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EVALUATION OF SURFACE ROUGHNESS IN LOW FREQUENCY VIBRATION TURNING OF ABNT-1020 CARBON STEEL

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Abstract. *The surface roughness is an important design parameter in the machining process control. This state of surface is associated to the manufacturing process and working conditions of the machines, tools and tribological systems, such as the friction and wear level present in the components. In the machining of ductile materials, the roughness values are influenced by the formation of the built up edge, by the microscopic adhesion of the ferrite and by the subsurface fracture phenomenon. Low Frequency Vibration (LFV) turning is an alternative used to improve the chip forming mechanism and, consequently, to guarantee better surface integrity of the machined parts. This work proposes the study of a mathematical model capable of determining the theoretical value of roughness* R_a *in the LFV turning of ABNT 1020 carbon steel, in order to be used as a process free response variables. This study proposes the elaboration of a mathematical model capable of determining the theoretical value of roughness* R_a *in the LFV machining of ABNT-1020 carbon steel, in order to be used as a parameter of process response. As indicative of the tendency behavior of the machined profile,* R_z *roughness values were also evaluated, which presented variations similar to* R_a *roughness. By statistical analysis, it was observed that the LFV machining presented higher values of roughness if compared to the conventional machining. However, the suggested mathematical model allowed approximation with the experimental roughness measurements, according to the position of the roughness gauge in the section of cut-off and the angular position of the measurement in relation to the specimens diameter.*

Keywords: *low frequency vibration, roughness, surface condition, turning, ductile material.*

1. INTRODUCTION

A machined surface reaches, after the manufacturing stage, new properties and characteristics that, if compared to the surface without work, constitute what is called a surface state or surface roughness (Davim, 2010, p.38). This state of surface is associated to the manufacturing process and working conditions of the machines, tools and tribological systems, such as the friction and wear level present in the components (Takadoum, 2008, p.2; Shizhu and Ping, 2012, p.226).

Ductile materials have limitations for chip formation and, consequently, result in a poor surface finish state. An incorrect roughness is usually associated to the occurrence of BUE (built up edge), the adhesion and incrustation of the free ferrite on the surface of the work material and to the subsurface fracture, where the maximum shear stress is reached. As an alternative to roughness optimization in these types of materials, a machining method called LFV (low frequency vibration) is used, where the tool has a linear displacement of the main cutting edge at a frequency different from the rotation of the drive shaft. This type of cut produces areas of indentation and repression, creating additional efforts for chip formation, improving its control and shearing.

However, the surface states roughness in LFV machining is affected by the characteristics of the frequency cutting mechanism, which produces surface roughness patterns that cannot be estimated by equations founder in the literature. The maim of this work is to perform the machining of ABNT-1020 carbon steel using the LFV turning and conventional turning machining methods, evaluating the surface roughness obtained by cutting parameters variation. It is intended to obtain an effective mathematical model to estimate the theoretical value of the roughness when the tool traverses a path variant in amplitude and frequency, comparing it with the theoretical trajectory that represents the feed cutting in the conventional machining.

2. LITERATURE REVISION

According to Machado et al. (2011, p. 305) and Diniz, Marcondes and Coppini (2013, p. 123), the average rugosity (R_a) is determined by the Equation 1. Its value represents the average height from the center line typically in micrometers.

$$R_a = \frac{f^2}{(18.\sqrt{3}).r_\varepsilon} \tag{1}$$

There are other measurement parameters are used for determining the surface state (R_q and R_z, for example), however, the parameter R_a is usually more sensitive to feed variation if compared to the other parameters. For this reason and its facility for measurement and verification, the R_a rugosity is the most widely used in general.

According Amaral et al. (2009, p.1), the study of concomitant rugosity parameters can be supply additional informations about a surface profile. When both surfaces present the same value of R_z rugosity, the diferences between the profiles will can be detected by the R_a parameter. In general, the roughness parameters will mainly depend on the manufacturing conditions employed, such as feed, depth of cut, cutting speed, machine tool and cutting tool rigidity. A complete modelling of these parameters should take into account the previous factors (Arbizu e Pérez, 2003, p.390). According Asilturk and Cunkas (2010, p.5829) the variables in the machining are multi-level and their outcome effects are not linear. In this case, the multiple regression modeling can be useful in estimating the coefficients of the machining equation.

In conventional turning process the feed is the same over time, while in LFV machining the feed is variable because although the primary feed is fixed the machine drive system oscillating in the direction of tool feed. To determine the roughness in this case, some authors have tried to determine the relationship between roughness in conventional and LFV machining. Song (2012, p.1355) evaluated the results of surface roughness obtained by Low Frequency Vibration turning. In his study, it was observed the surface roughness with relationship of the cutting engagement especially the combination of the vibratory frequency, amplitude, and the feed and cutting velocity to suppose that the mathematical model (Equation 2).

$$R_a = C_o a^x.f_r^{\,y}.f^z.n^k \tag{2}$$

Where C_0 ,x, y, z, k are all the coefficients to be determined, and a, fr, f, n are the vibratory amplitude, frequency, feed, and spindle revolution, respectively. Take the logarithm for the two sides of Equation 2 and substituted the estimated values for the constants in experiments, the original mathematical model was converted into the mathematical model of linear regression showed in Equation 3.

$$\log(R_a) = \log(Co) + x.\log(a) + y.\log(f_r) + z.\log(f) + k.\log(n) \tag{3}$$

The results showed that higher the frequency is in vibratory turning, the smoother the machined surface is, other conditions being equal, however the surface roughness increases with the feed, at the same frequency. And because of the vibration and the lubrication the BUE can hardly be built up, being good for the surface integrity. The low frequency vibratory machining expedites the breakage of the chip and chip removal, enhancing the machining accuracy.

Wen and Deyuan (2011, p. 236) has been studied the effect in roughness of ultrasonic elliptical vibration model (VAM2D). They concluded that height of vibration ripples of the cutting direction has a negative impact on the surface roughness. Increased frequency and decreased amplitude help reduce the height of vibration ripples of the cutting direction.

Maroju, Vamsi and Xiaoliang (2017, p.12) studied the effect of Low Frequency Vibration machining on the roughness of three different materials: Ti6Al4V, AISI 4340 and Al2024-T351. Comparing the roughness obtained between conventional machining and LFV machining, the authors observed worst results when was used in Ti6Al4V and AISI 4340 tools materials in LFV machining. And using Al2024-T351 tool material the rugosity was better in the conventional machining.

3. EXPERIMENTAL PROCEDURE

The material used in this work was ABNT-1020 hot rolled carbon steel bars of 88.9 mm in diameter, with hardness between 120 and 160 HB. The turning tests were performed on a Romi model Tormax 20A. In the LFV machining, a device manufactured for this purpose was used, where an ISO P20 carbide class was machined with an MA type chip and covered by TiN. Accorddingly Mitsubishi (2012, p. A-083), the key code for identification of the tool material used in experiments was WNMG080408.

The machining parameters used were two levels for cutting speed (v_{c1} = 172 m / min and v_{c2} = 273 m / min), two levels for feed cutting (f_1 = 0.057 mm / rev and f_2 = 0.104 mm / rev), two levels for machining depth (a_{p1} = 1.5 mm and a_{p2} = 2.5 mm) and four levels for VAM 1D vibration frequency (fr_1 = no frequency, fr_2 = 1.2, fr_3 = 1.5 and fr_4 = 1.8). The response variable studied was roughness R_a , with the parameter R_z evaluated in a complementary way. The roughness measurement was performed using a Mitutoyo Surftest SJ-201 model rugosimeter. The twelve diametrically equidistant points were evaluated in the specimens were fixed on a universal divider. This montage allowed the roughness to be taken in the same region of the specimen to facilitate comparison with the theoretical rugosity in the feed maps. For statistical analysis a fixed effects model was assumed, with totally randomized trials. The dependent variables were verified by testing normality and contrasts of difference in analysis of variance (ANOVA) considering a level of significance equal to 0.05.

4. RESULTS AND DISCUSSION

Feed maps were elaborated with feed rates, cut-off values according ISO 4288 and the variation of the angular position in the specimens diameter. The Figure 1 shows an example of feed map.

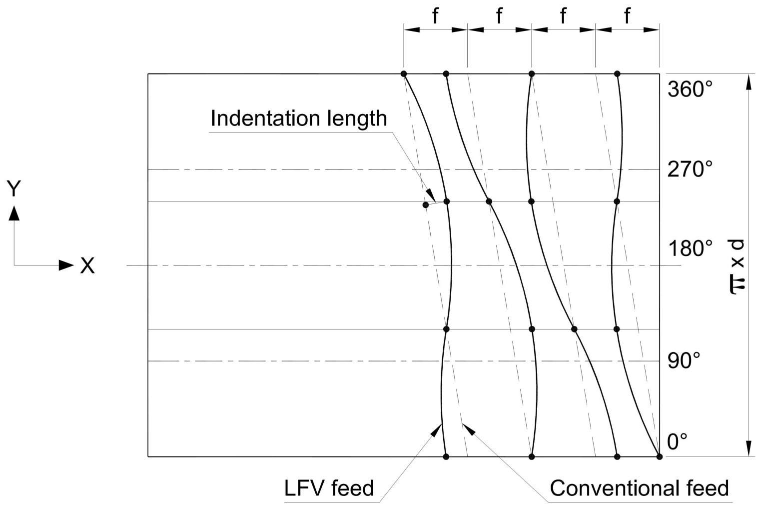


Figure 1. Feed map for fr_3 = 1.5 and repeating cycle every 4 turns.

Through these feed maps it was possible to locate the position of the tool and feed generated by the LFV frequency equipment in order to identify the real feed of the tool for each machined cut-off.

According to the feed rates used, different numbers of grooves were evaluated by the rugosimeter in the conventional turning machining and LFV turning machining, using an evaluation length of 4.0 mm and cut-off 0.8 mm. The results is shown in Table 1.

Table 1. Theorical rugosity relationship between conventional turning machining and LFV turning machining

Frequency	Feed (mm/rev)	Numbers of grooves per cut-off	Theorical R_a rugosity conventional (μm)	Theorical R_a rugosity LFV versus theorical R_a rugosity conventional
fr_1 = no frequency	0.057	14	0.130	-
	0.104	8	0.434	-
fr_2 = 1.2	0.057	14	0.130	1.1-1.4 upper
	0.104	8	0.434	1.1-1.6 upper
fr_3 = 1.5	0.057	14	0.130	1.5-2.3 upper
	0.104	8	0.434	1.7-2.0 upper
fr_4 = 1.8	0.057	14	0.130	0.9-1.5 upper
	0.104	8	0.434	0.9-1.4 upper

In the LFV machining, the indentation was repeated as follows: $fr_2 = 1.2$ (every 5 turns), $fr_3 = 1.5$ (every 4 turns) and $fr_4 = 1.8$ (every 10 turns). This pattern was established through Equation 4, where x (t) is the position in time (t), A is the tool displacement amplitude and ω is the angular frequency (represented by 2 x π x fr).

$$x(t) = A.\text{sen}(\omega.t) + Vt \tag{4}$$

Data analysing used to elaborate the feed maps showed there is a critical value for the frequency of indentation produced by the LFV mechanism. According simulated results, from an indentation frequency of 10, the theoretical roughness in LFV machining would be equivalent to conventional machining. Therefore, in this case, it is better to use LFV machining than conventional machining, because the control of the machining chip removal chip is more effective in LFV. An indentation frequency equal to 10 would be equivalent to limit frequency that classifies the LFV machining (up to 200 Hz), according to the higher cutting speed employed in this study. This frequency was not evaluated experimentally because good results were obtained in lower frequencies.

Very high indentation frequencies also induce to formation of grooves parallel to the center line of the specimen. This explains the reduction of the roughness, but in these cases, other techniques must be adopted to measure the roughness, for example, the three-dimensional profile analysis.

It was observed that higher theoretical values of LFV machining roughness were to $fr_3 = 1.5$ indentation frequency in both feeds rate. Tables 2 and 3 present the results of the statistical analysis for machining depht, a_{p1} and a_{p2}, respectively.

Table 2. Analysis of variance for machining depth a_{p1} = 1.5 mm.

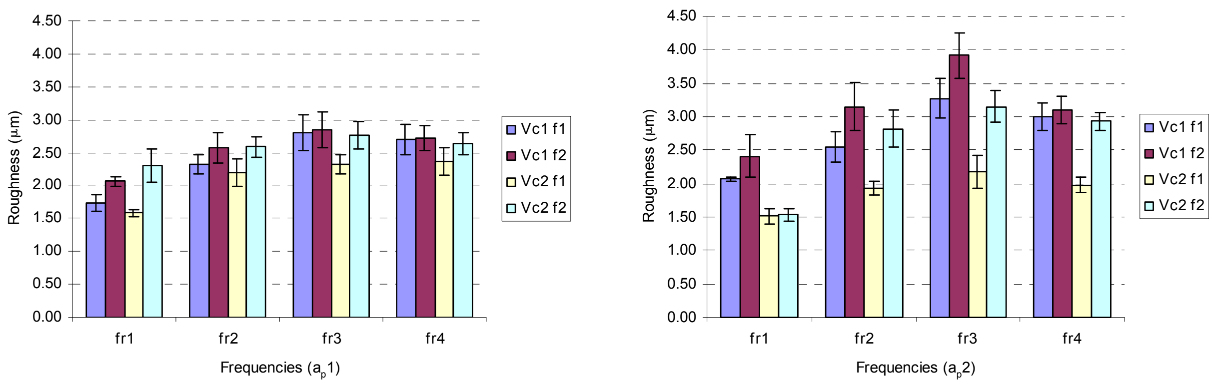
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	25.018	15	1.668	40.115	0.000
Intercept	1113.613	1	1113.613	26783.513	0.000
Cutting_speed	0.773	1	0.773	18.583	0.000
Feed	4.465	1	4.465	107.393	0.000
Frequency	16.25	3	5.642	135.690	0.000
Cutting_speed*Feed	1.030	1	1.030	24.763	0.000
Cutting_speed*Frequency	0.792	3	0.264	6.353	0.000
Feed*Frequency	0.911	3	0.304	7.307	0.000
Cutting_speed*Feed*Frequency	0.122	3	0.041	0.977	0.405
Error	7.318	176	0.042	-	-
Total	1145.950	192	-	-	-
Corrected Total	32.336	191	-	-	-

Table 3. Analysis of variance for machining depth a_{p2} = 2.5 mm.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	84.284	15	5.619	100.779	0.000
Intercept	1291.324	1	1291.324	23160.507	0.000
Cutting_speed	22.188	1	22.188	397.959	0.000
Feed	15.453	1	15.453	277.157	0.000
Frequency	39.386	3	13.129	235.468	0.000
Cutting_speed*Feed	0.951	1	0.951	17.050	0.000
Cutting_speed*Frequency	1.362	3	0.454	8.145	0.000
Feed*Frequency	2.861	3	0.954	17.105	0.000
Cutting_speed*Feed*Frequency	2.083	3	0.694	12.452	0.000
Error	9.813	176	0.056	-	-
Total	1385.422	192	-	-	-
Corrected Total	94.097	191	-	-	-

Analyzing Table 3, it can be observed that all independent variables and their interactions influenced the roughness both machining depths evaluated. Through the statistical contrast of the difference, it is observed that the fr_3 = 1.5 indentation frequency presents the highest roughness values, according theoretical approach of Table 1. This can be explained by the smaller amounts of turns needed to complete the repetition of the indentation cycle, generating larger spaces between the machining grooves to both feeds. It was also observed that a roughness decay occurred as the indentation frequency increased (fr_4 = 1.8). This experimental result suggests that increasing the frequency of indentation allows to improve the roughness. However, the difference between the roughness values found experimentally was higher for depth of cut a_{p2} = 2.5 mm.

In Figure 2, it can be seen that higher roughness values were obtained for the feed rate f_2, for both machining depths evaluated. It can also be observed that the highest roughness were found to LFV machining.



a) b)

Figura 2. a) Roughness R_a obtained em a_{p1}; b) Roughness R_a obtained em a_{p2}.

Based on the results obtained by the analysis of variance, a mathematical model was elaborated using linear multiple regression, where different roughness were evaluated and its approximation with the values found in the conditions of the tests. Equation 5 represents the model obtained through the experimental roughness R_a , which corresponds to the measured points measured in a diametrically equidistant way, excluding the vibration frequency fr_1, since this is conventional machining. For other regressions, the reference values of the theoretical R_a roughness for LFV machining (Table 1).

$$R_a = -8.41 + 14.32.fr + 0.0027.V_c - 10.19.f + 0.42.a_p - 4.881.fr^2 + 0.328.fr.a_p + 0.0337.V_c.f - 0.004796.V_c.a_p + 5.17.f.a_p \tag{5}$$

The value of P-value (<0.10) that the relationship between roughness R_a and the variables studied in this model, has a statistically significant relationship. However, the proposed regression model showed a correlation coefficient of 68%. This is due to the large dispersion of values obtained, especially when the indentation frequency fr_3 = 1.5 was observed. The value of R^2 was strongly influenced by the interaction between indentation frequency and cutting velocity.

As shown in Figure 3, it can be seen that the roughness decreases as the indentation frequency increases. Increasing the cutting speed also provided a decrease in roughness R_a. But the increase in feed and machining depth had an influence on the increase in roughness.

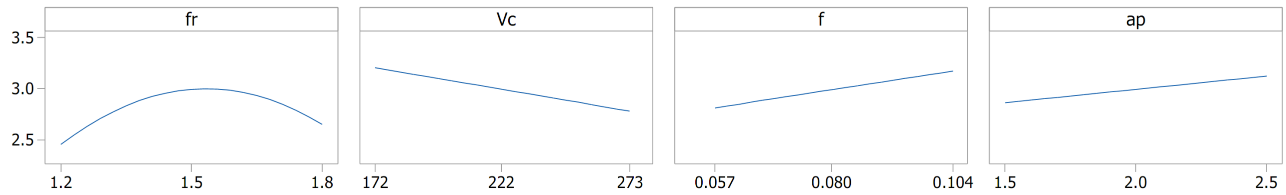


Figure 3. Roughness variation R_a for experimental values obtained.

The linear regression referring to the lower values of roughness obtained in the LFV machining, since Table 1 predicts ranges of variation as a function of frequency, Equation 6 represented 91.4% of the cases studied. This coefficient is considered representative, since it indicates that the proposed model presents a good correlation with the roughness measured experimentally. However, it was observed that the roughness R_a was influenced predominantly by the frequency of indentation, it can be related to the greater deformation caused by the cutting tool during the machining of the specimens.

$$R_a = -9.79 + 12.75.fr + 0.0106.V_c + 7.68.f + 2.091.a_p - 4.509.fr^2 - 0.00698.V_c.a_p - 6.85.f.a_p \quad (6)$$

Equation 7 presented to the values of the highest roughness variation, a correlation coefficient equal to 97.4% of the cases, with roughness influence similar to the variation represented by Equation 6. Although the experimental results did not reach the highest roughness obtained theoretically, this does not mean that they can not occur under similar machining conditions. This fact can be explained by the value selected for the tool displacement amplitude, which in the case of this study was equal to the feed rate.

$$R_a = -104.69 + 136.69.fr + 0.02356.V_c + 43.5.f + 4.429.a_p - 45.51.fr^2 - 0.01511.V_c.a_p - 14.27.f.a_p \quad (7)$$

Figure 4 shows the R_z roughness results measured experimentally. It can be observed that the tendency of increase and reduction of roughness were similar to those observed in Figure 2. This result indicates that the machined surface presents a distinct pattern only in magnitude, as the greater roughness was observed under similar conditions of frequency, cutting velocity and feed. The fact that LFV machining has shown greater roughness R_z than conventional machining can be related to the length of contact of the cutting tool. In LFV machining this length is greater than the apparent length, since the trajectory of feed and recoil tool results in greater linear distances traveled. However, variations in the thickness of the machining chip can interfere in its lateral flow and heterogeneous hardening regions. These regions, when removed by shearing, can produce grooves in the less crunched regions, promoting the obtaining of larger R_z values when compared to conventional machining.

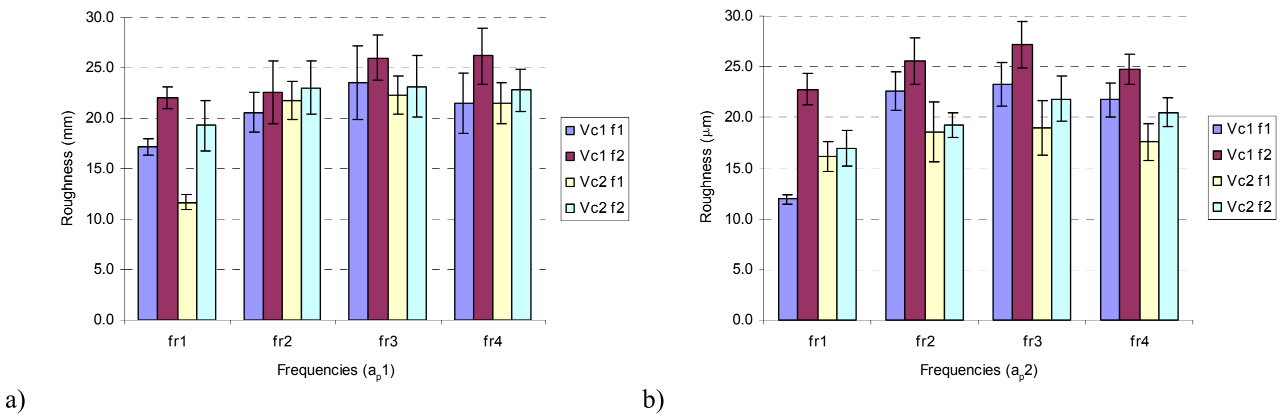


Figura 4. a) Roughness R_z obtained em a_{p1}; b) Roughness R_z obtained em a_{p2}.

5. CONCLUSIONS

From the obtained results, it is possible to conclude there is a relation between feed, surface roughness and LFV machining method. This relationship differs from conventional machining with the following tendency: higher indentation frequencies tend to decrease the roughness because the greater number of furrows produced by feed. However, from the critical value of the indentation frequency, feed does not produce significants variations in the roughness R_a.

Both R_a and R_z roughness present similar results of growth and reduction as a function of feed tool indentation. These results differ only in magnitude, but through them it is possible to note that the greatest roughness is obtained when the frequency $fr_3 = 1.5$ is used.

6. ACKNOWLEDGEMENTS

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