Multi Output Optimization of CNC High Speed Hard Turning of AISI 52100 Bearing Steel using Taguchi Method and Fuzzy Logic Unit

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Abstract— **In this paper the combination of Taguchi method with logical fuzzy reasoning was implemented for multi output optimization of high speed CNC turning of AISI 52100 steel alloy. The machining parameters (cutting speed, feed rate, depth of cut) are optimized with considerations of the multiple performance measures (surface roughness, material removal rate, machining time, tool wear). Taguchi's concepts of orthogonal arrays, signal to noise (S/N) ratio, ANOVA etc are used and the S/N ratios have been fuzzified to optimize the high speed CNC turning process parameters through a single comprehensive output measure (COM).**

Keywords— **CNC hard turning, fuzzy logic, AISI 52100, Taguchi, ANOVA.**

I. Introduction

The hard turning process is superior to grinding in terms of flexibility, ability to achieve higher material removal rates, possibility to operate without coolants etc [1]. For the above mentioned reasons hard turning is replacing grinding operations in industrial applications. AISI 52100 steel alloy also known as bearing steel is mainly used for manufacturing bearings and are well known for their hardness and toughness. They are always available in pre-hardened form.

The aim or objective of this work is to optimize the process parameters such as speed, feed and depth of cut by making use of fuzzy logic unit and to investigate the effect of these input parameters on surface roughness, material removal rate, machining time and tool wear. Then to achieve the surface roughness within the rejection criteria (1.6µm) when grinding operation is replaced by CNC high speed hard turning operation.

II. Multi Output Optimization Using Fuzzy Logic

In this work the use of fuzzy logics to the Taguchi method in optimization of the high speed CNC turning with multiple performance characteristics [2]. A fuzzy reasoning of the multiple performance characteristics has been performed by the fuzzy logic unit. As a result, four performance characteristics namely surface roughness, material removal rate, maching time and tool wear can be improved.

A. *Fuzzy Logic Unit*

The fuzzy logic unit comprises of

- Fuzzifier
- Membership function
- Fuzzy rule base
- An inference system
- Defuzzifier

Fuzzifier is used to convert the crisp values into values with membership function. The membership function is a graphical representation of the magnitude of participation of each input. It associates a weighting with each of the inputs that are processed, define functional overlap between inputs, and ultimately determines an output response. The rules use the input membership values as weighting factors to determine their influence on the fuzzy output sets of the final output conclusion. Once the functions are inferred, scaled, and combined, they are defuzzified into a crisp output which drives the system.

The degree of membership (DOM) is determined by plugging the selected input parameter into the horizontal axis and projecting vertically to the upper boundary of the membership function. In the inference system the logical products for each rule are combined or inferred (max-min'd, max-dot'd, averaged, root-sum-squared, etc.) before being passed on to the defuzzification process for crisp output generation. Several inference methods exist. The MAX-MIN method tests the magnitudes of each rule and selects the highest one. The horizontal coordinate of the "fuzzy centroid" of the area under that function is taken as the output. This method does not combine the effects of all applicable rules but does produce a continuous output function and is easy to implement.

The defuzzification of the data into a crisp output is accomplished by combining the results of the inference process and then computing the fuzzy centroid of the area. The weighted strengths of each output member function are multiplied by their respective output membership function center points and summed. Finally, this area is divided by the sum of the weighted member function strengths and the result is taken as the crisp output. The horizontal coordinate of the centroid of the area marked in Figure 8 is taken as the normalized, crisp output.

III. HIGH SPEED CNC HARD TURNING PROCESS

A. *Process Parameters*

The main process parameters selected for the work are speed (m/min), feed (mm/rev) and depth of cut (mm) .The process parameters and their levels are shown in the Table 1.

B. *Workpiece Material*

The workpiece material selected for the work is AISI 52100 bearing steel alloy. It is mainly used to manufacture bearings especially aerospace and automobile bearings. It is always available in prehardened form hence no heat treatments are required. It is delivered fully quenched and tempered to approximately between 700 to 900 HV.

C. *Tool Material*

The tool material selected for this work was tungsten carbide tool insert of 0.80 nose radius. The ISO coding is WNMG 120408.

D. *Experimental Setup*

The experimental work was carried out at Center for Research in Design and Manufacturing (CRDM), Karunya institute of technology and sciences under the university of Karunya. The design of experiments was done by making use of Taguchi's method and optimization was done by making use of Fuzzy logic unit. AISI 52100 bearing steel round bar of 25 mm diameter and 50 mm length was selected for this work.

The design of experiments are done using Taguhi's L9 orthogonal array and is shown in Table 2. The experimental design proposed by Taguchi involves using orthogonal arrays to organize the parameters affecting the process and the levels at which they should be varies. Instead of having to test all possible combinations like the factorial design, the Taguchi method tests pairs of combinations. This allows for the collection of the necessary data to determine which factors most affect product quality with a minimum amount of experimentation, thus saving time and resources.

TABLE I

PROCESS PARAMETERS AND THEIR LEVELS

Process parameters	**Level 1**	**Level 2**	**Level 3**
Speed(m/min)	120	160	200
Feed (mm/rev)	0.10	0.12	0.14
Depth of cut(mm)	0.20	0.35	0.50

TABLE 2

LAYOUT USING L9 ORTHOGONAL ARRAY

Experiment	**Speed (m/min)**	**Feed (mm/rev)**	**Depth (mm)**
1	120	0.10	0.20
2	120	0.12	0.35
3	120	0.14	0.50
4	160	0.10	0.35
5	160	0.12	0.50
6	160	0.14	0.20
7	200	0.10	0.50
8	200	0.12	0.20
9	200	0.14	0.35

IV. OPTIMIZATION OF CNC TURNING PARAMETERS

A. *Signal To Noise Ratio*

There are mainly three categories of performance characteristics

- Lower the better
- Nominal the better
- Higher the better

For 'lower the better' type of machining quality characteristic the S/N ratio will be

$$S/N = -10*\log[1/n*(y_1^2 + y_2^2 +\ldots\ldots.+ y_n^2)]$$

For 'nominal the better' type of machining quality characteristic the S/N ratio will be

$$S/N = 10*\log\left[\frac{\mu^2}{\sigma^2}\right]$$

For 'higher the better' type of machining quality characteristic the S/N ratio will be

$$S/N = - 10*\log[1/n*(1/y_1^2 + 1/y_2^2 +\ldots\ldots.+ 1/y_n^2)]$$

Here for surface roughness, machining time and tool wear we use lower the better type and for material removal rate we use higher the better type. Here y_1, y_2, y_n etc. are the measured values and n is the number of replications or trials performed.

B. Single Character Optimization

When a single-response problem is considered, Taguchi method and analysis of variance (ANOVA) can be employed to obtain the optimal level/factor combination of high speed CNC turning process. In the past a lot of researchers studied the effect of various machining parameters in optimizing the machined surface integrity using Taguchi's method. The S/N is used to represent quality characteristic and the largest S/N ratio is demanded. In addition, the contribution of each factor is evaluated using the ANOVA.

In this thesis work, for surface roughness, machining time and tool wear lower the better type characteristic equation was used to calculate the signal to noise ratio and for material removal rate higher the better type characteristic equation.

The following Table 3 shows the experimentally obtained surface roughness value for three replication of each experiment. The surface roughness of the machined part was measured by making use of surface roughness tester. The model of the tester is SJ 210 which is a MITUTOYO make. Since there are three replications for each experiment, three readings corresponding to three work specimens are taken and the average value is recorded. The three values are then used to find the S/N ratio.

TABLE 3
SURFACE ROUGHNESS AND S/N RATIO OF SR

SL.NO	Average Ra	S/N ratio
1	0.839	1.52
2	1.119	-0.997
3	1.287	-2.193
4	1.059	-.506
5	0.901	0.901
6	0.808	1.851
7	0.490	6.177
8	1.002	-0.025
9	1.308	-2.334

The S/N equation used here is lower the better type. Then each combinations corresponding to speed, feed and depth of cut for three different levels were taken and the one with highest average were chosen as the best level. Taguchi's method of analyzing means of the S/N ratio using conceptual approach is used here. The rank indicates the dominant machining parameter. The best combination of input parameters for the best surface roughness is given in the Table 4.

TABLE 4
RESPONSE TABLE FOR SURFACE ROUGHNESS

Variables	Average level 1	Average level 2	Average level 3
Speed	-0.556	-0.842	**1.272**
Feed	**0.807**	-0.040	-0.892
Depth	1.115	-2.866	**1.628**

From the table it is evident that the best combination for surface roughness will be speed at level 3, feed at level 1, depth of cut at level 3. Thus the values for speed, feed and depth of cut when surface roughness alone was considered were 200m/min, 0.10mm/rev, 0.20mm. Thus a factor level combination of S_3, F_1, D_3 was recommended. The results of ANOVA for the S/N ratios of the surface roughness are also shown in table 4.4. It can be seen that the contribution of factor D to the surface roughness was the largest (26.7%). Thus, depth of cut was most important factor as far as surface roughness is concerned. It is shown in table 5.

TABLE 5
ANOVA OF S/N RATIO OF SURFACE ROUGHNESS

Variables	DOF	SS	MS	Contribution %
S	2	5.323	2.662	9.84
F	2	17.498	8.749	32.3
D	2	14.450	7.225	26.7
Error	2	16.811	8.405	31.1
Total	8	54.083	7.617	100

Then the same method used in the case of surface roughness is adopted to calculate the best combinations of the input parameters for material removal rate, machining time and tool wear.

The factor/level combination of S_3, F_3, D_3 for material removal rate, S_4, F_4, D_4 for machining time and S_2, F_2, D_1 for tool wear are the recommended optimum parameters, for high speed CNC turning when all responses are considered independently.

C. Multi Output Optimization

A fuzzy logic unit (FLU) comprises a fuzzifier, membership functions, a fuzzy rule base, an inference system, and a defuzzifier. First, the fuzzifier uses membership functions to fuzzify the S/N ratios. Next, the inference system performs a fuzzy reasoning on fuzzy rules to generate a fuzzy value. Finally, the defuzzifier converts the fuzzy value into a COM. In the present work, fuzzy reasoning is based on the four input and one output fuzzy logic unit. The fuzzy rule base consists of a group of if–then control rules with the four inputs and one output y. The main if then rules are as follow

- Rule 1 : if x_1 is A_1 and $x_2$is $B_1$and x_3 is C_1 and x_4 is D_1 then y is E_1
- Rule 2 : if x_1 is A_2 and $x_2$is B_2 and x_3 is C_2 and x_4 is D_2 then y is E_2
- ……
- Rule N : if $x_1$is A_n and $x_2$is Bn and x_3 is Cn and x_4 is Dn then y is En

here A, B, C and D are fuzzy subsets for the four inputs. There are two fuzzy subsets which are assigned to the inputs for fuzzufication. The two subsets are low and high. The outputs were assigned with five fuzzy subsets. The main output subsets are low, lowest, medium, highest and high. E corresponds to any of the above mentioned output subsets. The above mentioned rule is used to generate the output subsets. In this work there are sixteen such if then rules. Here max-min operation is used to perform the fuzzification.

The crisp values in this project work are the S/N ratios corresponding to surface roughness, material removal rate, machining time and feed rate. These values are then converted to membership function. MATLAB 13 is used to convert the S/N ratio to corresponding membership function. The input values are subjected to two subsets low and high as shown in Fig 1.

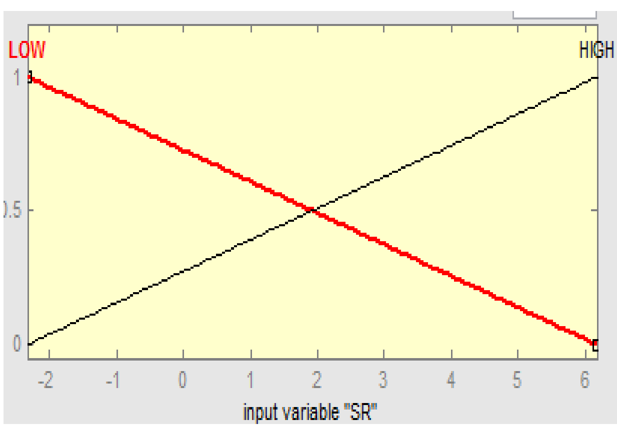


Fig. 1 Membership Function Of Surface Roughness

. Corresponding membership functions for each S/N value is generated considering two subsets low and high. Then the values of membership functions of surface roughness are given to each rule and compared with other membership functions. Then the membership function with minimum value is selected. Then the membership function is defuzzified to get the COM value. The output or COM is subjected to five subsets low, lowest, medium, high, and highest as shown in Fig 2. Sixteen such values are generated for one set of experiments. Then from those sixteen values the one with maximum value is selected.

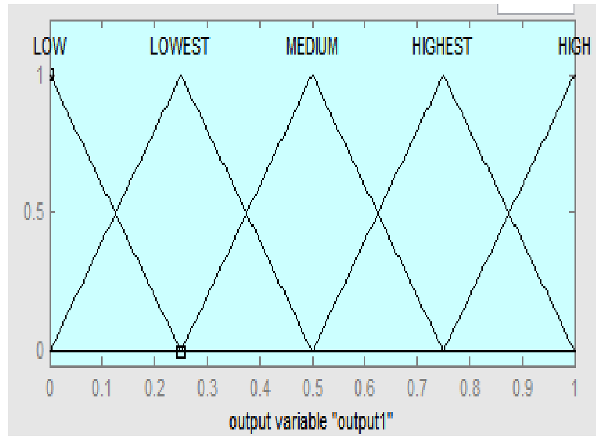
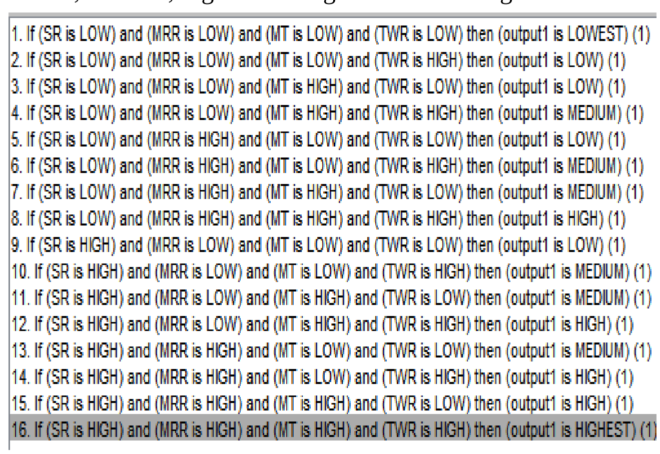


Fig. 2 Membership Function Of Output Or COM

From the fuzzy rules a corresponding membership function will be generated, based on the fact that its value is minimum and sixteen such membership functions will be generated. Among them the one with maximum value is selected and that membership function is used to obtain the COM value. The MATLAB 13 generated fuzzy rules are shown below in Fig 3. The out value or COM were subject to five subsets, low, lowest, medium, highest and high as shown in Fig 2.



1. If (SR is LOW) and (MRR is LOW) and (MT is LOW) and (TWR is LOW) then (output1 is LOWEST) (1)
2. If (SR is LOW) and (MRR is LOW) and (MT is LOW) and (TWR is HIGH) then (output1 is LOW) (1)
3. If (SR is LOW) and (MRR is LOW) and (MT is HIGH) and (TWR is LOW) then (output1 is LOW) (1)
4. If (SR is LOW) and (MRR is LOW) and (MT is HIGH) and (TWR is HIGH) then (output1 is MEDIUM) (1)
5. If (SR is LOW) and (MRR is HIGH) and (MT is LOW) and (TWR is LOW) then (output1 is LOW) (1)
6. If (SR is LOW) and (MRR is HIGH) and (MT is LOW) and (TWR is HIGH) then (output1 is MEDIUM) (1)
7. If (SR is LOW) and (MRR is HIGH) and (MT is HIGH) and (TWR is LOW) then (output1 is MEDIUM) (1)
8. If (SR is LOW) and (MRR is HIGH) and (MT is HIGH) and (TWR is HIGH) then (output1 is HIGH) (1)
9. If (SR is HIGH) and (MRR is LOW) and (MT is LOW) and (TWR is LOW) then (output1 is LOW) (1)
10. If (SR is HIGH) and (MRR is LOW) and (MT is LOW) and (TWR is HIGH) then (output1 is MEDIUM) (1)
11. If (SR is HIGH) and (MRR is LOW) and (MT is HIGH) and (TWR is LOW) then (output1 is MEDIUM) (1)
12. If (SR is HIGH) and (MRR is LOW) and (MT is HIGH) and (TWR is HIGH) then (output1 is HIGH) (1)
13. If (SR is HIGH) and (MRR is HIGH) and (MT is LOW) and (TWR is LOW) then (output1 is MEDIUM) (1)
14. If (SR is HIGH) and (MRR is HIGH) and (MT is LOW) and (TWR is HIGH) then (output1 is HIGH) (1)
15. If (SR is HIGH) and (MRR is HIGH) and (MT is HIGH) and (TWR is LOW) then (output1 is HIGH) (1)
16. If (SR is HIGH) and (MRR is HIGH) and (MT is HIGH) and (TWR is HIGH) then (output1 is HIGHEST) (1)

Fig 3 MATLAB 13 Generated Fuzzy Rules

The inference system performs a fuzzy reasoning on fuzzy rules to generate a fuzzy value. By taking the max–min compositional operation, the fuzzy reasoning of these rules yields a fuzzy output. Supposing that x_1, x_2, x_3 and x_4 are the four input values of the fuzzy logic unit, the membership function of the output of fuzzy reasoning can be expressed as

$$\mu C0(y) = (\mu A1(x1) \wedge \mu B1(x2) \wedge \mu C1(x3) \wedge \mu D1(x4)\ \mu E1(y)) \vee \ldots\ldots\ldots\ (\mu An(x1) \wedge \mu Bn(x2) \wedge \mu Cn(x3) \wedge \mu Dn(x4)\ \mu En(y))$$

Where μA_n, μB_n, μC_n, μD_n are the membership functions corresponding to the input values and μE_n is the membership function of the output value. Here$\vee$ the maximum operation and$\wedge$ is the minimum operation. Defuzzification is the method of converting the membership values of the output into crisp values. In this project work defuzzification method known as centroid method is adopted. In this paper, the non-fuzzy value y is called COM. Based on the above discussion, the larger is the COM then better is the performance characteristic.

The MATLAB 13 generated fuzzy rule COM graph for four input combinations is shown in Fig 2. The Fig 4 shows the generation of COM value. The input values is the S/N ratio of the surface roughness, material removal rate, machining time and tool wear.

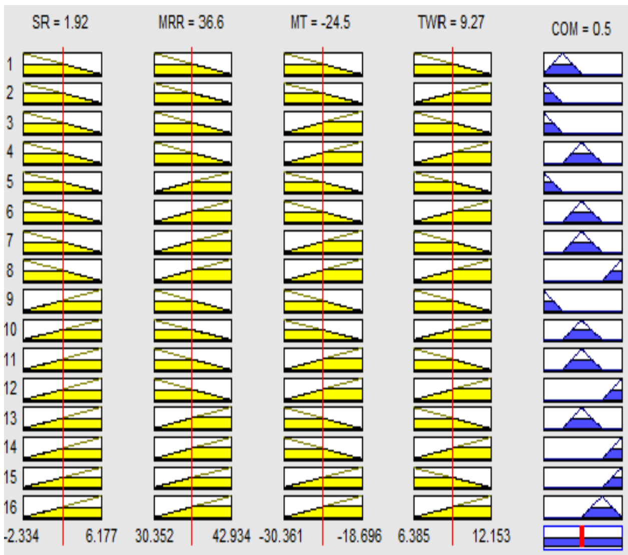


Fig 4 MATLAB 13 Generated Fuzzy Rule COM Graph

The membership functions are first generated and then compared with values of other membership functions, if low it will be selected. Sixteen such values will be generated and from those sixteen values the maximum value will be selected to get the output or COM value.

It is clear from the Fig 4 that for each set of combinations of S/N values of surface roughness, material removal rate, machining time and tool wear a corresponding output value will be generated. In the Fig 4 we can see that for the S/N values of 1.92 for surface roughness, 36.6 for material removal rate, -24.5 for machining time, 9.27 for tool wear an output value of 0.5 is generated. Nine such values of COM will be generated for nine sets of input values.

The orthogonality in the experimental data makes it possible to separate out the effect of each machining parameter at different levels. For example, the mean of COM for the cutting speed at levels 1, 2 and 3 can be calculated by averaging the multi-response performance indexes for experiments 1–3, 4–5 and 6–9 respectively. The results of COM is shown in the Table 6.

TABLE 6
RESULTS OF COM

SL:NO	COM Value
1	0.349
2	0.406
3	0.374
4	0.408
5	0.581
6	0.614
7	0.636
8	0.522
9	0.622

The mean of COM for each level of the other machining parameters can be computed in a similar manner and is summarized in the COM table 4.15. In addition, the total mean of the COM for the nine experiments is also calculated and listed in table 4.16. Basically, the larger is the COM, the smaller is the variance of the performance characteristics around the desired average COM value. However, the relative importance amongst the machining parameters for the multiple performance characteristics still needs to be known so that the optimal combinations of the machining parameter levels can be determined more accurately. The response table for COM is shown in the Table 7.

TABLE 7
RESULTS OF COM

Symbol	Machining parameter	Average level 1	Average level 2	Average level 3
S	Speed	0.377	0.464	**0.592**
F	Feed	0.464	0.503	**0.537**
D	Depth	0.495	0.479	**0.530**

From the response table it is evident that the best factor level combinations considering all four output parameters together were, speed at level three, feed at level three, depth of cut at level three. Thus the values for speed, feed and depth of cut are 200m/min, 0.14mm/rev, 0.50mm. The ANOVA table for the COM value is shown in the Table 8.

TABLE 8
ANOVA OF COM

Variables	DOF	SS	MS	Contribution %
S	2	0.079834	0.03992	72.9
F	2	0.007861	0.00393	7.2
D	2	0.004185	0.00209	3.8
Error	2	0.017503	0.00875	16
Total	8	0.109382	0.0089	100

The results of ANOVA for the COM values are shown in the Table 8. It can be seen that the contribution of factor S was the largest (72.9%) followed by factor F (7.2%). Thus, speed was most important factor followed by feed, as far as multi outputs were concerned. The contribution of feed and depth of cut is low when compared with speed. Thus the Table 8 clearly shows that speed is the major factor with a contribution of 72.9 % when all the four output parameters such as surface roughness, material removal rate, machining time and percentage tool wear are considered together.

V. CONCLUSIONS

This paper has presented the use of fuzzy logics to the Taguchi method in optimization of the high speed CNC turning with multiple performance characteristics. A fuzzy reasoning of the multiple performance characteristics has been performed by the fuzzy logic unit. As a result, four performance characteristics namely surface roughness, material removal rate, machining time and tool wear can be improved. It can be concluded that the optimization methodology developed in this study is useful in improving multiple performance characteristics in high speed CNC turning. The results are summarized as follows:

(1) The factor/level combination for surface roughness S_3, F_1, D_3 for material removal rate S_3, F_3, D_3 for machining time S_3, F_3, D_3 and for tool wear S_2, F_2, D_1 were the recommended optimum parameters, for high speed CNC turning when all four responses are considered independently.

(2) In the multi-response problem, all the four responses surface roughness, material removal rate, machining time and tool wear were simultaneously considered, and S_3, F_3, D_3 was the recommended optimum condition as per the hybrid Taguchi-fuzzy approach.

(3) It can be concluded that high level of cutting speed (200 m/min), high level feed of (0.14 mm/rev) and depth of cut (0.50mm) yield the optimal result.

(4) Thus, speed was the most important factor as far as multi outputs were concerned. The contribution of feed and depth of cut is low when compared with speed. This work clearly shows that speed is the major factor with a contribution of 72.9 % when all the four output parameters such as surface roughness, material removal rate, machining time and percentage tool wear are considered together and the surface roughness value lies within the rejection criteria of 1.6µm.

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