Machinability of a 53 % Silicon Aluminum Alloy

Oussama Chaieb[1], **Victor Songmene**[2] **and Mohammad Jahazi**[3]
1. Master degree student in mechanical engineering
2. Professor
3. Professor
École de technologie supérieure, Montréal, Canada
Corresponding author: oussama.chaieb.1@ens.etsmtl.ca

Abstract

This paper presents the experimental results on the milling process of an Al-53 % silicon alloy using a polycrystalline cubic boron nitride PCBN diamond coated tool. The influence of different cutting parameters on material removal rate, roughness evolution milling forces, machine vibration and the surface quality of the machined material was measured during the experiments. Cutting forces were measured using Kistler table and digital acquisition system. Surface roughness and morphology were quantified using a confocal laser-digital microscope.

Keywords: Machinability of aluminum-silicon alloy, milling, diamond coated tools.

1. Introduction

The aluminum microstructure composite reinforced with high volume fraction silicon particles (AlSi) has been identified as a potentially suitable material system for space applications, because it has high thermal conductivity, low coefficient of thermal expansion and low density, references [1 – 3]. However, the hardness of silicon is higher than that of aluminum alloy. Thus, it is necessary to study the effect of Si on the machinability of the material.

The surface finish, which includes the topography and defects of the machined surface, has been studied in several studies. The surface roughness parameters are the basic indicators of the quality of the machined surface. The work of Ammula and Guo [4] showed that the feed rate has a major effect on the surface integrity compared to cutting speed and the depth of cut on 6061-T651 alloy. The surface roughness trends were often associated with the formation of the built-up-edge (BUE). Gómez-Parra et al., [5] showed that the increase in BUE caused a decrease in the roughness, Ra. Indeed, the presence of the BUE increases the radius of the tool nozzle, thereby improving the surface roughness. However, Iwata and Ueda [6] stated that BUE leaves cracks on the machined surface. Thus, it increases the surface roughness and deteriorates the resistance of the part. Li et al., [7] studied the effect of high cutting speed on the integrity of the 7075 aluminum alloy surface. Their results showed the positive effect of high cutting speed on surface integrity.

Andrewes et al., [8] treated experimental results on the machinability of silicon-reinforced aluminum and 65 % of silicon carbide (Al / Sip + SICP) during the milling process with a carbide tool. They measured cutting forces, wear, tool life, and the quality of the machined surface. They showed that if the same volume fraction of the silicon particles is replaced by silicon carbide while keeping the particle size, the flexural strength and the Vickers hardness are improved. Therefore, machinability becomes more difficult.

As reported by El-Gallab and Skladb [9], machining performance is a good indication of the workpeace machinability. During the machining operation, many parameters can affect the machining performance. Many studies have considered some variables as criteria of performance of machining. In summary, the most used criteria are Tool wear (tool life), integrity of the machined surface, cutting forces (power consumption), chip formation, and precision of the machined part.

The above review showed that there are still many missing information regarding the influence of machining parameters on the surface quality of Al alloys containing very high amounts of silicon. The present work has been defined in this context and has for main objective to determine the optimum machining parameters for an Al-53 % Si alloy.

2. Experimental Procedures

2.1. Workpiece Material: MS43 AlSi Alloy

The workpiece material is MS43, aluminum alloy with 53 % silicon. It was manufactured by extrusion then ultra-fast cooling and supplied by MDA Corporation, Quebec, Canada. MS43 is an aluminum alloy containing 53 % Si, 3.5 % C, 0.43 % O (wt %), with the rest Al. The bulk hardness of the MS43 was 54 ± 4 HRB, measured as Brinell Superficial Hardness using a 1/16 in. (1.59 mm) diameter ball and a 15 kg load. The microstructure of the MS43 consisted of the Al matrix and eutectic silicon particles. However, there were zones as well that consisted more dense than the global structure as shown in the Figure 1.

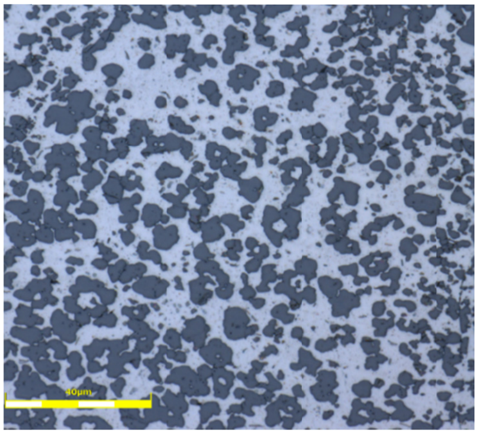

Figure 1. Micrographs of MS43 (53 volume % Si).

2.2. Properties of Tool and Physical Vapor Deposition (PVD) Coating

The cutting tools used for the milling were 3.175 mm diameter manufactured by Harvey tools [10]. The chemical composition of the PVD amorphous diamond coating improves lubricity and wear resistance. The characteristics of the tool are shown in the Table 1.

Table 1. Parameters of the milling tool.

	Tools	**32415-C4**
Geometric propriety	Cutter Diameter	3.175 mm
	Corner Radius	0.381 mm
	Length of Cut	12.7 mm
	Depth of Cut Radial	0.79375 mm
	Depth of Cut Axial	9.525 mm
	Number of teeth	4
Coating propriety	Coating / Substrate	Amorphous Diamond
	Structure	Mono-layer
	Hardness	78 - 88 GPa
	Coefficient of Friction	0.1
	Coating Thickness	0.5 - 2.5 microns
	Max. Working Temp	399 °C

2.3. Milling Tests

Milling tests were performed using a HURON K2X10 computer numerically controlled CNC machine with a maximum rotational speed 28 000 rpm. The maximum permissible weight is 3000 kg with 1150 x 800 mm for the working area. The milling station was equipped with an internal system lubrication.

The machined composite surface was observed with a scanning laser microscope (OLYMPUS OLS4100, LEXT). The arithmetic surface roughness Sa of the machined composite surface was measured by a microscope and its corresponding microphotograph system with a resolution of 0.0254 mm. The parameters and set-ups which the microscope was programmed to measure the roughness was taken from the work of Aidibe et. al., [11]. A non-contact magneto-static force sensor was mounted on the part to measure the vibration, using this dynamometer and a charge amplifier, the forces in x, y and z direction, could be measured. The accelerometer was placed on the machine bed in such a way that x is the normal direction, y is the feed direction and z the axial direction. For the thrust force generated during milling the part was fixed in a Kistler four-component piezoelectric platform dynamometer (Switzerland, KISTLER9272).

In order to reveal the effect of cutting parameters on the machinability of MS43 clearly, a fixed milling conditions were applied for all specimens. The milling tests were performed at a 137.2 cutting speed using a 0.0254 feed rate per tooth. During each milling cycle a 15.24 mm/min and 0.00005 mm/tooth was to be subtracted for 5 items, in total there will be 25 samples with different cut parameters to evaluate the effect of each parameter. The radial depth of cut was 0.3175 mm and axial depth of cut was 9.525 mm of all time.

3. Results and Discussion

3.1. Surface Integrity

The roughness measurements and the surface damage analysis were carried out on the machined part. In the direction of the displacement of the tool and in the axial direction, the 2D profiles were made as shown in Figure 2 to measure the arithmetic surface roughness Sa for the two ends of the cutting parameters. A quantitative analysis was developed to quantify the effect of cutting conditions on the surface topography. The amplitude distribution of the 2D surface roughness parameters was described by, Sa. The microscope applies several measurements on the surface concerned in the form of texture to generate an average value. Figure 2a illustrates undulations on the surface of the highest cutting speed 137.16 mm/min. However, Figure 2b shows peaks of roughness without undulations for the lower cutting speed of 76.2 mm/min.

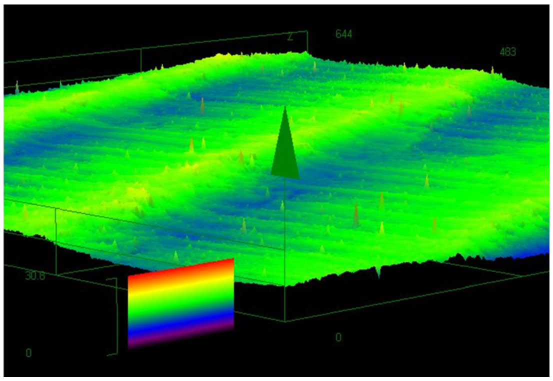

Figure 2a. Surface integrity of 137.16 mm/min, 0.0254 mm/tooth.

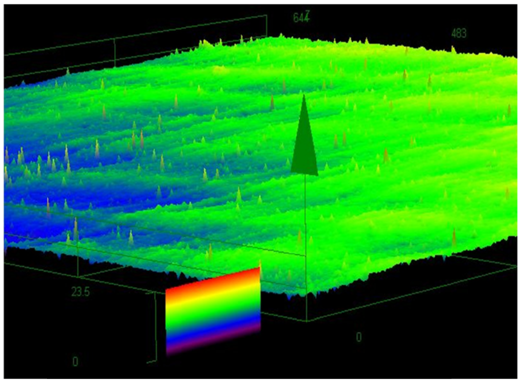

Figure 2b. Surface integrity of 78.2 mm/min, 0.02032 mm/tooth.

On the other hand, it can be observed that the roughness parameters are influenced by the feed rates and the cutting velocities. The surface roughness values are the average of several measurements made using the microscope. Figure 3 shows that the average of the arithmetic surface roughness is sensitive to variation of the cutting speed and feed rates, as well as to vibration and cutting forces. It illustrates the effect of cutting conditions on the amplitude distribution parameters. The roughness varies between 2.316 and 0.743 µm, the heights are not distributed on an average line but on an increasing or decreasing curve. Therefore, the surface profiles were random but at the same time showed a very rugged surface for the two cutting speeds of 137.16 and 121.92 mm/min.

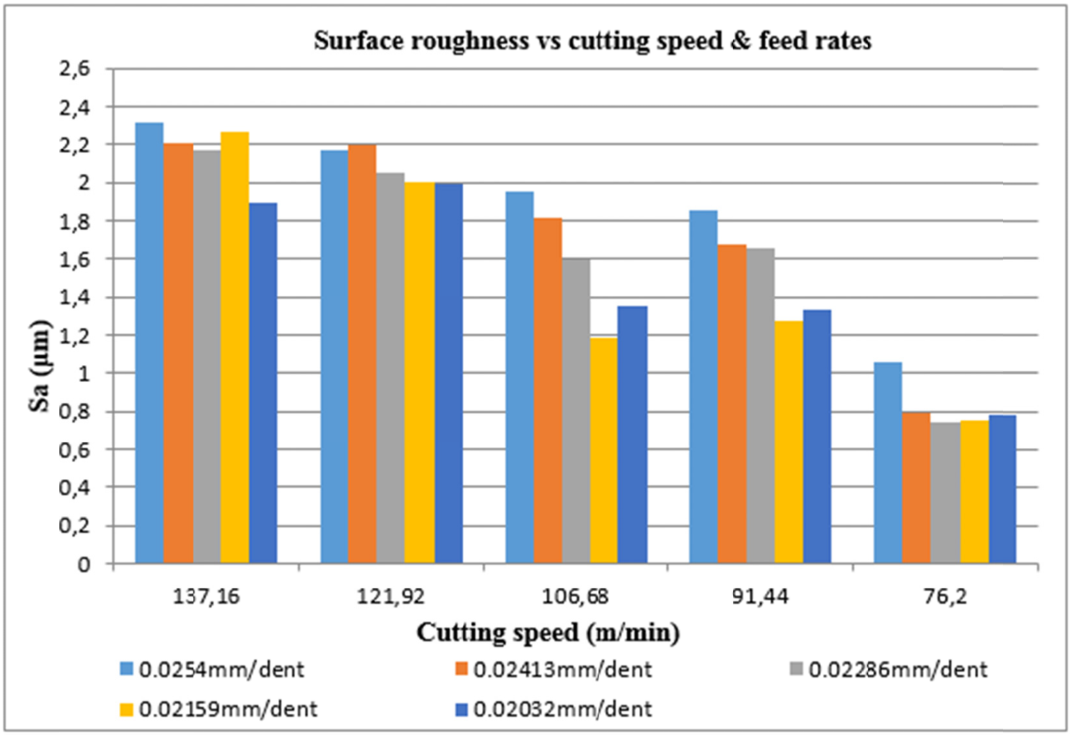

Figure 3. Surface roughness vs cutting speed & feed rates.

Figure 4 shows the average roughness analysis for a single cutting speed value and different feed rates. The mean roughness curve for a single feed value and different cutting speeds is shown in Figure 4a. It is noted that the roughness is significantly high for the 137.16 and 0.3048 cutting speeds, and then has a decreasing trend from 106.68 mm/min. This can be due to the significant vibration at the beginning of machining. Figure 4b shows that the roughness is always decreasing as a function of the decrease in the feed rates. However, the two curves below show that the effect of the cutting speed is greater on the surface integrity than the feed rates.

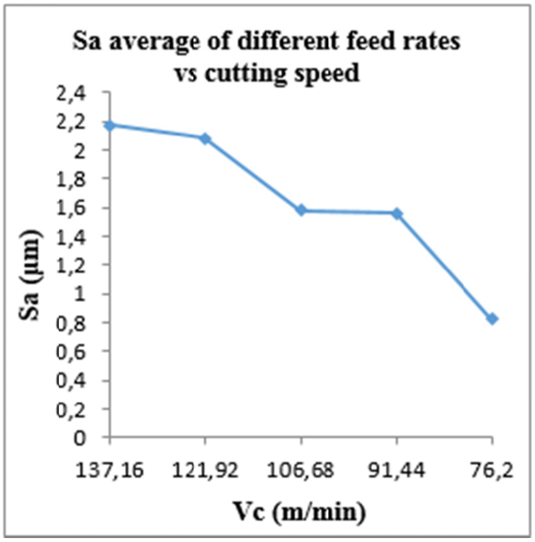

Figure 4a. Sa average of different feed rates per tooth vs cutting speed.

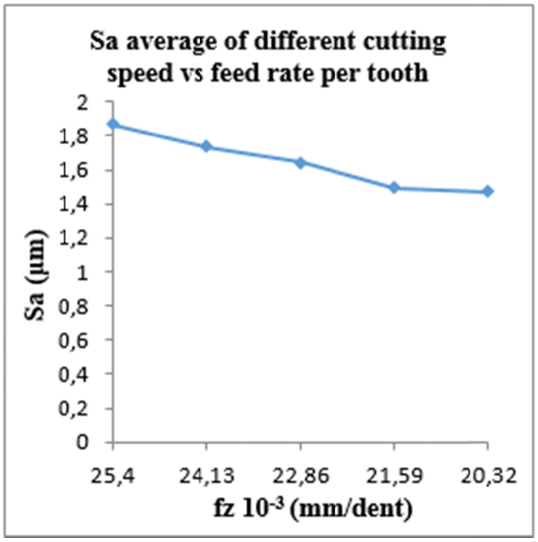

Figure 4a. Sa average of different cutting speed vs feed rates per tooth.

3.2. Cutting Force

An analysis of the workpiece cutting forces, obtained during the contouring operation of the MS43 material, was done by varying the cutting conditions. In these tests the depth of cut axial and radial were kept constant at 9.525 inches and 0.3175 inches, respectively. The variation of cutting forces on the X axis will be discussed later. The signal characterizing the cutting force along the X axis of the machine as a function of time during the machining is provided in Figure 5. For the study of the signal, the digital signal was divided into two parts. The first part consists of five peaks of signals, representing the force applied by the tool under the following cutting conditions: the feed rates per tooth of 0.0254, 0.02413, 0.02286, 0.02159, 0.02032 respectively, and a constant cutting speed of 137.16 mm/min. The second part represents the same variation of feed rate but with a cutting speed of 121.92 mm/min. For 137.16 mm/min, 0.0254 and 0.02413 mm/tooth cutting parameters, two very high peaks were observed. It should be noted that from the third peak, the signal stabilizes.

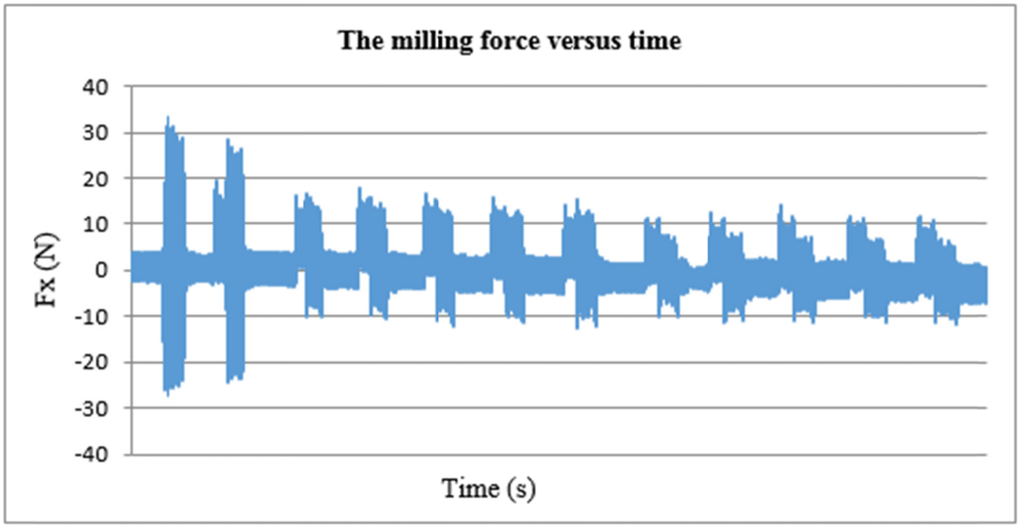

Figure 5. The milling force vs time.

The analyzed effects of machining, shows two force peaks, one with cutting speed 137.16 mm/min and feed rate 0.0254 mm/tooth and the second with 121.92 and 0.02413 mm/tooth. Figure 6a shows that the cutting force between 121.92 and 91.44 mm/min is almost stable, then declines from 91.44 mm/min. For the cutting speed 137.16 mm/min and in the range between 0.0254 and 0.02286 mm/tooth as shown in Figure 6b, the force Fx is high, but with the rest of the cutting speeds it is stable, its value is between 11 and 17 N with all the feed rates. The above results show that the machinability of MS43 AlSi alloy is better with cutting speeds less than or equal to 137.16 mm/min, and with feed rates values which vary from 0.0254 to 0.02159 mm/tooth. Above 121.92 mm/min, it is possible to have very high cutting forces especially with the feed rates 0.0254 and 0.02159 mm/tooth due to the material hardness. Under these conditions breakage of the tool could occur.

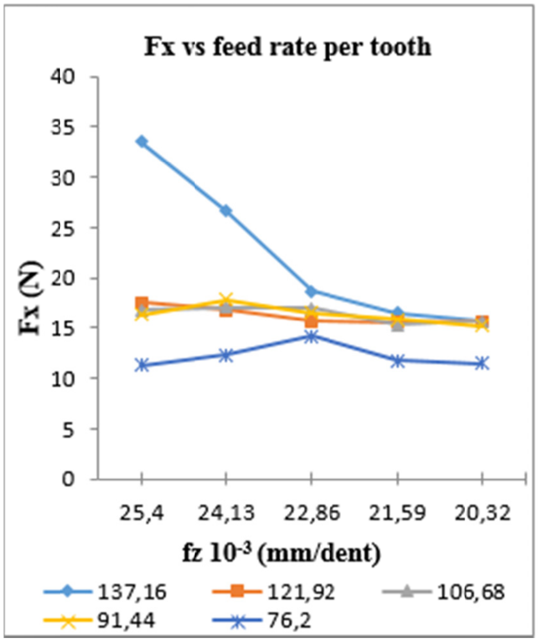

Figure 6a. Fx vs feed rates per tooth.

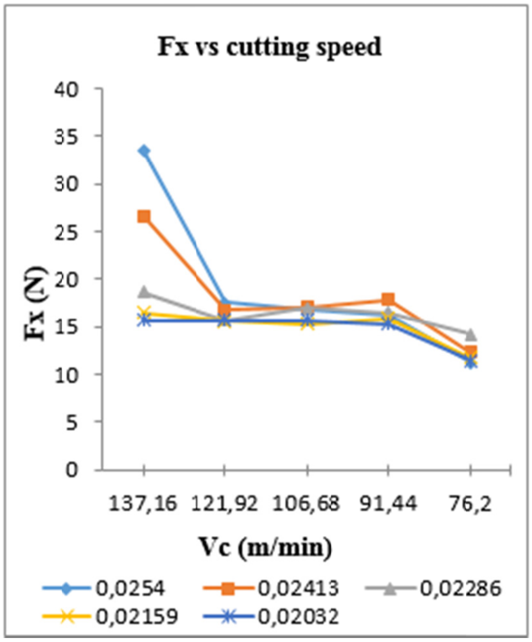

Figure 6b. Fx vs cutting speed.

3.3. Vibration

The vibration was also an important criterion for evaluating the machinability of the investigated alloy. The analysis of the vibration behaviour of the part as a function of the cutting parameters, allows us to confirm the effect of the cutting speed and the feed rates per tooth on the machining stability. The vibrations of the part along the three axes were measured during the milling process. Our study will focus on Vy, the vibration in the direction perpendicular to the tool axis, and in the same direction as the tool movement.

Figure 7 shows the influence of the cutting parameters on the vibration Vy during the milling process. It is noted that the signals of the vibration Vy are very similar to the signals of force Fx. For the cutting parameters of 137.16 mm/min, 0.0254 and 0.02413 mm/tooth, two very high peaks are observed. On the other hand, from the third peak the signal stabilizes.

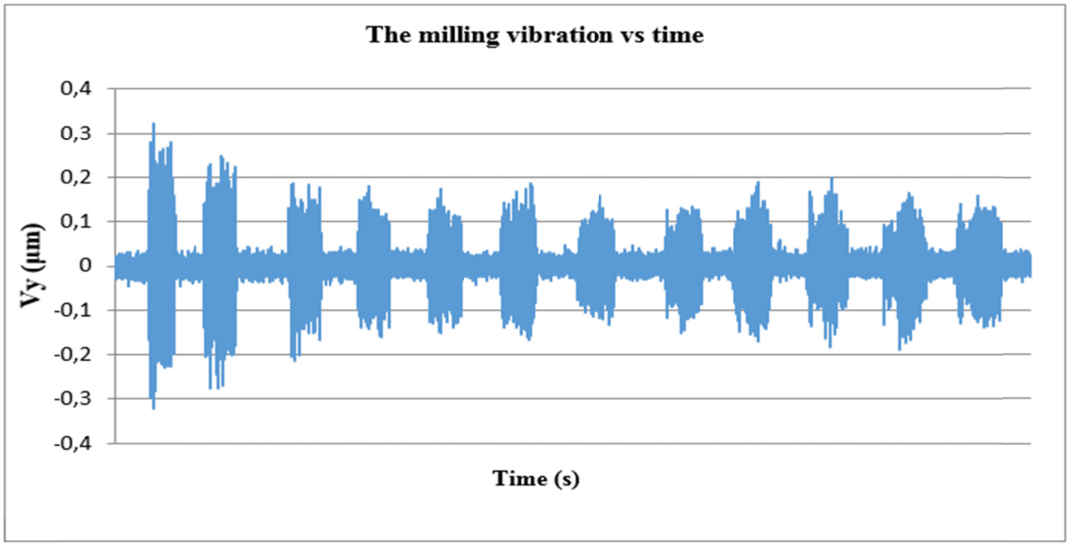

Figure 7. The milling vibration vs time.

Figure 8a shows that the vibration reaches the highest point when the machining is at 137.16 mm/min and 0.0254 mm/tooth. Then the second highest vibration point is registered at 137.16 mm/min and 0.02413 mm/tooth. The fact that the cutting speed decreases to 121.92 mm/min, the vibration also decreases and consequently the machinability of material improves.

The analysis clearly shows that the vibration stabilized between 0.15 µm and 0.36 µm of vibration for a cutting speed value of less than or equal to 121.92 mm/min, and for a feed rates range of 0.0254 to 0.02032 mm/tooth. On the other hand, the Figure 8b shows that it is possible to machine with 137.16 mm/min but with a maximum value of feed rate 0.02286 mm/tooth.

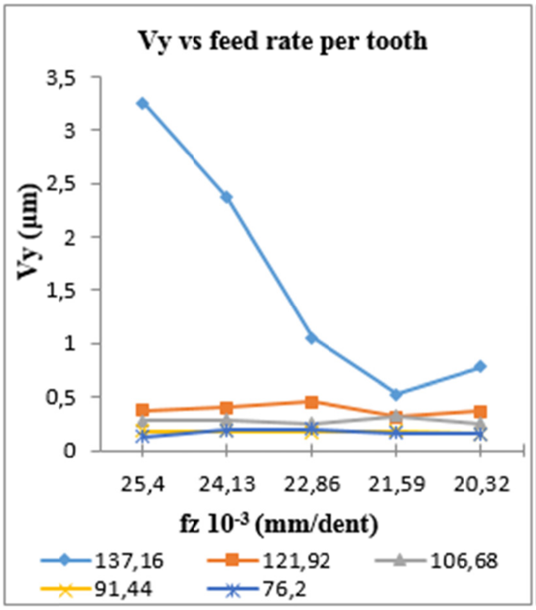

Figure 8a. Vy vs feed rates per tooth.

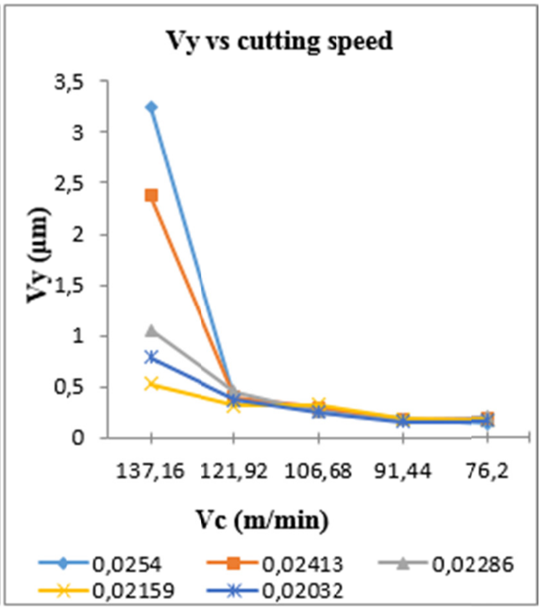

Figure 8b. Vy vs cutting speed.

4. Conclusions

This study led us to conclude that the cutting forces and the vibration increase with the cutting parameters. The signals of force and vibration are very high with the cutting speed 137.16 mm/min and 0.0254 mm/tooth. The force and vibration signals become stabilized for cutting conditions consisting of a cutting speed of 121.92 mm/min and a feed rate per tooth of 0.02286 mm/tooth. For the cutting force, depending on the axis of the displacement of the tool, the hardness of the workpiece increases continously. Above 137.16 mm/min and 0.02286 a force that varies between 18 and 33 N will be produced while for 121.92 mm/min the material can be machined with 0.0254 mm/tooth without having high cutting forces (less than 16 N). The variation of the cutting parameters greatly influences the surface roughness; in fact the increase in cutting speed increases the surface roughness.

Waves and roughness spikes were observed on the machined surfaces, they were caused by the vibration generated because of the severe cuts parameters. To have a better roughness (around 1.5 µm), the cutting parameters must not exceed 106.68 mm/min and 0.02159 mm/tooth.

5. References

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