9	1	3	3	0.1204	43200
10	2	1	1	0.1410	4800

11	2	1	2	0.1041	9600
12	2	1	3	1.1743	14400
13	2	2	1	0.8790	9600
14	2	2	2	1.3433	19200
15	2	2	3	1.3724	28800
16	2	3	1	1.2459	14400
17	2	3	2	0.5318	28800
18	2	3	3	0.6197	43200
19	3	1	1	0.4168	4800
20	3	1	2	0.5254	9600
21	3	1	3	2.7791	14400
22	3	2	1	2.5312	9600
23	3	2	2	2.6895	19200
24	3	2	3	1.0672	28800
25	3	3	1	0.3263	14400
26	3	3	2	1.0002	28800
27	3	3	3	0.1673	43200

Analysis of experimental data of surface finish (Ra) and Material Removal Rate (MRR) is finished by utilizing the Taguchi plan in Minitab-19 software and the estimated S/N ratio values. In Taguchi, higher values of the S/N ratio are desirable which demonstrates the best quality. From Figure 6 it can be seen that as spindle speed and depth of cut increases, surface roughness value decreases while feed rate decreases at first up to 400 mm/min, over that it is increases. Smaller the better characteristics were utilized to decide the surface finish. Table 4 shows that speed at position 1, feed rate at position 3, and depth of cut at position 1 are the best estimations of parameters for surface quality. In table 4, position 1, position 2 and position 3 are given to feed rate, cutting speed and depth of cut respectively which demonstrates that, the feed rate is having a most elevated effect on the S/N proportions of surface finish because of its delta worth and rank and later this is followed by the cutting speed & depth of cut respectively. Table 5 shows that speed at 1000rpm, feed rate at 600mm/min, and depth of cut at 0.4mm are ideal values of parameters for surface roughness.

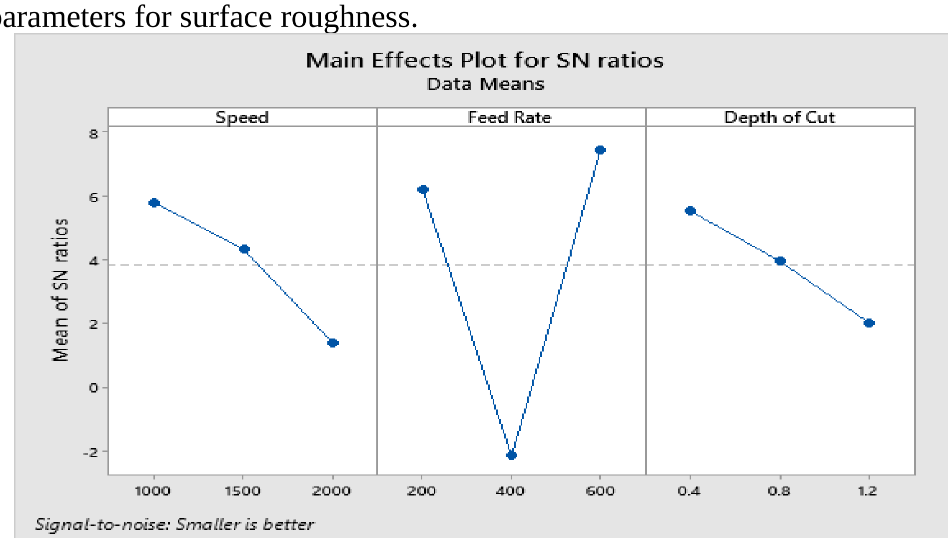

Fig.6. Main Effect Plot of S/N ratios for Surface Roughness

Table 4. Surface Roughness S/N ratio for each level of control parameters

Level	Speed (Rpm)	Feed Rate (mm/min)	Depth of Cut (mm)
1	**5.785**	6.186	**5.517**
2	4.312	-2.161	3.947
3	1.371	**7.443**	2.005
Delta	4.413	9.603	3.512
Rank	2	1	3

Table 5. Optimum Control Parameter Values for Surface Roughness S/N Ratio Analysis

Sr. No.	Parameters	Optimum Value
1	Speed (Rpm)	1000
2	Feed Rate (mm/min)	600
3	Depth of Cut (mm)	0.4

Larger the better characteristics was utilized to determine the material removal rate. From Figure 7 it can be seen that as Feed rate and depth of cut increases MRR increases whereas MRR is consistent for all values of speed. Table 6 shows that feed rate and depth of cut at level 3 are the best values of cutting parameters for MRR. From table 6, feed rate and depth of a cut have an equivalent impact on the S/N proportions of MRR because of its delta worth and rank. Cutting speed has no impact on the material removal rate. Table 7 concludes that any value of speed, feed rate at 600mm/min, and cutting depth at 1.2mm are the ideal values of processing parameters for MRR.

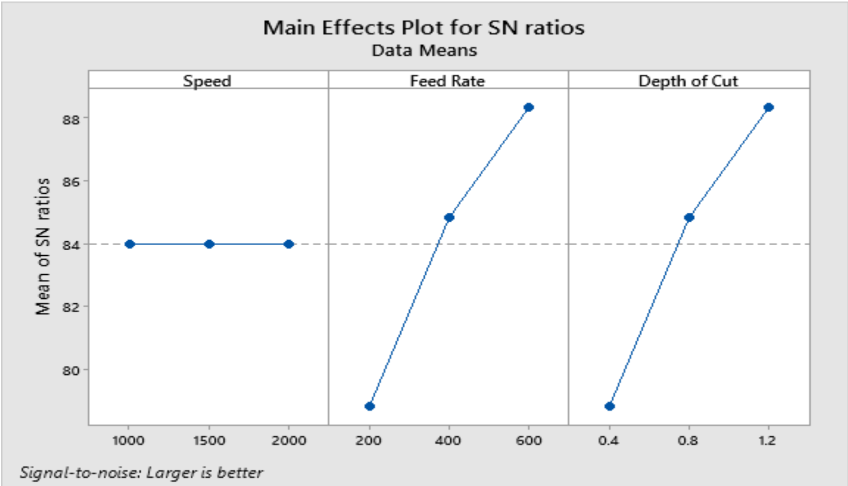

Fig.7. Main Effect Plot of S/N ratios for Material Removal Rate

Table 6. Material Removal Rate S/N ratio for each level of control parameters

Level	Speed (Rpm)	Feed Rate (mm/min)	Depth of Cut (mm)
1	84.00	78.81	78.81
2	84.00	84.83	84.83
3	84.00	**88.35**	**88.35**
Delta	0.00	9.54	9.54
Rank	3	1.5	1.5

Table 7. Optimum Control Parameter Values for Material Removal Rate S/N Ratio Analysis

Sr. No.	Parameters	Optimum Value
1	Speed (Rpm)	Any Value
2	Feed Rate (mm/min)	600
3	Depth of Cut (mm)	1.2

9. Analysis of Variance (ANOVA)

ANOVA is performed on the surface roughness and Material Removal Rate to explore the impact of process parameters.

Table 8. ANOVA table for Surface Roughness

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Speed	2	1.5153	0.7576	1.58	0.230
Feed Rate	2	3.5400	1.7700	3.70	0.043
Depth of Cut	2	0.5951	0.2976	0.62	0.547
Error	20	9.5648	0.4782		
Total	26	15.2152			

From the F value shown in Table 8, it is clear that the commitment of Feed Rate is high for the surface roughness and later this was followed by cutting speed and depth of cut respectively. P-estimation of feed rate is under 0.05, so this parameter is noteworthy to get the best quality surface while the P-estimation of other parameters is more prominent than 0.05, so these are not critical.

Table 9: ANOVA table for Material Removal Rate

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Speed	2	0	0	0.00	1.000
Feed Rate	2	1658880000	829440000	60.00	0.000
Depth of Cut	2	1658880000	829440000	60.00	0.000
Error	20	276480000	13824000		
Total	26	3594240000			

From Table 9 it is clear that for material removal rate, the involvement of feed rate & cutting depth is large, and cutting speed has no impact on it. P-value of feed rate & depth of cut is under 0.05, so these parameters are significant to get the high material removal rate while the P-value of cutting speed is more noteworthy than 0.05, so this is not critical.

10. Confirmation Test

In this paper optimal combination of parameters and their levels coincidently coordinate with one of the investigations in the orthogonal array (OA), in this manner confirmation test isn't required.

11. Multiresponse Regression Analysis

After analyzing the effect of machining parameters on a single response individually, Multiresponse Regression Analysis is carried out, for this purpose Response Optimizer is utilized to recognize the combined impact of input variables on a single or a many output factors and draws an optimization plot. Response optimizer also permits the statistician to perform sensitivity investigation and enhancement in the previous solution.

While performing the analysis and interpreting the result utilizing a response optimizer, make ensure that stored models should meet the assumptions of the main investigation and setting of variables should be inside the scope of the information that you used to fit the model.

Table 10. Responses and its Boundary conditions for Multiresponse Regression Analysis

Response	Goal	Lower	Target	Upper	Weight	Importance
Material Removal Rate	Maximum	4800	43200.0	43200	1	1
Surface Roughness	Minimum	0.1	0.1	2.7791	1	1

Table 10 demonstrated that the objective for Material Removal Rate is to expand it and the objective for Surface Roughness is to limit it. Target value, upper and lower cutoff points, weight, and importance for both responses are also shown in table 10. The weight decides the distribution of desirability on the interval between the lower (or upper) limit and the objective. The importance decides the impact of each response on the composite desirability. The values of weight & importance are considered from 0.1 to 10 which depict the shape of the desirability function and comparative significance of the response variable respectively. As per the significance of the one response over another, importance values are to be assigned. Higher values related to the most significant responses, lower values to less significant responses. Here both responses have the same importance value. Accordingly, both responses have an equivalent effect on the composite desirability.

Table 11. Multiple Response Prediction Table

Solution	Speed	Feed Rate	Depth of Cut	Material Removal Rate Fit	Surface Roughness Fit	Composite Desirability
1	1000	600	1.2	38400	0.727724	0.819154

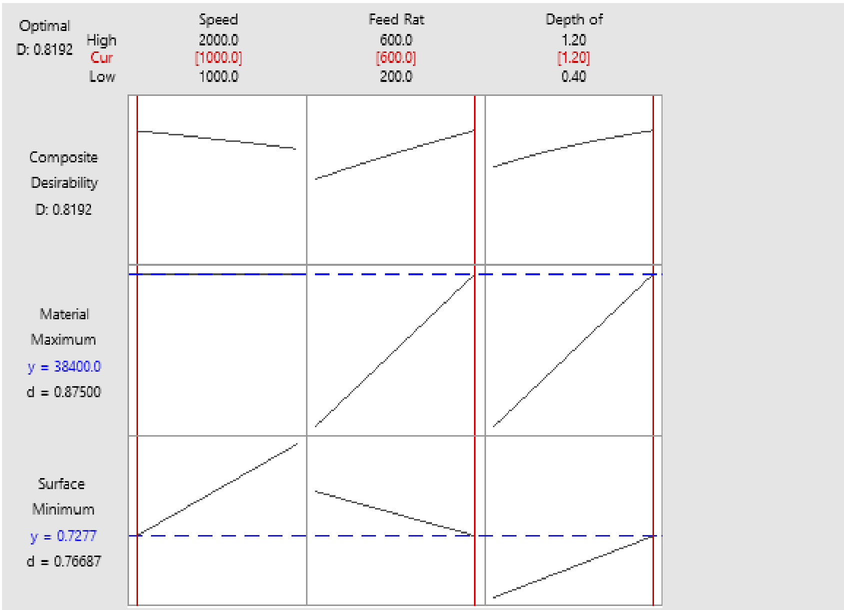

Fig. 8. Optimization Plot of Individual & Composite Desirability for Surface Roughness and Material Removal Rate

The optimization plot shows the impact of all three input factors on the output parameters or composite desirability. The Individual and composite desirability survey how well a blend of factors fulfils the objectives of the output factors. Optimized parameter settings of one and more than those responses are assessed by individual and composite desirability respectively. The value of desirability lies between 0 and 1. One indicates the perfect case; zero demonstrates that some responses are not lies within their adequate cut off points. An engineer can adjust the values of parameters from the plot to accomplish bigger individual desirability for the response as per the requirement.

Here, the composite desirability (0.8192) is near to 1, which shows the settings appear to accomplish good outcomes for all responses in general. However, the individual desirability indicates that the settings are more effective at maximizing MRR (0.87500) than at minimizing Surface roughness (0.76687). The present variable settings are speed = 1000 rpm, Feed rate =600 mm/min, depth of cut =1.2 mm.

Perceptions from the above optimization plot are as per the following:

1. Speed: Optimization plot shows that MRR is independent on speed and as speed increases Ra increases.
2. Feed rate: As Feed rate increases MRR increases and Ra decreases.
3. Depth of cut: As Depth of cut increases values of both responses are increases.

12. Conclusion

This research is governed by the Taguchi Method to identify the optimal set of parameters such as cutting speed, feed rate, and depth of cut on surface quality and material removal rate in the face milling process. From Taguchi S/N proportion investigation it can conclude that speed at 1000 Rpm, Feed Rate at 600 mm/min and Depth of Cut at 0.4mm are the ideal parameter setting for better surface roughness and any value of speed, Feed Rate at 600 mm/min and Depth of Cut at 1.2mm are the optimum parameter setting for material removal rate.

ANOVA examination is recognized that the commitment of feed rate is high on the surface finish then by speed and depth of cut respectively. On account of material removal rate the feed rate & depth of cut both are similarly contributed and cutting speed doesn't have any impact on MRR.

Multiresponse regression analysis conclude that speed at 1000 rpm, Feed rate at 600 mm/min, depth of cut at 1.2 mm are the optimum parameter setting for Multiresponse investigation.

13. Limitations and Future Scope

This research is restricted to optimize a couple of parameters including two response factors only. In future tool wear rate, tool life, cutting forces, energy consumption, etc. can be considered as a response factor, also tool material, type of work piece material, type of coolants, coolant flow rate, tool geometry, machine condition, operator skill, environmental condition, costing, etc. can be considered as processing parameters. At the same time, validation, and multiple objectives can likewise be accomplished by utilizing other techniques such as Genetic algorithm, neural network, etc.

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