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# AN ANALYSIS OF SURFACE ROUGHNESS IN TURNING/BORING UNDER DIFFERENT CHATTER CONDITIONS

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***Abstract.*** *Chatter is a self-excited vibration that leads to large tool vibrations, reduced tool life and overall diminished process productivity. The large vibrations associated with chatter increase the surface roughness of the finished machined piece, which can lead to out of tolerance pieces that need to be reworked. The use of slender tools for internal turning/boring aggravates this issue. Different chatter conditions can happen by a change in the machining parameters, such as varying the applied depth of cut and spindle speed, leading to stable and unstable cuts. This paper showcases an extensive analysis of the surface finishing of pieces machined under several unstable and stable conditions via an experimental analysis. A tree of experiments was developed in order to isolate each experimental variable. Pieces were machined under all designed conditions in a CNC lathe and both data gathered trough a profilometer, as well as visual data were then analyzed. Analytical statistical tools were used to measure the impact each different parameter has in the machined piece surface roughness. The surface roughness not only changes with the use of stable or unstable cutting conditions, but a large variation of roughness can also occur with the variation in the stable cutting conditions. Another important output of this experiment is the analysis of the profile of the machined pieces. The profile changes drastically under chatter and no chatter cutting conditions.*

***Keywords:*** *Turning/boring, chatter, roughness, variability study*

## 1. INTRODUCTION

Certain machining conditions can generate chatter, a self-excited vibration that leads to poor surface quality, excessive tool wear, loud noise and the necessity to rework parts (Wiercigroch and Budak, 2001). As slender tools are needed for internal turning/boring, chatter is aggravated and need to be either avoided or controlled. This vibration arises due to the complex interactions between the machine tool, the tool holder and the workpiece. Self-excited vibrations, as opposed to free and forced vibrations, are hard to predict and control, leading to this area being the subject of research for decades.

Chatter is highly dependent on the chosen machining conditions. A stability lobe diagram (SLD) can be drawn for each tool holder, relating the stability limit with the spindle speed. The stability limit in known to be closely related to the depth of cut. Being so, for the purpose of avoiding chatter, one may carefully choose the machining parameters in order to maintain the system under the stability limit (Erturk and Inman, 2008b; Silva *et al.*, 2013; Yigit *et al.*, 2014; Venter *et al.*, 2017; Venter and Da Silva, 2016), or increase this stability limit through control (da Silva *et al.*, 2015; Venter *et al.*, 2017; Silva *et al.*, 2013).

The method of carefully obtaining the SLD for each used tool holder, however, does not quantify the surface roughness in the stable and unstable areas, or gives any indication as to how the profile of the machined part surface will be. Some studies of finishing roughness related to the chatter phenomenon have already been done (Lin *et al.*, 2016; A.K.M Nurul Amin *et al.*, 2010). These studies, however, do not provide an extensive analysis of the surface roughness related to the known chatter parameters (depth of cut and spindle speed), do not perform ANOVA analysis and do not have an extensive base of experimental data. Several studies that implement the ANOVA method to analyze cutting conditions and surface roughness can be found (Bhattacharya *et al.*, 2009; Nalbant *et al.*, 2007; Bouacha *et al.*, 2010). Although providing an extensive background on this analysis, these papers do not study the roughness on chatter and no chatter conditions, only on stable cuts.

This paper showcases an extensive analysis of the surface roughness of pieces machined under several unstable and stable conditions via an experimental analysis. It begins with a brief mathematical overview on how to obtain the tool holder's lobe diagram, the basis of the ANOVA method and the roughness parameters used in this paper. The experimental setup and experimental results follow, portraying in details the setup and materials used, as well as the results and ANOVA analysis.

## 2. BASIC CONCEPTS

This section presents a brief overview on the basic concepts used in this paper. First, the formulation used to obtain the lobe diagrams using a single-degree-of-freedom model is exploited. Then, a brief introduction of the concept of the ANOVA method is shown. Finally, the Ra, Rt and Rz roughness parameters are explained.

### 2.1 Stability limit

The stability limit can be found using a simplification of the tool holder as single-degree-of-freedom model Euler-Bernoulli beam that represents the tool holder's flexibility in the x-direction Silva *et al.* (2013); Erturk and Inman (2008a).

Considering $T$ as the spindle revolution period, $w(t)$ and $w(t-T)$ as the displacements in two successive cuts and $h_0$ as the static depth of cut, the instantaneous depth of cut of the tool can be written as:

$$h_i(t) = h_0(t) + w(t-T) - w(t). \tag{1}$$

Assuming that the tool is flexible in the Euler-Bernoulli beam direction and that the cut can be simplified as an orthogonal cut, the cutting force $F$ can be found to be proportional to chip's front area. The cutting force can then be expressed as:

$$F(t) = K_f a(h_0(t) + w(t-T) - w(t)), \tag{2}$$

in which $K_f$ is an experimentally obtained cutting coefficient. In the Laplace domain, the relation between the cutting force $F$ and the tool holder's free-end displacement can be written by the system's transfer function $G(s) = W/F(s)$:

$$G(s) = \frac{W(s)}{F_c(s)} = \frac{1}{ms^2 + cs + k} \tag{3}$$

Using the relations $H_i(s)/W(s)$ and $W(s)/H_0(s)$, the relation between the instantaneous and static depth of cut can be found as:

$$\frac{H(s)}{H_0(s)} = \frac{1}{1 + K_{cut}(s)G(s)(1-e^{-sT})}, \tag{4}$$

in which $K_{cut}(s) = K_f a$. Using the closed loop characteristic equation $1 + K_{cut}(s)G(s)(1-e^{-sT}) = 0$, one can find the chatter frequency: $\omega_c$. Substituting $s = i\omega_c$ in the characteristic equation and using Euler's identity, one can find $K_{lim} = K_{cut}(i\omega_c)$ Ganguli *et al.* (2007).

Being the stability limit $K_{lim}$ a physical property, its imaginary is null. Hence, $\omega_c$ and $K_{lim}$ are found as:

$$\omega_c T = 2p\pi - 2tan^{-1}\Big(\frac{\Lambda_R}{\Lambda_I}\Big), \tag{5}$$

$$K_{lim} = -\frac{1}{2\Lambda_R}, \tag{6}$$

in which $\Lambda_R = Re(G(i\omega_c))$, $\Lambda_I = Imag(G(i\omega_c))$ and $p$=1, 2, 3 .... The solution of $K_{lim}$ for $p$=1, 2, 3 ... leads to the system's lobe diagram.

### 2.2 The basic concepts of ANOVA

Analysis of variation (ANOVA) is the statistical method used to interpret data (Ross, 1996). ANOVA is a statistically based decision tool for detecting any differences in average performance in either experimental or numerical data (Bhattacharya *et al.*, 2009). It is a mathematical tool that evaluates total variation on different accountable sources, as it decomposes the variation in components that are related to each parameter. In order to be able to break the variation's effects into the different variables' effects, a proper tree of experiments must be provided. In this paper, a multiple variable ANOVA (MANOVA) will be performed using the software Statistica.

### 2.3 The basic concepts of Ra and Rt

Ra is the average roughness of the machined part surface. It provides a good general guide for part performance over a wide range of applications. It can be mathematically calculated as the area between the roughness profile and its mean line, or the integral of the absolute value of the roughness profile height over the evaluation length (Galyer and Shotbolt, 1980):

$$R_a = \frac{1}{l}\int_0^l \mid y \mid dl = \frac{\sum_{i=1}^{i=n} y_i}{n}, \tag{7}$$

in which $l$ is the sampling length and $y$ is the ordinate of the profile. As it provides an arithmetic average of surface irregularities, it does not account for the profile (waviness) of the surface. Being so, two surfaces that have widely different profiles could have the same Ra, but perform rather differently.

Rt is the maximum distance between a valley and a peak in the limits of a sampling length $l$. As it does not average the surface, it gives a better estimate, although far from perfect, as to how different profiles and waviness can perform.

Rz is the ten point height, which calculates the average of ten maximum peak-to-valley differences within the sampling length $l$. It averages positive and negative peak values and could also be a better estimate to performance when different profiles are taken into account.

## 3. EXPERIMENTAL PROCEDURE

The tool holder A16T-SCLCR 4, from Sandivik Coromant ®, has been modified in such a way that its total length is $150mm$, which provides a $100mm$ of length from the lathe's fixation point and its free end. The modified tool holder was fixated in a CNC lathe and used for internal turning. The experimental setup is shown in Fig. 1.

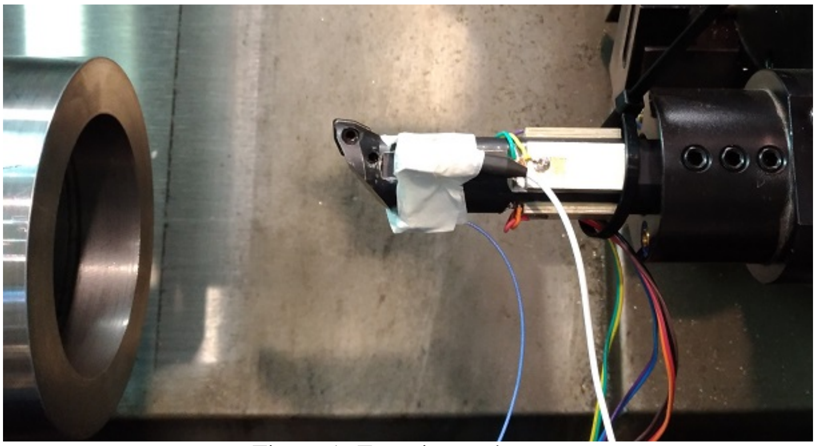


Figure 1: Experimental setup

In order to analyze the system's stability lobe diagrams and determine the stable and unstable cutting conditions to be used, a frequency response function (FRF) was obtained using an impact hammer and a data acquisition system. The data acquisition system used was DS1103 PPC Controller Board, from dSPACE. Both the accelerometer and the impact hammer used were from PCB Piezotronics. The H2 method was used to calculate the FRF (Ewins, 1984). The method explained by Erturk and Inman (2008b) was used to obtain the stability lobe diagrams.

An experimental SLD has been found using approximated second order transfer functions, $G(s) = K_p/(s^2 + 2\zeta\omega_n s + \omega_n^2)$, of the experimental FRF. Because of this estimation, the SLD is also an approximation and it should be fitted using operational data.

In order to analyze the cutting instability and the surface roughness, data acquisition occurs after internal turning machining operation. Operational experiments were performed using several different machining parameters combinations: the feed rate $f$ was fixed in $f = 0.1mm/rev$, the depth of cut $ap$ varied from $ap = 0.25mm$ to $ap = 0.75mm$, the spindle speed $n$ varied from $n = 350rpm$ to $n = 727rpm$. These parameters range from stable to unstable cutting conditions in the first lobe of the tool holder's lobe diagram.

In this paper, the surface profile is obtained using the profilometer TalySurf50. Using the software Ultra, the profiles could be analyzed in order to obtain the roughness parameters, as it provides a measure of the surface Ra, Rt and Rz. It is important to notice, however, that the profilometer tool is used, and not the rugosimeter tool, as the rugosimeter was not able to correctly gather the data from the profile of parts machined under chatter conditions (See Fig. 2).

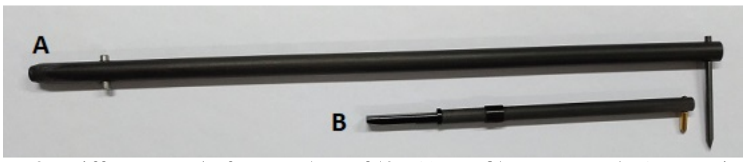
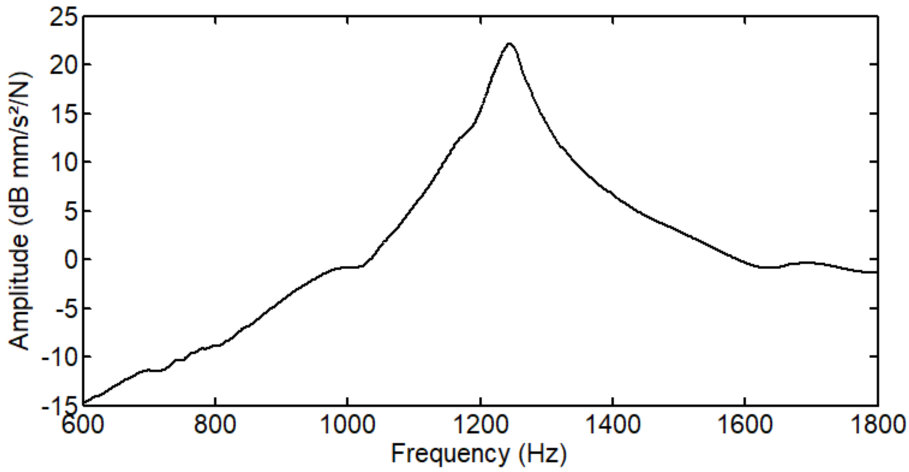



Figure 2: Different tools from Talysurf50: A) profilometer and B) rugosimeter

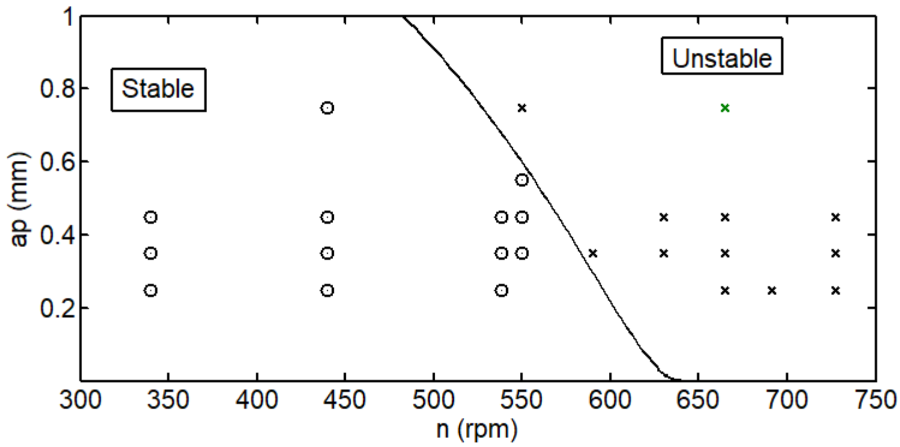
As a result, roughness measures must not be used in comparison to other roughness data, but it can be safely used in this comparative variational analysis as all the data is obtained using the same tool. As the parameters can only be used in these comparisons, the roughness data is provided without a unit. The surface finishing can also be qualitatively compared trough surface images and its raw profile.

### 3.1 Results and discussion

In order to find the tool holder's lobe diagram, it is first necessary to obtain its FRF. Using an impact test, the FRF that can be seen in Fig. 3a) can be found. The FRF can be fitted in a second order transfer function $G(s) = K_p/(s^2 + 2\zeta\omega_n s + \omega_n^2)$, in which $\zeta = 0.025$ and $\omega_n = 74700rpm$, $K_p$ needs to be fitted experimentally. Using experimental data collected from several operational experiments, it is possible to draw the stability lobe diagram seen in Fig. 3b).




(a)




(b)

Figure 3: Experimental stability lobe diagram: a) experimental amplitude FRF from the tool holder fixed in the CNC lathe; b) stability lobe diagram

The operational experiments were performed using several different machining parameters combinations, in which the feed rate $f$, depth of cut $ap$ and the spindle speed $n$ varied as previously discussed. Each dot seen in Fig. 3b) represents a machining parameter combination and each combination provides either a stable or unstable cut. The profile for each machined part was then taken 3 times in equidistant points of the part. The average of the surface roughness $\overline{R}_a$, $\overline{R}_t$ and $\overline{R}_z$, and their standard deviation $\sigma_a$, $\sigma_t$ and $\sigma_z$ can be seen in Table 1.

It is possible to see the difference between stable and unstable conditions in all measurements of roughness. The data shows, however, that similar roughness averages can be seen in both stable and unstable cuts, which testify to the limits of roughness measures to quantify the surface finishing in chatter conditions. It is also possible to see a variation of the roughness within the groups of stable and unstable conditions.

With the data provided in Tab.1, three different regions should be noted in the lobe diagrams (See Fig. 4). A and C are stable regions, in which there is no chatter. B is an unstable region, in which there is chatter. C is a regions in which can be found the best surface finishes in the experimental data.

Using the raw surface profile obtained from the TalySurf50, one can analyze the difference between the regions A, B and C from the lobe diagram (See Fig. 5).

As can be seen in Fig. 5, the profiles from regions A and C (stable regions) are very different from the one from region B (unstable region). Under chatter conditions, the tool vibrates in a manner that a waviness profile is imprinted

Table 1: Surface roughness in different machining conditions.

| $f(mm/rev)$ | $ap(mm)$ | $n(rpm)$ | $\overline{R}_a$ | $\sigma_a$ | $\overline{R}_t$ | $\sigma_t$ | $\overline{R}_z$ | $\sigma_z$ |
|---|---|---|---|---|---|---|---|---|
| 0.1 | 0.25 | 340 | 0.1046 | 0.0039 | 1.0421 | 0.2219 | 0.6501 | 0.0522 |
| 0.1 | 0.25 | 440 | 0.0830 | 0.0029 | 1.0093 | 0.3461 | 0.5309 | 0.0152 |
| 0.1 | 0.25 | 538 | 0.0760 | 0.0029 | 0.7482 | 0.0282 | 0.4856 | 0.0079 |
| 0.1 | 0.25 | 665 | 0.2002 | 0.0029 | 1.5589 | 0.0639 | 0.8302 | 0.0121 |
| 0.1 | 0.25 | 691 | 0.1869 | 0.0051 | 1.0882 | 0.0881 | 0.7730 | 0.0104 |
| 0.1 | 0.25 | 727 | 0.2487 | 0.0068 | 1.7237 | 0.0687 | 0.9266 | 0.0574 |
| 0.1 | 0.35 | 340 | 0.1123 | 0.0044 | 0.9903 | 0.0890 | 0.6770 | 0.0243 |
| 0.1 | 0.35 | 440 | 0.0601 | 0.0053 | 0.5485 | 0.0287 | 0.3990 | 0.0190 |
| 0.1 | 0.35 | 538 | 0.0388 | 0.0094 | 0.4394 | 0.1667 | 0.3370 | 0.1287 |
| 0.1 | 0.35 | 550 | 0.0374 | 0.0003 | 0.3940 | 0.0281 | 0.2885 | 0.0107 |
| 0.1 | 0.35 | 590 | 0.1219 | 0.0028 | 0.7210 | 0.0146 | 0.5798 | 0.0021 |
| 0.1 | 0.35 | 630 | 0.1226 | 0.0020 | 0.7795 | 0.0185 | 0.5965 | 0.0055 |
| 0.1 | 0.35 | 665 | 0.1373 | 0.0087 | 0.5939 | 0.4322 | 0.4333 | 0.3109 |
| 0.1 | 0.35 | 727 | 0.1496 | 0.0058 | 1.0164 | 0.0295 | 0.6872 | 0.0131 |
| 0.1 | 0.45 | 340 | 0.1204 | 0.0063 | 0.9874 | 0.0294 | 0.6843 | 0.0169 |
| 0.1 | 0.45 | 440 | 0.0669 | 0.0010 | 0.6813 | 0.1108 | 0.4483 | 0.0081 |
| 0.1 | 0.45 | 538 | 0.0391 | 0.0045 | 0.3870 | 0.0358 | 0.2960 | 0.0217 |
| 0.1 | 0.45 | 550 | 0.0364 | 0.0004 | 0.4045 | 0.0206 | 0.2928 | 0.0084 |
| 0.1 | 0.45 | 630 | 0.1258 | 0.0040 | 0.8107 | 0.0409 | 0.6228 | 0.0287 |
| 0.1 | 0.45 | 665 | 0.1268 | 0.0036 | 0.8660 | 0.0077 | 0.5948 | 0.0047 |
| 0.1 | 0.45 | 727 | 0.1314 | 0.0018 | 0.8750 | 0.0436 | 0.6583 | 0.0117 |
| 0.1 | 0.55 | 550 | 0.0393 | 0.0002 | 0.5014 | 0.0339 | 0.3042 | 0.0084 |
| 0.1 | 0.75 | 440 | 0.0510 | 0.0018 | 0.6024 | 0.0661 | 0.3751 | 0.0029 |
| 0.1 | 0.75 | 550 | 0.1028 | 0.0035 | 0.6280 | 0.0295 | 0.5105 | 0.0167 |
| 0.1 | 0.75 | 665 | 0.1316 | 0.0015 | 0.7520 | 0.0093 | 0.5972 | 0.0029 |

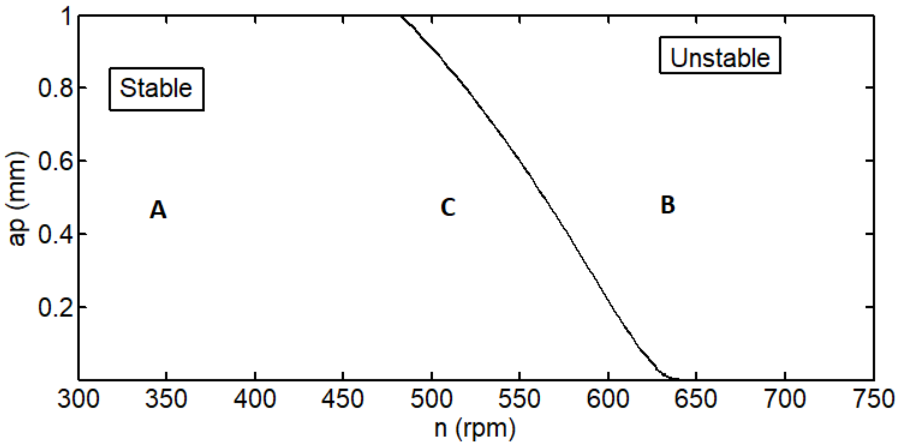


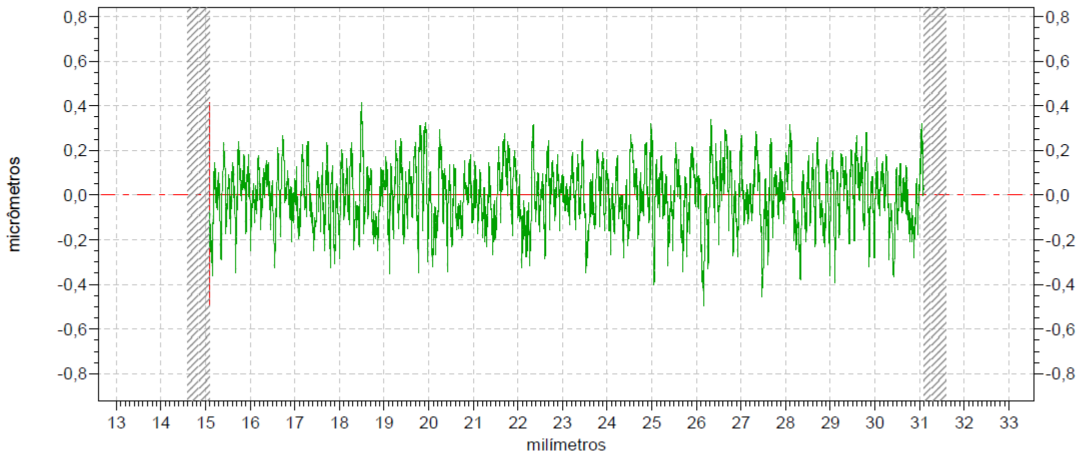

Figure 4: Stability lobe diagram divided into three regions

in the surface finishing. A part with such surface profile would be unacceptable in most practical uses, regardless of the roughness outcome. Little difference can be seen in profiles from regions A and C. The profile from region C has smaller peaks and valleys, and the distance between them is also smaller, providing a better surface finishing.

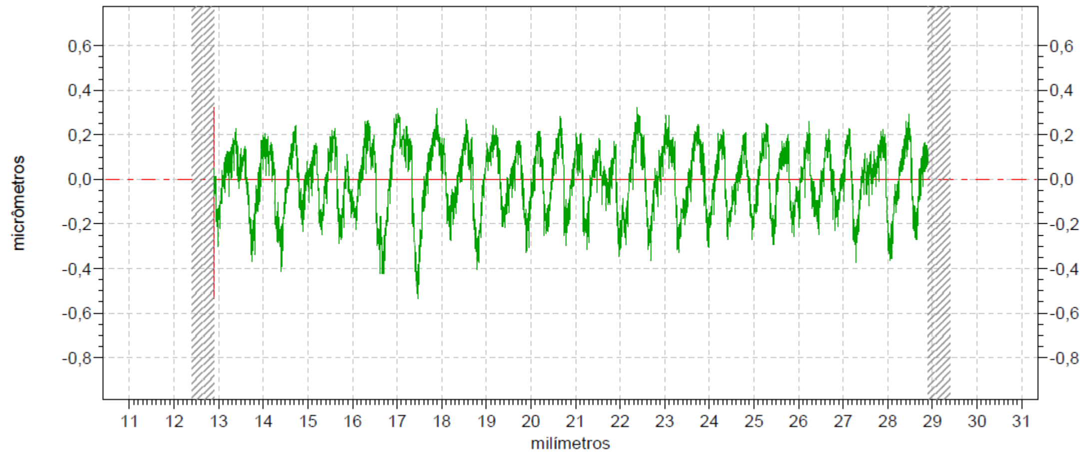
The surface finishing in these three regions can be seen in Fig. 6.

The surface finishing from region B (unstable region) is clearly the least desirable for practical uses, as the wavy profile can be seen imprinted in the surface. Although both regions A and C (stable regions) present a clear surface, it is possible to argue that the surface finishing from region C is better than the one from region A, which is supported by the roughness data found in Tab. 1. That supports the claim that the surface finishing can present variation even within the stable region, depending on the machining parameters.

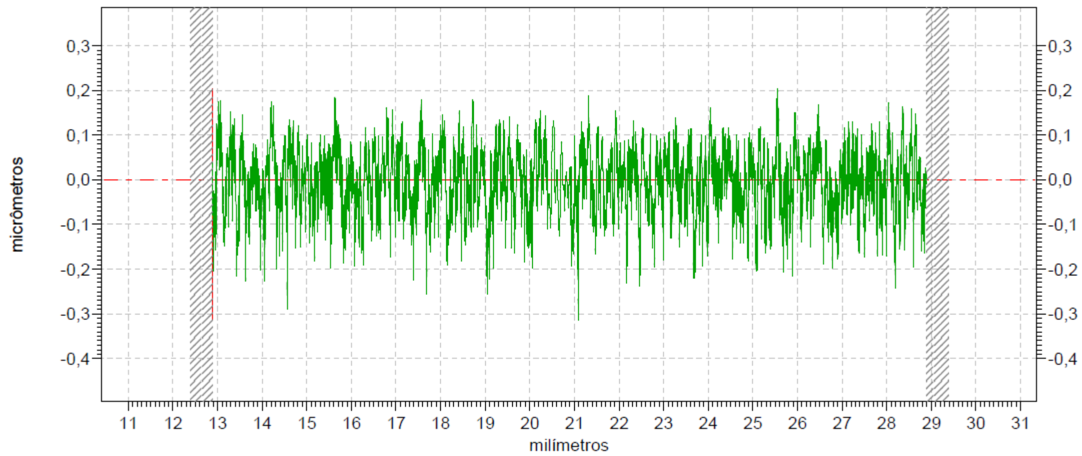
The data presented in Tab. 1, together with all the data collected from the three repeated measures to each parameter combination, was fed to the software Statistica in order to perform the MANOVA (Multiple variables ANOVA) analysis. The measures of roughness ($R_a$, $R_t$ and $R_z$) were the dependent variables to be analyzed and the depth of cut $ap$ and




(a)




(b)




(c)

Figure 5: Profiles of the surface finishing obtained from TalySurf50 in: a) area A with no chatter; b) area B with chatter; c) area C with no chatter

spindle speed $n$ were the factors. The levels used for the depth of cut variable were: $ap = [250, 350, 450]\mu m$. The levels used for the spindle speed variable were: $n = [340, 440, 538, 665, 727]rpm$. Figures 7, 8 and 9 present the analysis of variation results, with a 0.95 confidence interval.

One can see that for all three averages ($\overline{R}_a$, $\overline{R}_t$ and $\overline{R}_z$) there is a clear pattern, in which the effects on the roughness averages are affected primarily by the spindle speed $n$. $\overline{R}_t$ and $\overline{R}_z$ do not clearly benefit the profile analysis when compared to the use of $\overline{R}_a$. It is important to note that the smaller the $ap$, the higher the effect on all average roughness as well. The higher roughness averages are found when the $ap = 0.25mm = 250\mu m$ and $n = 665rpm$ or $n = 727rpm$.

(a)

(b)

(c)

Figure 6: Detail of the surface finishing in: a) area A with no chatter; b) area B with chatter; c) area C with no chatter

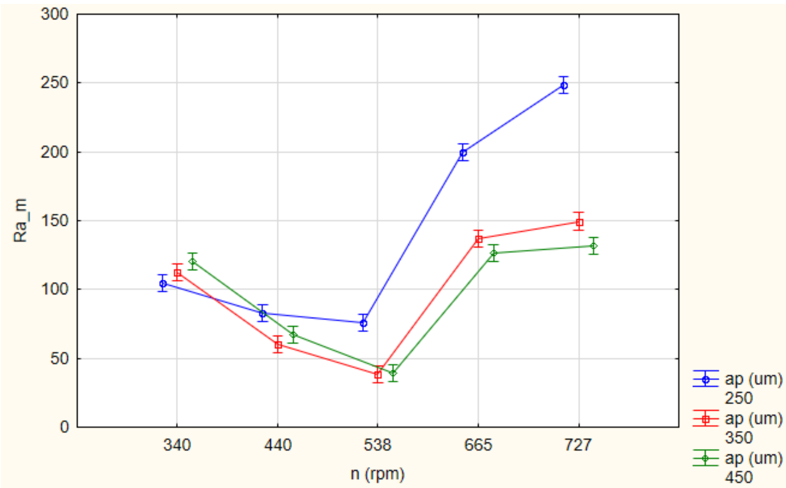



Figure 7: Means for a two-way interaction between effects of $n$ and $ap$ for the roughness average $\overline{R}_a$

The smallest roughness averages are found when both the $ap$ and $n$ are close to the stability limit, in the stable region of the SLD (region C), as was seen in the previous results.

As the chatter phenomenon is highly nonlinear, the surface finishing analysis must be performed using different tools. The analysis done solely with the surface roughness is not enough in order to determine the quality of the finished machined surface. As can be seen in Fig. 6, chatter clearly imprints a wavy profile to the part, which is not acceptable for expected applications. A comprehensive study must encompass a profile and roughness analysis. Users should intend to find region C and work in that region in order to obtain the best results.

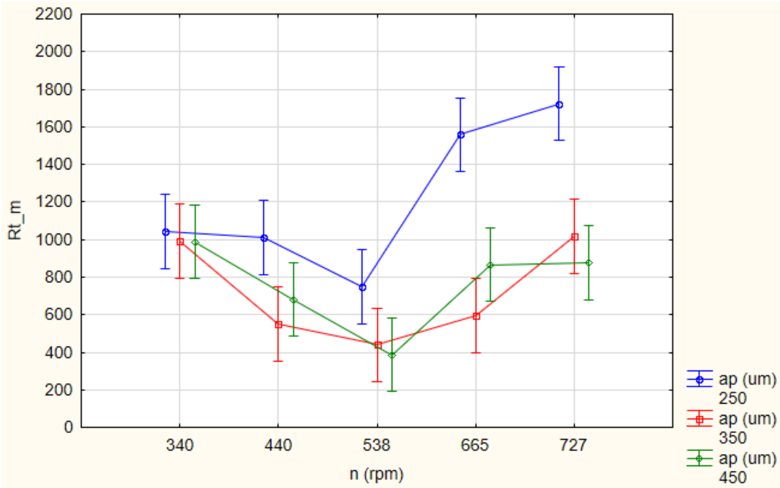



Figure 8: Means for a two-way interaction between effects of $n$ and $ap$ for the roughness average $\overline{R}_t$

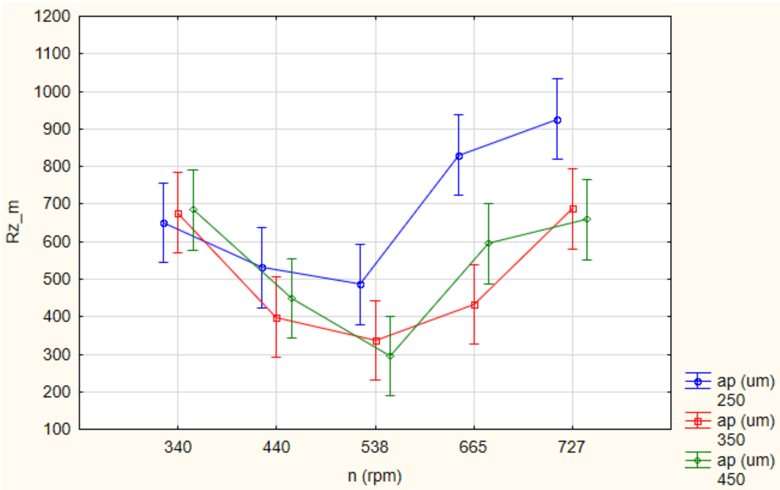



Figure 9: Means for a two-way interaction between effects of $n$ and $ap$ for the roughness average $\overline{R}_z$

## 4. CONCLUSION

This paper showcases an extensive analysis on the surface roughness of pieces machined under several unstable and stable conditions via an experimental analysis. The experimental SLD was obtained with both stable and unstable cutting parameters. The surface finishing was studied quantitatively and qualitatively, trough surface roughness data, photos and surface profile analysis.

A clear pattern in the effects could be seen, which was affected mainly by the spindle speed $n$. It should also be noted that, the smallest the depth of cut $ap$, the higher the roughness average.

Considering all present results, the surface finishing analysis in cases of chatter should be performed taking into account more data, taken with different tools. The analysis done solely with the surface roughness is not enough in order to determine the quality of the finished machined surface. As chatter imprints a profile in the machined parts that would not be accepted in the industry, a data that is not shown in the roughness analysis, a comprehensive study must encompass a profile and roughness analysis. Users should intend to find region C and work in that region in order to obtain the best results.

## 5. ACKNOWLEDGEMENTS

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