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USE OF DESIRABILITY FUNCTION APPROACH FOR OPTIMIZATION OF MULTIPLE PERFORMANCE CHARACTERISTICS OF THE SURFACE ROUGHNESS PARAMETERS IN CNC TURNING

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ABSTRACT:

This paper presents a desirability function approach in order to find out an optimal combination of machining parameters for multiple performance characteristics of the surface roughness parameters in CNC turning operation on mild steel. In the present study, experiments have been conducted using depth of cut, spindle speed and feed rate as cutting parameters for evaluating the roughness parameters such as centre line average (R_a), root mean square (R_q) and mean line peak spacing (R_{sm}). An orthogonal array (L_9) is generated using the Taguchi design to carry out the experiments on AISI 1040 mild steel bar. The individual desirability values of each roughness parameters have been calculated and accumulate to calculate the overall desirability of the surface roughness in turning operation. The signal-to-noise ratio is employed to investigate the optimal combination of cutting parameters to yield maximum overall desirability. After the optimal level of cutting parameters has been find out, verification test is to be carried out to control the accuracy of analysis of results taken from the experiment.

Key words: Overall Desirability, S/N Ratio, Surface Roughness, CNC Turning

1. INTRODUCTION

The surface finish is the one of most important quality characteristic in the manufacturing industries which influences the performance of mechanical parts as well as production cost. In recent times, modern industries are keeping in mind to achieve the high quality products in a very short time with less operator input. For that purpose, the computer numerically controlled (CNC) machine tools with automated and flexible manufacturing systems have been implemented. In actual practice, there are many factors which affect the surface roughness i.e. cutting conditions, tool variables and workpiece variables. Cutting conditions include speed, feed and depth of cut where as tool variables include tool material, nose radius, rake angle, cutting edge geometry, tool vibration, tool overhang, tool point angle etc. and workpiece variable include material hardness and other mechanical properties. It is very difficult to consider all the parameters that control the surface roughness for a particular manufacturing process. Cutting parameters influenced on surface roughness, surface texture and dimension deviation of the product. In a turning operation, it is the vital task to select the cutting parameters to achieve the high quality performance. Generally, the desired cutting parameters are selected based on experience or use by the hand book. Several mathematical models based on statistical regression or neural network techniques have been constructed to establish the relationship between the cutting performance and cutting parameters. A brief review of literature on roughness modeling in turning operation is presented here. K. palani kumar et al. [1] investigated feed rate is the factor which has greater influence on surface roughness parameter (R_a), followed by cutting speed and % volume fraction of SiC in machining of Al/SiC particulate composites using response surface methodology. Nalbant et al. [2] optimized the cutting parameters for the turning of AISI 1030 steel bars by using the Taguchi method. They investigated centre line average (CLA) roughness parameter (R_a) only. The use of greater insert radius, low feed rate and low depth of cut are recommended to obtain better surface roughness for the specific test range. Dilbag Singh et al.[3] developed mathematical model for centre line average (R_a) to optimize the tool geometry and cutting parameters for hard turning using genetic algorithm. Zhong & Khoo [4] predicted surface roughness heights R_a and R_t of turned surface was carried out using neural network. Sahin and Motorcu[5] developed mathematical model of surface roughness parameter R_a only for turning of mild steel with coated carbide tools using RSM. They conclude that feed rate was main influencing factor on the surface roughness. It increased with increasing the feed rate but decreased with increasing the cutting speed and depth of cut respectively. Among the other parameters depth of cut was found to be more intensive than that of the cutting speed. Noordin et al.[6] described the performance of coated carbide tools using response surface methodology when turning AISI 1040 mild steel. They found that feed rate is the most significant parameter influencing the surface roughness R_a and tangential force. The SCEA^2 and the feed and SCEA interaction factors provided secondary contribution to the responses investigated. The Taguchi method was used by Yang and Tarang [7] to find the optimal cutting parameters for turning operations. Choudhury and El Baradie [8] had predicted surface roughness parameter R_a using RSM and 2^3 factorial designs when turning high strength steel. C.L. Lin [9] used grey relational analysis to optimize turning operations with multiple performance characteristics. He has been analyzed tool life, cutting force and surface roughness R_a only in turning operations.

However, a surface generated by machining is composed of a large number of length scales of superimposed roughness and generally characterized by three different types of parameters, viz., amplitude parameters, spacing parameters and hybrid parameters. Amplitude parameters are measures of the vertical characteristics of the surface deviations and examples of such parameters are centre line average roughness, root mean square roughness, skewness, kurtosis, peak-to-valley height etc. Spacing parameters are the measures of the horizontal characteristics of the surface deviations and examples of such parameters are mean line peak spacing, high spot count, peak count etc. On the other hand, hybrid parameters are a combination of both the vertical and horizontal characteristics of surface deviations and example of such parameters are root mean square slope of profile, root mean square wavelength, core roughness depth, reduced peak height, valley depth, peak area, valley area etc. Thus consideration of only one parameter like centre line average roughness is not sufficient to describe the surface quality though it is the most commonly used roughness parameter. The present study aims at consideration of three different roughness parameters, viz., centre line average roughness (R_a), root mean square roughness (R_q), and mean line peak spacing (R_{sm}) for the surface texture generated in turning operation of AISI 1040 mild steel. An orthogonal array (L_9) is generated using the Taguchi design to carry out the experiments on AISI 1040 mild steel bar. The machining parameters, viz., depth of cut (d, mm), spindle speed (N, rpm) and feed rate (f, mm/rev) are considered as independent variables and surface roughness parameters are as response variables. The software package MINITAB 13 has been used for statistical analysis of the surface roughness parameters.

2. ANALYSIS OF TAGUCHI METHOD

According to the name of the developer, this method is called as Taguchi Method [10]. This method has been utilized widely in engineering analysis to optimize performance characteristics within the combination of design parameters. Taguchi technique is also a powerful tool for design of high quality systems. It introduces an integrated approach that is simple and efficient to find the best range of designs for quality, performance and computational cost. In this optimization technique, the process or product should be carried out in a three -stage approach such as system design, parameter design and tolerance design. System design reveals the usages of scientific and engineering information required for producing a part. This design includes the product design stage and process design stage. In the product design stage, the selection of materials, components, tentative product parameter values etc. are involved. Similarly, in process design stage, the analysis of processing sequences, the selection of production equipment, tentative process parameter values etc are incorporated. The parameter design is used to obtain the optimum levels of process parameters for developing the quality characteristics and to determine the product parameters values depending optimum process parameter values. In addition, it is expected that the optimal process parameter values obtained from parameter design are insensitive to variation in the environmental conditions and other noise factors. Therefore, the parameter design has the key role in the Taguchi method to achieve high quality without increasing the cost factor. Lastly, the tolerance design is employed to determine and to analyze tolerances about the optimum combinations suggested by parameter design. Tolerance design is required if the reduced variation obtained by the parameter design does not reach the required performance.

The experimental design methods, which were developed by Fisher having some complexity and not easy to use and another important thing is that, whenever the number of process parameters increases, a large number of experiments have to be carried out. To eliminate such problems, the Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments only. After obtaining the experimental results, these values transformed into a signal - to- noise ratio. In Taguchi method, the term ‘signal’ represents the desirable value (mean) for the output characteristic and term ‘noise’ represents the undesirable value (Standard Deviation.) for the output characteristic. Therefore, S/N ratio is the ratio of the mean and the S.D.

Taguchi offers the use of the signal-to-noise (S/N) ratio to identify the quality characteristics applied for engineering design problems. The S/N ratio characteristics can be divided into three categories such as the smaller- the- better; nominal- the- better and larger- the- better. The S/N ratio for each level of process parameter is calculated based on the S/N analysis. Irrespective of the category of quality characteristic, a greater S/N ratio seems to be better quality characteristics. Here, it is suggested that the optimal level of process parameters is the level with the greatest S/N ratio.

3. DESIRABILITY FUNCTION APPROACH

Desirability function approach is powerful tools for solving the multiple performance characteristics optimization problems, where all the objectives are attain a definite goal simultaneously. The basic idea of this approach is to convert a multiple performance characteristics optimization problem into a single response optimization problem with the objective function of overall desirability. Then the overall desirability function is optimized. The general approach is to first convert each response y_i, into an individual desirability function d_i , that may vary over the range $0 \leqslant d_i \leqslant 1$, where if the response y_i meets the goal or target value, then $d_i = 1$, and if the response falls beyond the acceptable limit, then $d_i = 0$. The next step is to select the parameter combination that will maximize overall desirability D.

$$D=(d_1.d_2........d_m)^{1/m} \tag{1}$$

Where, m= number of responses. …………………

The individual desirability functions are calculated as shown equations 2 to 4. If the objective or target T for the response y is a maximum value,

$$d=\begin{cases} 0, & y < L \\ \left(\dfrac{y-L}{T-L}\right)^r, & L \le y \le T \\ 1, & y > T \end{cases} \quad \text{…………….……… (2)}$$

When the weight r =1,the desirability function is linear. Selecting r>1 places more emphasis on being close to the target value, and selecting 0<r <1 makes this less important.
If the target for the response is a minimum value,

$$d=\begin{cases} 1, & y < T \\ \left(\dfrac{U-y}{U-T}\right)^r, & T \le y \le U \\ 0, & y > U \end{cases} \quad \text{……………………..(3)}$$

The two sided desirability function, assumes that the target is located between the lower L and upper U limits. For this case, desirability can be calculated as below,

$$d=\begin{cases} 0, & y < L \\ \left(\dfrac{y-L}{T-L}\right)^{r_1}, & L \le y \le T \\ \left(\dfrac{U-y}{U-T}\right)^{r_2}, & T \le y \le U \\ 0, & y > U \end{cases} \quad \text{…………………..(4)}$$

4. EXPERIMENTAL DETAILS

On the basis of Taguchi's orthogonal array, experiments were conducted on a CNC lathe series of JOBBERXL manufactured by ACE Designers Ltd., Bangalore, India assembled with FANUC Series Controller. The experiments were conducted at three different levels of cutting parameters: depth of cut, spindle speed and feed rate. The feasible range for the cutting parameters was recommended by a machining handbook (i.e., depth of cut in the range 0.1–0.3 mm, spindle speed in the range 800-1600rpm, feed rate in the range 0.07–0.21 mm/rev). The initial cutting parameters were depth of cut of 0.1 mm, spindle speed of 1200 rpm, and feed rate of 0.14 mm/rev. Cutting parameters with their notations, unit and values at different levels are listed in Table 1. Design of experiments have been selected based on Taguchi's Orthogonal Array of L_9 (3**3) consisting of 9 sets of coded conditions shown in the Table 2. The workpiece material selected for the experimentation was AISI 1040 mild steel bar of diameter 20mm and length of 60 mm. Table 3 depicts the chemical composition and physical properties of AISI 1040 steel bar. The tool holder used for turning is PTGNR-25-25 M16 050, WIDIA and insert used as TNMG 160404–FL, WIDIA, Coated with titanium nitride.

Roughness measurement was done using a portable stylus-type profilometer, Talysurf (Taylor Hobson, Surtronic 3+). The profilometer was set to a cut-off length of 0.8 mm, filter 2CR, traverse speed 1 mm/sec and 4 mm traverse length. Roughness measurements, in the transverse direction, on the work pieces were repeated four times and average of four measurements of surface roughness parameter values was recorded. The measured profile was digitized and processed through the dedicated advanced surface finish analysis software Talyprofile for evaluation of the roughness parameters.

Table 1: Process parameters and their levels

Paramet-ers	*Unit*	*Nota-tion*	*1*	*2*	*3*
Depth of cut	mm	d	0.1	0.2	0.3
Spindle speed	rpm	N	800	1200	1600
Feed rate	mm/rev	f	0.07	0.14	0.21

Table 2: Orthogonal array, L_9 (3**3) design matrix

Ex. no.	*Depth of cut(d)*	*Spindle speed(N)*	*Feed rate(f)*
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Table 3: Chemical composition and physical properties of AISI 1040 steel bar

Material	*Chemical composition*	*Physical Properties*
Mild Steel (AISI 1040)	0.42% C, 0.48% Mn, 0.17% Si, 0.02% P, 0.018% S, 0.1%Cu, 0.09%Ni, 0.07%Cr and balance Fe	Hardness-201 BHN, Density-7.85 g/cc, Tensile strength-620 MPa

4.1 Response Variables:

(i) Centre line average roughness (R_a):

It is defined as the arithmetic mean deviation of the surface height from the mean line through the profile while the mean line is defined so as to have equal areas of the profile above and below it. R_a may be expressed in the form:

$$R_a = \frac{1}{L}\int_0^L |Z(x)|\,dx$$

where $Z(x)$ is the ordinate of the profile curve, x is the profile direction and L is the sampling length. The unit of R_a is μm.

(ii) Root mean square roughness (R_q):

It represents the standard deviation of the distribution of surface heights. Its unit is also μm. It is defined as the root mean square deviation of the profile from the mean line and is expressed as:

$$R_q = \sqrt{\frac{1}{L}\int_0^L [Z(x)]^2\,dx}$$

(iii) Mean line peak spacing (R_{sm}):

It is defined as the mean spacing between peaks, with a peak defined relative to the mean line (a peak must cross above the mean line and then back below it). This parameter may be expressed in the form:

$$R_{sm} = \frac{1}{m}\sum_{n=1}^{m} S_n$$

where m is the number of peak spacing and S is the spacing between two consecutive peaks. Its unit is mm. The experimental results have been shown in the Table 4 for surface roughness parameters in CNC turning operations.

5. RESULTS AND DISCUSSION`

As per the desirability function approach, it converts multiple objectives into a single objective function. This objective function is called as overall desirability function. To get an optimum process condition, the overall desirability is being optimized.

Table 4: Experimental results of surface parameters

SL No	*R_a*	*R_q*	*R_{sm}*
1	1.7000	2.1250	0.1098
2	3.2275	3.9675	0.1522
3	3.3025	4.1280	0.1447
4	2.9325	3.5550	0.1465
5	2.2075	2.7400	0.1355
6	1.5525	1.9406	0.1082
7	3.9900	4.9875	0.1677
8	1.7950	2.2437	0.1100
9	2.1722	2.7152	0.0869

For optimization of surface roughness parameters such as R_a, R_q, & R_{sm} are to be minimized. First of all, the individual desirability is calculated as per the equations 3 and shown in the Table 5. The most acceptable dimensions for R_a, R_q & R_{sm} have been chosen as 1.52, 1.92 and 0.08 respectively. The overall desirability values have been calculated by using equation 1 and shown in the Table 6. S/N ratios of the overall desirability have been calculated based on the Taguchi's 'larger-the- better' criterion as mentioned in the Table 7. Higher the S/N ratio value treated as the closer towards the optimal solution. The corresponding factor combination having higher S/N ratio seems to be optimal process parameters. The S/N ratio graph for overall desirability has been shown in Fig. 1. It is clearly depicted that the S/N ratio is highest at d2 N3 f1. Therefore, optimal parametric combination becomes to be d2 N3 f1 i.e at medium depth of cut, highest spindle speed and low feed rate for minimization of R_a, R_q, & R_{sm} in CNC turning operations. A confirmatory experiment has been carried out to verify the optimal setting. It has been yielded a satisfactory result as shown in Table 8.

Table 5: Individual desirability value for Responses

Sl .No	*R_a*	*R_q*	*R_{sm}*
1	0.92592	0.91791	0.60200
2	0.36018	0.36791	0.17750
3	0.33240	0.32000	0.25250
4	0.46944	0.49104	0.23500
5	0.73796	0.73432	0.34500
6	0.98055	0.97295	0.61750
7	0.07777	0.06343	0.02250
8	0.89074	0.88247	0.60000
9	0.75101	0.74173	0.83025

Table 6: Overall desirability values of responses

Sl .No	*Overall desirability*
1	0.79981
2	0.28652
3	0.29947
4	0.37837
5	0.57180
6	0.83830
7	0.04806
8	0.77839
9	0.77333

Table 7: S/N ratio corresponding to Overall desirability.

Sl .No	**S/N ratio for overall desirability**
1	-1.9402
2	-10.8569
3	-10.4728
4	-8.4415
5	-4.8550
6	-1.5320
7	-26.3643
8	-2.1760
9	-2.2326

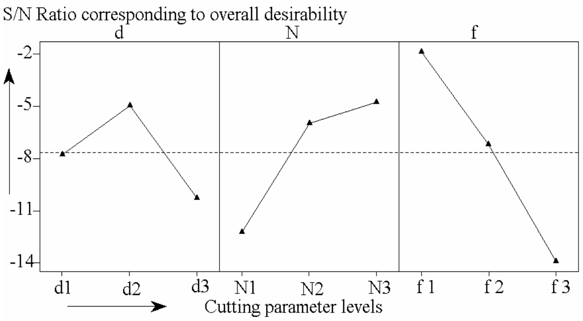

Fig 1: S/N ratio graph corresponding to overall desirability

Table 8: Results of verification test

	Initial machining parameter	*Optimal machining parameter by experiment*
Level	d 1 N 2 f 2	d 2 N 3 f 1
R_a	3.2275	1.5525
R_q	3.9675	1.9406
R_{sm}	0.1522	0.1082
S/N ratio	-10.8569	-1.532
Overall desirability	0.2865	0.8383

Improvement in overall desirability=0.8383-0.2865=0.5518

6. CONCLUSIONS

Orthogonal array with desirability function approach was employed to optimize the process parameters for surface roughness parameters in CNC turning operations. The multi response characteristics of surface roughness parameters have been taking place in the present study. The confirmatory result for the optimal setting depicts that there is considerable improvement of 0.5518 in overall desirability of the multi response characteristics. With a minimum number of experimental runs, this method is a quite efficient one for solution of optimization problems.

7. REFERENCES

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7. NOMENCLATURE

Symbol	Meaning	Unit
d	Depth of Cut	(mm)
N	Spindle Speed	(rpm)
f	Feed Rate	(mm/rev)
R_a	Centre Line Average(CLA)	micrometer
R_q	Root mean Square	micrometer
R_{sm}	Mean line peak spacing	mm
D	Overall desirability	--