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Statistical analysis and mathematical modeling of cutting parameters in the turning process of 1018 steel material

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Abstract: This paper presents an analysis and mathematical modeling of the cutting parameters in the turning process of 1018 steel material. For this analysis, an experiment was designed using 40 specimens of 1" diameter by 6" long. In this experiment, the control parameters were cutting speed in revolutions per minute (rpm), feed rate in inches per minute (inches/minute) and depth of cut in inches (inches), while the response variable is surface roughness in micro inches (µinches). The results show that the feed rate, cutting speed and the interaction between feed rate and cutting speed affect the surface roughness of the workpiece. Finally, with the RStudio software, a mathematical model was obtained with an R2 equal to 0.99, a value very close to previous experimental works and, in addition, a good predictor of surface roughness.

Keywords: Statistical analysis, turning process, mathematical modeling, cutting parameters.

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1. Introduction

In the industrial world, machining processes have been used more than other types of manufacturing processes; this is due to their technical characteristics in terms of precision and surface finish. Surface finish is one of the parameters that indicate the performance of machining processes; it is measured industrially through the surface roughness Ra; which is the average value of the sum of the ridge of a measured portion. Also, (Alam et al., 2023) argue that, "Nowadays, material removal rate and product quality have become important benchmarks in any industry". Currently in the case of conventional machining processes, manually operated by the worker, this surface roughness is obtained by the good praxis or skill of the operator and by properly combining some cutting parameters that affect the surface roughness of the metal machining process. (Wani et al., 2023) They also comment, "Traditionally, operator experience plays an important role in selecting the optimum cutting conditions. The nonlinear nature of the turning process has forced engineers to search for more effective methods to achieve optimization" (Wani et al., 2023, p.2). Some experts have studied this phenomenon by combining the cutting parameters, such as cutting speed expressed in m/s, in/s or revolutions per minute of the chuck (rpm), feed rate, expressed in in /in/rev, mm/rev, in/min, mm/min, depth of cut, expressed in mm or in, cutting tool radius, expressed in in or mm, among other factors. Thus, for example, (Kittali et al., 2022) used the Taguchi methodology to model and optimize the surface roughness and material removal rate in the turning operation for an EN1A steel alloy. In this study, the controlled variables included spindle revolutions per minute (rpm), feed rate (mm/rev), depth of cut (mm), and coolant (presence or absence). The results indicated that the feed rate has a greater significant impact on the surface roughness; in addition, it is also shown that the coolant contributes to obtaining a better material removal rate. On the other hand, (Stampfer, et al., 2022), in their study modeled the surface roughness and microhardness of AISI 4140 QT turned material. They used some mathematical algorithms such as: linear regression, stepwise regression, LASSO statistical method and elastic net logistic regression method. The results show that the quadratic LASSO method fits the data with a correlation coefficient R2 = .73, followed by the quadratic elastic net method with a correlation coefficient R2 = .71 (Paturi et al., 2022), in their study on the machining of an AISI52100 steel material, they conducted a study on the machining of AISI52100 steel. This material is widely used for its mechanical properties such as high strength, hardness and wear resistance. A multi-objective optimization model was structured to model surface roughness and cutting tool wear during dry machining. A full factorial design was used using the response methodology method. The results were a mathematical model to predict surface roughness with a correlation coefficient R2 =0.99121 and another mathematical model to predict cutting tool wear with a correlation coefficient R2 =0.9876, both quadratic equations. In addition, it was found that the feed rate is the factor that contributes the most on surface roughness with 85.56% contribution. Also, cutting speed is the most contributing factor on cutting tool wear. (Alam et al., 2023, p.1), they made a statistical study on a Ti-6Al-4V alloy material machined by a milling machine. The design of the experiment was structured and analyzed using response surface methodology, the control variables were, cutting speed, feed rate and depth of cut, whereas the output variables were surface roughness and material removal rate; furthermore, the optimum values of cutting parameters were subsequently found to obtain minimum surface roughness. In the results, two quadratic mathematical models were obtained to predict the surface roughness and material removal rate; furthermore, it was found that, as the feed rate decreases, the surface roughness improves, while increasing the cutting speed also improves the surface roughness. Wani et al. used the Taguchi method to structure a design of experiment to model and optimize the machining of OHNS steel material. The control variables were cutting speed (rpm), feed rate (mm/rev) and depth of cut (mm); while the response variables were surface roughness (Ra) and material removal rate (mm3 /min). According to (Wani et al., 2023, p.5), their results show that the feed rate is the most contributing factor, with 87.23% on surface roughness, moreover, the lower the feed rate, the lower the surface roughness decreases. On the other hand, the cutting speed has a contribution of 8.83% on the surface roughness; the depth of cut has a low contribution on the surface finish. Finally, two mathematical models were obtained to predict surface roughness and material removal rate. (Lakshmanan et al., 2023) used TOPSIS methodology to optimize the turning process on a titanium alloy material with various control parameters and under different coolants. The optimized cutting parameters were cutting speed (135m/min), depth of cut (0.5mm), and feed rate (0.102mm/rev). Karthik et al. (2020) conducted a design of experiment using Taguchi methodology for turning EN31 material, known for its high hardness, measuring above 60 HRC. This material is widely used in industries such as automotive and aerospace. In their research work, three control variables were used: cutting speed (m/min), feed rate (mm/rev) and depth of cut (mm). The results show that feed rate is the parameter that significantly has the most effect on surface roughness. Senthilkumar et al. (2022), proposed a Taguchi design to optimize cutting parameters in their experimental work on the turning process of duplex stainless steel, a material widely known for its anti-corrosion properties. For this experiment, the control variables were cutting speed (rev/min), feed rate (in/min) and depth of cut (in), while the response variable is surface roughness. The results show that feed rate is the parameter that has the highest contribution on the surface roughness, followed by the interaction of cutting speed and depth of cut. (Dutta & Narala, 2021), used the Taguchi method to find the factors that significantly affect the cutting forces and surface roughness on a magnesium alloy material used in different engineering sectors for its light weight and other mechanical properties. The control parameters were cutting speed, feed rate and depth of cut. The results show that the depth of cut has the maximum effect on the cutting forces, while the feed rate has the maximum influence on the surface roughness. Finally, Ramesh et al. made an experimental analysis on a heat-treated ductile material, this material is subjected to the turning process which according to (Ramesh et al., 2020), is the most used machine in the machining industry. In their work, Taguchi methodology was used to make the experimental design, three control variables were taken into account; cutting speed, feed rate and depth of cut, while the response variable was surface roughness and material removal rate. The results show that a high removal rate is obtained with a high cutting speed, a high feed rate and a high depth of cut rate. Now, by ANOVA test shows that feed rate has the highest effect (70.32%) on material removal rate, followed by cutting speed and finally, depth of cut. Now, with respect to surface roughness, a low surface roughness is obtained with a low feed rate; likewise, through an ANOVA test it was found that cutting speed has the highest effect (56.45%) on surface roughness, followed by feed rate and depth of cut.

Although there is a wide variety of literature dealing with the phenomena of the machining process and the parameters that affect its performance indicators such as surface roughness, there is still no consensus on which parameters affect these indicators. More empirical work is needed to inductively reach a law that explains surface roughness in the machining process. Therefore, this research presents a statistical analysis of the cutting parameters that significantly affect the surface roughness in the turning process of 1018 cold rolled steel material.

2. Materials and methods

The present study was carried out on a 1018 steel material whose chemical composition is shown in Table 1.

Table 1. Chemical composition of 1018 steel

Element	Percentage
Carbon, C	0.14 - 0.20 %
Iron, Fe	98.81 - 99.26 %
Manganese, Mn	0.60 - 0.90 %
Phosphorus, P	<= 0.040 %
Sulfur, S	<= 0.050 %

The experimental work was carried out on 40 specimens of 1-inch diameter by 6 inches long. The specimens were machined on a Horizontal clausing Metosa lathe, C1765SS model, its technical characteristics 9.5” *29.52”, see figure 1, the cutting tool was a tungsten carbide insert burin at 60 degrees. The figure 2 shows the setup of the cutting tool on the 1018 steel specimen.

Figure 1. Cutting machine.

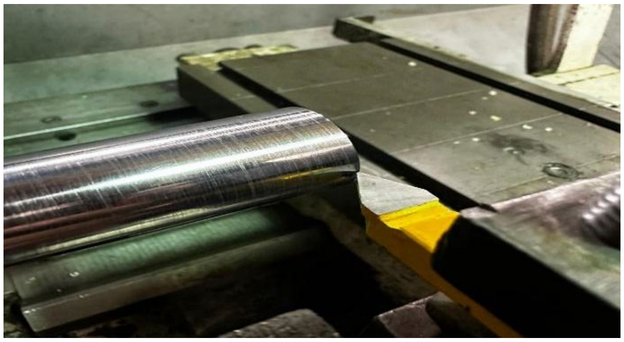

Figure 2. Set up cutting tool on 1018 steel specimen.

In addition, their surface roughness was measured with a Mitutoyo roughness tester, see figure 3. In this experiment, the control variables were cutting speed in revolutions per minute (rpm), feed rate, in inches per minute (inches/minute), and depth of cut, in inches (inches). The response variable was surface roughness in microinches (µinches). Table 2 shows the results of the experimental test. These values were selected based on the machine tool design and the range of parameters used on 1018 steel.

Figure 3. Set up of the roughness tester.

Table 2. Experimental test.

Cutting speed (rpm)	Feed rate (in/min)	Depth of cut (in)	Ra (µin)
350	20	0.05	191.5
350	20	0.05	194
350	20	0.05	193
350	20	0.05	196
350	20	0.05	201.75
750	20	0.025	75.25
750	20	0.025	77.75
750	20	0.025	74
750	20	0.025	76.43
750	20	0.025	76.75
350	5	0.025	49.5
350	5	0.025	45.23
350	5	0.025	49.65
350	5	0.025	53.5
350	5	0.025	46.5
350	5	0.05	33.25
350	5	0.05	32.8
350	5	0.05	34.3
350	5	0.05	30
350	5	0.05	57.25
750	20	0.05	65.5
750	20	0.05	62.78
750	20	0.05	64.56
750	20	0.05	68
750	20	0.05	69
350	20	0.025	190.25
350	20	0.025	190.89
350	20	0.025	189.25
350	20	0.025	190.73
350	20	0.025	182
750	5	0.025	27.5
750	5	0.025	27.76
750	5	0.025	30.65
750	5	0.025	31
750	5	0.025	33.25
750	5	0.05	18.75
750	5	0.05	19
750	5	0.05	18.96
750	5	0.05	21.25
750	5	0.05	24.75

Finally, using the free RStudio software, the data were statistically analyzed to obtain the parameters that significantly affect the surface roughness of the specimens, as well as to obtain a multiple regression model that explains the behavior of the phenomenon.

3. Results

Al though graphs serve as a visual verification tool, it is important to present scatter plots of the variables suspected to have a significant impact on surface roughness. Subsequently, the statistical results obtained from the analysis will be examined.

The scatter plots presented above visually show the effect of cutting parameters on surface Roughness. In figure 4, the points in the upper left corner within the light orange box indicate that with low feed rates, the surface roughness is low, which is desirable for obtaining minimal surface finishes. On the other hand, figure 5 shows that operating with high cutting speeds also results in low surface roughness. Although these plots provide a visual description of the parameter behavior, this will be corroborated later with a statistical analysis.

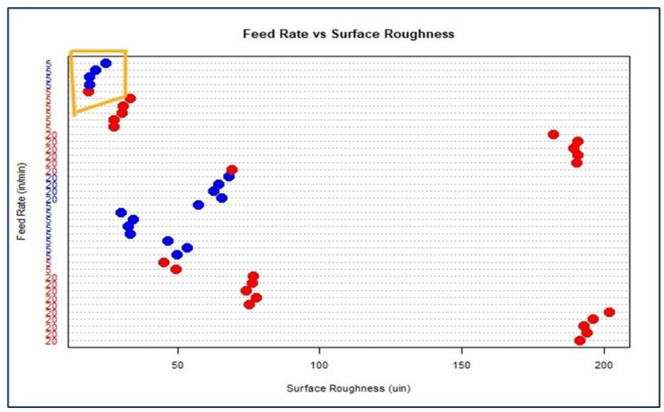

Figure 4. Scatter plot, feed rate vs. surface roughness.

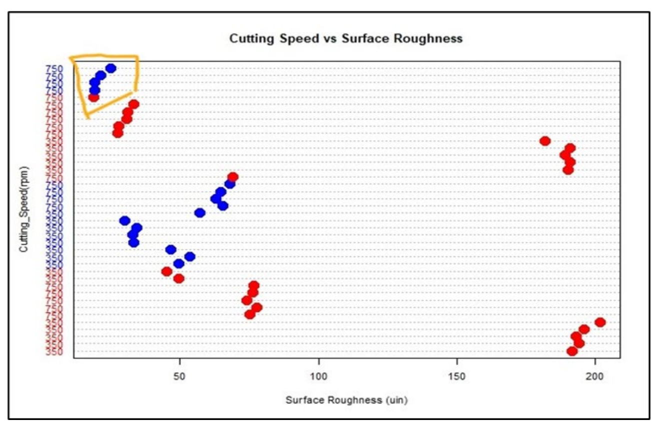

Figure 5. Scatter plot, cutting speed vs. surface roughness.

The statistical results shown on Table 3, were obtained with the RStudio software, showing with a significance level alpha equal to 0.05, that the parameters that significantly affect the surface finish or roughness of the machined part are: cutting speed, feed rate and the interaction between cutting speed and feed rate. The findings in this research corroborate to the experiments previously conducted where in their results, (Dutta & Narala, 2021; Kittali et al., 2022; Stampfer, et al., 2022), and (Ramesh et al., 2020), argue that the feed rate contributes significantly to the surface finish of the part, while (Senthilkumar et al., 2022) agree that cutting speed and feed rate significantly affect surface roughness. Likewise, in this model a correlation coefficient R2 =0.99 of fit was obtained with which its predictive ability of the Mathematical model is accepted.

Table 3. Statistical analysis results.

	Estimate	Std Error	t-value	Pr(>t)
Intercept	-1.606E+01	9.871E+00	-1.627	0.1132
CS	6.888E-02	1.522E-02	4.526	7.4E-05***
FR	1.506E+01	4.757E-01	31.646	2.0E-16***
DC	-1.252E+02	2.294E+02	-.546	0.5889
CSXFR	-1.717E-02	5.676E-04	-30.251	2.0E-16***
CSXDC	-7.414E-01	3.406E-01	-2.177	0.0367 *
FRXDC	2.321E+01	9.082E+00	2.555	0.0154 *
Signif. codes: 0"***", 0.05 "*"				
Residual standard error:5.385 on 33 degrees of freedom Multiple R-Squared:0.9944, Adjusted R-Squared:0.9934 F-Statistic:976.9 on 6 and 33 DF, p-value :<2.2E-16				

Where:
CS=Cutting speed
FR=Feed rate
DC=Depth of cut
CSXFR=Interaction by cutting speed and deed Rate
CSXDC=Interaction by Cutting Speed and Depth of cut
FRXDC= Interaction by feed rate and depth of cut
The mathematical model obtained was as follows:

$$SR = 16.06 + 0.06888 * CS + 15.06 * FR - 125.2 * DC - .01717 * CSXFR - 0.7414 + CSXDC + 23.21 * FRXDC + 5.385$$

Where:
SR=Surface roughness.

The behavior of surface roughness and the feed rate of the lathe can now be seen graphically. In Figure 6, as it was stated by Alam et al. (2023) and (Ramesh et al., 2020), as the feed rate increases, there is a higher surface roughness, while, as the feed rate decreases, the surface roughness is reduced.

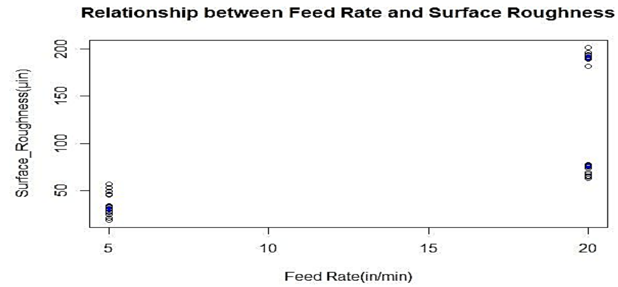

Figure 6. Relationship between surface roughness and cutting speed.

On the other hand,

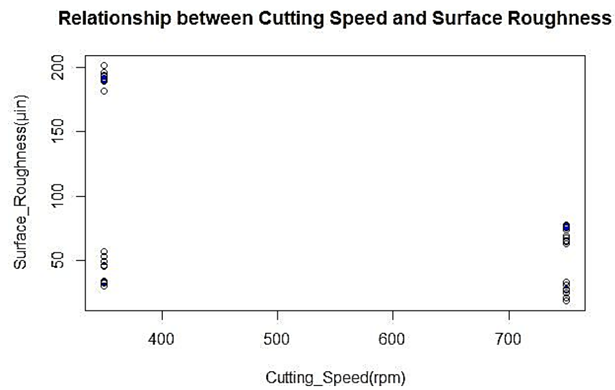

Figure 7. Relationship between cutting speed and surface roughness.

Although the feed rate is another parameter that significantly affects the surface roughness of the workpiece, it has a greater influence when it interacts with the feed rate as described in the statistical analysis. Finally, analyzing the feed rate (Figure 7), which is one of the factors that mostly impact the surface finish of the work piece according to previous studies mentioned (Dutta & Narala, 2021; Praveen et al., 2022), and (Ramesh et al., 2020), and this one as well, the first because that provokes this phenomenon is the Archimedes spiral, which relates the feed rate with the turns of the piece to obtain the determined pitch. Figure 8 schematizes the Archimedean spiral, where the pitch is the distance from crest to crest, and this is equivalent to the feed of the cutting tool for each revolution of the chuck.

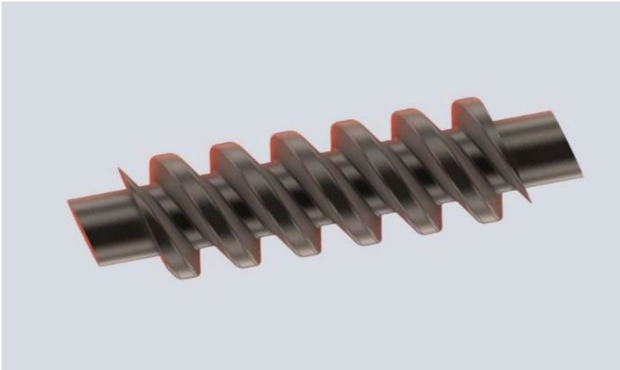

Figure 8. The Archimedean spiral.

4. Conclusions

The results indicate that two cutting parameters, feed rate and cutting speed, and, one interaction, cutting speed *feed rate, significantly affect the surface finish of the workpiece as perceived by its surface roughness in micro inches. It is important to mention that previous mentioned experimental work (Dutta & Narala, 2021; Praveen et al., 2022; Ramesh et al., 2020; Stampfer, et al., 2022) show that the feed rate is a factor that significantly affects the surface finish of the workpiece, therefore, a universal law that explains the surface finish or surface roughness as a function of the cutting feed rate can be idealized. Also, a mathematical model was obtained to predict surface roughness as a function of cutting parameters. This mathematical model has an R2 equal to 0.99, considered a good predictor of surface roughness. Finally, it is recommended for future works to continue increasing the experimental evidence in machining processes including other control variables such as vibration and cutting tool wear among others on different working materials. Also, experimental evidence gathered from other works shows that the feed rate significantly affects the surface roughness. Now, with the experience gained, it is possible to idealize a universal law of surface roughness as a function of feed rate. Summarize and bring together the main results and give a final comment and make suggestions for improvement and include speculations on future directions.

Conflict of interest

The authors have no conflict of interest to declare.

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