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Optimization of Cutting Parameters during CNC Turning of a Steel

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Abstract:- The surface roughness obtained by optimizing the cutting parameters when turning on a CNC machine tool is used to control the quality of machining processes. The objective is to simulate a CNC program designed for this process. The machining parameters, including cutting speed (Vc), feed rate (f), and depth of cut (ap), are carefully calibrated to achieve a minimum surface roughness (Ra). Analysis of variance (ANOVA) was used to determine the dependence of surface roughness. This analysis allows the effect of each parameter on surface roughness to be estimated. The results of this analysis are then used to construct a mathematical model that establishes a correlation between cutting parameters and surface roughness.

Keywords:- *Roughness (Ra), CNC Turning, Machining Process, Initial Parameters, Numerical Modeling.*

I. INTRODUCTION

In the context of manufacturing, design and layout are of paramount importance. Process design refers to the rational organization of the production process, including the design of production process routes, the selection and design of production equipment, process molds, tools, and other relevant components, and the formulation of sound operating procedures and production schedules based on product characteristics and requirements [1].

A comprehensive understanding of the product, including its structure, functions, performance requirements, and related factors, is paramount to effective manufacturing process design. The optimal approach is determined by analyzing and studying the manufacturing technology and experience to ensure the quality and performance of the product [2].

Mastering the CNC turning process is one of the most important tasks in industry, as it allows not only to reduce raw material losses, but also to obtain rotationally symmetric parts (cylinders, planes, cones, or complex rotationally symmetric shapes) with improved mechanical properties. The improvement of the surface quality during machining has been shown to influence the durability, reliability and overall performance of the components [2],[3].

The C1018 carbon steel was used in the design and simulation of the CNC turning process. In the context of turning with ceramic cutting tools, the primary factors contributing to surface roughness can be categorized into three distinct aspects: geometric causes, physical causes, and changes in cutting conditions. Achieving the desired surface quality of the finished component depends on the manipulation of parameters such as cutting speed (Vc), feed rate (f) and depth of cut (ap). The resulting component is a bolt used in the manufacture of industrial equipment, the final shape of which is dependent on the cutting tool path strategy [4].

It has been shown that a high cutting speed (Vc) is effective in reducing the formation of edges and burrs, thereby minimizing the surface roughness [5]. It has been found that increasing the cutting speed reduces the plastic deformation of the chip and machined surface, thereby reducing surface roughness. When the feed rate is reduced, a similar effect is observed. The effect of the depth of cut ap on the surface roughness Ra is found to be negligible. In the present study, therefore, it can be ignored. However, it becomes difficult to maintain normal shearing of the part if the depth of cut during machining is too shallow ($ap < 0.02$ mm). Extrusion and friction occur under such conditions. As a result, an increase in surface roughness is well known [6].

II. METHODS

The CNC turning process for C1018 steel is designed and controlled by a computer program that guarantees high precision and accuracy of the machined part. This software contains alphanumeric data corresponding to the XYZ coordinate axes in three-dimensional space. The program automates the cutting cycle from a CAD file, ensuring the production of parts with the highest precision. The cutting movement produced by the rotation of the workpiece is combined with the movement of the cutting tool to form the final part. The interaction of these two movements results in the removal of material in the form of chips.

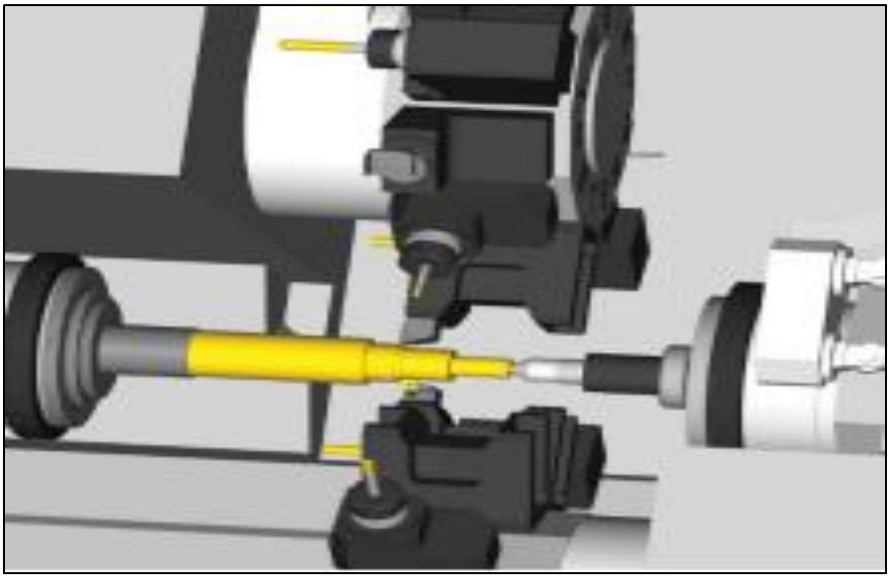

Fig 1: Image Showing CNC Turning.

➤ *Modeling Process and Materials Used*

The material used is cold-rolled carbon steel C1018. Its composition is shown in Table 1. C1018 steel has good strength and some ductility. It is relatively easy to weld and machine. Heat treatment such as tempering and surface hardening can improve its strength, hardness, toughness and wear resistance.

Table 1: Composition of C1018 steel [7].

Atoms	**C**	**Si**	**Mn**	**P**	**S**
Compositions	0,15 – 0,2	0,15 – 0,35	0,6 – 0,9	≤ 0,04	≤ 0,05
Density	7750 - 8050 kg/m^3				
Tensile strength	410 MPa				

The turning process of C1018 steel was carried out by numerical simulation, implemented in SolidWorks CAD software, using a diamond-shaped ceramic cutting tool. The objective of this study is to investigate the effect of different cutting conditions (Vc, f, ap) on the surface roughness measurement (Ra). Then, a computer numerical control (CNC) program was designed to ensure optimal surface roughness. Incorporating cutting parameters with a uniform or normal distribution law transforms the problem into a stochastic one, resulting in a response that is random due to error propagation. Therefore, statistical processing becomes essential at this stage to transform the problem into a deterministic one [8].

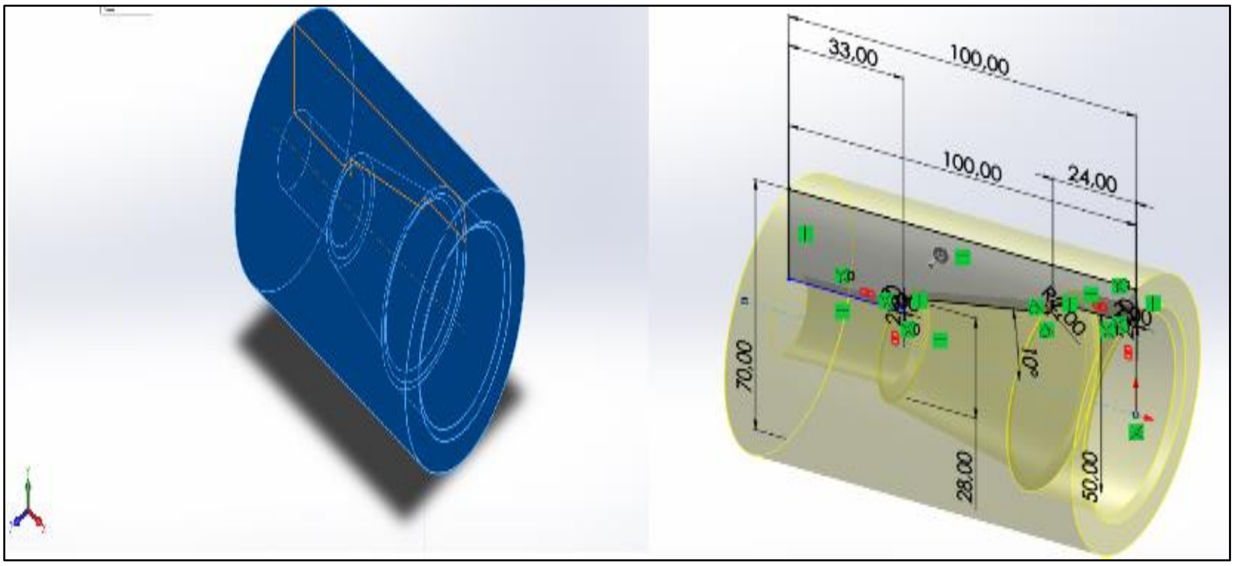

Fig 2: Modeling a Test Part Using SolidWorks CAD Software

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As shown in Figure 2, the modeled component is a cylindrical element made of C1018 steel that is subject to internal stress. After the model is created, the X-axis is oriented upward. The sequence of CNC turning operations applied to the C1018 steel part includes facing, centering, drilling prior to reaming, and finishing the interior with a precision bore. The subsequent toolpath modeling involves adjusting the cutting parameters to produce the finished part, as shown in Figure 3.

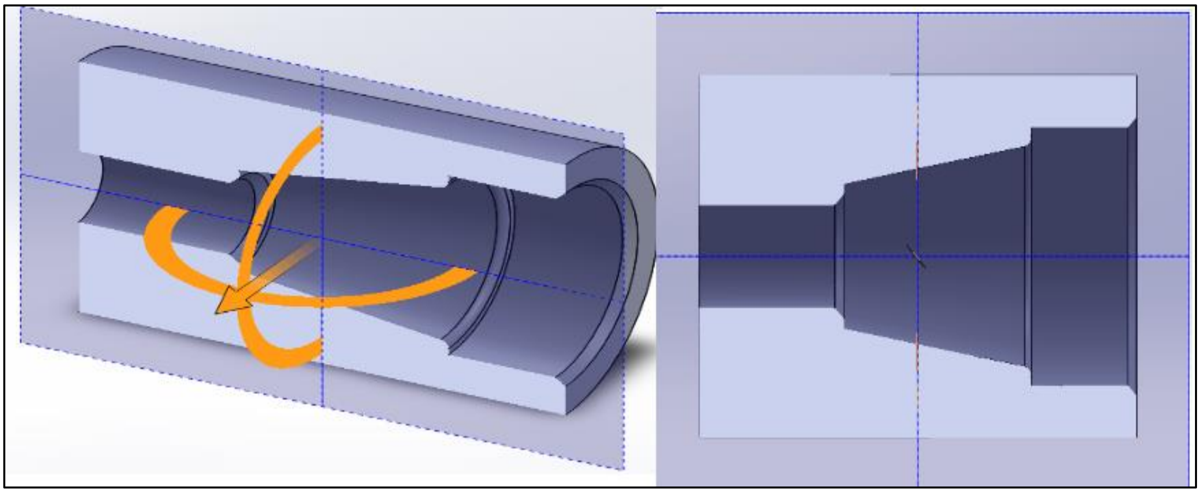

Fig 3: Sectional View of Steel Part C1018 Obtained after Modeling

III. RESULTS AND DISCUSSION

To determine which factors and interactions have a statistically significant effect on surface roughness (Ra), a statistical analysis known as analysis of variance is performed. Each test is repeated three times. The effect of the input parameters (Vc, f and ap) on the output (Ra) is studied. By varying the cutting conditions and measuring the roughness Ra, turning operations are performed. The roughness values according to the chosen experimental design are summarized in Table 2. The cutting conditions that are used for the different tests are different in the following ranges: Vc [150 - 480] m/min; f [0.05 - 0.15] mm/tr; ap [0.5 - 0.7] mm.

Table 2. Roughness values

Test No.	***Vc*** (m/min)	***f*** (mm/tr)	a_p (mm)	***Ra*** (µm)			Ra_{moy} (µm)
1	150	0,05	0,5	1,94	1,83	1,96	1,91
2	320	0,05	0,6	1,59	1,61	1,63	1,61
3	480	0,05	0,7	1,45	1,68	1,60	1,60
4	150	0,1	0,5	1,96	1,89	1,92	1,58
5	320	0,1	0,6	1,44	1,42	1,32	1,92
6	480	0,1	0,7	1,46	1,50	1,22	1,39
7	150	0,15	0,5	1,83	1,90	1,73	1,82
8	320	0,15	0,6	1,79	1,84	1,66	1,76
9	480	0,15	0,7	1,52	1,69	1,40	1,54

The mathematical relationship between input parameters (Vc, f and ap) and output parameters (Ra), defined as technological processing parameters, is represented as follows.

$$R_a = \varphi(V_c, f, a_p) \quad (1)$$

Where φ is the response function.

This relationship is called regression. An approximation Ra is proposed using a quadratic (nonlinear) mathematical model suitable for studying the interaction effects of cutting parameters and given by the following equation:

$$R_a = b_0 + \sum_{i=1}^{k} b_i X_i + \sum_{ij}^{k} b_{ij} X_i X_j + \sum_{i=1}^{k} b_{ii} X_i^2 + \beta_{ij} \quad (2)$$

Where $\beta_{ij} = R_{ij} - \overline{R_{ij}}$

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In this relationship, b_0 is a constant term of the regression equation, the coefficients b_1, b_2 ... b_k and b_{11}, b_{22}, b_{kk} are linear and quadratic terms, respectively, and b_{12}, b_{13}, b_{k-1} are interaction terms. X_i denotes the input parameters, and β_{ij} represents the fit error for the regression model. R_{ij} denotes the appropriate test response, and $\overline{R_{ij}}$ represents the fitted value.

The P-value is used to assess the statistical significance of quadratic prediction models. This is the probability (on a scale from 0 to 1) that the observed results could have been the result of chance.

If P < 0.05, the parameter is considered insignificant. Conversely, if P < 0.05, the parameter is considered statistically significant. The analysis of accelerations and cutting forces in the tangential direction (Z) is shown in Figure 4.

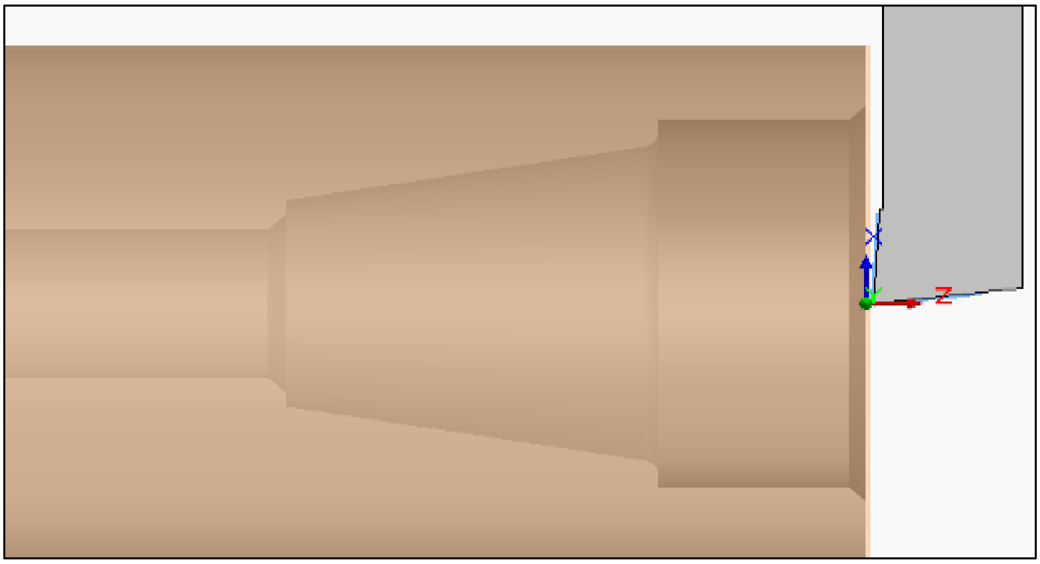

Fig 4: Cutting Motion

The results of the analysis of variance for surface roughness (Ra) as a function of Vc, f, and ap are shown in Table 3. This analysis was performed at a 5% significance level and a 95% confidence level. The table presents the values of degrees of freedom (DF), sum of squared deviations (SS), mean square deviation (MS), statistical property (F), percentage contribution (Cnt%) of each factor and various interactions, indicating the degree of influence on the results.

Table 3. Analysis of variance for Ra

Variance analysis Source	DF	SS	MS	F-Value	P-Value	Cnt%	Comments
Model	9	1,11128	0,123475	0,51	0,001	97,86%	significant
Vc (m/min)	1	0,08080	0,080798	0,56	0,033	60,58%	significant
f (mm/tr)	1	0,00120	0,001203	0,00	0,001	22,15%	significant
ap (mm)	1	0,10480	0,104805	0,43	0,525	0,48%	insignificant
Vc (m/min) *Vc (m/min)	1	0,11373	0,113728	0,47	0,048	5,18%	significant
f (mm/tr)*f (mm/tr)	1	0,21598	0,215984	0,90	0,036	2,75%	significant
ap (mm)* ap (mm)	1	0,00386	0,003855	0,02	0,902	0,09%	insignificant
Vc (m/min) *f (mm/tr.)	1	0,56180	0,561800	2,33	0,006	5,87%	significant
Vc (m/min) *ap (mm)	1	0,00980	0,009800	0,844	0,04	1,03%	significant
f (mm/tr) *ap (mm)	1	0,05120	0,051200	0,21	0,655	1,23%	insignificant
Error	10	2,41292	0,241292				
Pure error	5	0,65388	0,130777				
Total	19	3,52420				100%	

This table shows that cutting speed, Vc, is the most significant factor influencing surface roughness, Ra. The effect of this factor is significant with a contribution of 60.58%. Feed rate (f) contributes 22.15% of the variance in surface roughness. Interactions such as Vc^2, f^2, Vc*f, and Vc*ap are also significant with contributions of 5.18%, 2.75%, 5.87%, and 1.03%, respectively. The regression equation for Ra as a function of Vc, f, and ap was obtained with a correlation coefficient R^2 = 96.56%, represented by the following mathematical formula:

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$$R_a\ (\mu m) = 0{,}13 - 0{,}00284 \times V_c + 9{,}6 \times f + 3{,}8 \times a_p - 0{,}000003 \times V_c^2 - 49{,}0 \times f^2 - 1{,}6 \times a_p^2 + 0{,}0312 \times V_c \times f + 0{,}0021 \times V_c \times a_p - 16{,}0 \times f \times a_p \qquad (3)$$

Figure 5 shows a three-dimensional representation of the response surfaces. The figure shows a significant decrease in surface roughness (Ra) as the cutting speed (Vc) increases. In addition, it was observed that the feed rate (f) has a significant effect on the surface roughness (Ra), as evidenced by its proximity to the slope of the cutting speed (Vc). The roughness (Ra) shows minimal variation over a range of depth of cut (ap). Consequently, the depth of cut is found to have no significant effect on the roughness, which is explained by 96.56%, while 3.14% remains unexplained. This result suggests that the model used to derive the roughness measurements is a highly effective representation. The minimum roughness, Ra = 1.52 µm, was obtained for the following cutting parameters: Vc = 320 m/min, f = 0.1 mm/tr, and ap = 0.6 mm.

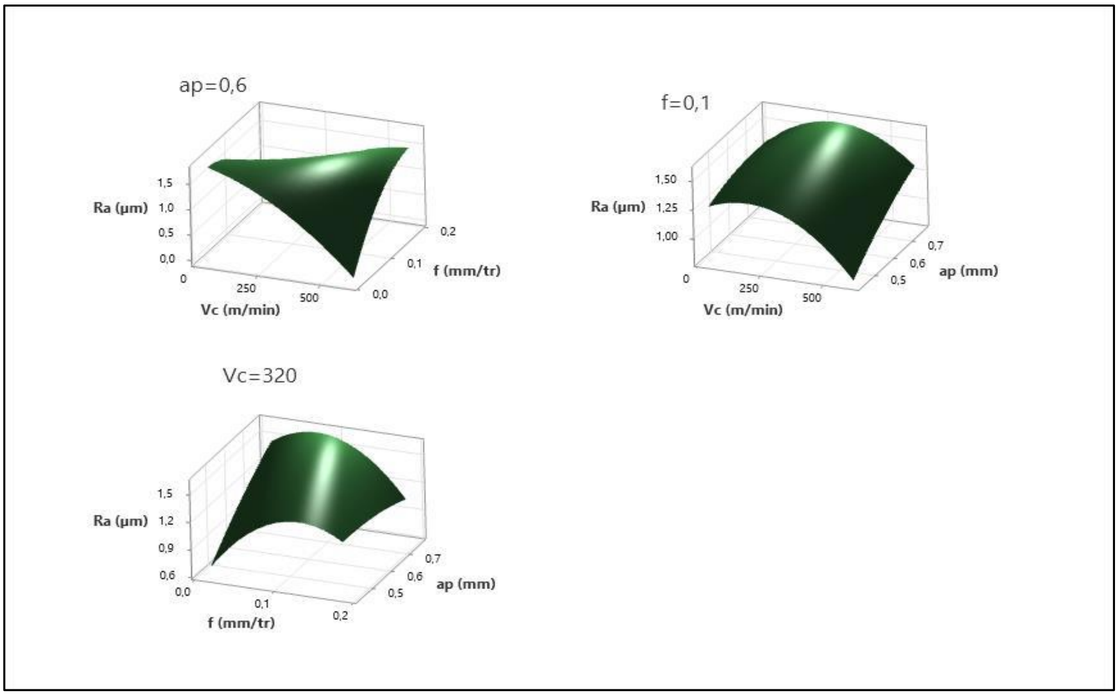

Fig 5: 3D Image of Surface Roughness Ra: *Vc=320 m/min, f=* 0.1 mm/tr and *ap=0.*6 mm.

IV. CONCLUSION

A numerical approach to CNC turning of C1018 steel was used to study the effect of cutting conditions on the output parameter, machined surface roughness (Ra). The result was the development of a cutting condition model. The subsequent analysis showed that the most significant conditions were the cutting speed (Vc) and the feed rate (f). They contributed to the resulting surface roughness by 60.58% and 22.15%, respectively. The results indicate that the surface roughness is increased by a combination of feed rate reduction and cutting speed increase. It is noteworthy that the higher the percentage contribution (Cnt %), the more significant is the influence of this factor on the studied parameters. (Vc=320 [m/min]), (f=0.1 [mm/tr]) and (ap=0.6 mm) is the optimal combination of cutting parameters for achieving minimum surface roughness. Under these cutting conditions, surface quality is improved. Wear is reduced. The result is an increase in tool life and an optimum surface finish. This assertion is supported by analogous results reported in [9]. It is possible to ensure product quality and increase production efficiency by integrating modern technologies and management methods. In today's industry, this is a key issue.

➢ *Abbreviations*

CNC, Computer Numerical Control; ANOVA, analysis of variance; CAD, Computer-aided design; DF, Degrees of Freedom; SS, Sum of Squared deviations; MS, Mean Square deviation

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➢ *Authors' Contributions*

JuT coordinated and supervised the work; NZ performed the simulations and wrote the manuscript. All authors read and approved the final manuscript.

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➢ *Data Availability*

Data will be made available on request.

➢ *Declarations*

- *Competing Interests*

  The authors declare no competing interests.

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