Available online at www.elixirpublishers.com (Elixir International Journal)

Mechanical Engineering

Elixir Mech. Engg. 45 (2012) 7831-7839

ISSN: 2229-712X

Optimization study on drilling of al-6061 with coated tools under MQL condition using hybrid approach

G.Vijaya Kumar and P.Venkataramaiah

Department of Mechanical Engineering, S V University College of Engineering, Tirupati, Andhra Pradesh, India.

ARTICLE INFO

Article history:

Received: 27 February 2012;

Received in revised form:

25 March 2012;

Accepted: 10 April 2012;

Keywords

Drilling, Design of experiments,

Taguchi,

Grey,

Fuzzy logics,

Controllable parameters,

Optimal combination.

ABSTRACT

In this paper, a Hybrid approach has been developed by combining Taguchi Method, grey relational analysis method and fuzzy logic, to reap their advantages in the drilling process. Using hybrid approach a single hybrid grade is determined for multiple response characteristics. Drilling experiments has been performed on Al6061 material with coated and uncoated HSS tools under Minimum Quantity Lubrication (MQL) condition. The controllable parameters such as speed, feed, lubricant, tool material and point angle which influence the responses like power, temperature, Burr height, surface roughness are identified. The responses are analyzed using this hybrid approach and optimum controllable parameter combination is identified.

Introduction

Taguchi method analyzes the influence of parameter variation on response characteristics. Thereby, and an optimal result can be obtained from the sensitivity analysis respect to parameter variation[1, 2]. Several researchers have successfully applied this method for analyzing the drilling of metals, composites and metal matrix materials[3-5]. However, Taguchi method has shown some defects in dealing with the problems of multiple performance characteristics [6-10]. The grey system theory proposed by Deng [11] has been proven to be useful for dealing with poor, insufficient, and uncertain information. The grey relational theory is more useful for solving the complicated inter-relationships among multiple performance characteristics [12, 13] like Multi response optimization of drilling parameters of Al/SiC metal matrix composite and EDM process, to Determination of optimum parameters for multi-performance characteristics[14, 15]. The theory of fuzzy logics, initiated by Zadeh, has proven to be useful for dealing the uncertain and vague information [16].

The definition of performance characteristics used for this research such as lower-the-better, higher-the-better, and nominal-the-better contains a certain degree of uncertainty and vagueness. Hence, fuzzy logics can be a proper basis to perform the optimization process [17-19].

The cutting conditions which influence the machining process are coolant, tool type, speed, feed, depth of cut. Among those, coolant is an important factor largely affects the machining process. The modern industries are therefore looking for a cooling system to provide dry (near dry), clean, neat and pollution free machining . Minimum Quantity Lubrication (MQL) refers to the use of cutting fluids of only a minute amount-typically of a flow rate of 50-500 ml/hour which is about three to four orders of magnitude lower than the amount commonly used in flood cooling, for example, up to 10 liters of fluid can be dispensed per minute. The concept of MQL, sometimes referred to as 'near dry lubrication' or 'micro lubrication' Machining under minimum quantity lubrication (MQL) condition is perceived to yield favorable machining performance over dry or flood cooling condition [20, 21]. Coatings on drill tools also play an important role to improve multi performance characteristics like Burr height, Surface roughness, etc. [22, 23].

The literature reveals that there is need of a systematic approach for analyzing the multi-response machining processes and identification of optimum combination of controllable parameters.

In this view, the present paper focused on development of a systematic approach by combining the grey-relational theory with fuzzy logic for analyzing of multiple performance characteristics in Drilling of Al6061 material under different conditions like MQL, coated tools, etc.

Experimental Work

Work material

In this paper drilling operation is performed on Al-6061, which is used in various applications like aircraft parts, ship building, automobile parts, etc. The composition and mechanical properties of this material is given in the table 1 & table 2

Experimental design and drilling of work material

Drilling tests have been performed on Al6061 work material using radial drilling machine(figure1) with HSS, TIN and TIAlN coated HSS tools under MQL environment by considering different speed –feed, cutting fluid combination. The parameters such as power requirement, temperature, burr height, surface roughness are selected as indexes to evaluate cutting performance in drilling. Therefore these are considered as response characteristics in this study. Basically power, temperature, burr height and surface roughness should be low in drilling process for the better cutting performance (lower the better).

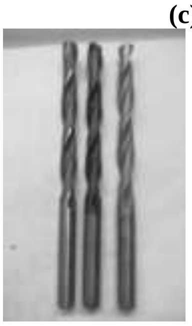
Tele:

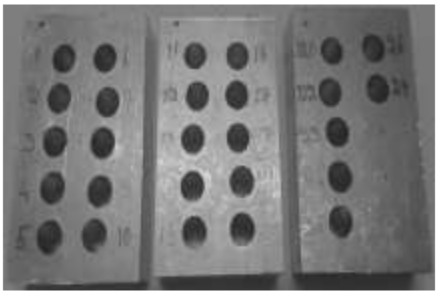
E-mail addresses: vijayluther2003@yahoo.co.in, pvramaiah@gmail.com

(a).drilling machine

(b).tool dynamometer

(c). Talysurf surface meter





(d).Drill bits **(e).drilled Al-6061 pieces**

Figure 1. Experimental setup and drilled work pieces

In this experiment five controllable parameters are considered and each parameter is set at three levels. The parameters and its levels are shown in Table 3. For full factorial design, the experimental runs required are $(\text{levels})^{(\text{factors})}$ equal to 3^5=243. To minimize the experimental cost, fractional factorial design is chosen, ie.3^{5-2}=27 runs. Therefore Taguchi experimental design L_{27} chosen for conducting experiments (Table 4). Experiments are performed according to this design and the values of power required, temperature, burr height and surface roughness are recorded (Table5).

Steps in hybrid approach

In this approach the advantages of Taguchi technique, Grey Relational analysis, and fuzzy logics are utilized by combining them. The steps in hybrid approach are as follows.

3.1 Step-I: Calculation of S/N ratios

S/N ratios for the corresponding responses are calculated for different cases according to the required quality characteristics as follows.

i) Larger - the – better

$$\frac{S}{N} Ratio(\eta) = -10 log_{10} \left(\frac{1}{n}\right) \sum_{1}^{n} \frac{1}{y_{ij}^2} \quad \text{--------- 1}$$

ii) Smaller - the – better

$$\frac{S}{N} Ratio(\eta) = -10 log_{10} \left(\frac{1}{n}\right) \sum_{1}^{n} y_{ij}^2 \quad \text{---------- 2}$$

Where n=number of replications, y_{ij} = Observed response value where i=1, 2 ...n; j=1,2...k Larger the better is applied for problem where maximization of the quality characteristic is sought and smaller the better is applied where minimization of quality characteristic is sought. For the present problem, smaller the better is applicable. Hence, its S/N ratios are calculated using Eq2.

Step II: Pre-processing of S/N ratios

Data pre-processing is required where the range and unit in one data sequence may differ from the others. In data pre-processing, the original sequence is transformed to a comparable sequence. Depending on the quality characteristic of a data sequence, there are various methodologies of data pre-processing available for the grey relational analysis.

For quality characteristic of the “larger – the - better”, the original sequence can be normalized as

$$x^{*}_{i}(k) = \frac{x^{o}_{i}(k) - \min x^{o}_{i}(k)}{\max x^{o}_{i}(k) - \min x^{o}_{i}(k)} \quad \text{---------- 3}$$

for the “smaller – the - better” is a characteristic of the original sequence, then the original sequence can be normalized as

$$x^{*}_{i}(k) = \frac{\max x^{o}_{i}(k) - x^{o}_{i}(k)}{\max x^{o}_{i}(k) - \min x^{o}_{i}(k)} \quad \text{---------- 4}$$

Where i = 1…, m; k = 1…, n. m is the number of experimental data items and n is the number of parameters. $x^{o}_{i}(k)$ Denotes the original sequence, $x^{*}_{i}(k)$ the sequence after the data pre-processing, max $x^{o}_{i}(k)$ the largest value of $x^{o}_{i}(k)$, min $x^{o}_{i}(k)$ the smallest value of $x^{o}_{i}(k)$, and x^{o} is the desired value. In this problem smaller the better is applicable and its S/N ratios are pre processed using Eq.4 as shown in Table7.

Step III: Determine the grey relational coefficient

In grey relational analysis, the measure of the relevancy between two systems or two sequences is defined as the grey relational grade. After data pre-processing, the grey relation coefficient $\xi_i(k)$ for the k^{th} performance characteristics in the i^{th} experiment can be determined using the Eq.5

$$\xi_i(k) = \frac{\Delta_{\min} + \zeta \Delta_{\max}}{\Delta_{oi}(k) + \zeta \Delta_{\max}} \quad \text{---------- 5}$$

Where, Δ_{oi} is the deviation sequence of the reference sequence and the comparability sequence.

$$\Delta_{oi} = \| x^*_o(k) - x^*_i(k) \|$$

$$\Delta_{\min} = \min_{\forall j \in i} \min_{\forall k} \| x^*_o(k) - x^*_j(k) \|$$

$$\Delta_{\max} = \max_{\forall j \in i} \max_{\forall k} \| x^*_o(k) - x^*_j(k) \|$$

$x^*_o(k)$ denotes the reference sequence and $x^*_i(k)$ denotes the comparability sequence. ζ is distinguishing or identification coefficient and its value is between '0' and '1'. The value may be adjusted based on the actual system requirements. A value of ζ *is* the smaller and the distinguished ability is the larger. $\zeta = 0.5$ is generally used. The Grey Relational coefficients of power, Temperature, Burr Height and surface roughness are shown in the Table.8

Step IV: Determination of Hybrid grade

A fuzzy logic unit comprises a fuzzifier, membership functions, a fuzzy rule base, an inference engine and a defuzzifier. In the fuzzy logic analysis, the fuzzifier uses membership functions to fuzzify the grey relational coefficient first. Next, the inference engine performs a fuzzy reasoning on fuzzy rules to generate a fuzzy value. Finally, the defuzzifier converts the fuzzy value into a Hybrid grade. The structure built for this study is a four input- one-output fuzzy logic unit as shown in Fig. 2. The function of the fuzzifier is to convert outside crisp sets of input data into proper linguistic fuzzy sets of information. The input variables of the fuzzy logic system in this study are the grey relational coefficients for

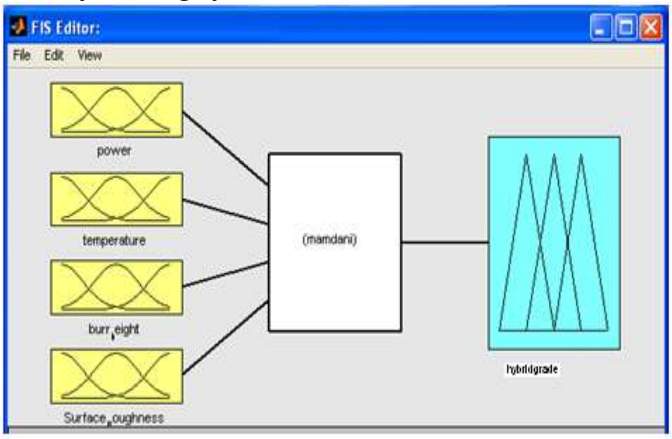


Figure 2. **Four input- one-output fuzzy logic unit**

Power, Temperature, Burr Height, Surface Roughness. They are converted into linguistic fuzzy subsets using membership functions of a triangle form, as shown in Fig. 3, and are uniformly assigned into three fuzzy subsets—small (S), medium (M), and large (L) grade. The fuzzy rule base consists of a group of if-then control rules to express the inference relationship between input and output. A typical linguistic fuzzy rule called Mamdani is described as

Rule 1: if x1 is A1, x2 is B1 ,x3 is C1 andx4 is D1 then y is E1 else

Rule 2: if x1 is A2 , x2 is B2 ,x3 is C2 andx4 is D2 then y is E2 else

………………………………………………………………..

…………………………………………………………………

Rule n: if x1 is An , x2 is Bn ,x3 is Cn andx4 is Dn then y is En else

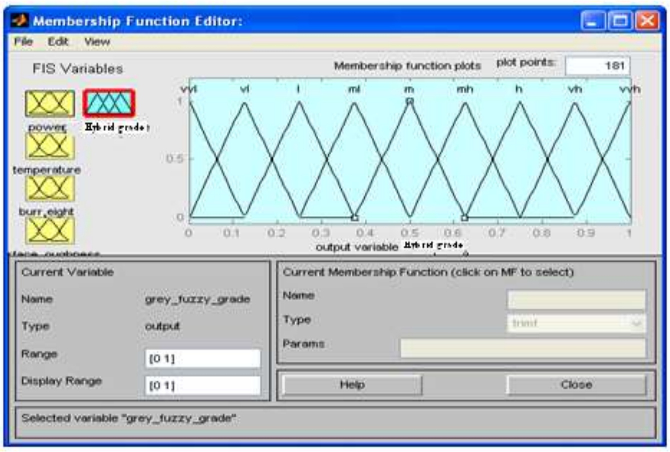


Figure 3 Membership functions for Power, Temperature, Burr Height, Surface Roughness

In above Ai, Bi, Ci and Di are fuzzy subsets defined by the Corresponding membership functions i.e., α/4Ai, α /4Bi, α /4Ci, and α /4Di. The output variable is the Hybrid grade yo, and also converted into linguistic fuzzy subsets using membership functions of a triangle form, as shown in Fig. 4.

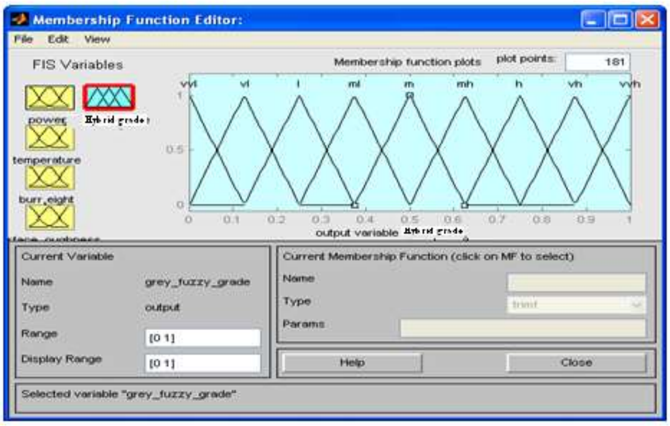


Figure 4. Membership function for Hybrid Grade

Unlike the input variables, the output variable is assigned into relatively nine subsets i.e., very very low (VVL), very low (VL), small(S)medium low(ML),medium (M), medium high(MH) high(H), very high (VH), very very high(VVH) Then, considering the conformity of four performance characteristics for input variables, 81 fuzzy rules are defined and listed in Table 9. The fuzzy inference engine is the kernel of a fuzzy system. It can solve a problem by simulating the thinking and decision pattern of human being using approximate or fuzzy reasoning. In this paper, the max-min compositional operation of Mamdani is adopted to perform calculation of fuzzy reasoning. Suppose that x1, x2, x3 and x4 are the input variables of the fuzzy logic system,the membership function of the output of fuzzy reasoning can be expressed as

$$\mu_{C_0}(y) = \left(\mu_{A_1}(x_1) \Lambda \mu_{B_1}(x_2) \Lambda \ \mu_{C_1}(x_3) \Lambda \mu_{D_1}(x_4) \Lambda \ \mu_{E_1}(y)\right) \vee \ldots \left(\mu_{A_n}(x_1) \Lambda \mu_{B_n}(x_2) \Lambda \ \mu_{C_n}(x_3) \Lambda \mu_{D_n}(x_4) \Lambda \ \mu_{E_n}(y)\right)$$

Where V is the minimum operation and Λ is the maximum operation. Hybrid Grade is shown in the Table 10.

Results from the hybrid approach

After determining the hybrid grade (Table.10.), the effect of each cutting parameter is separated based on Hybrid grade at different levels. The mean values of Hybrid grade for each level of the controllable parameters and the effect of parameter on multi responses in rank wise are summarized in Table 11. Basically, large Hybrid grade means it is close to the product quality, thus, a higher value of the Hybrid grade is desirable. From the Table 11, the cutting parameters with the best level are spindle speed at level 3 (*i.e.* 630 rpm), feed at level 3 (*i.e.* 0.3 mm/rev), lubricant at level 1 (*i.e.* diesel), tool material at level 1 (*i.e.* HSS) and point angle at level 2 (*i.e.* 118). The optimal level for the controllable parameters obtained from this methodology is verified. The experiments are conducted for initial and optimal conditions of controllable parameters and responses are recorded as in Table 12.

Conclusions:

In this paper, the developed method has been applied effectively for optimizing the controllable parameters in drilling of Al6061. The results revealed that the proposed method provides a systematic and effective methodology for optimizing the cutting parameters. The confirmation test proved that the performance characteristics of the drilling process such as power, temperature, burr height, and surface roughness are minimized simultaneously through the use of optimal combination of the controllable parameters obtained from the proposed method, which in turn reduce manufacturing cost and greatly enhance manufacturing efficiency. This method can be also used for other process while machining different materials.

Acknowledgements

The authors would like to acknowledge the technical staff of mechanical engineering department of SVUCE, Tirupati, for their help in conducting the experiments

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Table1. The alloy composition of Al6061

Aluminum	95.85%-98.56%
Chromium	0.04 - 0.35
Copper	0.15 - 0.4
Iron	0 - 0.7
Magnesium	0.8 - 1.2
Manganese	0.15 max
Other	0.15 max
Remainder Each	0.05 max
Silicon	0.4 - 0.8
Titanium	0.15 max
Zinc	0.25 max

Table2. Mechanical and Physical Properties of Al-6061

Poisson's ratio	0.33
Elastic modulus (Gpa)	70-80
Brinell Hardness Number (BHN, 500kg load, 10mm ball)	30-33
Density(g/cm^3)	2.7
Ultimate Tensile Strength (MPa)	110-152
Yield strength (MPa)	55 MPa
Elongation (%)	14-16
Impact strength (J)	65-110

Table 3. Process Parameters and their levels

Parameter	Level 1	Level 2	Level 3
Speed (RPM)	220	440	630
Feed (mm/Rev)	0.15	0.2	0.3
Lubricant (MQL)	Diesel oil	Vegetable oil	Cutting oil
Tool Material	HSS	TiN coated HSS	TiAlN coated HSS
Point Angle (Deg)	90	118	135

Table 4. Experimental Design

Runs	Speed	Feed	Lubricant	Tool material	Point Angle
1	1	1	1	1	1
2	1	1	2	2	2
3	1	1	3	3	3
4	1	2	1	2	2
5	1	2	2	3	3
6	1	2	3	1	1
7	1	3	1	3	3
8	1	3	2	1	1
9	1	3	3	2	2
10	2	1	1	2	3
11	2	1	2	3	1
12	2	1	3	1	2
13	2	2	1	3	1
14	2	2	2	1	2
15	2	2	3	2	3
16	2	3	1	1	2
17	2	3	2	2	3
18	2	3	3	3	1
19	3	1	1	3	2
20	3	1	2	1	3
21	3	1	3	2	1
22	3	2	1	1	3
23	3	2	2	2	1
24	3	2	3	3	2
25	3	3	1	2	1
26	3	3	2	3	2
27	3	3	3	1	3

Table 5. Experimental Results

S l. no	Power (Watts)	Temperature (°c)	Burr height (mm)	Surface Roughness (μm)
1	700	42	1.43	1.01
2	600	36	0.17	3.9125
3	600	39.3	0.17	1.2025
4	650	39	0.35	1.47
5	600	40.2	0.47	3.7
6	700	45	0.28	1.33
7	650	42	0.37	0.42
8	900	43.5	0.31	0.91
9	700	39	0.31	2.5925
10	1000	45.3	0.32	1.8775
11	950	38	0.23	0.996667
12	900	41	0.31	3.35
13	1100	45	0.39	0.62
14	950	45.3	0.26	4.406667
15	950	45.4	0.29	1.826667
16	1100	43	0.11	2.88
17	1000	43.6	0.40	2.27
18	1150	40	0.35	0.436667
19	1250	44	0.58	1.703333
20	1200	45	0.54	2.896667
21	1500	44	0.31	0.646667
22	1300	40	0.86	2.193333
23	1500	39	1.33	1.226667
24	1300	46.1	0.33	2.003333
25	1800	52	1.45	1.323333
26	1500	49	0.29	2.31
27	1400	48	0.39	1.806667

Table 6. S/N Ratios for experimental Results

Sl. no	Power	Temperature	Burr height	Surface Roughness
1	-56.902	-32.465	-3.1067	-0.0864
2	-55.563	-31.1261	15.391	-11.8491
3	-55.563	-31.8879	15.391	-1.6017
4	-56.2583	-31.8213	9.1186	-3.3463
5	-55.563	-32.0845	6.558	-11.364
6	-56.902	-33.0643	11.0568	-2.477
7	-56.2583	-32.465	8.636	7.535
8	-59.0849	-32.7698	10.1728	0.8192
9	-56.902	-31.8213	10.1728	-8.2744
10	-60	-33.122	9.897	-5.4716
11	-59.5545	-31.5957	12.7654	0.029
12	-59.0849	-32.2557	10.1728	-10.5009
13	-60.8279	-33.0643	8.1787	4.1522
14	-59.5545	-33.122	11.7005	-12.8822
15	-59.5545	-33.1411	10.752	-5.2332
16	-60.8279	-32.6694	19.1721	-9.1878
17	-60	-32.7897	7.9588	-7.1205
18	-61.214	-32.0412	9.1186	7.197
19	-61.9382	-32.8691	4.7314	-4.626
20	-61.5836	-33.0643	5.3521	-9.238
21	-63.5218	-32.8691	10.1728	3.7864
22	-62.2789	-32.0412	1.31	-6.8221
23	-63.5218	-31.8213	-2.477	-1.7745
24	-62.2789	-33.274	9.6297	-6.0351
25	-65.1055	-34.3201	-3.2274	-2.4334
26	-63.5218	-33.8039	10.752	-7.2722
27	-62.9226	-33.6248	8.1787	-5.1376

Table 7.Normalized S/N ratios

Sl.no	Power	Temperature	Burr Height	Surface Roughness
1	0.1403	0.4192	0.9946	0.3733
2	0	0	0.1688	0.9494
3	0	0.2385	0.1688	0.4475
4	0.0729	0.2177	0.4488	0.533
5	0	0.3001	0.5631	0.9256
6	0.1403	0.6068	0.3623	0.4904
7	0.0729	0.4192	0.4704	0
8	0.3691	0.5146	0.4018	0.3289
9	0.1403	0.2177	0.4018	0.7743
10	0.465	0.6249	0.4141	0.637
11	0.4183	0.147	0.286	0.3676
12	0.3691	0.3537	0.4018	0.8834
13	0.5517	0.6068	0.4908	0.1657
14	0.4183	0.6249	0.3336	1
15	0.4183	0.6309	0.3759	0.6254
16	0.5517	0.4832	0	0.8191
17	0.465	0.5209	0.5006	0.7178
18	0.5922	0.2865	0.4488	0.0166
19	0.6681	0.5457	0.6447	0.5956
20	0.6309	0.6068	0.617	0.8215
21	0.834	0.5457	0.4018	0.1836
22	0.7038	0.2865	0.7974	0.7032
23	0.834	0.2177	0.9665	0.456
24	0.7038	0.6725	0.426	0.6646
25	1	1	1	0.4882
26	0.834	0.8384	0.3759	0.7252
27	0.7712	0.7823	0.4908	0.6207

Table 8.Grey relational coefficients

S l. no	Power	Temperature	Burr	Surface Roughness
1	0.3677	0.4626	0.9893	0.4438
2	0.3333	0.3333	0.3756	0.9081
3	0.3333	0.3964	0.3756	0.4751
4	0.3504	0.3899	0.4757	0.517
5	0.3333	0.4167	0.5337	0.8705
6	0.3677	0.5598	0.4395	0.4952
7	0.3504	0.4626	0.4856	0.3333
8	0.4421	0.5074	0.4553	0.427
9	0.3677	0.3899	0.4553	0.689
10	0.4831	0.5714	0.4604	0.5794
11	0.4622	0.3696	0.4119	0.4416
12	0.4421	0.4362	0.4553	0.8109
13	0.5273	0.5598	0.4954	0.3747
14	0.4622	0.5714	0.4287	1
15	0.4622	0.5753	0.4448	0.5717
16	0.5273	0.4917	0.3333	0.7343
17	0.4831	0.5107	0.5003	0.6392
18	0.5508	0.412	0.4757	0.3371
19	0.601	0.5239	0.5846	0.5529
20	0.5753	0.5598	0.5662	0.7369
21	0.7508	0.5239	0.4553	0.3798
22	0.628	0.412	0.7117	0.6275
23	0.7508	0.3899	0.9372	0.4789
24	0.628	0.6042	0.4656	0.5985
25	1	1	1	0.4942
26	0.7508	0.7557	0.4448	0.6454
27	0.6861	0.6967	0.4954	0.5686

Table 9. Fuzzy Rules

Rule no	Grey-Relational coefficients as input variables				Output variables
	Power	Temperature	Burr height	Surface roughness	Hybrid grade
1	low	low	low	low	vvl
2	low	low	low	medium	vl
3	low	low	low	high	l
4	low	low	medium	low	vl
5	low	low	medium	medium	l
-	-	-	-	-	-
-	-	-	-	-	-
-	-	-	-	-	-
-	-	-	-	-	-
77	high	high	medium	medium	h
78	high	high	medium	high	vh
79	high	high	high	low	h
80	high	high	high	medium	vh
81	high	high	high	high	vvh

*Here: vvl-very very low, vl-very low, l-low, ml-medium low, m-medium, mh-medium high, h- high, vh-very high, vvh-very very high

Table 10. Hybrid grade

Slno	Hybrid grade
1	0.537
2	0.4445
3	0.3699
4	0.4134
5	0.5136
6	0.4549
7	0.3893
8	0.4275
9	0.4515
10	0.5333
11	0.3991
12	0.4971
13	0.4945
14	0.6077
15	0.5188
16	0.5184
17	0.5384
18	0.4289
19	0.5927
20	0.6185
21	0.5149
22	0.6142
23	0.6148
24	0.6065
25	0.8728
26	0.6501
27	0.6301

Table.11 Hybrid grade for each level of controllable parameter

Cutting Parameter	Level 1	Level 2	Level 3	max-min	Rank of effect on multi performance
Speed (N)	0.444622	0.504022	0.634956	0.190334	1
Feed(F)	0.500778	0.537600	0.545222	0.044444	4
Lubricant (L)	0.551733	0.534911	0.496956	0.054777	2
Tool Material(TM)	0.545044	0.544711	0.493844	0.051200	3
Point Angle (PA)	0.527156	0.531322	0.525122	0.006200	5

Table.12 comparison between initial and optimal combination

	Combination of Controllable Parameters	Power (watts)	Temperature (^{o}c)	Burr Height (mm)	Surface Roughness (µm)	Hybrid Grade
Initial Combination	N2,F2,L1,TM2,PA2	1000	40	0.714	2.57	0.543107
Optimal Combination	N3,F3,L1, TM1,PA2	600	34	0.25	1.24	0.679773
Gain	N/A	400	6	0.59	1.33	0.136666
% of Gain	N/A	40	15	65	48	25