euspen's 24th International Conference & Exhibition, Dublin, IE, June 2024
www.euspen.eu

Analysis of the influence of cutting conditions on surface roughness of turning workpieces using a focus variation optical system

Sergio Aguado[1,2], Marcos Pueo[1,2], Raquel Acero[1,2], Ana C. Majarena[1,2], Jorge Santolaria[1,2]

[1]Department of Design and Manufacturing Engineering department, University of Zaragoza, C\María de Luna3, Zaragoza 50018, Spain
[2]Instituto de Investigación en Ingeniería de Aragón (I3A), 50018 Zaragoza, Spain

Email: saguadoj@unizar.es

Abstract

This work aims to analyse the influence of machining cutting conditions on the surface quality of machined Steel 11SMnPb30 pieces using a CNC parallel lathe. The parameters whose influence is studied are cutting speed (v_c), feed rate (f), and depth of cut (a_p). To achieve this, a series of analysis techniques and a method for constructing statistical models were employed. The measurement of the surface roughness of the machined pieces is performed using a focus variation optical system from the Alicona brand, InfiniteFocusSL model. The surface quality metric used is the average surface roughness (Ra). The influence of cutting conditions on the surface quality metrics is assessed using analysis of variance (ANOVA) or the statistical design of experiments (DOE), studying the machining temperature also as a result of the process. In this context, the Scheffler regression equation is used in an attempt to extrapolate the roughness values of a series of control pieces.

Keywords: focus variation optical system, surface roughness, machining conditions, machining temperature, statistical analysis

1. Introduction

Machining industry demands high quality products. The surface finish and texture of machining pieces have a crucial role in wear and fatigue resistance, lubrication and the external appearance of the parts. Hence, it is crucial to take into account parts' surface roughness. Achieving the required surface roughness values depends on a proper selection of cutting parameters during the machining operation.

Current models for predicting surface quality in machining are divided into four groups [1]: models based on machining theories that consider that surface quality is strongly affected by the geometry of the problem and the associated vibrations [2]; models that examine the effects of different cutting parameters on factors such as residual stresses, microstructure, micro hardness and roughness, by the execution of experiments and analysis of results [3]; models created through Design of Experiments (DOE) [4] or Taguchi techniques [6]; and models developed using artificial intelligence like Fuzzy Logic, Artificial Neural Networks or Genetic Algorithms [5].

This paper aims to analyse the influence of machining temperature and cutting parameters on the surface quality of 11SMnPb30 steel machined parts using a numerical control parallel lathe. Experimental details are presented in the second section, while the third section covers the results and discussion of the empirical real tests.

2. Materials and methods

The details of the methodology followed, experimental conditions, equipment and measurement systems used on the study are presented in this section.

2.1. Workpiece material

Pieces to be machined are made of F-212 steel according to UNE standard, equivalent to 11SMnPB30 on DIN standard. Lead is added to this steel to enhance machinability without affecting the mechanical or metallurgical properties of the base steel. However, it is not suitable for welding. It is commonly used in screws, bolts, bushings, fittings, and washers due to its mechanical properties [7].

2.2. Cutting tool

Experimental tests were carried out using a cutting insert Sandvick CNMG 12 04 08 QF 4025 as cutting tool. It is a hard metal tool used in finishing operations with an effective cutting edge length of 12.096 mm, a tip radius of 0.794 mm, a hole fixing diameter of 5.156 mm, an inscribed circle of 4.762 mm, a CVD coating of TiCN+Al203+TIN, and four cutting edges per insert.

2.3. Machine tool

The machine tool to be used for machining the parts is a manually assisted conventional CNC lathe Pinacho Rayo 180 Ø 360 x 1000 mm with a spindle power of 5.5 Hp, weight capacity of 1.5 Ton, swing over bed of 360 mm, swing over carriage of 198 mm, distance between centres of 1000 mm, a spindle hole diameter of 42 mm and a speed range 100 – 4000 rpm.

2.4. Cutting Conditions

Cutting conditions must be a balance between the cutting conditions provided by the cutting tool, the characteristics of the material to be machined, and the real limitations of the machine tool.

The insert selected is designed to work with materials until 180 HB with a depth of cut (a_p) in range (0.2 – 2.5) mm, feed rate (f) in range (0.11 – 0.38) mm/rev and cutting speed (v_c) in range (320 – 450) m/min. As the material to be machined has a hardness of 140.5 HB, v_c can be increased to (450 – 562) m/min. The dimensions of the workpiece to be machined are 48 mm diameter and 75 mm length. Facing and turning operations of length 45.5 mm will be carried out.

Considering the specifications of section 2.3, the machine should be able to operate on these ranges without issues. However, preliminary tests showed excessive system vibrations due to structural problems. Therefore, the cutting conditions ranges were adjusted to a_p (0.25 – 1.0) mm, f (0.05– 0.2) mm/rev and v_c (100 – 220) m/min.

2.5 Thermal camera

The camera used to measure the temperature of machining process is a FLIR E60. The measurement conditions employed were emissivity value of 0.6 and reflected temperature 21°C. The camera was used in video recording mode. Both capture and data processing were done using Matlab.

2.6 Surface roughness measurement

The measurements of average surface roughness (*Ra*) were done on an Alicona InfinityFocusSL optical system using an objective of 10x. The equipment specifications are presented in Table 1.

Table 1 InfinityFocusSL specifications

Objective magnification	**10X**
Lateral measurement area (X x Y))	4 mm^2
Distance of measurement points	1 µm
Calculated lateral optical limiting resolution	1.09
Measurement noise	40 nm
Vertical resolution	100 nm
Finish lateral topographic resolution	2 µm
Vertical measurement range	16 nm
Min. measurable roughness (Ra)	0.3 µm
Min. measurable roughness (Sa)	0.15 µm

The workflow to measure the roughness in the workpieces was the following:

1. Set lateral and vertical resolution as 1.76 µm and 100 µm respectively.
2. Define a measurement area
3. Choose true or polynomial form to remove its influence on the measurement: cylinder on turning operation or plane on facing one.
4. Adjust the reference plane to remove the polynomial form.
5. Define profile width as 5 mm and a lineal path of 4 mm.
6. Define the area of measurement. On the turning surface three measurement areas were defined, rotating the piece 120 degrees among each one. On the facing surface three areas were aleatory defined.
7. Choice Lc filtering as 800 µm for R_a between 0.1 µm and 2 µm and 2500 µm for R_a between 2 µm and 10 µm, according to ISO 4288 [8].
8. Calculate roughness parameter *Ra*.

2.7. Experimental plan procedure

The impact of cutting conditions on the surface roughness will be studied using two statistical tools. Initially, a three-factor with two-level Design of experiments (DOE), see Table 2,will be conducted, resulting in a total of 8 test, calculating the effect and basic contribution of each factor as well as their interactions. . Each test is replicated seven times with facing and turning operations.

Table 2 DOE d matrix

	Factor 1	Factor 2	Factor 3
Test Id	V_c (m/min)	f (mm/rev)	a_p (mm)
1	100	0.05	0.25
2	100	0.05	1.00
3	100	0.20	0.25
4	100	0.20	1.00
5	220	0.05	0.25
6	220	0.05	1.00
7	220	0.20	0.25
8	220	0.20	1.00

A total of 56 workpieces are machined and six roughness zones are measured on each piece, three for each operation. To eliminate potential outliers, Chauvenet's criterion is applied [9].

After machining the pieces, an analysis of variance technique (ANOVA) is used to determine the parameters that are the most significant in relation to surface roughness.

The F-test or variance ratio is essentially the correlation between the variance of the process parameter and the error. It serves to quantify the significance of the different study factors concerning the overall variance, encompassing all factors, including the error, as shown in equation 1. Where *e* is the experimental variance error and *V* is the variance of the parameter analysed.

$$F = \frac{V}{e} \tag{Eq.1}$$

The percentage of influence (P) is the percentage value of influence for each study factor, as defined in Equation 2, where S is the residual sum of squares and ST is the sum of total squareness, as shown in equation 3.

$$P = S\, x \frac{1}{ST}\, x\ 100 \tag{Eq.2}$$

$$ST = S - C * F \tag{Eq.3}$$

The sum of squares (ST) allows quantifying the variability of a dataset by focusing on the difference between each data point and the mean of all points in the set. Where *S* and *C*F* are presented in equation 4 and 5, representing y_i the value of R_a for piece *i* with *i = 1 ... 56.*

$$S = \sum_{i=1}^{n} y_i^2 \tag{Eq.4}$$

$$C * F = \left(\frac{1}{n}\right) \left[\sum_{i=1}^{n} y_i\right]^2 \tag{Eq.5}$$

Degrees of freedom equations are a measure taken from a certain amount of information, determined based on the number of data. Total degree of freedom (DF_{total}) is defined as number of machined pieces minus one. The parameters' degree of freedom (DF) is defined as the number of level of parameters minus one. The difference between both is defined as the degree of freedom of the error (DFe). These values are used to obtain the variance of the parameter to study *VF*, given by equation 6, and the variance of the error *Ve*, shown in equation 7, where *j* represents the parameter to study a_p *, f or* v_c.

$$VF = \frac{S}{DF} \tag{Eq. 6}$$

$$Ve = \frac{Se}{DFe} = \frac{ST - \sum_{j=1}^{m} VFj}{DFe} \tag{Eq. 7}$$

After conducting the ANOVA analysis, a Design of Experiments (DOE) analysis is performed, examining both the main effects and the fundamental contribution of the parameters and their interactions [10].

Additionally, five extra pieces are machined. The machining conditions for these pieces are fixed within the studied ranges. The Scheffler regression equation is used as a tool to predict the roughness of future pieces considering the machining conditions within the ranges established in the experiments [11].

The experiments are carried out in the precision mechanics workshop at the University of Zaragoza, following the set up shown in Figure 1. This set up includes a Flir E60 thermal camera to perform the radiometric measurement.

Figure 1. Set up of machining tests

The measurement of the surface roughness of machined parts is carried out in a metrology laboratory under controlled environmental conditions at 20±1°C using the Alicona InfiniteFocusSL variation equipment, see Figure 2. Before measuring the pieces, they were stabilized for a minimum of one day and a maximum of seven days to prevent issues such as surface oxidation.

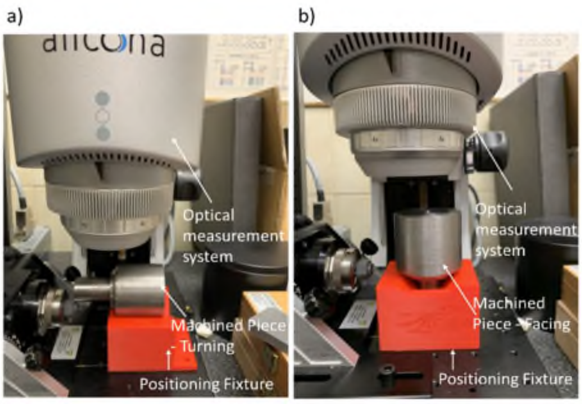

Figure 2. Measurement of roughness a) turning operation b) facing operation

3. Results

Table 3 presents the results of the surface roughness and the temperature measurement of the machined parts. It includes the roughness parameter *Ra* as the most representative one. The mean value and standard deviation of *Ra* are obtained from the measurement of roughness in three positions for each of the seven pieces that were machined on each test. In regard to the temperature values, the maximum value of temperature (Maximum Area), comes from the maximum temperature in the ROI rectangular measurement area shown in Figure 3. The second column (Temperature control point) shows the temperature of the control point located on the piece, Figure 3.

Both rectangular measurement area and control point are the same for all tests and pieces.

Table 3 Experimental results

	Facing *Ra* (µm)		Turning *Ra* (µm)		Temperature (°C)	
Test Id	Average	Std	Average	Std	Maximum Area	Control Point
1	1.08	0.27	1.19	0.17	71.7	29.5
2	1.37	0.30	1.44	0.31	36.4	26.9
3	3.74	1.21	3.46	0.41	52.9	27.9
4	2.80	0.88	2.82	0.88	56.7	30.5
5	1.13	0.19	1.41	0.11	86.9	32.7
6	1.11	0.76	1.70	0.88	115	33.8
7	1.75	0.41	1.88	0.23	60.4	37.1
8	2.89	1.86	1.98	0.23	84.5	39.8

The results obtained show small variations in the surface roughness depending on the measured area and the piece machined. Similarly, if the results of turning and facing *Ra* are compared, see table 3, these provide similar results between facing and turning to the same test, except in the test 8. This discrepancy is attributed to a deflection issue in the tool turret that increase its influence using more aggressive cutting conditions.

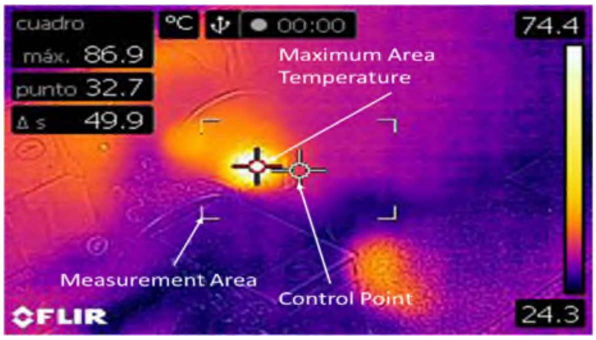

Figure 3. Machining thermal image (area , maximum temperature, and control points)

Temperature results in Table 3 show that changes on cutting conditions affect to machining temperature. However, experimental results show how the maximum temperature value in an area cannot be considered representative of the process due to reflections from older chips, glare or environmental factors. In the temperature of the control point, these influences are reduced. However, it is not possible to isolate the machining process from its surrounding radiation.

Table 4 Summary of ANOVA analysis.

	DF	V (μm^2)	F	% P	S (μm^2)
V_c	1	3.73	4.36	4.33	3.73
f	1	39.26	45.98	45.63	39.26
a_p	1	0.282	0.33	0.33	0.03
Error	52	0.86			
ST Total C*F = 214.76	55				86.04

ANOVA analysis results, presented in Table 4, show that the machining parameter with the most significant impact on the surface roughness is the feed rate. It has a Fisher's F test of 45.891 and a percentage of influence of 45.63 %. The second parameter on influence is the cutting speed with a value F of 4.36 and a P value of 4.33%.

The *Ra* analysis carried out through DOE shown in Figure 4, corroborates the results of the ANOVA analysis. It illustrates that higher feed rates lead to an increase in surface roughness. In the same way, a low cutting speed increases *Ra,* contrary to expected results and cut depth effect is negligible. Similarly, Figure 4 shows how the influence of iterations is smaller than individual effect's contribution. The interaction with the greatest influence is the relationship between the cutting speed and the feed rate with a value of -0.73.

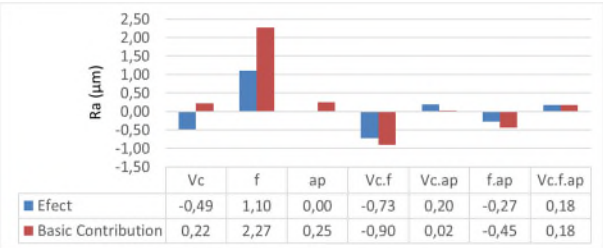

Figure 4. Summary of Ra DOE analysis (influence on surface roughness (Ra) of machining conditions Vc, f and ap)

DOE analysis of the influence of cutting conditions on the control point temperature in the turning process in Figure 5, shows that the parameter with the greatest influence is the cutting speed, followed by feed rate and cut depth. In relation with interaction influence, their influence is similar in value and can not be negligible.

Figure 5. Summary of Control point Temperature °C DOE analysis (influence on the machining control point temperature of machining conditions Vc, f and ap)

Table 4 Adaptation of the Scheffler equation to control components

Piece	V_c (m/min)	f (mm/rev)	a_p (mm)	Measured Ra (µm)	Scheffler Ra (µm)
1	150	0.05	0.70	1.14	1.19
2	210	0.10	0.50	0.81	2.50
3	180	0.20	1.00	1.65	3.13
4	120	0.15	0.25	0.97	2.59
5	220	0.15	0.40	1.02	1.71

Table 4 presents the adequacy of Scheffler regression to predict *Ra* behaviour, using five extra pieces used as control parts with different cutting conditions within the ranges performed in the experimental tests. As can be observed, only the first piece has similar results. Therefore, there is not a linear relationship between *Ra* and cutting conditions. Hence, more complex methods like neural networks are necessary to infer further conclusions among the factors relations.

4. Conclusions

This work provides a generalizable procedure to establish the correlation between cutting conditions with machined part's surface roughness and temperature on machining process.

ANOVA analysis determined that the parameter with the greatest influence on roughness is the feed rate, with an influence percentage of 45.63% followed by cutting speed and cut depth, with influences of 4.33% and 0.33%, respectively.

DOE analysis showed that the surface roughness decreases with increasing cutting speed, especially when interacting with the feed rate, representing the optimal combination of factors. On the other hand, recognizing that the feed rate is the most relevant factor, it can be inferred that higher feed rates result in increased surface roughness. In relation with machining temperature and based on the Scheffler regression equation results, it is concluded that cutting conditions has not a linear relationship with *Ra.*

Based on the results of this work, further exploration will be undertaken to establish the relationship between cutting conditions, temperature, and surface roughness, employing artificial intelligence techniques for this purpose.

Acknowledgments

This research was funded by the Ministerio de Economía, Industria y Competitividad with project number PID2021-125530OB-I00 (Diseño y calibracion de un sistema modular de inspeccion inteligente para verificacion y Calidad en linea 4.0), and by Aragon Government (Department of Education, Science and University) through the Research Activity Grant for research groups recognized by the Aragon Government (T56_23R Manufacturing Engineering and Advanced Metrology Group).

Authors would like to acknowledge the use of Servicio General de Apoyo a la Investigación-SAI, Universidad de Zaragoza.

References

[1] Benardos P G and Vosniakos G C 2003 Predicting surface roughness in machining: A review *Int. J. Mach. Tools Manuf.* **43** 833–844.

[2] Baek D K, Ko T J and Kim H S2021 Optimization of feedrate in a face milling operation using a surface roughness model *Int. J. Mach. Tools Manuf.* **41** 451–462.

[3] Akkuş H and Yaka H 2021 Experimental and statistical investigation of the effect of cutting parameters on surface roughness, vibration and energy consumption in machining of titanium 6Al-4V ELI (grade 5) alloy *Meas. J. Int. Meas. Confed.* **167**p. 108465.

[4] Venkata Rao K, Suvarna Raju L, Suresh G, Ranganayakulu J and Krishna J 2024 Modelling of kerf width and surface roughness using vibration signals in laser beam machining of stainless steel using design of experiments *Opt. Laser Technol.* **169**, p. 110146.

[5] Huang P, Lee C-H 2021 Estimation of tool wear and surface roughness development using deep learning and sensors fusion *Sensors.* **22**, 6pp.

[6] Nangare K and Chavan S 2023 To predict the surface roughness of Black ABS component with variable parameters by applying the Taguchi method *Mater. Today Proc.* **72**, 706–712.

[7] Grade S Steel Grade 11 SMnPb 28 Chemical information,Mechanical properties. Accessed: Jan. 08, 2024. [Online]. Available: http://www.steel-grades.com/.

[8] ISO 4288:1996 - Surface texture: Profile method - Rules and procedures for the assessment of surface texture. 1998.

[9] Rochim 2016 A Chauvenet ' s Criterion , Peirce ' s Criterion , and Thompson ' s Criterion 2nd Quantitative and Qualitative Analysis Course Homework pp 3-5.

[10] 5.4. Analysis of DOE data." https://www.itl.nist.gov/div898/handbook/pri/section4/pri4.htm (accessed Jan. 10, 2024).

[11] B. L. Iverson and P. B. Dervan 2014 *Applied Linear Regresion*. Sanford Weisberg University of Minnesota.