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Design of experiments to evaluate the equation to obtain the operating parameters in a 3-axis Numerical Control Machine

Diseño de experimentos para evaluar la ecuación de obtención de los parámetros de operación en una Máquina de Control Numérico de 3 ejes

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Abstract

This article aims to evaluate the efficiency of the application of equations with which the operating parameters of the manufacturing process are obtained in a three-axis numerical control machine, in order to determine through analysis tests which is the most appropriate option when planning production in machines of this type. The methodology applied to obtain the results is based on the collection and analysis of data generated on a test bench to submit it to a design of 2K experiments, whose response variable is based on the roughness of the surface; using a roughness meter to determine the difference in finishes on a piece of aluminum 6160 T6 and jointly in the machining time; comparing theoretical vs real times. To obtain the comparative analysis, the revolutions per minute and the progress of the cutting tool will be considered as variables, it is expected that this will contribute to identifying the adjustment values that provide better results and standardize the correct use of the equations involved in obtaining the parameters.

Cutting Parameters, Roughness, Standardize

Resumen

El presente articulo tiene por objetivo evaluar la eficiencia de la aplicación de ecuaciones con las que se obtienen los parámetros de operación del proceso de manufactura en una máquina de control numérico de tres ejes, con la finalidad de determinar mediante pruebas de análisis cual es la opción más adecuada al planear la producción en máquinas de este tipo. La metodología aplicada para la obtención de los resultados se basa en la recolección y análisis de datos generados en un banco de pruebas para someterlo a un diseño de experimentos 2K, cuya variable de respuesta se basa en la rugosidad de la superficie; empleando para ello un rugosímetro a fin de determinar la diferencia en los acabados sobre una pieza de aluminio 6061 T6 y de manera conjunta en el tiempo de maquinado; comparando los tiempos teóricos vs los reales. Para obtener el análisis comparativo se procederá a considerar como variables las revoluciones por minuto y el avance de la herramienta de corte, se espera que con ello se logre contribuir a identificar los valores de ajuste que provean de mejores resultados y estandarizar el uso correcto de las ecuaciones implicadas en la obtención de los parámetros.

Parámetros de Corte, Rugosidad, Estandarizar

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Introduction

In the different machining processes there are variants that make the surface finishes denote the quality of machining, with the advent of numerical control machines these processes are more controlled because the parameters and conditions of the machine tool are programmed and thus human error is eliminated from the variation of the feed rate and depth of cut.

The metal removal process known as milling is one of the most widely used manufacturing processes in industry because the degree of understanding of the operation is not complex for the operators performing this task. Furthermore, due to the variety of shapes that can be created through displacements and/or trajectories, as well as the production speeds of mechanical components from scratch, milling is one of the most versatile and widely used processes in the manufacturing world. (Groover, 2007).

We can summarise that milling consists of passing a fixed workpiece in front of a tool with a cylindrical geometry that has a defined number of edges with a certain cutting edge and rotating it in order to remove the excess material from the part to be machined.

The rotation in this case takes place in the work tool which is mounted on the milling machine head and the movement is perpendicular to the direction of feed, i.e. the sharp edges hit the surface to be machined to rough and give the desired dimensions to the workpiece.

On a three-axis numerical control milling machine, it is sufficient to define the revolutions per minute at which the cutting tool is to rotate, the cutting feed rates in the different axes of the machine (X, Y, Z...) and the depth of cut, so that the workpiece goes from being a raw material to a finished product.

Once any machining process has been carried out we will notice that the surface of the workpiece has an attribute called, "roughness". Roughness is the deviations that occur on the surface of the part and in other words, irregularities that are a consequence of the parameters set when a specific manufacturing process is carried out. Apud Kalpakjian & Schmid, 2008.

This does not mean that the part is defective, but rather that the properties of the material cause it to respond in a certain way to the mechanical wear generated by the process itself.

The surface roughness causes the physical properties of a final part to be immersed in variations such as: dimensional accuracy; how precise the geometric tolerances are for assembly with other components, the coefficients of friction and wear; the contact of the surface with another part will suffer more or less wear due to roughness, among others, the fatigue limit, corrosion resistance, thermal and electrical resistance will also be affected in an indirect way.

It is worth mentioning that whether a part requires a certain level of finish will also influence the production cost of the part; the more precise the level of finish, the more manufacturing processes will have to be adapted to achieve the desired result.

Problem Statement

Given the complexity of the geometry and assembly precision of today's mechanical components, it is important to consider roughness as an essential factor that allows these components to meet the desired characteristics in order to comply with the standards considered in their design so that they are functional.

In this sense, it is important to establish the operating parameters of the numerical control machine with which these components are to be manufactured, in order to have a notion of which formulas give us a better surface finish, so that the variation in the different edges and/or faces of the final part are the required ones.

Starting from the formulas for obtaining the revolutions per minute of the spindle and the machine feed rate, we can define a design of experiments that allows us to apply an adjustment to these formulas to obtain an average roughness (Ra) closer to 1.6 µm, this value is recommended for narrow assembly fits that are subject to stress, as well as for surfaces that have little movement and do not need to withstand too much load. (Xometry, 2022). Based on the fact that we want to know the roughness on a surface to start developing aluminium moulds, this average roughness value is adequate.

Methodology

Considering the above, the methodology proposed for the development of the design of experiments is shown below.

1.- Choice of the material to be machined to carry out the tests.

2.- Choice of the cutting tool to be used for machining the material.

3.- Calculate the spindle speed parameter (S = RPM).

4.- Calculate the spindle feed parameter (F= mm/min).

5.- Design of the experiment matrix from the nominal parameters.

6.- Numerical control machine test manufacturing.

7.-Measurement and recording of the average roughness (Ra) and maximum average roughness (Ramax).

8.- Analysis of the data and the roughness graphs generated.

Figure 1 Methodology for the design of experiments to evaluate the equation to obtain the parameters.
Source: Own Authorship

This methodology seeks to evaluate the effectiveness of the application of the formulas for CNC machining parts, taking as the main attribute the surface roughness with which the part ends up at the end of the process. It is worth mentioning that this methodology also seeks to standardise how this experiment can be carried out on other ferrous and even non-ferrous materials.

Development of the methodology

Choice of material

For this experiment we will take as reference the aluminium 6061 T6 since it is a type of material used in the industry dedicated to the manufacture of moulds, this is due to its mechanical properties such as: mechanical strength, corrosion resistance, good ability to be deformed, has a medium machinability and a hardness of around 100-120 HB. (GGD Metals, 2015).

Choice of cutting tool

It was decided to use a ½" inch diameter helical high speed steel cutter with 4 cutting edges similar to the following design.

Figure 2 Endmill Design Basics 1
Source: https://mastercuttool.com/endmill-design-basics/

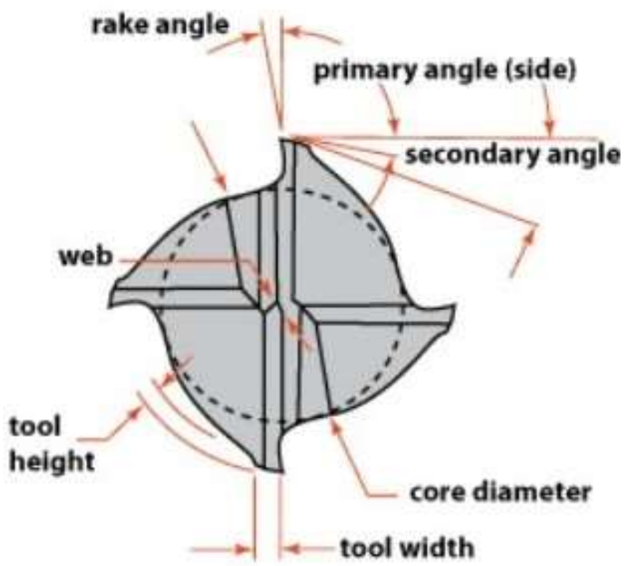

Figure 3 Endmill Design Basics 2
Source: https://mastercuttool.com/endmill-design-basics/

Calculation of RPM

To calculate the revolutions per minute of the spindle, the formula was applied:

$$S = \frac{1000 \times V_c}{\pi \times D_c}\ (rpm) \quad (1)$$

Where:

V_c =Cutting speed of the material.
D_c =Cutting diameter of the cutter.
S =Spindle revolutions per minute.

Now some of the values applied to the variables are:

V_c = 100 mts/min
D_c = 12.7 mm

Substituting is:

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$$S = \frac{1000 \times 100 \frac{\text{mts}}{\text{min}}}{\pi \times 12.7\ \text{mm}} = 2506.37 \cong 2506$$

This means that 2506 revolutions per minute will be taken as the nominal value for the design of the die to program the spindle speed of the machine.

Calculation of the feed rate

To calculate the feed rate of the spindle on the material to be machined, the formula was applied:

$$F = S \times f_z \times z_n \quad \left(\frac{mm}{\text{min}}\right) \tag{2}$$

Where:

S=Spindle revolutions per minute.
F=Feed speed of the tool with respect to the material.
Fz=Chip size at the moment of cutting for each cutting edge of the tool.
Zn=Number of cutting edges of the tool.

Now some of the values applied to the variables are:

S= 2506.37 RPM
fz= 0.079 mm/edge
Zn= 4 cutting edges

Substituting is:

$$F = 2506.37\ RPM \times 0.079 \frac{mm}{edge} \times 4\ edges$$

$$F = 792.01 \cong 792$$

This means that as a nominal value for the die design, 792 millimetres per minute will be used to program the feed rate of the machine spindle.

Die design

		Spindle speed (S = rpm)		
Advance (F =mm/min)		Under (-30%)	Nominal	Hihg (+30%)
		1754	2506	3258
Under (-30%)	554	1	3	5
		2	4	6
Nominal	792	7	9	11
		8	10	12
High (+30%)	1030	13	15	17
		14	16	18

Table 1 Matrix to be used to evaluate the machining parameters
Source: Own Authorship

Once the nominal values of the RPM and spindle feed rate parameters were obtained for machining tests on the 3-axis machining centre, it was considered that it was congruent to lower and increase them by 30%, because they cannot be varied too much as it would not make sense to calculate the nominal values as a reference.

As can be seen in the table, for each test, two replicates will be made in order to evaluate that the machined surface under certain parameters, really has the value given by the roughness test and looking for repeatability under certain operation scenarios.

Test manufacturing

The machining process was carried out on a Sunmill® 3-axis vertical numerical control machine, model JHV-1300, equipped with a Fanuc® Series Oi-MD controller model A02B-0309-B522.

At the foot of the machine and with the programming of a code that allows a lateral cut to be made on the 6061 T6 aluminium blocks, the number of tests obtained in the matrix is carried out, varying the RPM and advance parameters in every two tests.

Figure 4 Test manufacturing
Source: Own Authorship

The following equation was used to determine the lateral depth of cut:

$$5\%\ of\ stepover = D_c \times 5\% \tag{3}$$

Where:

D_c=Cutter cutting diameter.

So the value of the variable is:

D_c= 12.7 mm

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Substituting it is:

$$5\%\ of\ stepover = 12.7mm\ \times 5\%$$
$$5\%\ of\ stepover = \ 0.635\ mm$$

This means that the side cut will be carried out giving a depth of cut of 0.635 mm on the test pieces, as can be seen in the following figure.

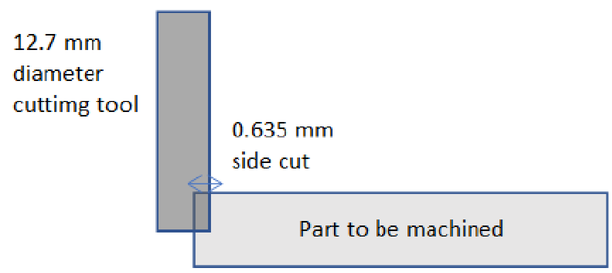

Figure 5 Machining at 5% stepover
Source: Own Authorship

Measurement and recording of roughness

Once the 18 tests werecompleted on the numerical control machine, the Ra (average roughness) and Ramax (maximum average roughness) were evaluated in pairs.

A Mitutoyo® surface roughness meter, model SURFTEST SV-2000, was used to carry out the measurement.

Figure 6 Mitutoyo SURFTEST SV-2000 roughness tester
Source: Own Authorship

Firstly, the device was calibrated by carrying out the measurement on a standard block whose Ra and Ramax should be 3.0 µm.

Figure 7 Standard block test
Source: Own Authorship

In the computer interface screen we can indicate the para-metres that we wish to obtain through the interpretation of the measurement in it we must select Ra, Ramax and Ry.

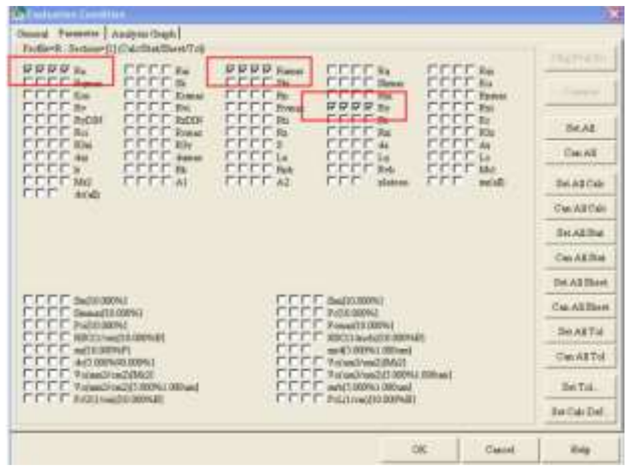

Figure 8 Selection of the measurement to be assessed
Source: Own Authorship

Once the test had been carried out on the standard block, the results obtained were as follows:

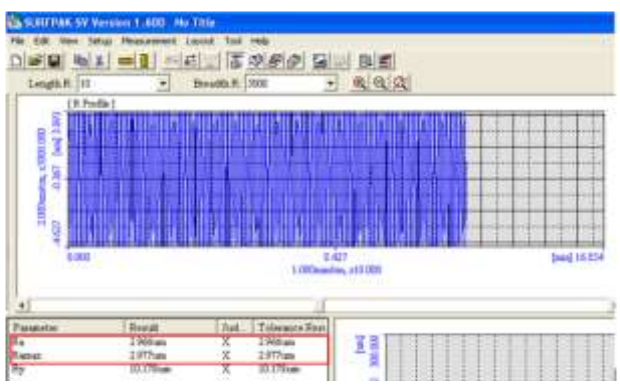

Figure 9 Results of the master block
Source: Own Authorship

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The blue graph indicates the variation in the surface of the part on which the measurement was taken (in this case the pattern block), up and down oscillations were detected continuously on the surface, the Ra is 2.966 μm and the Ramax is 2.977 μm.

Once the roughness tester was calibrated, a "C" type press was used to hold each of the machined parts so that they would not move when the test was carried out.

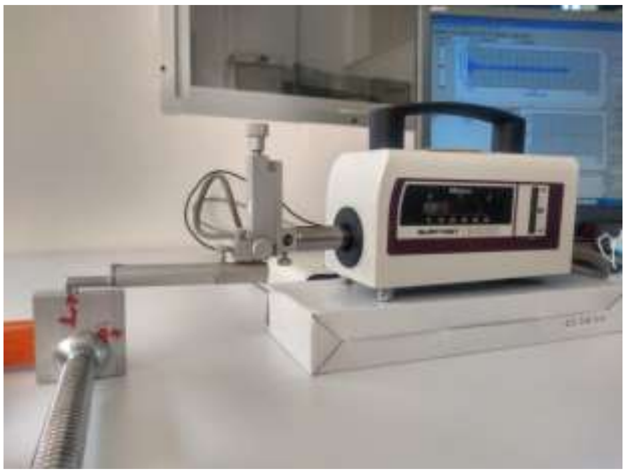

Figure 10 Test performed on each of the machined parts.
Source: Own Authorship

The 18 tests performed were recorded in the matrix now putting the value of Ra (Table 2.) and Ramax (Table 3.).

Advance (F =mm/min)		Spindle speed (S = rpm)		
		Under (-30%)	Nominal	High (+30%)
		1754	2506	3258
Under (-30%)	554	1.094	1.501	1.569
		1.261	1.566	1.496
Nominal	792	1.690	1.406	1.235
		1.600	1.326	1.281
Alto (+30%)	1030	2.003	1.527	1.406
		1.955	1.403	1.281

Table 2 Ra Register
Source: Own Authorship

Advance (F =mm/min)		Spindle speed (S = rpm)		
		Under (-30%)	Nominal	High (+30%)
		1754	2506	3258
Under (-30%)	554	1.146	1.688	1.840
		1.495	1.738	1.727
Nominal	792	1.756	1.582	1.394
		1.763	1.400	1.394
High (+30%)	1030	2.120	1.604	1.777
		2.061	1.461	1.393

Table 3 Ramax Register
Source: Own Authorship

Results

Analysis of data and graphs

From the recording of the Ra and Ramax data, it is possible to identify the values that comply with the roughness characteristic closest to 1.6 μm and that are below this value, which is suitable for CNC machining, as mentioned in the problem statement of this article.

Advance (F =mm/min)		Spindle speed (S = rpm)		
		Under (-30%)	Nominal	High (+30%)
		1754	2506	3258
Bajo (-30%)	554	**1.094**	**1.501**	**1.569**
		1.261	**1.566**	**1.496**
Nominal	792	1.690	**1.406**	**1.235**
		1.600	**1.326**	**1.281**
High (+30%)	1030	2.003	**1.527**	**1.406**
		1.955	**1.403**	**1.281**

Table 4 Ra analysis
Source: Own Authorship

Advance (F =mm/min)		Spindle speed (S = rpm)		
		Under (-30%)	Nominal	Alto (+30%)
		1754	2506	3258
Under (-30%)	554	**1.146**	1.688	1.840
		1.495	1.738	1.727
Nominal	792	1.756	**1.582**	**1.394**
		1.763	**1.400**	**1.394**
High (+30%)	1030	2.120	1.604	1.777
		2.061	1.461	1.393

Table 5 Ramax analysis
Source: Own Authorship

In "Table 4" and "Table 5" we can see values in bold, these are below the desired value (1.6 μm) so we can take into account the parameters with which they were obtained for the programming of our machining, since this indicates a good surface finish.

The data that are shaded orange indicate that the machining parameters are the least effective decision to obtain the roughness that is common on a numerical control machine.

The data that is shaded in grey is the data that has the lowest average roughness measurement, which means that it is the option that leaves the best surface finish, theoretically speaking.

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The data shaded in green are the best option in theory and practice, given that the parameters used at the time of machining show an increase in the revolutions per minute used on the machine spindle and as this data correlates with the machine feed rate, we can infer that the machining time is reduced, also note that the average roughness values are very similar to those obtained in grey.

In addition to this, if we analyse the graphs of the tests that are shaded in grey, green and orange, we can visually obtain what is shown below.

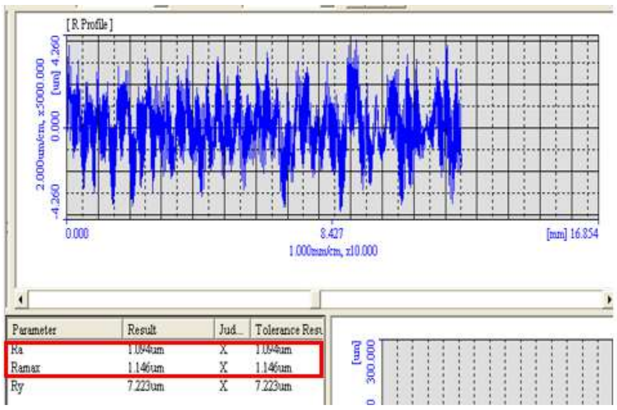

Figure 11 Exhibit 1
Source: Own Authorship

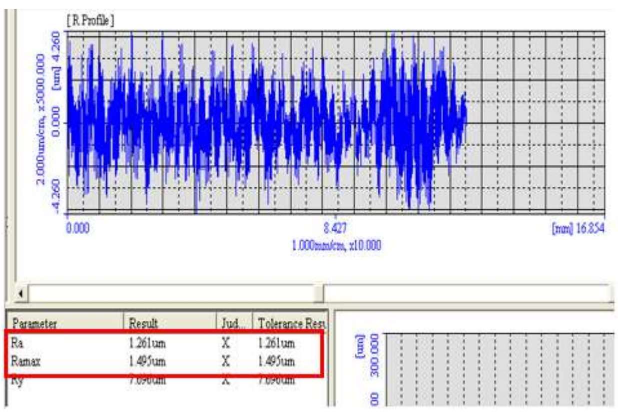

Figure 12 Test number 2
Source: Own Authorship

These graphs (Figure 11 and Figure 12) show a particular irregularity with little deviation in the surface roughness of test 1 and test 2 (data in grey) correspondingly.

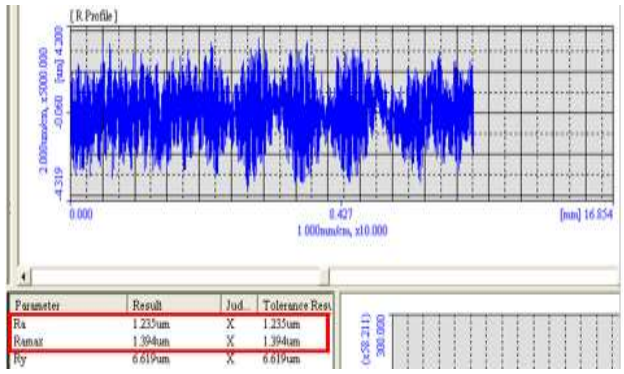

Figure 13 Test number 11
Source: Own Authorship

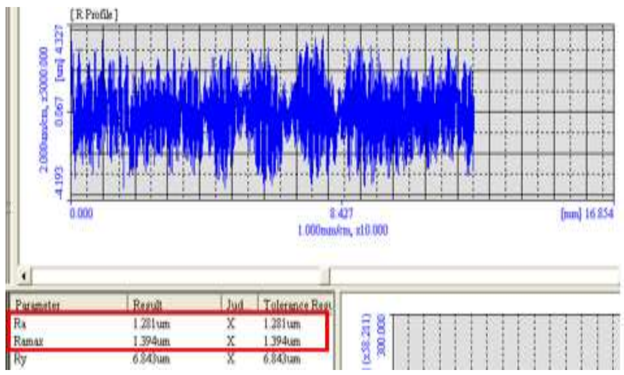

Figure 14 Test number 12
Source: Own Authorship

These graphs (Figure 13 and Figure 14) show homogeneity in the surface roughness deviation of test 11 and test 12 (data in green) correspondingly, it can be said that the surface has a symmetrical finish and is the most normalised in terms of roughness.

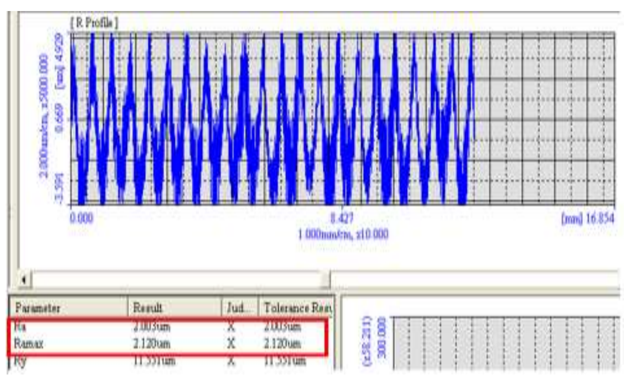

Figure 15 Exhibit 13
Source: Own Authorship

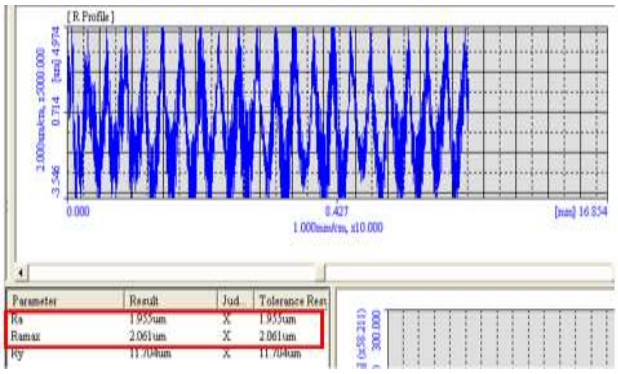

Figure 16 Test number 14
Source: Own Authorship

These graphs (Figure 15 and Figure 16) show too much variation in the surface roughness deviation of test 13 and test 14 (data in orange) correspondingly, it can be said that this is the least viable option given that translated into practice the surface has a more irregular finish.

Conclusion

From the analysis of the data and the graphs obtained by means of the software with which the roughness tester is coupled, it has been reached the conclusion that it is convenient to apply an adjustment to the machining parameters from the previously established formulas as suggested below.

Obtain by means of the formulas the nominal values for both:

Spindle revolutions per minute.

$$S_0 = \frac{1000 \times V_c}{\pi \times D_c}\ (rpm) \qquad (4)$$

Where:

V_c=Cutting speed of the material.
D_c=Cutting diameter of the cutter.
S0=Nominal revolutions per minute of the spindle.

As well as, for the feed speed of the tool with respect to the material.

$$F_0 = S \times f_z \times z_n \quad \left(\frac{mm}{\min}\right) \qquad (5)$$

Where:

S_0=Nominal spindle speed per minute.
F_0=Nominal feed speed of the tool with respect to the material.
f_z=Chip size at the moment of cutting for each cutting edge of the tool.
z_n=Number of cutting edges of the tool.

Then, an increase of 30% must be applied to the nominal value of the revolutions per minute, i.e. the new formula would be as follows:

$$S_1 = 1.3\, S_0 \qquad (6)$$

Where:

S_0=Nominal revolutions per minute of the spindle.
S_1=Revolutions per minute of the spindle to be used in machining.

It is necessary to clarify that the nominal calculations of the parameters must be made first, given that as the revolutions per minute are correlated with the calculation of the spindle feed rate, the 30% increase in the value of the nominal revolutions cannot be applied directly, as this would affect the value obtained for the calculation of the nominal feed rate.

The aim of the present study was to lay the foundations for the development of experiments of this type, so this same methodology can be applied to any other type of ferrous or non-ferrous material.

It should be noted that in the tables as well as the graphs, values of Ra and Ramax were obtained, so it is up to the person in charge of replicating the experiment to decide which value to take as a critical factor to implement the parameters in the machining.

The main difference is that Ra is the average of the absolute values on the surface to be measured taking as reference the midline while Ramax is the measurement of the highest roughness in the partial measurements of the surface. (GTM, 2022).

It is expected that with the application of the adjustment in the formulas of the operating parameters in the numerical control machine, the mechanical components, as well as the parts manufactured in the same, will be of better quality in terms of mechanical characteristics and properties.

Let's remember that roughness directly influences how the different components of a final part are assembled and the mechanical properties such as: friction and wear coefficients, fatigue limit, corrosion resistance, thermal and electrical resistance.

Finally, it is only necessary to add that thanks to the work carried out, we now have new knowledge about the efficiency of the nominal values of the equations for the calculation of the operating parameters in a numerical control machine, which will help us to obtain better results in the parts machined on this equipment.

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