# INTERRUPTED CUTTING EVALUATION BY MEANS OF MONITORING CUTTING FORCES AND VIBRATION SIGNALS

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***Abstract.*** *Turning process, in which interrupted cutting occurs, is usually verified during manufacture of mechanical components, since a particular geometry is necessary for the application of the device or due to the geometry resulted from the previous manufacturing process, such as forging. This work deals with monitoring the cutting forces and vibration signals during the turning of a square section bar made of SAE 52100 steel. The forces and the vibration signals were recorded in different steps of the turning, considering geometrical features of the sample. The square section bar was the starting geometry and the round section was the final. The cutting parameters were: feed rate 0.2mm/rot, depth of cut 1mm, 60 and 120 m/ min of cutting speeds, and the tool was a cemented carbide tool (TPUN 160304 type). A tool holder equipped with strain gages and an accelerometer was used to monitoring the turning process. The cutting edge of the tool was set perpendicular to the direction of the tool motion. Although, the results are preliminary, they allow showing a relationship between the average and maximum cutting forces, and the contact rate throughout the interrupted cutting. Therefore, forces and vibrations could be related to the geometry of the sample by means the experimental apparatus developed.*

***Keywords***: *machining, cutting forces, interrupted cutting, vibration*

## 1. INTRODUCTION

The turning is a machining process in which a single point tool removes unwanted material to produce a surface of revolution (Shaw, 1984), and the raw material is usually cylindrical. Hence, the cutting can be considered continuous as defined by Pekelharing (1980): "as a long cut where the interruptions are, or are assumed to be, of little importance". Although, during turning of forged materials, the interrupted cutting occurs causing thermo-mechanical cycles in the tool due to tool entry and tool exit (Pekelharing, 1980), which considerably decreases the tool life. Previous work (Rodrigues, *et al.* (2008)) showed an evaluation of wear behavior of tools throughout interrupted cutting. The results showed the interrupted cutting is always more severe than continuous one. Otherwise, the evaluation of turning process can be carried out by means of different techniques. There are many works relating the cutting forces, vibrations, and roughness during machining. The measures and data can be obtained by means of tool holders equipped with strain gages or piezoelectric sensors linked to interfaces to analyze and record the forces during machining. Therefore, these results can be used to determine relationships between the cutting parameters, roughness, damage on the machined surface, tool wear, and the cutting forces (Lin et al., 2001; Strafford, 1997; Dimla and Dimla, 2000a; Dimla and Dimla, 2000b). However, the modelling of the mechanical behavior of the material is difficult since during the manufacturing processes the strain, the strain rate, temperature and the microstructure are not homogeneous (Shaw, 2005; Dimla and Dimla, 2000a; Dimla and Dimla, 2000b). Other than that, it is important considering the geometric features of the workpiece, as showed above. Materials with different geometries presenting edges, and interrupted surfaces are also usually turned and other variables have to be evaluated to model the process.

The evaluation of the interrupted cutting can be carry out by analysing the mechanical cycles during cutting processing, and it can be conducted based on the contact rate, which is defined as the ratio between real cutting length and the whole path length of one revolution (Tonshoff,1990). Different geometries lead to different contact rates such as for cylindrical bars the contact rate is 1; for a polygonal bars, the contact rate is constant and lower than 1; and for a bar with transversal holes the contact rate is variable. The same type of analysis can be performed in relation to the cutting forces, which increase after the entry of tool and decrease after the tool exit (Tonshoff, 1990), and also with the increase of the contact rate.

This work deals with monitoring the cutting forces and vibration signals during the turning of a square section bar. The sample machined was made of SAE 52100 steel. The forces and the vibration signals were recorded in different steps, considering geometrical features of the sample. The square section bar was the starting geometry and the round section was the final. The cutting edge of the tool was set perpendicular to the direction of the tool motion, and two different cutting speeds were used, the other cutting parameters were kept constant. A tool holder equipped with strain gages and an accelerometer was used to monitoring the turning process. The results made it possible to show that forces and vibrations could be related to the geometry of the sample by means the experimental apparatus developed.

## 2. MATERIALS AND METHODS

### 2.1 Materials

The chemical composition of the hot rolled bar used in this work is shown in Tab. 1.

Table 1. Chemical composition of the SAE 52100 (wt%)

| Element | C | Mn | Si | P | S | Cr | Ni | Mo | Al | Cu | Ti |
|---|---|---|---|---|---|---|---|---|---|---|---|
| wt% | 1.000 | 0.310 | 0.260 | 0.012 | 0.007 | 1.380 | 0.080 | 0.020 | 0.005 | 0.110 | 0.003 |

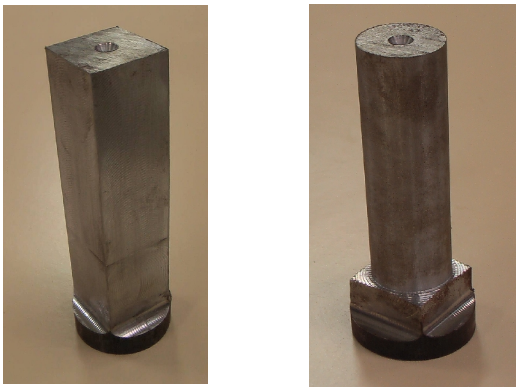
### 2.2 Materials characterization

The microstructure of the material was observed by means of optical microscopy (OM) Olympus BX60M. The metallographic sample preparation for OM observations consisted of grinding down to 600-grit paper, followed by 1μm diamond polishing. After polished, the samples were etched for a few seconds in Nital 3% for general microscopical examinations.

Hardness was measured in the longitudinal and transverse sections of the samples, using a Struers hardness tester (load of 300 N).

### 2.3 Interrupted turning tests

The specimens for interrupted turning had the starting geometry as square section bar (35.4 x 35.4 mm) and the round section was the final (34 mm diameter), as can be seen in Fig. 1. The cutting parameters were: feed rate 0.2mm/rot, and 60 and 120 m/ min of cutting speed. The depth of cut of 1mm was carried out in each pass. Table 2 shows the experimental parameters used.



a) b)

Figure 1. Specimens geometry for the interrupted turning tests (a) starting geometry and (b) final geometry.

Other important parameter in the analysis carried out was the contact rate, which can be defined as a relation between the length where the tool is in contact with the workpiece, measured over one revolution, and the total length of the revolution. The contact rate is minimal and it increases as the bar geometry changes from the square up to the round section, that is, the contact rate varies from 0 to 1, respectively. The changes in the geometry are shown in Fig. 2, where a schematic of each pass can be observed.

(a) (b) (c) (d) (e) (f) (g) (h)

Figure 2. Pass progression used in the interrupted machining tests. Contact rates for each case can be calculated by the ratio between red portion lengths and the revolution length (π x diameter).

The tests were carried out by means of the machine tool (CNC lathe, Traub 360– Ergomatic), with 38 kW of power in the main motor. A hydraulic 3-jaw chuck was used to fix the specimens. The tool used in the tests was a TPUN 160304 (cemented carbide without coating and chip breaker). The geometric features of the tool are: rake angle is 0º, relief angle is 11º, the cutting edge 0.4 mm radius (Fig 3). Although, this tool was not the best to be used in these conditions, it is important mentioning that the main objective was to evaluate and model the cutting. Therefore, the use of this type of tool reduced the variables to be analyzed. The experimental parameters for interrupted turning tests are shown in Tab. 2.

Table 2. Experimental parameters for interrupted turning tests.

| Sample | Pass number | Initial Diameter (mm) | Final Diameter (mm) | Cutting speed (m/min) | Cutting | Contact Rate |
|---|---|---|---|---|---|---|
| 1 | 1 | 50 | 48 | 60 | Interrupted | 0.054 |
| | 2 | 48 | 46 | 60 | Interrupted | 0.116 |
| | 3 | 46 | 44 | 60 | Interrupted | 0.188 |
| | 4 | 44 | 42 | 60 | Interrupted | 0.274 |
| | 5 | 42 | 40 | 60 | Interrupted | 0.380 |
| | 6 | 40 | 38 | 60 | Interrupted | 0.522 |
| | 7 | 38 | 36 | 60 | Interrupted | 0.759 |
| | 8 | 36 | 34 | 60 | Continuous | 1.000 |
| 2 | 1 | 50 | 48 | 120 | Interrupted | 0.054 |
| | 2 | 48 | 46 | 120 | Interrupted | 0.116 |
| | 3 | 46 | 44 | 120 | Interrupted | 0.188 |
| | 4 | 44 | 42 | 120 | Interrupted | 0.274 |
| | 5 | 42 | 40 | 120 | Interrupted | 0.380 |
| | 6 | 40 | 38 | 120 | Interrupted | 0.522 |
| | 7 | 38 | 36 | 120 | Interrupted | 0.759 |
| | 8 | 36 | 34 | 120 | Continuous | 1.000 |

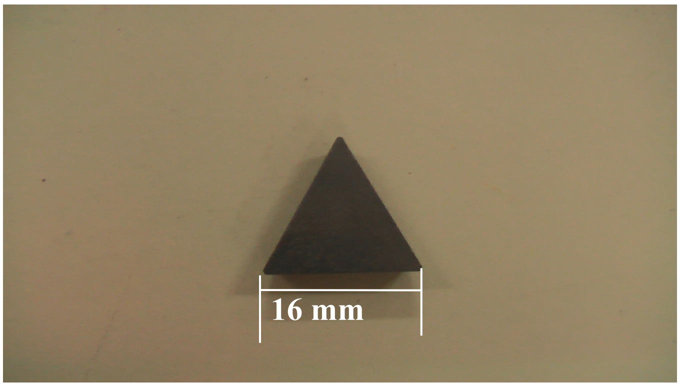


Figure 3. Tool utilized in the interrupted tests.

The cutting and feed forces were obtained from data acquired during the turning tests by means a tool holder equipped with strain gages and linked to an acquisition system. Figure 4 shows the tool holder and strain gages (Wheatstone bridges). The passive force was not evaluated. The tool holder position in relation to the workpiece was 90º. The calibration curves for cutting and feed forces are shown in Fig. 5, where it can be observed the linear relation between the measured forces and the output voltages of the Wheatstone bridges. The evaluation of the cutting process was also carried out by means of accelerometer, to analyze the vibrations. A Kistler 8702B50M1 accelerometer was placed in the tool holder. The acquisition system used was the ADS–2000 (Lynx Eletrônica Ltda). The frequency of acquisition was 15kHz. The data was acquired and recorded by means a microcomputer. The MATLAB 6.5 R13 software was used to analyze the results and carry out the discrete Fourier Fast Transform (FFT), which allowed obtaining the frequency components of the forces and vibration signals.

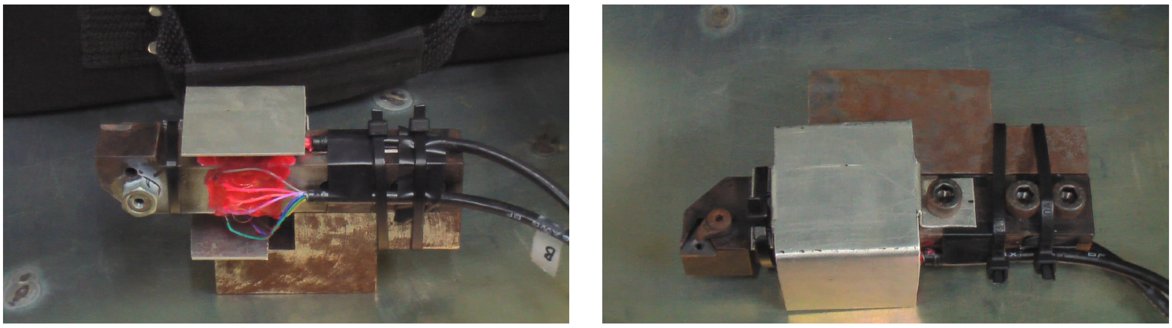
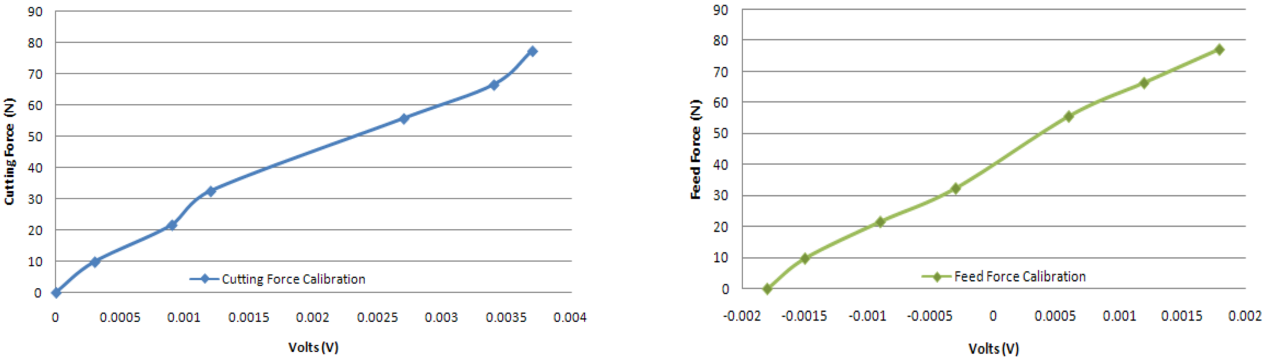


Figure 4. Tool holder equipped with strain gages.



(a) (b)

Figure 5. Calibration curves (a) cutting force and (b) feed force.

# 3. RESULTS

## 3.1 Material characterization

The microstructure of the transverse and longitudinal sections of the SAE 52100 bar are shown in Fig. 6 and Fig. 7, where a spheroidized pearlite can be observed. The microstructure, and also the hardness were homogeneous in the material studied. Ten measures of Vickers hardness were carried out and the average and standard deviation was calculated. The hardness was measured from the surface to the inner of the bar was (195±2)HV.

Figure 6. Transverse section of the samples. Optical microscopy.

Figure 7. Longitudinal section of the samples. Optical microscopy.

### 3.2 Turning tests

The graphics in Fig. 8 show an example of the results obtained for each pass in the workpiece. The graphic in blue represents the accelerometer signal, below there is the feed force graphic, in red, and the last one, in brown, is the cutting force graphic. Due to the large vibration involved in interrupted cutting turning, the accelerometer reached the amplitude limits during the tests, allowing analyzing only the frequencies domain by observing the interrupted cutting frequency. On the other hand, the cutting and feed forces signals can be analyzed by both time-domain and frequency-domain. For the first one, it was possible to obtain the maximum and average force values and for the second, the frequencies related to the interrupted cutting (Fig. 9). The frequency related to the interrupted cutting, named as cut frequency, is almost the same and independent of the signal analyzed, that is, the power spectrum gives the same results for the different passes as can be seen in Tab. 3. The machining tests were carried out only once for each condition.

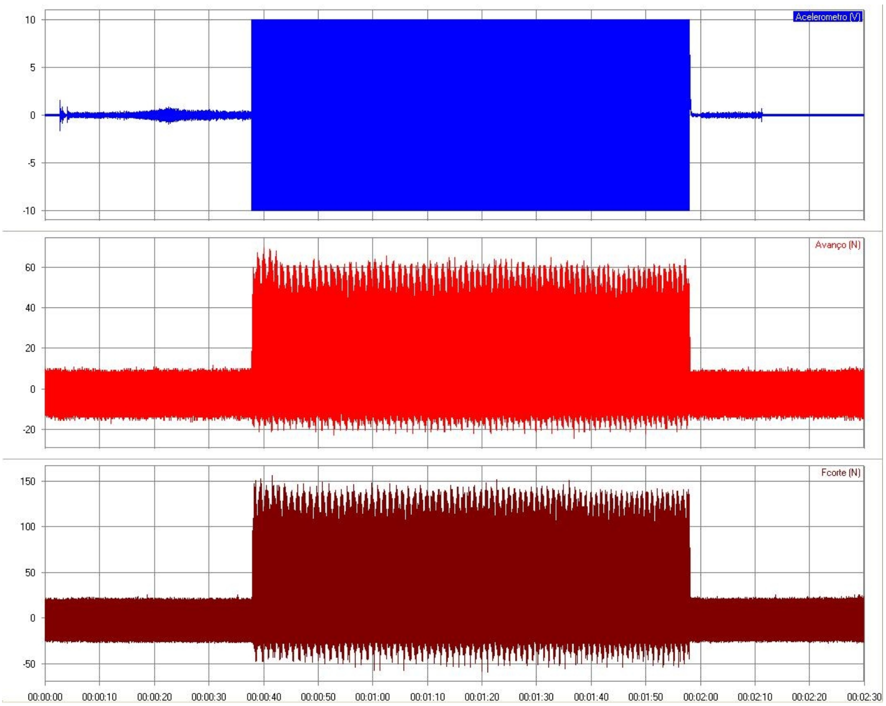


Figure 8. Time-domain graphics for the accelerometer (blue), feed force (red) and cutting force (brown) signals. Data extracted from the third pass test (contact rate 0.188), cutting speed of 60 m/min.

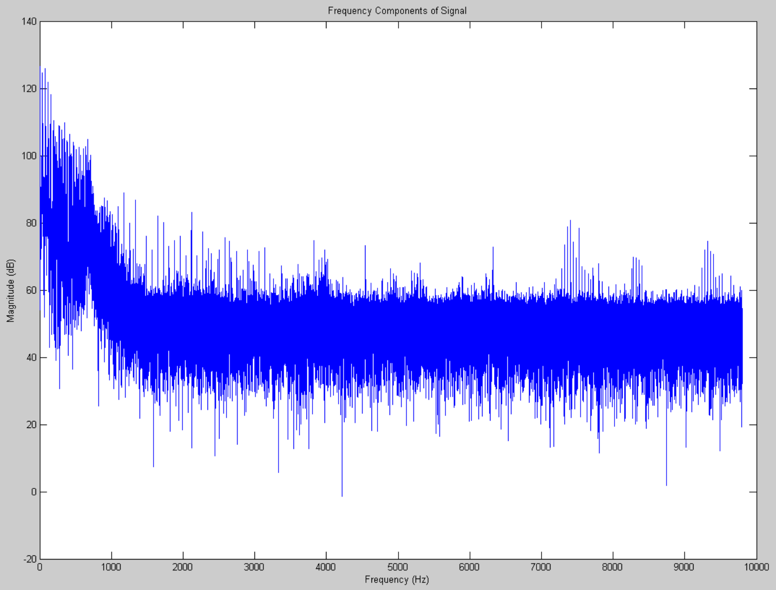


Figure 9. Example of FFT analysis processed in the MATLAB software. Data extracted from the third pass test (contact rate 0.188), cutting speed of 60 m/min, for the cutting force signal.

Table 3. Results obtained of forces and vibration signals during interrupted turning tests.

| | **Workpiece 1 (Cutting Speed = 60 m/min)** | | | | | | | | **Workpiece 2 (Cutting Speed = 120 m/min)** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Pass** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| **Initial diameter (mm)** | 50 | 48 | 46 | 44 | 42 | 40 | 38 | 36 | 50 | 48 | 46 | 44 | 42 | 40 | 38 | 36 |
| **Final diameter (mm)** | 48 | 46 | 44 | 42 | 40 | 38 | 36 | 34 | 48 | 46 | 44 | 42 | 40 | 38 | 36 | 34 |
| **Contact Rate** | 0.054 | 0.116 | 0.188 | 0.274 | 0.380 | 0.522 | 0.759 | 1.000 | 0.054 | 0.116 | 0.188 | 0.274 | 0.380 | 0.522 | 0.759 | 1.000 |
| **Rotation (rpm)** | 401 | 419 | 438 | 459 | 482 | 508 | 536 | 568 | 802 | 838 | 876 | 918 | 965 | 1016 | 1073 | 1137 |
| **Cutting Force (N) Average** | 0.52 | 6.92 | 14.78 | 23.42 | 32.69 | 50.54 | 87.90 | 133.31 | 4.83 | 8.73 | 15.81 | 23.32 | 36.01 | 52.25 | 80.54 | 128.20 |
| **Cutting Force (N) Maximum** | 148.7 | 148.8 | 151.2 | 164.3 | 161.9 | 164.3 | 258.0 | 272.8 | 193.1 | 169.3 | 161.9 | 151.2 | 138.9 | 137.2 | 130.6 | 129.4 |
| **Cutting Force Cut Frequency (Hz)** | 27.0 | 28.3 | 29.6 | 30.9 | 32.2 | 33.9 | 35.8 | 38.0 | 54.2 | 56.6 | 59.0 | 61.9 | 64.9 | 68.2 | 72.0 | - |
| **Feed Force (N) Average** | 0.72 | 2.32 | 5.39 | 9.29 | 13.36 | 19.93 | 33.57 | 72.13 | 5.95 | 7.74 | 9.95 | 11.62 | 16.35 | 19.80 | 25.20 | 49.02 |
| **Feed Force (N) Maximum** | 55.8 | 60.8 | 65.7 | 64.9 | 64.9 | 62.4 | 73.9 | 101.8 | 67.3 | 59.1 | 56.7 | 51.7 | 57.5 | 54.2 | 55.8 | 67.3 |
| **Feed Force Cut Frequency (Hz)** | 27.0 | 28.3 | 29.6 | 30.9 | 32.2 | 33.9 | 35.8 | 37.8 | 54.2 | 56.6 | 58.9 | 62.0 | 64.9 | 68.2 | 71.9 | - |
| **Accelerometer Cut Frequency (Hz)** | 27.0 | 28.5 | 29.5 | 30.9 | 32.2 | 34.0 | 35.8 | - | 54.2 | 56.6 | 59.0 | 61.9 | 64.9 | 68.2 | 71.9 | - |
| **Accelerometer Higher Frequency (Hz)** | 526.8 | 531.0 | 516.4 | 540.0 | 545.0 | 615.9 | 596.8 | 611.5 | 596.1 | 621.9 | 649.3 | 618.8 | 648.4 | 733.4 | 756.2 | 749.0 |

It is easier to understand the meaning of the cut frequency (Tab. 3) by means of an example. For instance, for the testing conditions: cutting speed of 60 m/min (419 rpm), and 4 impacts for each rotation, due to the geometry of the workpiece, one can found 26.7 Hz (Tab. 3), which is very similar to value calculated by means Fourier transform (27

Hz). The rotation and the cut frequency proportionality can be observed for all the passes, excepted for the 8th pass at 120 m/min, in which there is no interrupted cutting. Therefore, during interrupted cutting, the increase of the cut frequency occurs with the increase of the rotation, since the cutting speed is constant and diameter of the workpiece variable. The discrepancy in the 8th pass at 60 m/min can be related to the geometry or set up of the sample, which probably it was only near cylindrical in the 8th pass. Although, these results are preliminary and more tests have to be carried out, they show a relationship between the parameters, and the experimental apparatus worked satisfactorily.

Other relation could be observed, as shown in Figs 10 and 11, in which the average and the maximum resulting cutting and feed forces throughout the interrupted machining tests are displayed. The average feed force (Ff) is always lower than cutting force (Fc) (about a half of cutting force). The relation between the average forces and the contact rate is almost linear. This result was expected since the contact between the tool and the workpiece increase with the contact rate, leading to higher forces. The cutting speeds used in this work seemed not influenced much the cutting forces.

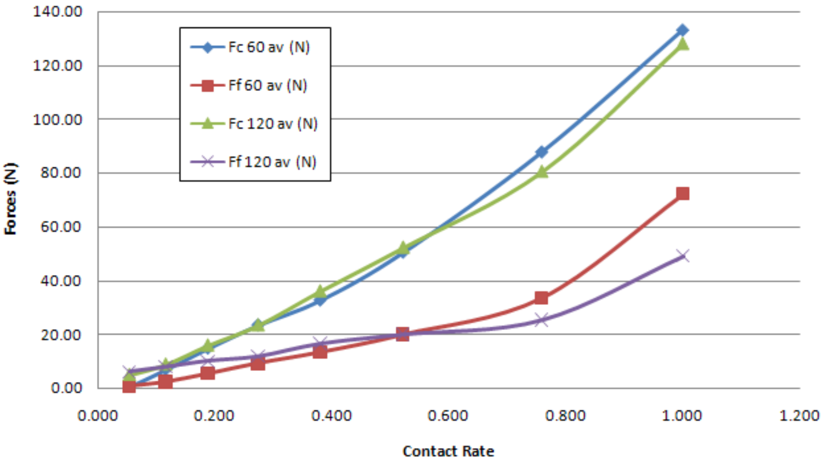


Figure 10. Average resulting cutting and feed forces throughout the interrupted machining tests.

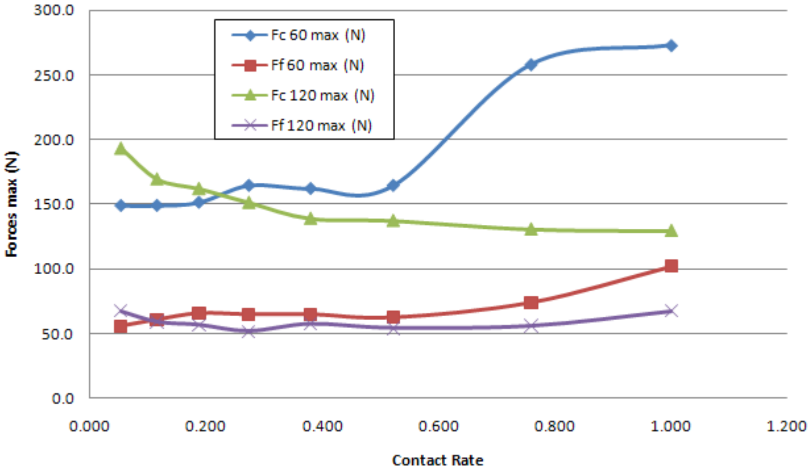


Figure 11. Maximum resulting cutting and feed forces throughout the interrupted machining tests.

Although, the maximum cutting forces are also higher, the proportion is different (Ff=0.3Fc), and the maximum cutting and feed forces showed to be independent of the contact rate. The exception was the 7th and 8th passes at 60 m/min, in which a higher vibration was observed. Although the vibration has increased, it occurred without causing the same effect on the average cutting forces. A possible explanation for this phenomenon, it could be related to the natural frequency of the tool holder, which could be reached during the tests. However, the natural frequency was not measured.

Figure 12 shows the results of the higher frequencies obtained (Tab. 3) and the contact rate. These frequencies could be related to the chip formation. However, it was not confirmed, and a careful investigation have be carried out to understand and evaluate these results. The data obtained, throughout the machining tests by the means of the accelerometer, cannot be carried out by analyzing the resulting forces, since the response by using the strain gages takes more time than the piezoelectric sensor. The relation between the higher frequency and the contact rate presented the same features for the both cutting speeds. As this work was preliminary, the results have to be repeated, and the chip morphology, size and microstructural characterizations have to be carried out. However, a possible explanation for the increasing the higher frequency, mainly at contact rates higher than 0.5, could be related to difference in the thermo-mechanical cycles. Less impact and high temperatures developed, probably, could have changed the chip formation behavior. It is important mentioning that the microstructure and hardness of the material were homogeneous since the vibrations cannot be directly related to the microstructural features.

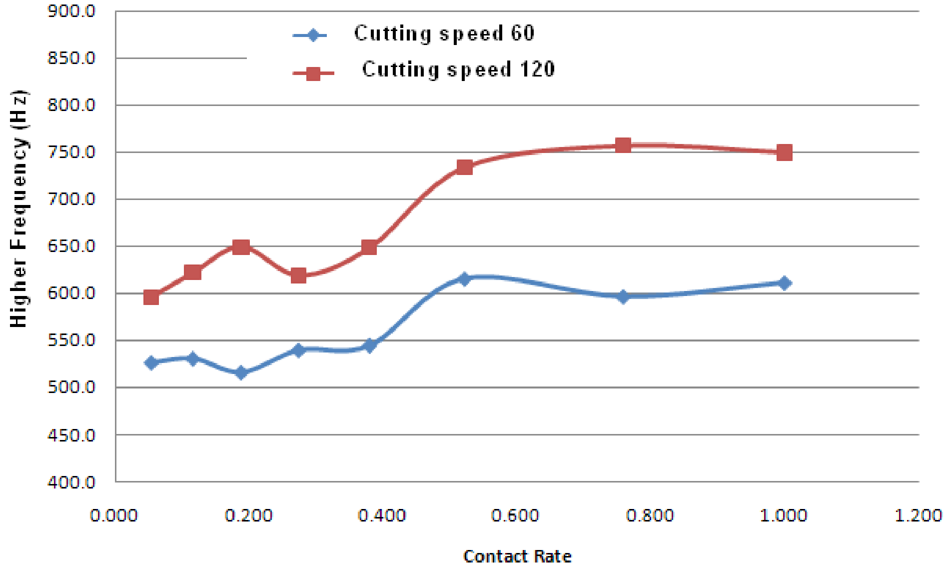


Figure 12. Chip formation frequencies throughout the interrupted machining tests.

## 4. CONCLUSIONS

This work deals with monitoring the cutting forces and vibration signals during the turning of a square section bar made of SAE 52100 steel. This work was preliminary and the tests have to be repeated for a better evaluation. However, some relations were observed throughout the tests and allow the following conclusions and comments:

1. The experimental apparatus set for the interrupted cutting tests worked. Although, some results could be considered qualitative, the analysis conducted showed the behavior of the material and a relation between the forces and vibrations can be performed.
2. The average cutting and feed forces showed almost linear relation with the contact rate. However, the maximum cutting and feed forces did not show the same behavior, mainly at the higher contact rates. The evaluation of the natural frequency of the tool holder, and more tests have to be carried out to improve the analysis.
3. Two different ranges of frequencies were identified during the machining tests. The lower was related to the rotation and the geometry of the samples, and the higher, probably, can be related to the chip formation. However, a careful analysis have to be carried out since the results are not conclusive and the chip and microstructure features have to be characterized.

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