Optimization of Metal Removal Rate for ASTM A48 Grey Cast Iron in Turning Operation Using Taguchi Method

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Abstract: Optimization is a technique through which better results are obtained under certain circumstances. The main objective of today's modern manufacturing industries is to produce low cost and high quality products in short time. The selection of optimal cutting parameters is a very important issue for every machining process in order to enhance the quality of machining products and reduce the machining costs. This research work represents on an optimization of metal removal rate in turning operation by the effects of machining parameters applying Taguchi & ANOVA (Analysis of Variance) method to improve the quality of manufactured goods & engineering development of designs for studying variations. For investigation ASTM A48 grey cast iron is considered as workpiece and spindle sped, feed rate & depth of cut have been considered as cutting parameters, while a HSS (High Speed Steel) has been used as cutting tool. This research work reveals that spindle speed has the most significant contribution on the metal removal rate among all the three parameters.

Key words: ANOVA, design of experiments, orthogonal array, Taguchi method.

1. Introduction

Turning is one of the most commonly used metal removal operations in industry because of its ability to remove material faster giving reasonably good surface quality. It is used in a variety of manufacturing industries including aerospace and automatic sectors. During turning process we expect highest metal removal rate in order to achieve highest production at reduced time and cost. Metals from the outer periphery of a cylindrical work piece are removed and the volume of metal removed per unit time is known as metal removal rate or MRR. A turning machine or lathe, work piece, fixture, and cutting tool are required during the turning operation. The workpiece is a piece of re-shaped metal that is secured to the fixture, which itself is attached to the turning machine, and allowed to rotate at high speeds. The cutter is typically a single-point cutting tool that is also secured in the machine. The cutting tool feeds into the rotating work piece and cuts away material in the form of small chips to create the desire shape.

In the turning operation, vibration is a frequent problem, which affects the result of the machining and in particular the surface finish. Tool life is also influenced by vibrations. Severe acoustic noise in the working environment frequently results as a dynamic motion between the cutting tool and the work piece. In all cutting operations like turning, boring and milling vibrations are induced due to deformation of the work piece. In the turning process, the importance of machining parameter choice is increased, as it controls the surface quality required. [1]

Dr Genichi Taguchi is a Japanese quality management consultant who has developed and promoted a philosophy and methodology for continuous quality improvement in products and processes. Within this philosophy, Taguchi shows how the statistical design of experiments (SDOE or DOE) can help industrial engineers design and manufacture products that are both of high quality and low cost. His approach is primarily focused on eliminating the causes of poor quality and on making product performance insensitive to variation. DOE (Design of Experiment) is a powerful statistical technique for determining the optimal factor settings of a process and thereby achieving improved process performance, reduced process variability and improved manufacturability of products and processes. Taguchi (1986) advocates the use of orthogonal array designs to assign the factors chosen for the experiment. The most commonly used orthogonal array designs are L8 (i.e. eight experimental trials), L16 and L18. The power of the Taguchi method is that it integrates statistical methods into the engineering process. Bendell *et al.* (1989) and Rowlands *et al.* (2000) report success of the Taguchi method in the automotive, plastics, semiconductors, and metal fabrication and foundry industries. [2]

The Taguchi method has been widely used in engineering analysis and is a powerful tool to design a high quality system. Moreover, the Taguchi method employs a special design of orthogonal array to investigate the effects of the entire machining parameters through the small number of experiments. By applying the Taguchi technique, the time required for experimental investigations can be significantly reduced, as it is effective in the investigation of the effects of multiple factors on performance as well as to study the influence of individual factors to determine which factor has more influence. [3]

The aim of this experimental investigation is to estimate the effects of cutting speed, feed rate, and depth of cut on Material Removal Rate in Turning of mild steel. Design of experiment techniques, i.e. Taguchi's technique have been used to accomplish the objective and to generate optimized value. Here L27 orthogonal array used for conducting the experiments and ANOVA technique was employed to analyze the percentage contribution and influence of Process Parameters.

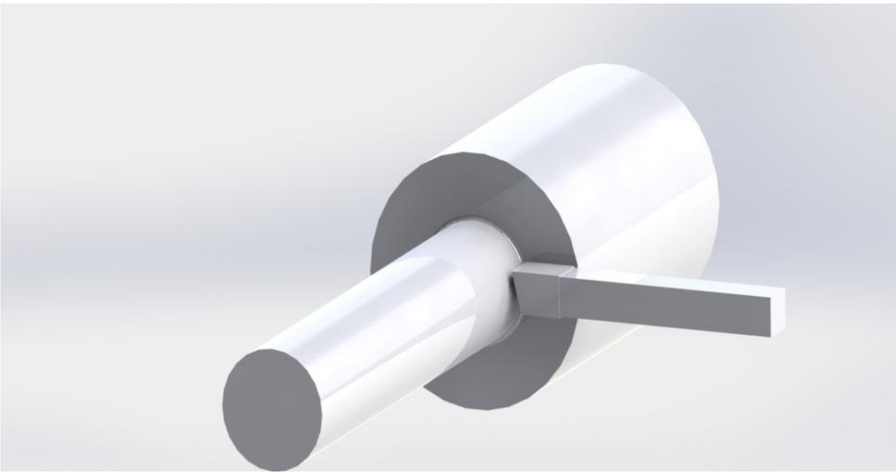

Fig. 1. Rendered picture of turning operation (Drawn in Solid Works 2013)

2. Literature Review

Traditionally, the selection of cutting conditions for metal cutting is left to the machine operator. In such cases, the experience of the operator plays a major role, but even for a skilled operator it is very difficult to attain the optimum values each time. The main machining parameters in metal turning operations are cutting speed, feed rate and depth of cut etc. The setting of these parameters determines the quality characteristics of turned parts. K. Palanikumar, *et al*. [4] discussed the application of the Taguchi method with fuzzy logic to optimize the machining parameters for machining of GFRP (Glass Fiber Reinforced Plastic) composites with multiple characteristics. A multi response performance index (MRPI) was used for optimization. The machining parameters like work piece (fiber orientation), cutting speed, feed rate, depth of cut, and machining time were optimized with consideration of multiple performance characteristics like metal removal rate, tool wear, and surface roughness. T. Srikanth and V. kamala [5] developed a real coded Genetic Algorithm (RCGA) approach for optimization of cutting parameters in turning. This RCGA approach is quite advantageous in order to have the minimum surface roughness values, and their corresponding optimum cutting parameters, for certain constraints [5]. S. S. Mahapatra *et al*. [6] an attempt has been made to generate a surface roughness prediction model and optimize the process parameters using Genetic algorithms. Adeel H. Suhail *et al* [7] conducted experimental study to optimize the cutting parameters using two performance measures, work piece surface temperature and surface roughness. Optimal cutting parameters for each performance measure were obtained employing Taguchi techniques. The orthogonal array, signal to noise ratio and analysis of variance were employed to study the performance characteristics in turning operation.

The experimental results showed that the work piece surface temperature can be sensed and used effectively as an indicator to control the cutting performance and improves the optimization process. T.G Ansalam Raj and V. N Narayanan Namboothiri [8] formed an improved genetic algorithm for the prediction of surface finish in dry turning of SS 420 materials.

Taguchi offers a simple and systematic approach to optimize a performance, quality and cost. The quality of design can be improved by improving the quality and productivity in various company-wide activities. Those activities concerned with quality include in quality of product planning, product design and process design (Park 1996, Ranjit 2001) [9] [10].

Taguchi's parameter design offers a simple and systematic approach which can reduce number of experiments to optimize design for performance, quality and cost. Signal to Noise(S/N) ratio and orthogonal array (OA) are two major tools used in robust design. S/N ratio measures quality with emphasis on variation, and OA accommodates many design factors simultaneously (Park 1996, Phadke 1998) [9] [11].

Tong L. *et al*. (1997), proposed a procedure in this study to achieve the optimization of multi-response problems in the Taguchi method which includes four phases, i.e. computation of quality loss, determination of the multi-response S/N ratio, determination of optimal factor/level condition and performing the confirmation experiment [12].

Ficici F. *et al*. (2011) have used the Taguchi method to study the wear behavior of bronzed AISI 1040 steel. They have used orthogonal array, S/N ratio and ANOVA to investigate the optimum setting parameters [13].

3. Methodology

3.1. Specification of Work Material

For performing turning operations ASTM A48 grey cast iron materials have been used. They were in the form of cylindrical bar of diameter 30mm and cutting length 67mm. The material composition of ASTM A48 grey cast iron has given below.

Table 1. Chemical Composition of ASTM A48 Grey Cast Iron

C	Si	Mn	Fe
3.40	1.80	0.50	Balanced

3.2. Process Parameters

Table 2. Process Parameter for Investigation

Level	Spindle Speed (s) (rpm)	Feed rate(f) (mm/rev)	Depth of cut(d) (mm)
1	112	0.125	0.25
2	175	0.138	0.30
3	280	0.153	0.35

3.3. Taguchi Method

The Taguchi experimental design method is a well-known, unique and powerful technique for product or process quality improvement. It is widely used for analysis of experiment and product or process optimization. Taguchi has developed a methodology for the application of factorial design experiments that has taken the design of experiments from the exclusive world of the statistician and brought it more fully into the world of manufacturing [14]. Traditional experimental design methods are very complicated and difficult to use. Additionally, these methods require a large number of experiments when the number of process parameters increases. In order to minimize the number of experiments required, Taguchi experimental design method, a powerful tool for designing high-quality system. This method uses a special design of orthogonal arrays to study the entire parameter space with minimum number of experiments [15]. Taguchi strategy is the conceptual framework or structure for planning a product or process design experiment

3.4. Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) is a statistical method for determining the existence of differences among several population means. While the aim of ANOVA is the detect differences among several populations means, the technique requires the analysis of different forms of variance associated with the random samples under study- hence the name analysis of variance. The original ideas analysis of variance was developed by the English Statistician Sir Ronald A. Fisher during the first part of this century. Much of the early work in this area dealt with agricultural experiments where crops were given different treatments, such as being grown using different kinds of fertilizers. The researchers wanted to determine whether all treatments under study were equally effective or whether some treatments were better than others [16].

ANOVA is used to determine the influence of any given process parameters from a series of experimental results by design of experiments and it can be used to interpret experimental data. Since there will be large number of process variables which control the process, some mathematical model are require to represent the process. However these models are to be developing using only the significant parameters which influences the process, rather than including all the parameters.

4. Experimentation and Mathematical Modeling

4.1. Choice of Orthogonal Array Design

The choice of a suitable orthogonal array (OA) design is critical for the success of an experiment and depends on the total degrees of freedom required to study the main and interaction effects, the goal of the experiment, resources and budget available and time constraints. Orthogonal arrays allow one to compute the main and interaction effects via a minimum number of experimental trials (Ross, 1988). ‘‘Degrees of freedom’’ refers to the number of fair and independent comparisons that can be made from a set of observations. In the context of SDOE, the number of degrees of freedom is one less than the number of levels associated with the factor. In other words, the number of degrees of freedom associated with a factor at *p*-levels is (*p*-1). As the number of degrees of freedom associated with a factor at two levels is unity. The number of degrees of freedom associated with an interaction is the product of the number of degrees of freedom associated with each main effect involved in the interaction (Antony, 1998) [2].

4.2. Mathematical Formulation and Experimental Data

The experiment is conducted for Dry turning operation (without cutting fluid) of using cast iron as work material and high speed steel as tool material on a conventional lathe machine. The tests are carried for a 67 mm length work material. The process parameters used as spindle speed (rpm), feed (mm/rev), depth of cut (mm). The response variable is material removal rate and the experimental results are recorded in Table 3. Material removal rate is calculated by following formula.

Let,

D_i = Initial diameter of the metal bar,

D_f = Final diameter of the metal bar,

L =Cutting length of workpiece,

t =time

π =3.1416(Constant value)

Now,

$$\textbf{Volume} = \pi/4L\,D^2_i - \pi/4L\,D^2_f$$
$$= \pi/4L\,(D^2_i - D^2_f)$$
$$= \pi/4L\,(D_i + D_f)\,(D_i - D_f)$$
$$= \pi\,L\,\{(D_i + D_f)/2\}\,\{(D_i - D_f)/2\}$$
$$= \pi\,L\,(\text{Average diameter})\,(\text{Depth of cut})$$

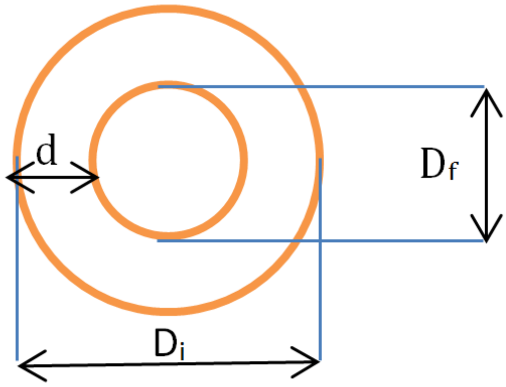

Fig. 2. Schematic view of cutting section.

From Fig. 1,

$$D_i - D_f = 2d \qquad [\text{Where, } d = \text{Depth of cut}]$$
$$\Rightarrow \quad d = (D_i - D_f)/2$$

And,

$$(D_i + D_f)/2 = \text{Average diameter of the cutting section} = D_{avg}$$

So, **Experimental formula for M.R.R**

$$= \frac{\pi \times L \times d \times D_{avg}}{t} \quad \text{mm}^3/\text{sec} \tag{1}$$

Creating orthogonal arrays for the parameter design indicates the number of condition for each experiment. The selection of orthogonal arrays is based on the number of parameters and the level of variation for each parameter.

For the maximum material removal rate, the solution is "Larger is better" and S/N ratio is determined according to the following equation:

$$S/N = -10 \log_{10} \{n^{-1} \sum y^{-2}\} \quad (2)$$

where,

S/N = Signal to Noise Ratio,
n = No. of Measurements,
y = Measured Value

(a)

(b)

Fig. 3. (a) Cast iron after turning operation (b) High speed steel (HSS) cutting tool

From the Table 3 it is seen that at the same spindle speed and feed rate, the time should be longer with depth of cut deeper but it is opposite in this table because it is actual experimental value & cutting fluid is not used. In this experiment, at first the tip of the cutting tool was sharp, but after continuous turning operation it was gradually blunted. So the blunted tip is the reason for the fluctuation of time during metal removal operation.

Table 3. Experimental Data and Results for L27 Orthogonal Array

Exp no.	Spindle speed (rpm)	Feed rate (mm/rev)	Depth of cut (mm)	Time t(sec)	Initial dia, D_i (mm)	Final dia, D_f (mm)	Average dia, D_{avg} (mm)	Metal removal rate, MRR (mm^3/s)
1.	112	0.125	0.25	458	29.70	29.20	29.45	3.38
2.	112	0.125	0.30	455	29.20	28.60	28.90	4.01
3.	112	0.125	0.35	457	28.60	27.90	28.25	4.55
4.	112	0.138	0.25	439	27.90	27.40	27.65	3.31
5.	112	0.138	0.30	435	27.40	26.80	27.10	3.93
6.	112	0.138	0.35	438	26.80	26.10	26.45	4.45
7.	112	0.153	0.25	421	26.10	25.60	25.85	3.23
8.	112	0.153	0.30	418	25.60	25.00	25.30	3.82
9.	112	0.153	0.35	420	25.00	24.30	24.65	4.32
10.	175	0.125	0.25	276	24.30	23.80	24.05	4.59
11.	175	0.125	0.30	271	23.80	23.20	23.50	5.48
12.	175	0.125	0.35	274	23.20	22.50	22.85	6.14
13.	175	0.138	0.25	248	22.50	22.00	22.25	4.72
14.	175	0.138	0.30	245	22.00	21.40	21.70	5.59
15.	175	0.138	0.35	247	21.40	20.70	21.05	6.28
16.	175	0.153	0.25	225	20.70	20.20	20.45	4.78
17.	175	0.153	0.30	221	20.20	19.60	19.90	5.69
18.	175	0.153	0.35	223	19.60	18.90	19.25	6.36
19.	280	0.125	0.25	185	18.90	18.40	18.65	5.30
20.	280	0.125	0.30	181	18.40	17.80	18.10	6.31
21.	280	0.125	0.35	183	17.80	17.10	17.45	7.02
22.	280	0.138	0.25	166	17.10	16.60	16.85	5.32
23.	280	0.138	0.30	163	16.60	16.00	16.30	6.31
24.	280	0.138	0.35	164	16.00	15.30	15.65	7.03
25.	280	0.153	0.25	145	15.30	14.80	15.05	5.46
26.	280	0.153	0.30	142	14.80	14.20	14.50	6.45
27	280	0.153	0.35	144	14.20	13.50	13.85	7.09

Table 4. Response Table of Means for MRR of Cast Iron

Level	Spindle speed	Feed rate	Depth of cut
1.	3.89	5.20	4.46
2.	5.51	5.22	5.29
3.	6.26	5.24	5.92

The mean value of the cutting parameters are shown in the Table 4, and this is used to calculate the analysis of variance (ANOVA) which is shown in the Table 5.

Table 5. ANOVA for the Response Metal Removal Rate

Source	Degree of freedom	Sum of square	Mean of square	F ratio	% of contribution
Spindle speed	2	26.37	13.19	62.81	72.35
Feed rate	2	0.0072	0.0036	0.017	0.02
Depth of cut	2	9.65	4.83	23.00	26.48
Error	2	0.42	0.21		1.15
Total	8	36.45			100

From the above Table 5, it is observed that the spindle speed (72.35%), depth of cut (26.48%) have great influence on metal removal rate. The parameter feed rate (0.02%) has small influence. Since this is a parameter based optimization design, from the above values it is clear that spindle speed (72.35%) is the prime factor to be effectively selected to get the effective material removal rate.

Design of experiment for material removal rate L9 orthogonal array is prepared by carrying out a total number of 9 experiments along with 2 verification (X and Y data) experiments. For Y data, 9 set of new experiments is conducted in terms of data representation of Table 6. In L9 array 9 rows represent the 9 experiment to be conducted with 3 columns at 3 levels of the corresponding factor. The matrix form of this array is shown in Table 6.

Classical experimental design methods are too complex and are not easy to use a large number of experiments have to be carried out when the number of process parameters increases. To solve this problem, the Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with only a small number of experiments [8].

Table 6. Calculation of Signal to Noise Ratio for MRR

Exp. No	Parameters level			MRR (mm^3/s)		Signal to noise ratio (S/N ratio)
	Spindle speed	Feed rate	Depth of cut	X	Y	
1.	112	0.125	0.25	3.38	3.43	39.67
2.	112	0.138	0.30	3.93	3.96	45.39
3.	112	0.153	0.35	4.32	4.36	43.72
4.	175	0.125	0.30	5.48	5.51	48.27
5.	175	0.138	0.35	6.28	6.30	52.96
6.	175	0.153	0.25	4.78	4.82	44.59
7.	280	0.125	0.35	7.02	7.04	53.93
8.	280	0.138	0.25	5.34	5.37	48.04
9.	280	0.153	0.30	6.45	6.46	53.19

The experimental data for the metal removal rate values and the calculated signal-to-noise ratio are shown in Table 6. The S/N ratio values of the material removal rate are calculated, using higher the better characteristics. Conceptual S/N ratio approach of Taguchi method provides a simple, systematic and efficient methodology for optimizing of process parameters and this approach can be adopted rather than using engineering judgment. This implies that engineering systems behave in such a way that the manipulated production factors that can be divided into three categories:

1) Control factors, which affect process variability as measured by the S/N ratio.
2) Signal factors, which do not influence the S/N ratio or process mean.
3) Factors, which do not affect the S/N ratio or process mean.

In practice, the target mean value may change during the process development applications in which the concept of S/N ratio is useful are the improvement of quality through variability reduction and the improvement of measurement. The S/N ratio characteristics can be divided into three categories when the characteristic is continuous: nominal is the best, smaller the better and larger is better characteristics. Based on Taguchi prediction that the bigger different in value of S/N ratio shows a more effect on material removal rate or more significant. Therefore, it can be concluded that, augmentation of the spindle speed increases the metal removal rate significantly and it is shown in Table 7. Here delta is the difference between the maximum and minimum value of signal to noise ratio for each parameter. The highest delta value is ranked as first parameter which possesses the maximum influence in metal removal rate of ASTM A48 grey cast iron.

Table 7. Response Table for Signal to Noise Ratio for MRR

level	Spindle speed	Feed rate	Depth of cut
1.	42.93	47.29	44.22
2.	48.61	48.80	48.95
3.	51.72	47.17	50.20
Delta(max-min)	8.79	1.63	5.98
Rank	1	3	2

From Table 7 it is clear that the spindle speed is the most significant parameter for maximizing metal removal rate as its rank is first.

5. Results and Discussions

5.1. Equation for Optimization of Metal Removal Rate

From the linear regression analysis (running a program in Minitab 17) the following equation has derived:

MRR= -1.92+0.0134*(Spindle speed) +1.67*(Feed rate) + 14.60*(Depth of cut)

5.2. Graphical Representation

In the above experimental results, two techniques of data analysis have been used. Both techniques draw similar conclusions. The spindle speed has found to be the most significant effect to produce high value of average metal removal rate (MRR). The explanation for the influence of cutting speed on metal removal rate is still not available. This could be explained in terms of the velocity of chips that is faster at high cutting speed than at low cutting speed. This leads to a shorter time for the chips to be in contact with the newly formed surface of workpiece and the tendency for the chips to wrap back to the new face form is little as compared to low speed. The condition of seizure and sub layer plastic flow occurred at high speed and the term flow-zone is used to describe secondary deformation in this range [17]. The time taken for the chips at this flow-zone for high speed cutting is short as compared to lower speed, as the velocity of chip is faster [18]. The use of S/N ratio for selecting the best levels of combination for metal removal rate (MRR) value suggests the use of high value of spindle speed in order to obtain good removal rate. Therefore, it is preferable to set the depth of cut to a high value. From the Table 3 it is clear that the optimal cutting parameters are level 3 of spindle speed, feed rate, and depth of cut in Table 2 to obtain good quantity of metal removal rate (MRR) and which is also indicated in Table 8. From the result, the interaction of spindle speed and depth of cut is more important than the effect of the individual factors. In other words, in order to get the best result it requires experience to combine these two factors to achieve a suitable combination of spindle speed and depth of cut. Form the graph of the Minitab it is clear that spindle speed have the maximum influence for high metal removal rate.

Table 8. Optimal Sequence for Maximum MRR

Spindle speed	Feed rate	Depth of cut	Metal removal rate (MRR)
280	0.153	0.35	7.09

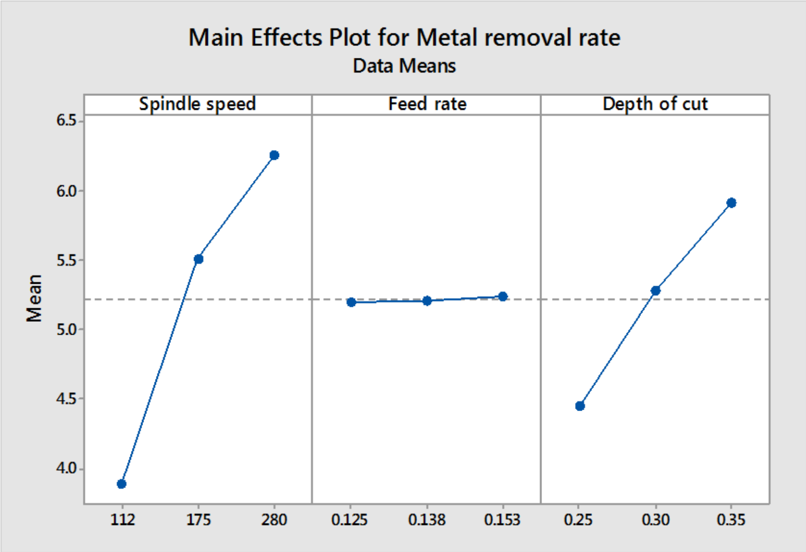

Fig. 4. Main effects plot of mean value for metal removal rate

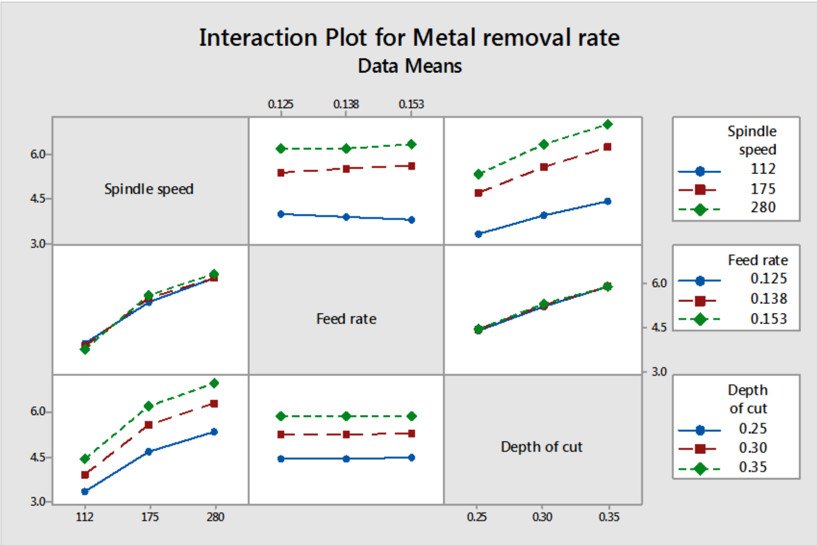

Fig. 5. Interaction plot for metal removal rate

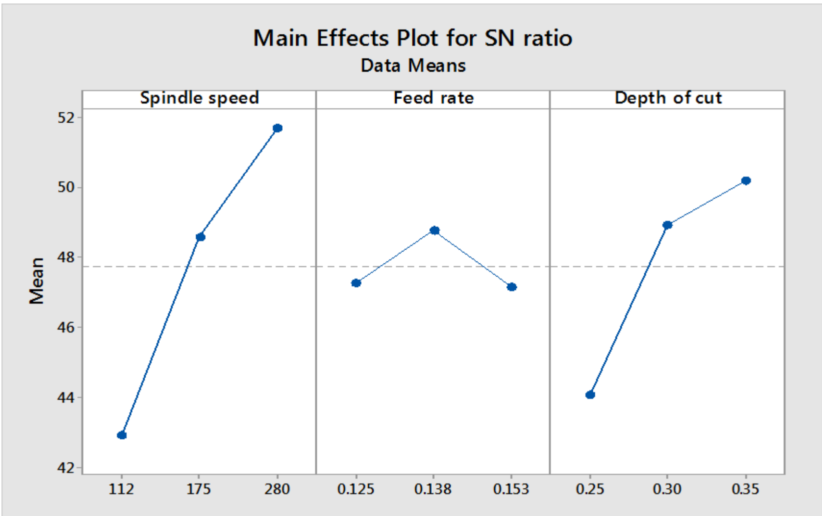

Fig. 6. Main effects plot of mean value for S/N ratio

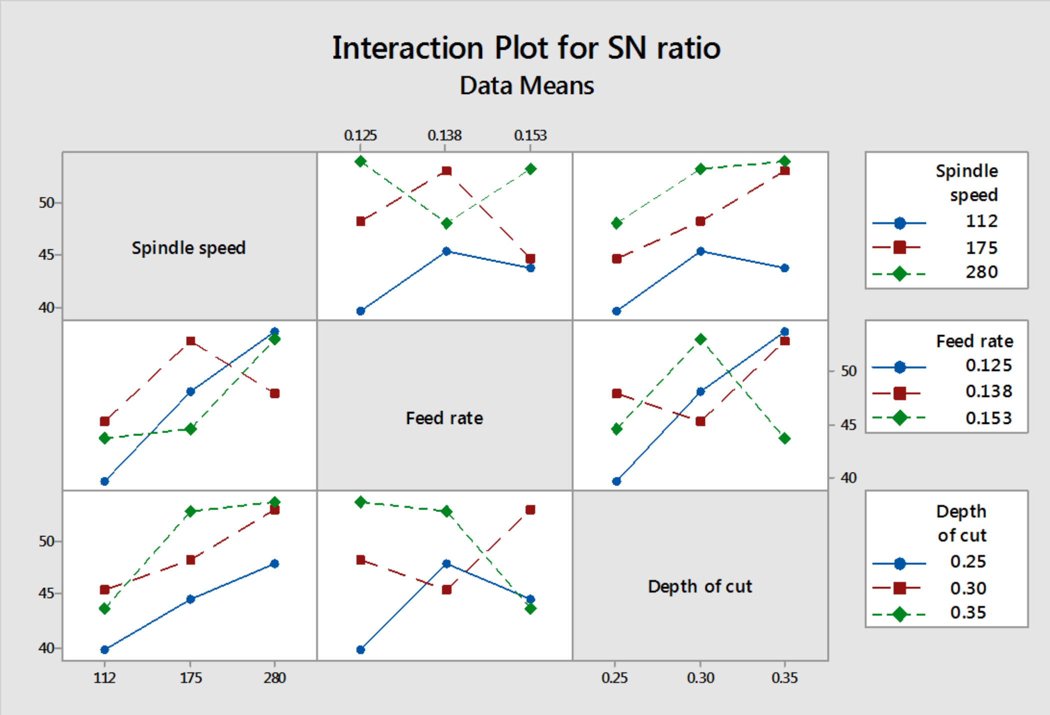

Fig. 7. Interaction plot for S/N ratio

6. Scope of Future Work

Some recommendations are given below:

1) The verification of the model for MRR may be developed by using other parameters.
2) Same analysis can be conducted for milling, facing, drilling, grinding and other metal removing processes.
3) Optimization of cutting parameters may be done by Fuzzy Logic and genetic algorithm.
4) Same analysis may be done for other materials (like Copper, Brass and Aluminum etc.).
5) Consideration of tool wear, surface roughness, and power consumption may be done.
6) Cutting fluids or lubricants are not used in this project work, cutting fluids can be used.

7. Conclusion

This paper illustrates the application of the parameter design (Taguchi method) in the optimization of metal removal rate of ASTM A48 grey cast iron in turning operation. ANOVA is required to know the contribution of each factors and their quantitative percentage during operation. To get the accurate percentage of contribution L27 orthogonal array is used in ANOVA analysis whereas for Taguchi's method L9 orthogonal array is used. Taguchi's method of parameter design can be performed with lesser number of experimentations and for this reason 9 consecutive experiments (L9 in Taguchi's method) have taken instead of 27 consecutive experiments (L27 in ANOVA). For both ANOVA and Taguchi's method, same result has been found that the spindle speed is the most significant parameter. The percentage of contribution of the spindle speed parameter is 72.35% in ANOVA analysis and the spindle speed is the first rank in Taguchi's method. Taguchi's method can be applied for analyzing any other kind of problems as described in this paper. It is found that the parameter design of the Taguchi method provides a simple, systematic, and efficient methodology for optimizing the process parameters and it is one of the most effective tools in the field of optimization problem solution.

Nomenclature

s : Spindle speed, rpm.
f : Feed rate, mm/rev.
d : Depth of cut (DOC), mm.
D_i : Initial diameter of the metal bar, mm.
D_f : Final diameter of the metal bar, mm.
L : Cutting length of workpiece, mm.
t : time, sec.
D_{avg} : Average diameter of the cutting section, mm.
M.R.R. : Metal removal rate, mm^3 /sec.
S/N ratio : Signal to noise ratio.
X : Metal removal rate for first stage.
Y : Metal removal rate for second stage

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