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RESEARCH PAPER

EXPERIMENTAL PREDICTION AND OPTIMIZATION OF MATERIAL REMOVAL RATE DURING HARD TURNING OF AUSTENITIC 304L STAINLESS STEEL

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ABSTRACT

This work involves a predictive model for material removal rate (MRR). It investigates the influence of machining process parameters such as cutting speed, feed rate and depth of cut on the material removal rate (output parameter) during hard turning of AISI 304L austenitic stainless steel (0.03 wt. % C (max)). A total of 27 experiments were conducted using a MORI SEIKI SL-253B CNC machine with cemented carbide cutting tool under three different spindle speeds (1000, 1200, 1400rev/min), feed rates (0.05, 0.10, 0.15mm/rev) and depths of cut (0.4, 0.8, 1.2mm). The machining parameter settings were determined using the Taguchi experimental design method. The Taguchi method and relationship between MRR and input parameters were arrived at through MINITAB16 software package. The optimum machining parameters combination was obtained by using larger-the-better analysis of signal-to-noise (S/N) ratio. The optimal cutting condition is at spindle speed level 2 (1200 rpm); feed rate at level 3 (0.15mm/rev) and Depth of cut at level 3 (1.2 mm) which gave an optimum MRR of 77.80243mm^3/min. The S/N ratio response table, main effect plots and the relationship between cutting parameters and the MRR was obtained. A mathematical model was developed using multiple regression analysis to predict MRR during hard turning of AISI 304L austenitic stainless steel. The level of importance and performance characteristics of the machining parameters on MRR was determined by using analysis of variance (ANOVA). From the results, the feed rate had the most significant effects on the MRR followed by depth of cut.The spindle speed has the least effect on MRR. It was also revealed that the predicted results found a good correlation with the experimental results as the regression line fits well for both results data at 95% confidence interval.

Keywords: *Machining, material removal, optimization*

INTRODUCTION

In order to respond effectively to the increasing demand for quality products, manufacturing units must adopt optimization techniques in metal cutting processes. In view of this, several considerations such as production process, production time reduction, process development and eco-friendliness among others must be met. Several manufacturing enterprises have made efforts to increase their competitiveness through adjustment of machining factors such as tool preparation, replacement and regrinding times, ordering time etc. Tonshoff *et al.* (1995) stated that hard turning offers a 60% reduction in time as compared to the grinding time. With this, it is advantageous to replace finish grinding with hard turning operations. The main aim of hard turning is to remove work piece material in a single cut compared to lengthy grinding operations. This ensures reduction of processing time, production cost, surface roughness and setup time in order to remain competitive and maximize profits. Tonshoff *et al.* (1996) found that MRR in hard turning can be much higher than in grinding for various applications. The need for grinding is not eliminated by hard turning, but it relieves the production challenges on the more expensive grinders in rightly chosen applications (Konig *et al.*, 1993).

It should be kept in mind that cutting force is the important technological response parameter to be controled in machining processes. It is the main parameter that influences the evaluation of the necessary power for machining, dimensioning of machine tool components and tool body. Korkut and Donertas (2007) discovered that when cutting AISI 1020 and AISI 1040 steel, increase in the cutting speed increases the cutting forces.

Nithyanandhan (2014) investigated the effects of process parameters on surface finish and MRR. Analysis of variance (ANOVA) was used to analyze the influence of cutting parameters during machining. Using tungsten carbide tool, AISI 304 austenitic stainless steel was turned on conventional Lathe. It was revealed that the feed and nose radius were the most significant process parameters on the work-piece surface roughness. However, the depth of cut and feed were the significant factors on MRR.

Ramakrishna and Karanam (2015) investigated and analyzed the effect of cutting parameters in CNC turning of aluminum. The experiments were conducted on aluminum work piece on a CNC turning machine using carbide insert. Initial trial experiments were conducted to fix the ranges for the control parameters. After conducting the experiments the MRR was measured and recorded. The effects were studied after plotting the graphs between the input process parameters and the output response. It was concluded that as the spindle speed, feed rate and depth of cut increased the removal of material per unit time also increased. The chips removed per unit time increased and consequently the quantity of material removed also increased. As the depth of cut increases, the cutting force increases thereby increasing the removal of material. In interactive effect the best condition for maximum MRR is obtained by keeping feed rate constant and increasing the depth of cut.

Tejas *et al.* (2014) carried out investigation on analysis and prediction of milling process on vertical milling center (VMC) by using response surface methodology (RSM). Face milling parameters were analyzed to determine their significance on mild steel by design of experiments (DOE) while employing response surface method designs to obtain response parameters (MRR and surface roughness). The effects of the following three parameters: spindle speed, depth of cut and feed were investigated upon following two performance measures: MRR and surface roughness on material of mild steel. The experimental results were analyzed using ANOVA and the significance of effects of all the tested parameters upon performance measures was determined. Empirical models for tensile strength and distortion, in terms of significant parameters, were developed and numerical optimization was performed according to the desirability for the maximization of tensile strength and minimization of distortion. The results revealed that depth of cut and feed rate have greater combined effect on MRR.

Rajesh *et al*. (2014) investigated the effect of the spindle speed, feed rate and depth of cut on MRR, in turning of AISI 1045 steel using uncoated cutting tool in dry conditions. The machining condition parameters were the spindle speed of 600, 800 and 1000 rpm, feed rate of 0.5, 1.0 and 1.5 mm/rev, and depth of cut (DOC) of 0.15, 0.20 and 0.25 mm. The effects of cutting parameter on MRR were studied and analyzed. Experiments were conducted based on the Taguchi design of experiments (DOE) with orthogonal L9 array, and then followed by optimization of the results using ANOVA to find the maximum MRR. The optimum MRR was obtained when setting the cutting parameter at high values. FEM based Deform-3D was used to validate the results with experiments. The results obtained for MRR using the proposed simulation model were in agreement with the experiments.

Yang and Tarng (1998) discussed the application of Taguchi method for optimization of cutting parameters in turning operations. The Taguchi method offers a systematic and efficient methodology for the design optimization of the cutting parameters with appreciably less effect than required for most optimization techniques.

Sijo and Biju (2011) stated that several conventional techniques had been used for solving machining optimization problems, but they lack robustness and have issues when applied to the turning process, which involves a number of variables and constraints. The Taguchi method is therefore used to overcome the numerous problems in this work. In this study, the major factor affecting surface finish was feed rate. Hard machining was also employed to increase the MRR and at the same time keep the quality of machined parts in accordance with the design specification.

Traditional methods of machining hard-to-wear materials like AISI 304L austenitic stainless steel include grinding, which is a time-consuming metal cutting process. Hard turning is capable of giving better surface finish, increasing tool life, and achieving high metal removal in less time. Therefore it will be of great benefit to the manufacturing industry to have a predictive model for MRR during hard turning of AISI 304L stainless steel. This will increase the utility for machining economics, increase product quality appreciably and ultimately reduce manufacturing cost. The MRR during a turning operation is the product of cutting speed, feed rate and depth of cut. Therefore, if MRR is to be maximized, then a proper selection of these three cutting parameters is required. In Identifying the significance of the cutting parameters (spindle speed, feed rate and depth of cut) in relation to the MRR, an attempt is made in this work to study the effect of the three cutting parameters on MRR during the hard turning of AISI 304L austenitic stainless steel.

MATERIALS AND METHODS

Materials

The materials used for this research work are lathe machine (MORI SEIKI SL-235B/500) with rated power of 28kVA, cemented tungsten carbide cutting tools(with composition 87.70% W, 2.90% Ti, 5% Ta, 5% Co, 0.40% C), power saw, vernier caliper, meter rule, and AISI 304L austenitic stainless steel rods. The stainless steel was purchased from Orile market Surulere, Lagos and the carbide tool was obtained from the factory work-shop of Nestle Nigeria Plc., where the experiment was performed.

The following process parameters were used:

Spindle speed of 1000rpm, 1200rpm and 1400rpm.

Feed rate of 0.05mm/rev, 0.10mm/rev and 0.15mm/rev.

Depth of cut of 0.4mm, 0.8mm, and 1.2mm

Experimental procedures

The CNC lathe was checked and prepared ready for performing the machining operations.The stainless steel rod was cut with power saw and initial turning operation was performed on the lathe to obtain the desired dimension of the work pieces (length-50mm; diameter-20mm). Twenty-seven samples of the same material and dimensions were prepared from the steel rod. The weight of each specimen was measured by the high precision digital balance before machining. Plate 1 shows some of the samples before they were machined.Straight turning operation was performed on the specimens involving various combinations of process parameters such as spindle speed (1000, 1200 and 1400rpm), feed (0.05, 0.10, and 0.15mm/rev) and depth of cut (0.4, 0.8, and 1.2mm). The time taken to machine each specimen was recorded. The final weight of each machined sample was measured again by the digital balance and recorded.

The levels of the cutting parameters for subsequent design of experiment, based on Taguchi's L_{27} orthogonal array (OA) design were selected. In the experiment, spindle speed, feed rate, and depth of cut were considered as process variables. The process variables are as listed in Table 1.

The experiments were carried out using Taguchi's L_{27} orthogonal array (OA) experimental design which consists of 27 com-

Plate 1: Sample specimens of AISI 304L stainless steel before machining

Table 1: Process variables and their limits

Code	Spindle speed, rpm	Feed, mm/rev	Depth of cut, mm
-1	1000	0.05	0.4
0	1200	0.10	0.8
+1	1400	0.15	1.2

binations of spindle speed, feed, and depth of cut. This method employs a generic signal-to-noise (S/N) ratio to quantify the present variation. The commercial software MINITAB16 was used to analyze the main effect of signal-to-noise (S/N) ratio to achieve the multi-objective features of the optimization analysis for MRR.

For each revolution of the work piece, a ring layer of material is removed. The MRR was calculated from the difference of weight of work piece before and after the experiment as

$$MRR = (w_i - w_f)/\rho t, \text{ mm}^3/\text{min} \qquad (1)$$

Where, w_i is the initial weight of work piece in "g", w_f is the final weight of work piece in "g", t is the machining time in minutes and ρ is the density of the material in g/mm^3 as described by Kaladhar *et al* (2012).

ANALYSIS OF RESULTS AND DEVELOPMENT OF EMPIRICAL MODEL FOR MRR

The results of the experiment for MRR are presented in Table 2. The signal-to-noise (S/N) ratio recorded in the table are all positive values. This implies that the MRR is maximized. These data are employed in the determination of direct effect of each of the machining parameters on the MRR. The plots

Table 2: Experimental results for MRR and corresponding S/N ratio

Exp. No.	Spindle speed (N), rpm	Feed (f), mm/ rev	Depth of cut (d), mm	MRR, mm^3/min	S/N ratio (dB)
1	1000	0.05	0.4	9.9957	19.9963
2	1000	0.10	0.8	35.6778	31.0480
3	1000	0.15	1.2	65.5823	36.3357
4	1200	0.05	0.4	11.9466	21.5449
5	1200	0.10	0.8	39.3812	31.9058
6	1200	0.15	1.2	77.8024	37.8199
7	1400	0.05	0.4	14.1634	23.0234
8	1400	0.10	0.8	43.6677	32.8032
9	1400	0.15	1.2	84.1570	38.5018
10	1000	0.05	0.8	20.6787	26.3105
11	1000	0.10	1.2	50.4341	34.0545
12	1000	0.15	0.4	27.7797	28.8745
13	1200	0.05	0.8	22.7486	27.1391
14	1200	0.10	1.2	48.6968	33.7500
15	1200	0.15	0.4	38.0996	31.6184
16	1400	0.05	0.8	25.8896	28.2625
17	1400	0.10	1.2	65.5692	36.3340
18	1400	0.15	0.4	32.1839	30.1528
19	1000	0.05	1.2	27.2909	28.7204
20	1000	0.10	0.4	21.3235	26.5772
21	1000	0.15	0.8	48.6785	33.7467
22	1200	0.05	1.2	32.1390	30.1406
23	1200	0.10	0.4	21.2121	26.5317
24	1200	0.15	0.8	54.2978	34.6956
25	1400	0.05	1.2	37.2215	31.4159
26	1400	0.10	0.4	25.5978	28.1640
27	1400	0.15	0.8	62.4241	35.9071

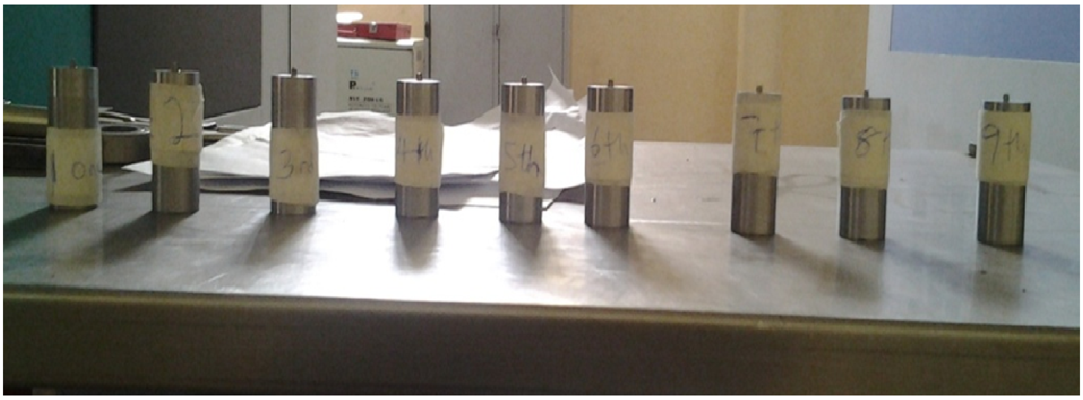

Plate 2: The AISI 304L stainless steel after machining

of combined effect and the interactive effect of the parameters are also obtained and discussed. Some of the machined samples are presented in Plate 2.

Effect of spindle speed and depth of cut on MRR at constant feed rate

Fig. 1 shows the effect of spindle speeds of 1000, 1200, and 1400rpm on MRR for all values of the feed rate of 0.05, 0.10, and 0.15mm/rev. As the spindle speed increased from 1000rpm up to 1400rpm, the MRR increased from 9.996mm^3/min to 37.222mm^3/min, approximately 272.4% increase in MRR at constant feed of 0.05mm/rev. It can be seen that high MRR is obtained with a combination of spindle speed 1400rpm and feed 0.05mm/rev (see Fig. 1a). This agrees with the results obtained by Deepak *et al.* (2011) which states that the cutting variables (spindle speeds; feed rate) have a major effect on the MRR. The same trend was observed at feed rate of 0.10mm/rev(Fig. 1b). As the spindle speed increased from 1000rpm up to 1400rpm, the MRR increased from 21.32348mm^3/min to 65.56919mm^3/min (i.e. 207.5% increase). This showed that as the spindle speed increases, the velocity increases and the cutting force increases resulting in more material removal. As a result of the stated conditions, the material experiences increased shear stress in creating the chips and more volume of material is removed. At 0.15mm/rev feed rate (Fig. 1c), the MRR increased appreciably from 27.77967mm^3/min to 84.15699mm^3/min, approximately 202.9% as the spindle speed increased. The decreasing trend in the percentage increase in MRR as the spindle speed increased occurs because at high speed and high feed rate, lubricating effect is reduced (Thiele and Melkote, 1999) and the temperature of the tool-tip is elevated. This causes chips to be welded to the tool-tip and vibration of the system is pronounced leading to system imbalance, discontinuous chip formation, tool failure and hence decrease in MRR.

Effect of feed rate and depth of cut on MRR at constant spindle speeds

Fig. 2 shows the effect of feed rate (0.05, 0.10, 0.15mm/rev) on material removal rate (MRR) for all values of spindle speeds (1000, 1200, 1400rpm). As the feed rate increased from 0.05mm/rev up to 0.15mm/rev, the MRR increased from 9.99572mm^3/min to 65.58232 mm^3/min at constant spindle speed of 1000rpm, approximately 556.1% increase in MRR(Fig. 2a). This is because at the higher feed rate, there is more contact between the cutting tool and the work piece, so there are larger volumes of deformed material being removed in the machining process. This agrees with Rajesh *et*

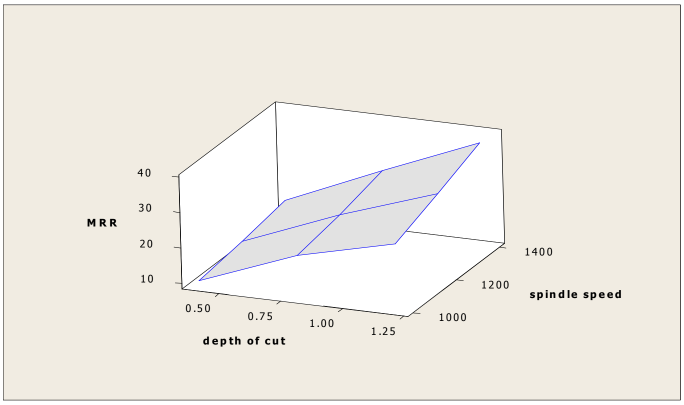

Fig. 1a: Effect of spindle speed on MRR at constant feed rate of 0.05mm/rev

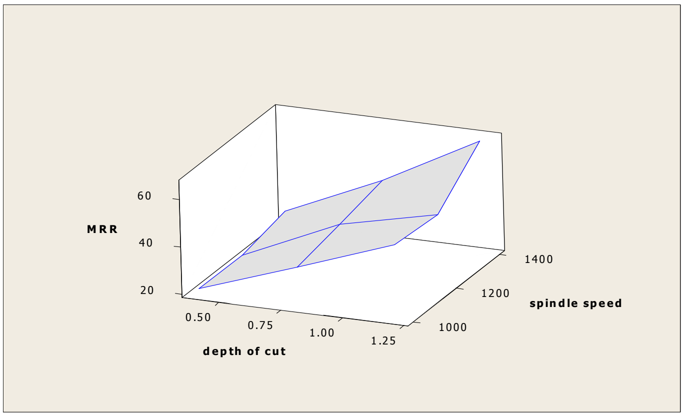

Fig. 1b: Effect of spindle speed on MRR at constant feed rate of 0.10mm/rev

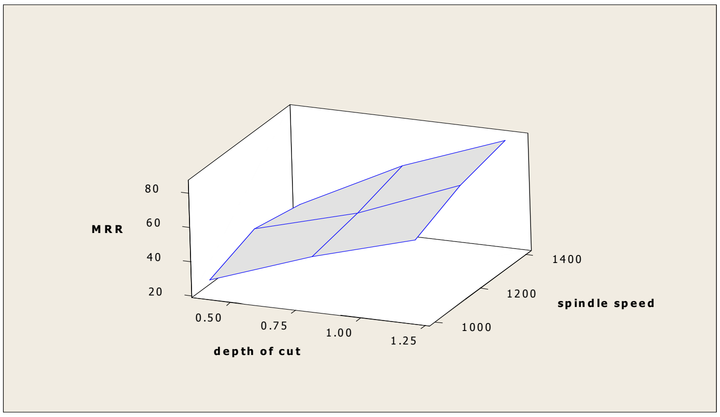

Fig. 1c: Effect of spindle speed on MRR at constant feed rate of 0.15mm/rev

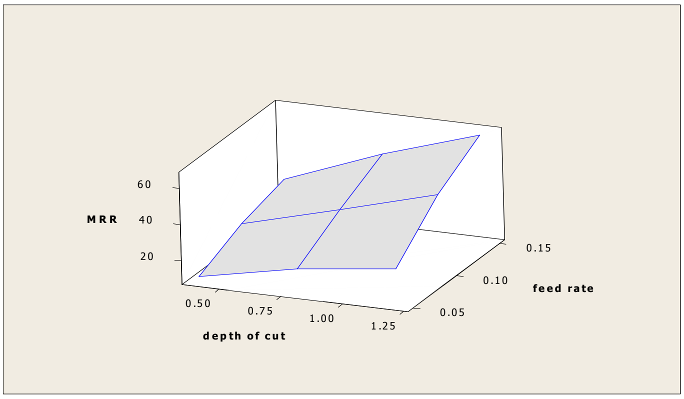

Fig. 2a: Effect of feed rate on MRR at constant spindle speed of 1000rpm

Fig. 2b: Effect of feed rate on MRR at constant spindle speed of 1200rpm

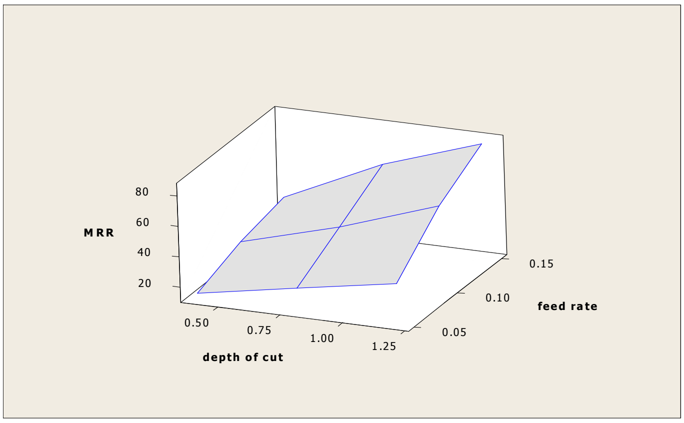

Fig. 2c: Effect of feed rate on MRR at constant spindle speed of 1400rpm

al. (2014) that increase in feed rate gives higher MRR. The same trend was observed at a spindle speed of 1200rpm, as the feed rate increased from 0.05mm/rev to 0.15mm/rev(Fig. 2b). The MRR increased from 11.94661mm^3/min to77.80243mm^3/min i.e. 551.3% increment. Subsequently as the feed rate increased from 0.05mm/rev to 0.15mm/rev at a constant spindle speed of 1400rpm (Fig. 2c), the MRR increased from 14.1634mm^3/min to 84.15699mm^3/min, which is an increase of 494.2%. The decreasing trend in the percentage increase in MRR occurs because at high feed rate and spindle speed there is larger contact area resulting in high temperature effects. Larger contact area resulted in more friction that generated more heat at the tool-chip interface, thus decreasing tool life, leading to poor machining and hence a drop in the MRR.

Interactive effect of machining parameters on MRR

Fig. 3 displays full interaction plot matrix for the MRR. This combines the effects of all the independent variables in a single chart as shown in Fig 3. It can be seen that there are significant interactions with significant effects (i.e. the removal of more volume of materials in less time as the cutting parameters are increased in direct effect and in interaction effects) between the cutting parameters and the MRR.

Main effect plot for the signal-to-noise (S/N) ratio and MRR

The effect of each of these factors is calculated by determining the range (delta) as shown in the S/N response table for means (Tables 3-4). The cutting feed has the largest effect on the

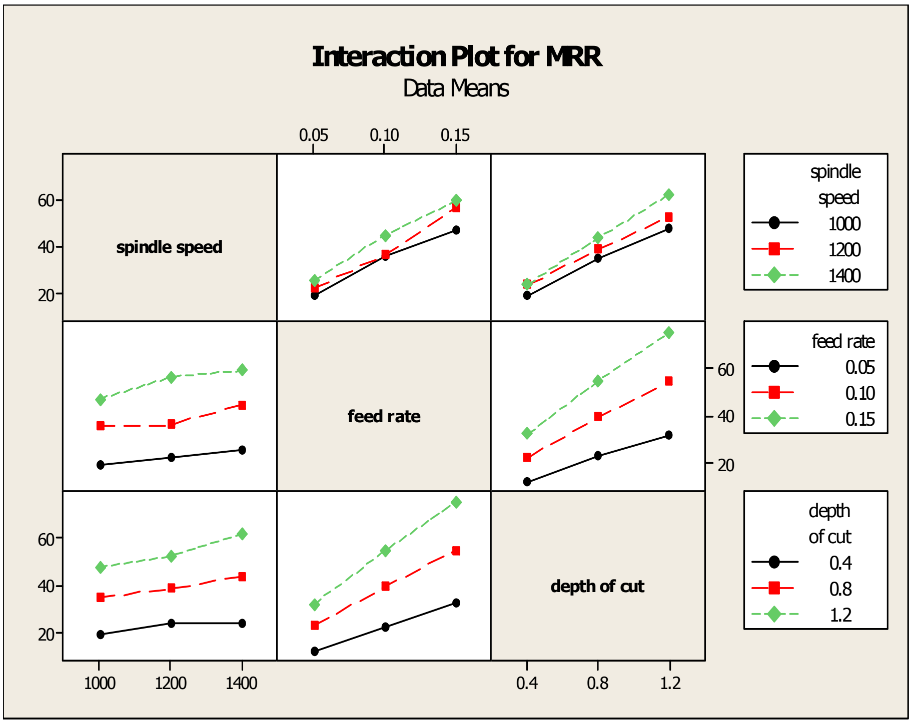

Fig. 3: Interaction plot for MRR

Table 3: Response table for signal to noise ratios (larger is better)

Level	Spindle speed	Feed rate	Depth of cut
1	29.52	26.28	26.28
2	30.57	31.24	31.31
3	31.62	34.18	34.12
Delta	2.10	7.90	7.84
Rank	3	1	2

Table 4: Response table for means (MRR)

Level	Spindle speed	Feed rate	Depth of cut
1	34.16	22.45	22.48
2	38.48	39.06	39.27
3	43.43	54.56	54.32
Delta	9.27	32.10	31.84
Rank	3	1	2

MRR followed by the depth of cut and then the spindle speed has the smallest effect on the MRR. This agrees with work done by Davim (2011) who had earlier reported that depths of cut and feed rate are the significant factors on MRR.

This analysis of interaction of the S/N ratio to MRR with process parameters was made with the aid of MINITAB 16 software. The main effect plots are as shown in Figs 4a and 4b. These show the variation of an individual response variable with changes of three parameters i.e. cutting speed, feed, and depth of cut separately. The main effect plots are used to determine optimal design conditions, to obtain optimum MRR. According to the main effect plots shown, the optimal condition for optimum MRR are: spindle speed (1400 rpm); feed rate (0.15mm/rev); and depth of cut (1.2 mm). This combination gives optimum MRR of 77.80243mm^3/min.

Multiple regressions modeling of MRR

Using multiple regression analysis, a mathematical model was developed to predict MRR by relating it with the machining process parameters. This model was set at 95% confidence interval and 0.05 significance level. In this case the MRR is a linear function of three independent variables which are spindle speed (N), feed (f) and depth of cut (d). This is a multiple linear regression and MRR is a linear function of N, f, and d as represented by equation (2)

$$MRR = a_0 + a_1 N + a_2 f + a_3 d + e \qquad (2)$$

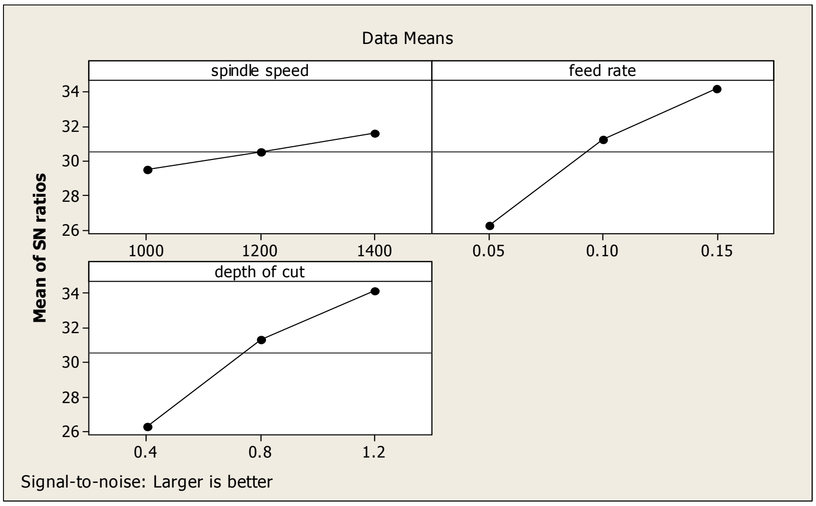

Fig. 4a: S/N ratio main effect plot for material removal rate

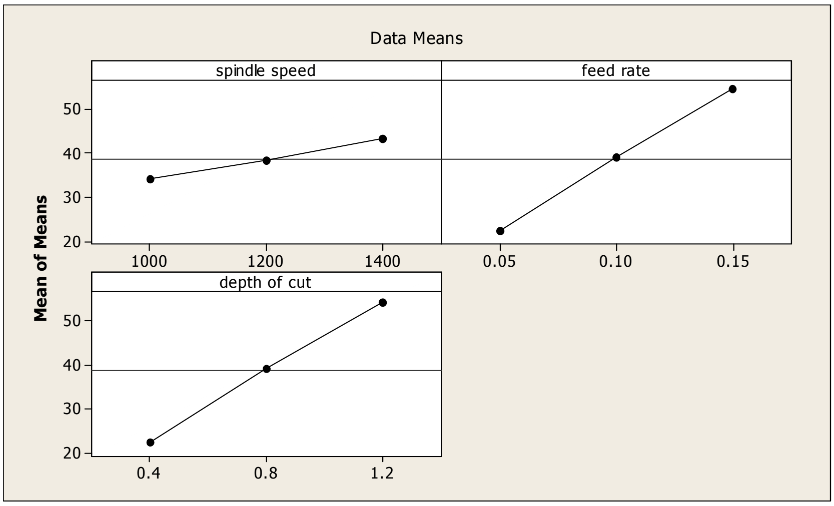

Fig. 4b: Means main effect plot for MRR

Where, *e* denotes error associated with experimental data or residuals and it quantifies the discrepancy between the function and the predicted model.

The best values of the coefficients of the variables are determined by formulating the sum of squares of the residuals:

$$S_r = \sum_{i=1}^{m} (MRR_i - a_0 - a_1 N_i - a_2 f_i - a_3 d_i)^2 \quad \text{(Chapra, 2006)} \tag{3}$$

Differentiating with respect to each of the unknown coefficients we have:

$$\frac{\partial S_r}{\partial a_0} = -2\sum(MRR_i - a_0 - a_1N_i - a_2f_i - a_3d_i) \quad (4)$$

$$\frac{\partial S_r}{\partial a_1} = -2\sum(MRR_i - a_0 - a_1N_i - a_2f_i - a_3d_i)N_i \quad (5)$$

$$\frac{\partial S_r}{\partial a_2} = -2\sum(MRR_i - a_0 - a_1N_i - a_2f_i - a_3d_i)f_i \quad (6)$$

$$\frac{\partial S_r}{\partial a_3} = -2\sum(MRR_i - a_0 - a_1N_i - a_2f_i - a_3d_i)d_i \quad (7)$$

The minimum sum of squares are obtained by setting the partial derivatives equal to zero and thus the discrepancy between the curve and the data points is minimized. So equating to zero we have:

$$\sum MMR_i = \sum a_0 + a_1\sum N_i + a_2\sum f_i + a_3\sum d_i \quad (8)$$

$$\sum MRR_iN_i = a_0\sum N_i + a_1\sum N_i^2 + a_2\sum f_iN_i + a_3\sum d_iN_i \quad (9a)$$

$$\sum MRR_if_i = a_0\sum f_i + a_1\sum N_if_i + a_2\sum f_i^2 + a_3\sum d_if_i \quad (9b)$$

$$\sum MRR_id_i = a_0\sum d_i + a_1\sum N_id_i + a_2\sum f_id_i + a_3\sum d_i^2 \quad (9c)$$

It should be noted that $\sum_{i=1}^{n}$ is written as $\sum$ for the purpose of simplicity.

Now substituting the value of all the sums in equations (8)-(9c) as obtained from the experiments, we have

$$1044.639 = 27a_0 + 32400a_1 + 2.7a_2 + 21.6a_3$$

$$1270254 = 32400a_0 + 39600000a_1 + 3240a_2 + 25920a_3$$

$$118.9105 = 2.7a_0 + 3240a_1 + 0.315a_2 + 2.16a_3$$

$$950.3479 = 21.6a_0 + 25920a_1 + 2.16a_2 + 20.16a_3$$

This implies

$$a_0 = -53.0688, a_1 = 0.0232, a_2 = 321.0356, and a_3 = 39.8044$$

Equation (2), the mathematical model for material removal rate becomes

$$MRR = -53.0688 + 0.0232N + 321.0356f + 39.8044d$$

(Emperically developed model) (10)

The regression equation was also obtained using MINITAB 16 software and the model for MRR during turning of AISI 304L stainless steel is determined as represented by equation (11) as follows:

MRR = -53.0676 + 0.0231758 N +321.035 f + 39.8043 d (11) (Mathematical model developed from MINITAB)

Summary of MRR model

Fig. 5 shows the scatter plot of observed values and predicted values of MRR for all samples and it indicated that the relationship between the actual MRR and predicted MRR is linear and there is good correlation between them at 95% confidence interval.

From Table 5, it can be observed that the confidence interval for this analysis is 95% and the significance is 5% which relates to an alpha (α) level of 0.05. This implies that the regression coefficient of the various parameters at 95% confidence level are in the following ranges: constant term (-70.148, -35.987), spindle speed (0.010 - 0.036), feed rate (269.920 - 372.149), and depth of cut (33.415 - 46.194). If the p-value (P) of a coefficient is less than the chosen α-level, such as 0.05, the relationship between the predictor and the response is statistically significant. The p-value for the estimated coefficient of spindle speed is 0.001, while that for feed rate is 0.000, and that for the depth of cut is 0.000. These are all lower

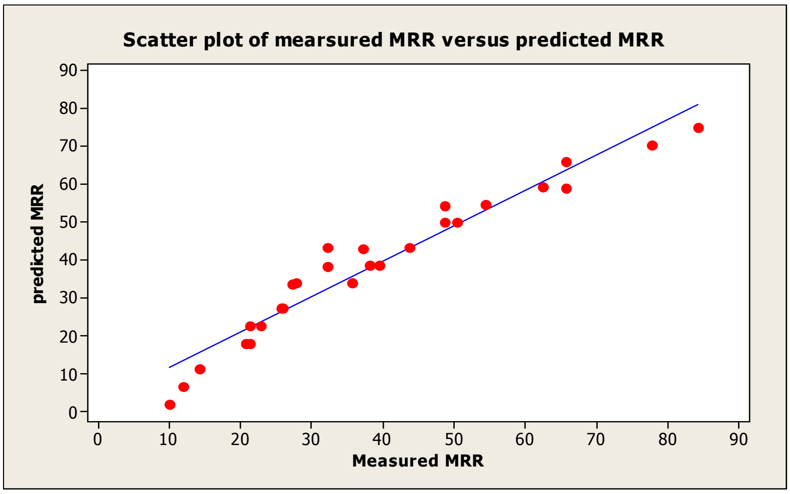

Fig. 5: measured MRR versus Predicted MRR

Table 5: MRR regression coefficients

Term	Coef	SE Coef	T	P	95% CI
Constant	-53.068	8.2569	-6.4270	0.000	(-70.148, -35.987)
Spindle speed	0.023	0.0062	3.7518	0.001	(0.010, 0.036)
Feed rate	321.035	24.7090	12.9926	0.000	(269.920, 372.149)
Depth of cut	39.804	3.0886	12.8874	0.000	(33.415, 46.194)

than 0.05, indicating that they are significantly related to MRR. The bigger the absolute t-value (T), the more likely the predictor is significant. The t-value (T) of the spindle speed (N) for MRR is 3.7518, feed rate is 12.9926 and depth of cut is 12.8874. This shows that feed rate with the biggest absolute t-value (T) is the most significant parameter followed by depth of cut and then the spindle speed with the least significant effect on MRR. In multiple linear regression analysis, R^2 is the regression coefficient for the models. The magnitude of R^2 indicates whether the regression provides accurate prediction of the criterion variables or not. The R^2 value indicates that the predictors explain 93.82% of the variance in MRR, indicating that the model fits the data fairly well. The adjusted R^2 is 93.01%, which accounts for the number of predictors in the model. Both values indicate that the model fits the data well. The predicted R^2 value is 90.77%. Since the predicted R^2 value is close to the R^2 and adjusted R^2 values, the model does not appear to be over fitted and has adequate predictive ability.

Analysis of variance (ANOVA) on MRR

The ANOVA was performed to investigate the statistical significance of the process parameters affecting the MRR. Analysis of varrance of the MRR with the objective of analyzing the influence of spindle speed (N), feed rate (f) and depth of cut (d) on the total variance of the results was performed. Table 6 shows the results of the ANOVA for MRR. This analysis was undertaken for a significance level of 5%. The spindle speed, feed rate and depth of cut have degree of freedom 1 for each of them. The last column of the ANOVA table (Table 6) depicts the p-values. The P-values range from 0 to 1.

From Table 6, it can be observed that the p-value for each regression coefficients of the machining parameters are spindle speed N=0.0010398, feed rate f=0.0000000 and depth of cut d=0.0000000 are less than the significant α-level=0.05 as depicted in the ANOVA table. Here, the default test is to determine if the coefficient of each independent variable is different from zero. Therefore, the null hypothesis H_0 states that the coefficient equals zero while the alternative hypothesis H_a states that it is not equal to zero. With a p-value lower than the significant level α= 0.05 the null hypothesis is rejected and the alternative hypothesis is accepted.

CONCLUSION

In the present work, experimental prediction and optimization of MRR were achieved for hard turning of AISI 304L austenitic stainless steel. The theoretical results have been compared with the experimental results and there is a good correlation between them at 95% confidence interval and 0.05 significant levels.

From the results it can be concluded that the machining parameters (spindle speed, feed rate, and depth of cut) have direct effects on the MRR. MMR increased as these parameters, spindle speed (1000, 1200, 1400rpm), feed rate (0.05, 0.10, 0.15mm/rev), and depth of cut (0.4, 0.8, 1.2mm) all increased because the cutting forces are also increased, thereby causing more amount of the material to be removed in less time. It can also be seen from the results of the main effect and ANOVA analyses that the spindle speed, feed rate, and depth of cut, all have significant effects (the corresponding increase in MRR as the cutting parameters are increased) on the MRR. The optimum combinations of the machining parameters are a spindle speed of 1200rpm, a feed rate of 0.15mm/rev and a depth of cut of 1.2mm. This combination gives optimum MRR of 77.80243mm^3/min.

The predictive mathematical model for MRR = -53.0676 + 0.0231758 N +321.035 f + 39.8043d (Mathematical model developed from MINITAB16) and the best combination of cutting variables are determined to obtain optimum MRR during machining. From the experimental results, it was also revealed that if

Table 6: ANOVA table for MRR

Analysis of Variance **Source**	**DF**	**Seq**	**Adj SS**	**Adj MS**	**F**	**P**
Regression	3	9587.6	9587.60	3195.87	116.323	0.0000
Spindle speed	1	386.7	386.73	386.73	14.076	0.0010
Feed rate	1	4637.9	4637.85	4637.85	168.808	0.0000
Depth of cut	1	4563.0	4563.02	4563.02	166.084	0.0000
Error	23	631.9	631.90	27.47		
Total	**26**	**10219.5**				

cutting parameters were selected appropriately, it will in turn reduce manpower, reduce machining time, save energy, increase cutting tool life, ensure continuous quality improvment and eventually reduce manufacturing cost. It can therefore be concluded that optimization of MRR is a function of proper selection of cutting parameters.

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