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A Study of the Effect of Cutting Factors on the Metal Removal in Lathe Turning of AISI 1045 Steel

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Abstract

The metal removal rate is considered one of the most important factors affecting productivity during the turning process; however, in many workshops, cutting parameters are still selected based on tables in the operating manual or based on the operator's experience. This study examined the effects of spindle speed (262,412, and 600 rpm), depth of cut (0.9, 1.6, and 2.0 mm), and feed rate (0.15, 0.18, and 0.24 mm/rev) on the material removal rate of medium-carbon steel A1045 when turned on a conventional lathe using a carbide-tipped tool and cutting fluids. The Taguchi methodology was used to determine the number of experiments required and to analyze the signal-to-noise ratio (S/N) under the criterion "the higher the value, the better". Nine experiments were conducted using the L9 orthogonal array, Experiment No. 3, which involved the following parameters (rotational speed 262 rpm, cutting depth 2 mm, feed rate 0.18 rev/min), which achieved the highest metal removal rate of 16.454 g/min, corresponding to the highest S/N ratio of 24.325. An ANOVA analysis was also carried out to determine the expected optimal operating parameters; the experiment with the following conditions (rotational speed 600 rpm, cutting depth 2 mm, feed rate 0.18 rev/min), which falls outside the nine experiments carried out and is expected to yield the highest S/N ratio of 24.766 and the highest MRR of 17.31 g/min, representing a 5.2 % increase on the optimum value previously obtained. As shown by the analysis of variance, cutting depth played the greatest role in increasing MRR, accounting for 95.7%, whilst cutting speed accounted for 0.6% and the feed rate for 0.62%. A multiple linear regression model was also developed with a statistical significance of 94.85% (R =, P < 0.001), where the predictive value showed a high degree of agreement with the experimental results; it can therefore be used to estimate (MRR) within the ranges studied.

Keywords: material removal rate; cutting parameters; AISI 1045 steel; turning; orthogonal array

الملخص

يحدد معدل إزالة المعدن (MRR) إنتاجية عملية تشغيل المعادن بالخراطة، ومع ذلك لا تزال بارامترات القطع التي تتحكم في هذا المعدل تختار في العديد من الورش بناء على الخبرة أو الجداول الواردة في كتيبات التشغيل. تبحث هذه الدراسة في مدى تأثير ثلاثة بارامترات تشغيل بثلاثة مستويات تمثلت في سرعة الدوران (262 و412 و600 دورة في الدقيقة)، وعمق القطع (0.9 و1.6 و2.0 مم)، ومعدل التغذية (0.15، 0.18 و0.24 ملم/دورة) على معدل إزالة المعدن (MRR) للفولاذ متوسط الكربون AISI

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1045اثناء تشغيله على مخرطة تقليدية باستخدام ادة قطع كربيدية و سائل تبريد. حيث استخدمت منهجية Taguchi لتحديد عدد التجارب اللازمة و تحليل نسبة الإشارة إلى الضوضاء (S/N) ضمن معيار "كلما زادت القيمة كان ذلك أفضل". تم إجراء 9 تجارب بواسطة المصفوفة المتعامدة L9 ، فكانت التجربة رقم 3 ذات المستويات (سرعة الدوران 262 rpm، عمق القطع 2 mm، معدل التغذية 0.18 rev/min) هي التي حققت اعلى معدل إزالة للمعدن 16.454 g/min والذي يقابل اعلى S/N=24.325. كما تم اجراء تحليل التباين ANOVA لغرض تحديد افضل بارامترات التشغيل المتوقعة فكانت التجربة ذات المستويات (سرعة الدوران 600 rpm، عمق القطع 2 mm، معدل التغذية 0.18 rev/min) التي تقع خارج التجارب 9 التي تم تنفيذها و من المتوقع ان تسجل اعلى S/N=24.766 و اعلى معدل إزالة للمعدن 17.31 g/min أي بمقدار زيادة 5.2%عن القيمة المثلى التي سبق الحصول عليها. كما تبين من خلال تحليل التباين ان عمق القطع كان له الدور الأكبر في زيادة معدل إزالة المعدن حيث وصلت نسبة مشاركته 95.7% في حين ان سرعة القطع كانت 0.6% و معدل التغذية 0.62% . كما تم استحداث نموذج للانحدار الخطي المتعدد ذو دلالة إحصائية R=٪94.85، (P < 0.001)، حيث أظهرت القيمة التنبؤية تطابق كبير مع النتائج التجريبية وبالتالي يمكن استخدامه لتقدير معدل إزالة المعدن (MRR) ضمن النطاقات التي تم المدروسة.

الكلمات المفتاحية: *معدل إزالة المعدن، بارامترات القطع، الفولاذ AISI 1045 , الخراطة، المصفوفة المتعامدة*

1. Introduction

The material removal rate is the most direct measure of the productivity of a turning operation, as it determines how long a part occupies the lathe and therefore a large share of its machining cost.

However, obtaining the best results depends on the capabilities of the machine, the tool, and the required quality of the part; therefore, selecting cutting parameters is an optimization problem rather than simply a matter of increasing every setting. In many small and medium-sized workshops, parameters are still derived from the operator's experience or from tables provided by the machine manufacturer, which does not guarantee performance close to the optimum for a specific machine, tool, and workpiece.

Recent studies on AISI 1045 steel show how widely MRR is used as a response. A review of the turning literature for this steel found that MRR, together with surface roughness and tool wear, is among the most frequently measured outputs, and that speed, feed, and depth of cut are the most frequently varied inputs [1]. Abbas et al. calculated MRR from the cutting parameters of dry turning and built regression models for it before applying multi-objective algorithms, and they found that the best setting depended on the order in which objectives were prioritized [2]. In a study of AISI 5140 steel, the response surface methodology gave better MRR results than Taguchi's S/N method, and the authors noted that maximizing MRR conflicts with minimizing cutting power [3]. Machining AISI 1045 steel with double-edged carbide tools rather than single-edged configurations significantly improves the material removal rate (MRR) while concurrently reducing overall machining time [4]. The results confirm that the impact of individual process parameters as well as their optimal combination is mainly determined by the particular machine, cutting tool geometry, and experimental conditions. The Taguchi method, as a way of systematically studying these kinds of interactions, provides a very powerful and practical experimental design. Based on the idea of using orthogonal arrays for this method, the main effects can be assessed with a very small number of experimental runs, while the signal-to-noise (S/N) ratio plays a role in picking those parameter combinations that deliver very stable/robust quality [5, 6]. This methodology has proved to be an efficient tool not only for the current situation but also the previous one and is being used in the context of turning AISI 1045 steel through Taguchi L9 orthogonal array experiments that were performed on CNC turning centers [7]. When integrated with analysis of variance (ANOVA) to quantify individual factor contributions to total variance, and coupled with regression analysis to

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formulate predictive models, it establishes a streamlined and comprehensive analytical workflow [8].Consequently, this paper aims, first, to quantitatively determine the effect of cutting parameters on the material removal rate (MRR) using an L9 factorial design, second, to determine the parameter settings that maximize the material removal rate (MRR); third, to determine the percentage contribution of each parameter and its statistical significance using analysis of variance (ANOVA); fourth, to create a regression model to predict the material removal rate (MRR) within the tested ranges.

2. EXPERMENT SETUP

2.1 Experimental workflow

The procedure is summarized in Figure 1. Specimens were prepared, cleaned, and weighed; nine turning runs defined by the L9 plan were carried out in random order; each specimen was cleaned, dried, and weighed again to obtain the MRR; and the data were analyzed by S/N analysis, ANOVA, and regression before the predicted optimum was checked in confirmation experiments.

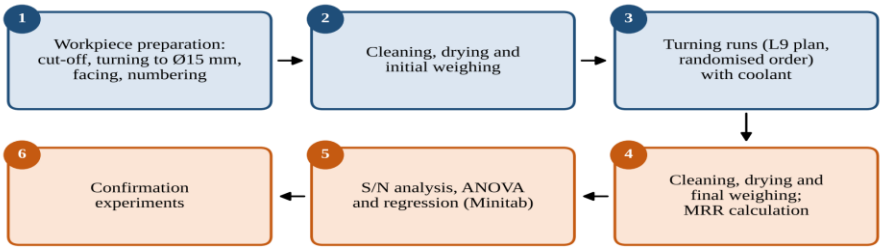


Figure 1. *Experimental and analysis workflow of the study*

2.2 Machine tool and measuring instrument

All runs were performed on an AL-PIN 180 N conventional center lathe (Italy) with a maximum spindle speed of 1600 rpm and a rated power of 5.5 kW (Figure 2a,b). The speed, feed, and depth of cut were set on the machine's control panel. A carbide cutting insert was used throughout, and AQUAMET 101 metal-cutting fluid was supplied as coolant during machining. The specimen mass was measured using an electronic analytical balance (Scaltec) with a resolution of 0.0001 g (Figure 2c).



Figure 2. *Experimental equipment: (a) AL-PIN 180 N lathe, (b) headstock control panel, and (c) electronic balance.*

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2.3 Workpiece material and specimen preparation

The workpiece material was AISI 1045 medium-carbon steel, which combines good strength and hardness and is widely used for shafts, bushings, crankshafts, and other machine parts. Its chemical composition and mechanical properties are listed in Tables 1 and 2, and its hardness was reported as 280 BHN.

Table 1. Chemical composition of the AISI 1045 workpiece (wt. %)

Element	C	Si	Mn	Cr	Ni	Mo	S	P	W	V	Fe
Content	0.451	0.253	0.780	0.336	0.040	0.001	0.009	0.011	0.160	0.004	98.406

Table 2. Mechanical properties of AISI 1045 steel

Property	Value
Tensile strength	585 MPa
Yield strength	450 MPa
Modulus of elasticity	200 GPa
Shear modulus	80 GPa
Elongation at break	12%

Nine specimens of 70 mm length were cut from a 25 mm diameter bar using a reciprocating power saw. Each was turned from Ø25 mm to Ø15 ± 0.002 mm, faced at both ends and numbered (Figures 3 and 4).



Figure 3. *Specimen geometry (dimensions in mm).*



Figure 4. *Specimen preparation: (a) turning of the bar to the working diameter, (b) prepared specimens, and (c) numbered specimens.*

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3. METHDOLOGY

3.1 Response: material removal rate

The MRR was obtained gravimetrically from the mass removed per unit of machining time

$$\text{MRR} = \frac{W_i - W_f}{t} \ (\text{g/min}) \qquad (1)$$

where W_i and W_f are the specimen masses before and after machining, respectively, and t is the machining time. Before every weighing, the specimens were cleaned and dried with tissue paper and compressed air. Because a higher MRR indicates higher productivity, MRR was treated as a larger-the-better characteristic [6].

3.2 Selection of factors and Orthogonal array

A cause-and-effect (Ishikawa) diagram was used to identify the variables that may influence the turned part (Figure 5). Spindle speed, depth of cut, and feed rate were considered controllable factors, while the tool, workpiece, and environmental variables were held constant. The factor levels (Table 3) were chosen from preliminary trials, and three levels were used for each factor to allow for non-linear effects. The interactions between factors were neglected. Levels are numbered in ascending order of magnitude, so feed levels 1, 2 and 3 correspond to 0.15, 0.18 and 0.24 mm/rev.

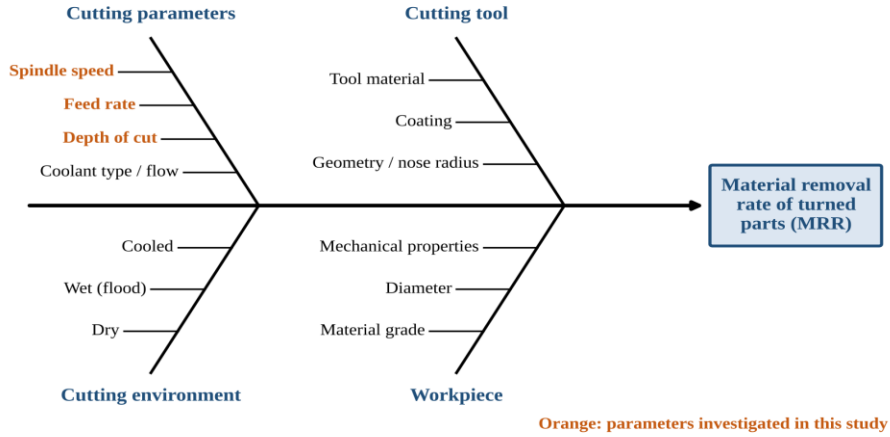


Figure 5. *Cause-and-effect diagram for turning process.*

Table 3. Process parameters and their corresponding levels.

Parameter	Symbol	Unit	Level 1	Level 2	Level 3
Spindle speed	N	rpm	262	412	600
Depth of cut	a_p	mm	0.9	1.6	2.0
Feed rate	f	mm/rev	0.15	0.18	0.24

The orthogonal matrix is selected by comparing the degrees of freedom (DOF) according to the following equation [5]:

$$\boldsymbol{DOF} = [(number\ of\ levels - 1) * number\ of\ parameters] + 1 \qquad (2)$$

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Three three-level factors require $(3-1)\times 3+1=7$ degrees of freedom, and the smallest standard three-level array that meets this requirement is the L9 array

The run order was randomized to spread the effect of uncontrolled sources of variation. The feed column of the array used here is the standard L9 column with levels 2 and 3 interchanged, which preserves orthogonality; the resulting design is given with the results in Table 4.

For a larger-the-better characteristic measured once per run, the S/N ratio, in decibels is

$$\eta = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (3)$$

where y_i is the observed MRR, and n is the number of repetitions per run ($n = 1$). The level with the largest mean S/N ratio is preferred [5,6].

3.3 Prediction

The S/N ratio at the optimum combination was predicted from the main effects as

$$\hat{\eta} = \eta_m + \sum_{i=1}^{q}(\bar{\eta}_i - \eta_m) \quad (4)$$

where η_m is the total mean S/N ratio, $\bar{\eta}_i$ is the mean S/N ratio at the optimum level of factor i and q is the number of factors. Confirmation experiments then compare the predicted and measured values with those at the initial setting [5].

3.4 Analysis of variance

ANOVA separates the total variation into the part attributable to each factor and the residual error [8]. With T the sum of all nine observations, the total sum of squares is

$$SS_T = \sum_{i=1}^{9} y_i^2 - \frac{T^2}{9} \quad (5)$$

and the sum of squares of a factor F with three levels (each level occurring three times) is

$$SS_F = \sum_{j=1}^{3}\frac{F_j^2}{3} - \frac{T^2}{9} \quad (6)$$

where F_j is the sum of observations at level j. The error sum of squares follows by subtraction

$$SS_e = SS_T - \left(SS_N + SS_{a_p} + SS_f\right) \quad (7)$$

and because each factor has two degrees of freedom, the error has $8-6=2$. The F ratio and percentage contribution of each factor are

$$F = \frac{SS_F/\nu_F}{SS_e/\nu_e}, \qquad P_F = \frac{SS_F}{SS_T}\times 100 \quad (8)$$

where ν denotes the degree of freedom. Because the error estimate rests on only two degrees of freedom, the test has a low power. All analyses were performed using Minitab.

3.5 Regression modelling

A first-order multiple linear regression model with uncoded variables was fitted to the MRR data by least squares

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$$\text{MRR} = \beta_0 + \beta_1 N + \beta_2 a_p + \beta_3 f + \varepsilon (9)$$

Model adequacy was judged from the coefficient of determination (R^2), adjusted R^2, overall F test of the regression at the 95% confidence level, normality of the residuals, and agreement between measured and fitted values [6].

4. Results and Discussion

4.1 Experimental results

Table 4 lists the L9 design, the measured MRR, and the corresponding S/N ratios. The MRR ranged from 6.668 g/min (run 4:412 rpm, 0.9 mm, 0.24 mm/rev) to 16.454 g/min (run 3:262 rpm, 2.0 mm, 0.18 mm/rev). The three lowest values (runs 1, 4, and 7) all occurred at the smallest depth of cut, and the three highest (runs 3, 6, and 9) at the largest, which already points to depth of cut as the dominant parameter.

Table 4. L9 design, measured MRR, and S/N ratios (level codes in brackets).

Run	N (rpm)	a_p (mm)	f (mm/rev)	MRR (g/min)	S/N ratio (dB)
1	262 (1)	0.9 (1)	0.15 (1)	6.813	16.666
2	262 (1)	1.6 (2)	0.24 (3)	11.174	20.964
3	**262 (1)**	**2.0 (3)**	**0.18 (2)**	**16.454**	**24.325**
4	412 (2)	0.9 (1)	0.24 (3)	6.668	16.479
5	412 (2)	1.6 (2)	0.18 (2)	14.094	22.980
6	412 (2)	2.0 (3)	0.15 (1)	15.183	23.627
7	600 (3)	0.9 (1)	0.18 (2)	7.107	17.033
8	600 (3)	1.6 (2)	0.15 (1)	13.499	22.606
9	600 (3)	2.0 (3)	0.24 (3)	16.050	24.109
			Mean S/N		**20.9766**

4.2 Optimum parameters for MRR

The mean S/N ratio at each level was obtained by averaging the S/N ratios of the runs in which the level occurs (Table 5). The depth of cut has by far the largest range (7.29 dB), followed by feed rate (0.93 dB) and spindle speed (0.60 dB), so the response is mainly driven by the depth of cut (Figure 6a). The largest S/N ratio occurs at 600 rpm, 2.0 mm and 0.18 mm/rev, i.e. the combination N3–a_p3–f2

Table 5. Response table of means S/N ratios

Symbol	Parameter	Level 1	Level 2	Level 3	Max − Min	Rank
N	Spindle	20.65	21.03	**21.25**	0.60	3
a_p	Depth of cut	16.73	22.18	**24.02**	7.29	1
f	Feed rate	20.97	**21.45**	20.52	0.93	2

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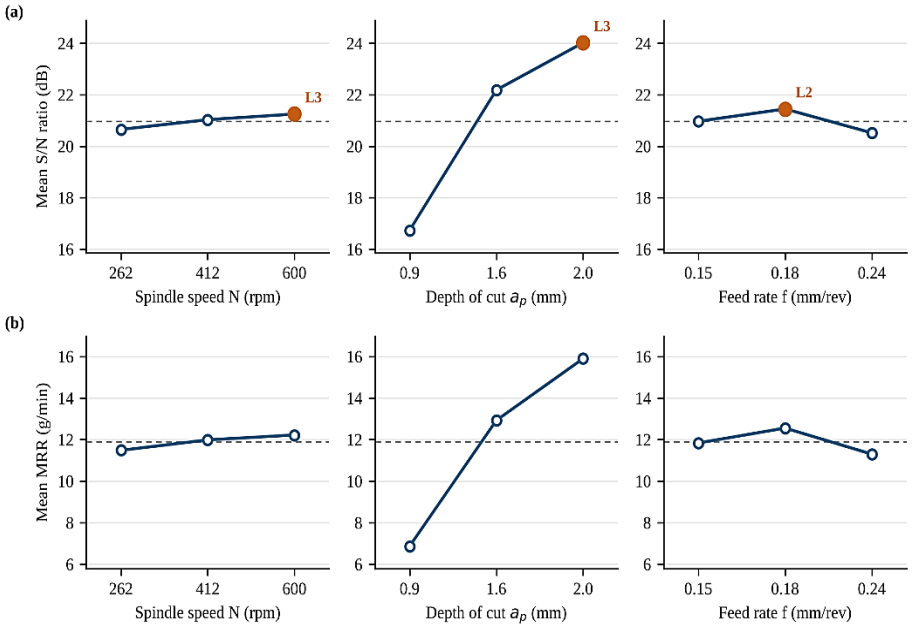


Figure 6. *Main effects plots for MRR: (a) mean S/N ratio and (b) mean MRR. The dashed line is the overall mean, and the filled marker indicates the optimal level.*

Table 6. Response table of means MRR

Symbol	Parameter	Level 1	Level 2	Level 3	Max − Min	Rank
N	Spindle	11.480	11.982	12.219	0.738	3
a_p	Depth of cut	6.863	12.922	15.896	9.033	1
f	Feed rate	11.832	12.552	11.297	1.254	2

The mean MRR increased from (6.86 g/min at 0.9 mm) to (12.92 g/min at 1.6 mm) and (15.90 g/min at 2.0 mm) as shown in (Table 6) and (Figure 6b), as the difference between the two largest depths diminished. This dependence is consistent with the kinematics of the process: the volume removed per unit time is proportional to the product of cutting speed, feed, and depth of cut [9,10], so a deeper cut directly enlarges the chip cross-section. The spindle speed has a small, slowly rising effect (11.48, 11.98 and 12.22 g/min at 262, 412 and 600 rpm), and the effect of feed is not monotonic (11.83, 12.55 and 11.30 g/min at 0.15, 0.18 and 0.24 mm/rev). Both dependences are weaker than the proportional increase with speed and feed that the kinematic relation would suggest. This indicates that the gravimetric measurement, including the determination of machining time, carries noise of the same order as these two effects, and the drop in MRR at the highest feed should not be interpreted as a real effect.

4.3 Analysis of variance

The ANOVA for MRR (Table 7) shows that the depth of cut is the only significant factor ($F = 51.36$, $P = 0.019$) and accounts for 95.7% of the total variation (Figure 7). Spindle speed (0.64%, $P = 0.744$) and feed rate (1.8%, $P = 0.510$) were not significant, and the error term contributed 1.86%. The

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small error share indicates that the three factors explain almost all of the variation observed in the nine runs.

Table 7. ANOVA for the means of MRR

Source	DF	SS	Adj MS	*F*	*P*	Contribution (%)
Spindle speed	2	0.853	0.4263	0.34	0.744	0.64
Depth of cut	2	127.155	63.5777	51.36	0.019	95.7
Feed rate	2	2.377	1.1886	0.96	0.510	1.8
Residual error	2	2.476	1.2378			1.86
Total	8	132.861				100

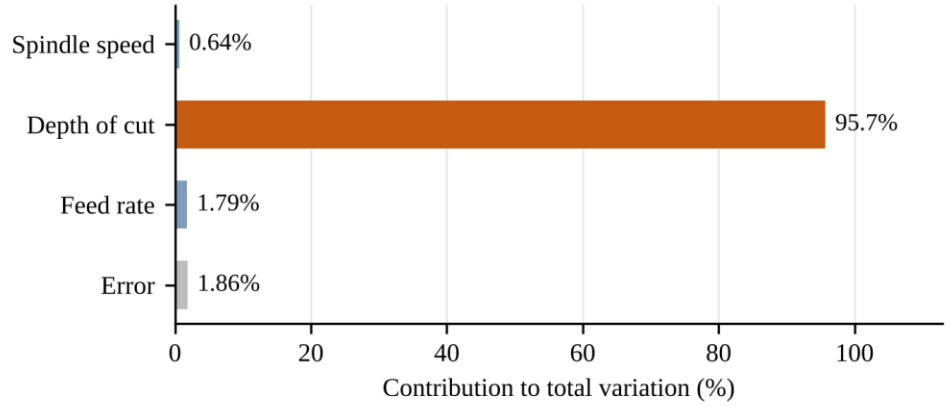


Figure 7. *Percentage contribution of each factor and of the error to the total variation of MRR*

4.4 Regression model for MRR

Multiple linear regression on the nine experiments gave

$$\text{MRR} = 0.12 + 0.00215\,N + 8.262\,a_p - 8.08\,f \qquad (10)$$

with R^2 = 96.78% and an adjusted R^2 of 94.85%. The ANOVA of the model (Table 8) shows that the regression is significant (F = 50.06, P < 0.001) and that depth of cut is the only significant term (P < 0.001), while the terms for spindle speed (P = 0.380) and feed rate (P = 0.372) are not. The residuals fall reasonably close to a straight line on the normal probability plot (Figure 8), supporting the normality assumption, and the fitted values follow the measured values closely (Figure 9). The largest residual was 1.32 g/min (run 5, 9.4% of the measured value).

Table **8**. ANOVA of the MRR regression model

Source	DF	SS	Adj MS	*F*	*P*	Contribution (%)
Regression	3	128.580	42.860	50.06	< 0.001	96.78
Spindle speed	1	0.793	0.793	0.93	0.380	0.60

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Source	DF	SS	Adj MS	*F*	*P*	Contribution (%)
Depth of cut	1	126.966	126.966	148.31	< 0.001	95.7
Feed rate	1	0.822	0.822	0.96	0.372	0.62
Error	5	4.281	0.856			3.22
Total	8	132.861				100

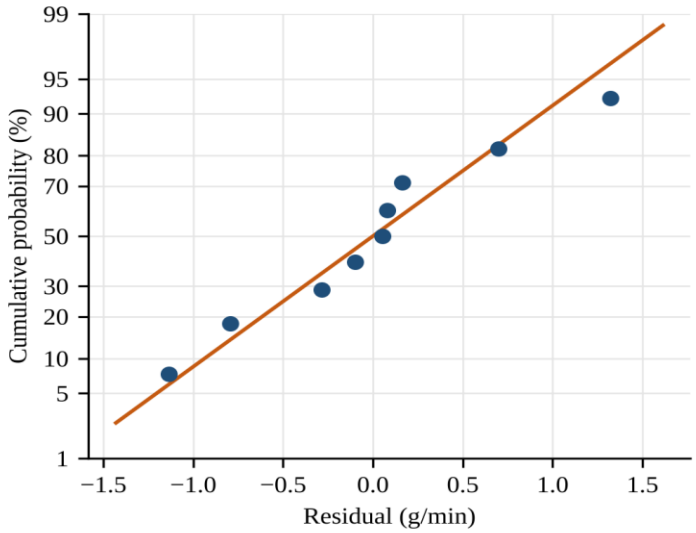


Figure 8. *Normal probability plot of the residuals of the MRR model*

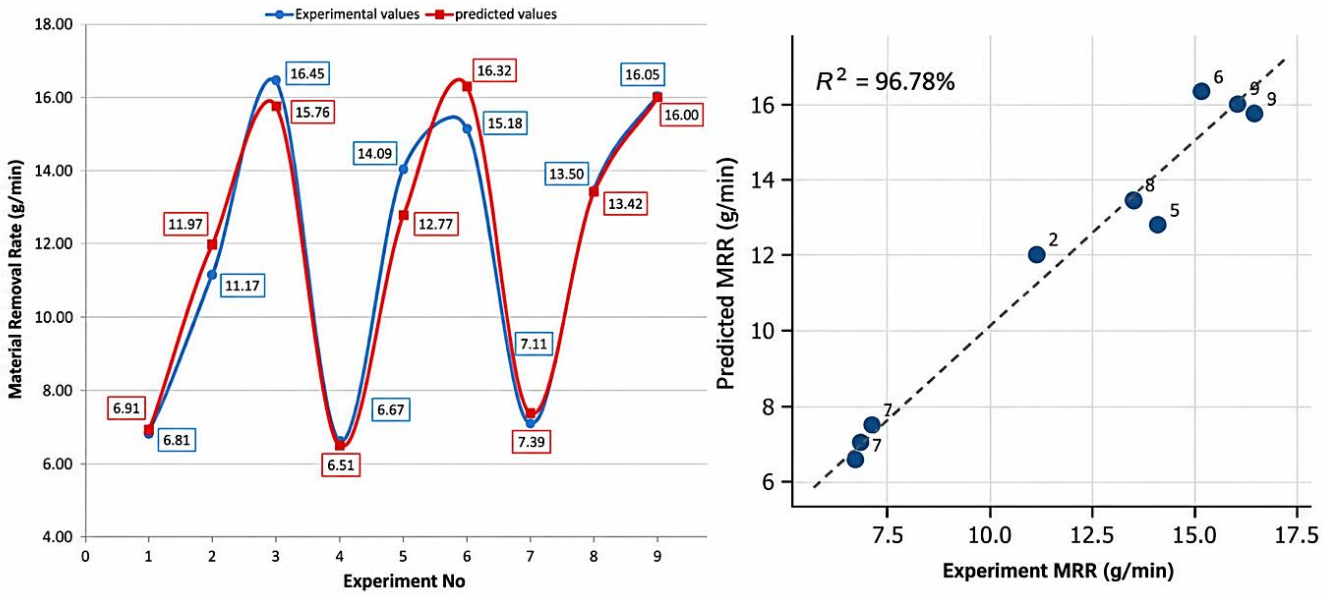


Figure 9. ***(a)*** *Comparison between Experimental and predicted values of MRR,* ***(b)*** *parity plot with run numbers*

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5. Conclusions and Future Work

An L9 experimental design with ANOVA and regression analysis was used to study the effect of spindle speed, depth of cut, and feed rate on the MRR of AISI 1045 steel turned on a conventional lathe with a carbide insert and cutting fluid. The main conclusions are as follows:

1.The depth of cut was the dominant parameter. It was the only significant factor (95.7% contribution, $P = 0.019$); feed rate (1.8%) and spindle speed (0.64%) were not significant within the tested ranges.

2. The S/N analysis yields the MRR-maximizing setting of 600 rpm, 2.0 mm, and 0.18 mm/rev (N3–a_p3–f2).

3. Relative to the initial setting, the measured MRR at the confirmation condition increased from 6.813 to 16.454 g/min (2.42-fold), an S/N improvement of 7.66 dB, and was within 4.9% of the prediction.

4. The regression model $\text{MRR} = 0.12 + 0.00215N + 8.262a_p - 8.08f$ is significant and adequate within the tested ranges ($R^2 = 96.78\%$, adjusted $R^2 = 94.85\%$, $P < 0.001$), with the depth of cut as its only significant term.

5. A Study of the Effect of Cutting Parameters on the Surface Roughness of AISI 1045 Steel During Machining.

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