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MACHINING STRATEGIES IN THIN-WALLS USING SACRIFICE STRUCTURES

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Abstract. *The objective was to establish a new machining strategy in the milling of thin-walled parts, which due to their low stiffness, are more susceptible to dynamic instabilities. The aluminum alloy 7050 T7451, which due to its structural properties is widely used in the aerospace industry, was chosen for the study. A method used for the machining of thin-walled parts consists on the addition of wax or similar material, to serve as a reinforcement for the part and to favor the damping's factor during the milling process. Another approach is to select strategies and parameters that minimize the vibration such as the use of sacrificial structures. These structures are generated during the roughing of the part and are removed after the subsequent finishing operation. In view of the foregoing, it was proposed ways of increasing the rigidity of the part by means of sacrificial structures. Experiments were carried out in machine to experimentally evaluate the strategies. For the tools adopted and the cutting parameters defined, the structure that presented the highest efficiency was the waterline structure, where the thinnest section is supported by thicker sections below as they are machined.*

Keywords: *Thin-walled milling; Structures of sacrifice; Cutting forces*

1. INTRODUCTION

The machining process is one of the most used methods for manufacturing components for the aeronautical sector. Among the machining processes, milling is one of the most versatile because of its ability to provide different geometries.

The machining of the materials is constantly accompanied by vibrations between the workpiece and the tool, mainly due to the intermittent nature of processes such as milling being aggravated in the machining of low stiffness components.

Low rigidity parts, usually thin-walled, are found in turbine components and aircraft structural parts. Conditions of low stiffness of the part are favorable to the occurrence of vibrations and in metal cutting processes, excessive vibration worsens the surface finish (POLLI, 2005). One method used for the machining of low thickness parts is the addition of wax or similar material to serve as a reinforcement for the part and to favor the damping factor during the milling process. The disadvantage of this process is the time required for the part to be prepared and for the removal of the wax, which in some cases needs to be removed by heating the part or using chemical solvents (MUNDIM, 2014).

According to Coromant (2005), the most common approaches to milling these components consider alternating tool passages on both sides of the structure in different patterns in order to minimize partial deflection due to the machining efforts. However, the dynamic behavior of the structure is not considered by these strategies. Considering the dynamic behavior, another group of approaches that can be used is to choose strategies and parameters that minimize vibrations. By virtue of this, the use of sacrificial structures is used. These structures are created during the roughing of the part and are removed in the finished. Smith et. al. (2012) argue that the geometries of sacrificial structures must be designed to reduce the consumption of part material while providing sufficient rigidity for machining.

Thin-walled parts also have the drawback of being susceptible to warpage after milling. According to Reis (2009), the warping of a mechanical component is defined as the geometric distortion when the material is subjected to a state

of imbalance of the initial or residual stresses. After warping, the piece will present a new state of equilibrium of tensions, presenting a new geometry, due to the distortion.

This work focuses on the study of machining strategies in thin-walled structures machined in Aluminum 7050 T7451. The aluminum alloys of the AA 7000 series are widely used in applications in the aerospace industry because of their mechanical properties and corrosion resistance. The weight reduction of aircraft components is a design premise. However, the geometry of the parts is limited in order to maximize rigidity and ensure stability of the manufacturing process. This work aims to reduce these limitations of geometry, which are imposed on the designer in order to increase the efficiency of the components to be manufactured.

In view of the above, were sought ways to increase the rigidity of the part being machined, through sacrificial structures, aiming to decrease the process time and to improve the surface finish.

2. METHODOLOGY

The method used consisted in selecting a representative component using the Siemens NX® software as interface and choosing sacrificial structures that increase the stiffness of the component during machining. The machining paths of these components were modeled using the defined intermediate structures, selecting cutting parameters based on recent developments on the subject and seeking to escape from resonant frequencies. A merit index was created to quantify the effectiveness of sacrificial structures. Wall milling was performed using the selected strategies were performed to experimentally evaluate the proposed strategies. During milling, was measured the cutting forces, in order to monitor dynamic instabilities during the removal of the reinforcement. The surface finish obtained by the implemented strategies was compared through surface roughness and shape deviations using an optical scanning equipment. From the analysis of the surface of the parts, the most efficient strategy was identified.

2.1 Choice of part geometry and sacrificial structures

The component consisted of a low thickness part (t) of 0.8 mm with a thin wall height (H) of 48 mm, hence a ratio (H/t) of 60. On the sides were added fillets simulating a condition usually found in real components. Figure 1 shows the geometry of the workpiece and its dimensional tolerances. The influence of the dimensions on the process variables (H/t ratio and shear force) and the positioning of the workpiece on the dynamometer (distance between holes, length and bolt diameter) were taken into consideration to define the tolerance of the part.

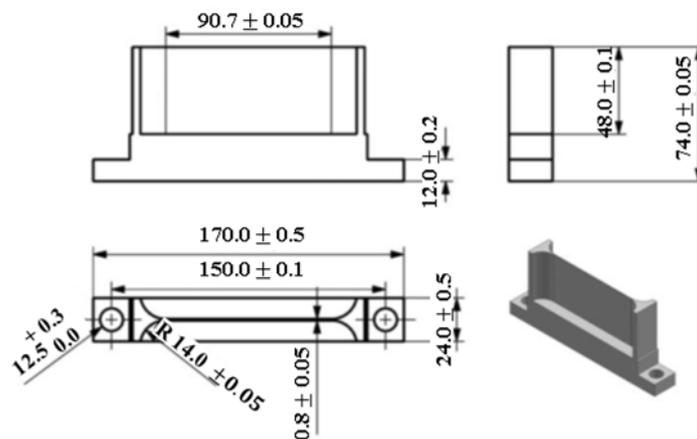


Figure 1: Geometry defined for analysis

A conceptual study was carried out on the structures of sacrifice that could be used to increase the rigidity of the part. The sacrificial structures were used in order to increase the rigidity of the part while facilitating the removal of material.

In thin-walled machining, dynamic instabilities are less damaging when the wall height quotient by its thickness (H/t) is less than 15 and can therefore, be machined from the thin wall to its final shape while this ratio is obeyed. In all the strategies adopted, before obtaining the sacrificial structures, the part was milled at a height of 10 mm, obtaining the final wall thickness (0.8 mm), therefore an H/t ratio of 12.5. In this way, the sacrificial structures have a maximum height of 38 mm. After this operation, each strategy diverges by the geometric form of the sacrificial structure and the best way to remove it.

A merit index was created to evaluate the efficiency of the sacrificial structures to be used. The merit index consisted in evaluating the average rigidity of the piece, with the addition of the sacrificial structure and the volume of the reinforcement to be removed in the finishing phase.

Finite element analysis using the NX Nastran[®] software was used to estimate the structural stiffness of the candidates to evaluate their resistance to shear forces. The Figure 2 shows the structures of sacrifices studied.

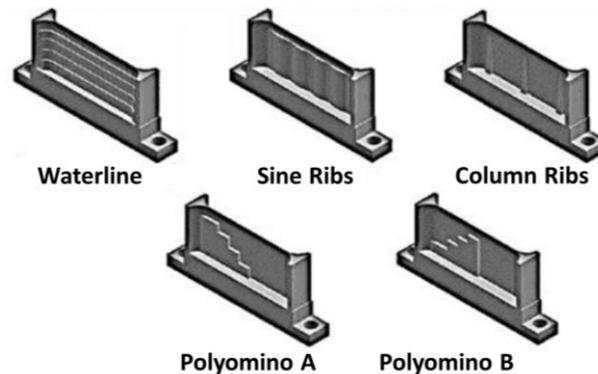


Figure 2: Structures of Sacrifice analyzed

The Waterline type sacrifice structure was inspired by the structure (Figure 3) proposed by Coromant (2005). This structure is characterized by the fact that the thinner section is supported by thicker sections below them as they are machined. Such a structure is employed in industry to increase the stiffness of slender components in the finishing phase.

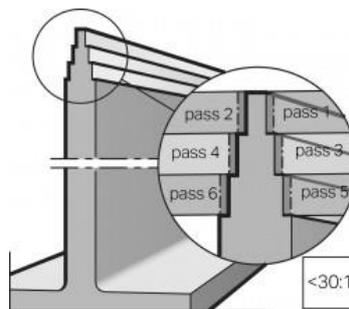


Figure 3: Waterline Sacrifice Structure
Source: SANDVIK COROMANT, 2005

In the same way, in the Sine Ribs structure, inspired by the work of Smith et. al. (2012), it was sought to remove the same level of material from both sides of the wall. The geometric shape of the sacrificial structure resembles of a waveform. Defining the shape of the structure as a Sine Ribs, the wavelength adopted was 22 mm and the wave amplitude equal to 0.8 mm, with the wave not intercepting the thin wall, with its displaced origin at 1.8 mm, with this, the peaks having 2.6 mm of thickness and the valleys 1 mm.

The column-type structure, inspired by the work of Smith et. al. (2012), consists of six rib-shaped structures, positioned, three on each side of the wall. It was sought to position the ribs in order to increase the rigidity of the part. At its base, the reinforcement is 3 mm thick and 6 mm wide with a height of 38 mm, forming a 4.5° wedge. At the most flexible point of the structure (center of the part), the ribs on both sides were positioned. For the remaining four ribs, on the side 1 the ribs were positioned at the edges, close to the fillets, while on the opposite side, each rib was positioned 15 mm away from the rib located at the center of the piece.

The Polyomino A structure consists of steps, with its origin located near one of the fillets on the side 1 of the thin wall, while on the other side, the origin of the steps starts in the opposite fillet, making the sides antisymmetric with respect to the thin wall. This strategy was considered because due to the rigidity of the part to be higher on the fillets, this it allows greater removal of material in this region. The steps are 3 mm thick and 10 mm long with their respective heights of 10, 20, 30 and 38 mm. In the thinning operation, material is removed from the part until the final thickness (0.8 mm) is obtained in the region close to the fillets that do not have the reinforcing material. As the structure is antisymmetric, there is an excess of material, where the removal occurred, that increases the rigidity of the part. After thinning, with the attainment of the sacrifice structure, the reinforcement was removed with alternating passes throughout the part until the final geometry was obtained.

Considering the stiffness of the part being higher near the fillets, the behavior of the Polyomino structure was investigated with the relative position of the inverted steps, structure called Polyomino B. Therefore, the highest step is located in the most flexible region of the part (center). Material removal was performed in a manner analogous to the previous strategy.

The volumes of the sacrificial structures were obtained by the difference between the volume of the part with the addition of the reinforcement and the volume of the part after finishing.

In order to calculate the merit index, it was considered that the part should have sufficient stiffness to withstand the cutting forces while having a low volume of material in the finishing phase. The merit index was created according to equation (1), seeking to evaluate the ratio between the magnitude to be maximized (rigidity) and the quantity to be minimized (volume to be removed).

$$MI = (\text{stiffness}/\text{volume}) * 1000 \quad (1)$$

Table 1 shows the calculated merit index for the sacrificial structures. The highest merit indices were observed in the Column Ribs and Polyomino B structures.

Table 1: Merit Index of Sacrifice Structures

Sacrifice structure	Volume [mm ³]	Stiffness	MI
Waterline	28707.2	172.27	6.00
Sine Ribs	14383.3	235.74	16.39
Column Ribs	2160.0	62.50	28.93
Polyomino A	8454.2	34.13	4.04
Polyomino B	7444.4	212.81	28.59

From the merit index created, were tested the structures of sacrifices with higher indices of merit (Column Ribs and Polyomino B) comparing its efficiency with the Waterline structure (traditional strategy adopted in the industry).

2.2 Parameter selection and cutting tools

A ROMI[®] machining center model D 800 was used for the milling of the components. The cutting parameters (Tab. 2) were defined aiming at a balance between surface quality and process time. In order to evaluate the efficiency of the sacrificial structures, the cutting parameters were kept constant throughout the process and for all the specimens, with only the geometry of the sacrifice structure to be removed being varied, only the radial depth of cut became dependent on the sacrificial structure to be used.

Table 2: Process parameters

Roughing		
Milling cutter (Sandvik)	Diameter [mm]	25
	Number of teeth	2
	Tool holder code	R390-025A25L-17L
	Coding of the interchangeable insert	R390-17 04 04M-KM H13A
Cutting parameters	Cut depth [mm]	3
	Feed per tooth [mm/tooth]	0.1
	Cutting speed [m/min]	750
Finishing		
Milling cutter (Sandvik)	Diameter [mm]	20
	Number of teeth	3
	Tool holder code	E20-A20-SS-120
	Interchangeable encoding	316-20SM345-20000A H10F
Cutting parameters	Cut depth [mm]	2
	Feed per tooth [mm/tooth]	0.05
	Cutting speed [m/min]	750

The precision of the cutting edge of the tool directly affects the surface finish and tool life. The beating on the tool causes one tooth to remove more material than the others, consequently causing dimensional deviation and unwanted vibration. For this reason, the beating of the machine-secured tools was verified as shown in Fig. 4. A dial indicator was coupled to a magnetic base that was attached to the machine. Approaching the tool from the tip of the instrument, and pressing it until it deflects 0.01 mm. By resetting the dial indicator in this position, and rotating the tool, it was possible to analyze the beating level.

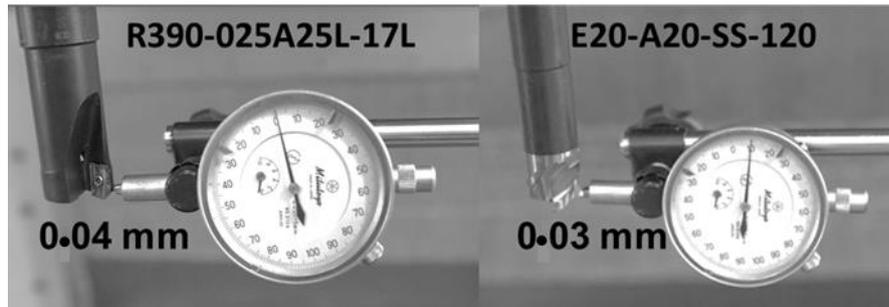


Figure 4: Beating between teeth

2.3 Acquisition of cutting forces and data processing

The components of the machining force were obtained through a Kistler 9265 B dynamometer. For each milling step, a data acquisition file was created in the software coupled to the equipment (Dynoware Type 2825 D-02). All measurements were taken in a measuring range of 800 N, chosen based on the milling of the first test piece, with an acquisition rate of 8000 Hz (highest acquisition rate of the equipment) in order to make the measurement more precise.

For all the conditions tested, strength signals were acquired for stability evaluation. Figure 5 shows the fixation of the specimen on the dynamometer fixed to the work table and the direction of the force components measured along the milling.

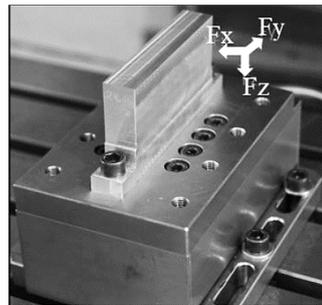


Figure 5: Assembling the test piece in the dynamometer

Due to the position in which the workpiece was attached to the machine, the most significant component of the machining force was oriented in X direction, since this is the direction of less rigidity of the machined structures (fact demonstrated by the amplitude of the forces observed in the test). Accordingly, to analyze the process stability, the component used was the force component in that direction.

The data treatment was done to verify the stability of the structure through the analysis of vibration frequencies. The procedure consisted in filtering and treating the time signal with fast Fourier transform (FFT), obtaining the frequency spectrum of the signal.

2.4 Inspection

In this step, the process variables were compared and the actual model finished (dimensions and surface roughness) with the expected values. In the machining of the component, a shoulder was created in one of the faces of the part in order to assist in the identification of the specimens.

The inspection was performed in a Coordinate Measuring Machine (Mitutoyo® model Beyond Crysta C 7106) with the objective of verifying the flatness and parallelism of the thin wall. In addition, in an optical scanning equipment (Cyber model CT 100) the surface finish and the face profile were analysed. The area inspected by the optical scanning equipment was limited to the region defined as the most unstable of the specimen (central region, upper part of the specimen), using a measuring area of 700 mm² (Fig. 6). After scanning, the roughness parameters (Ra, Rz and Rt) were measured in six regions of the inspected area, taking the mean of the results as the value. These parameters were chosen in order to verify the roughness profiles of the parts and the existence of surface defects due to vibrations of the machine-tool-part assembly. It was also evaluated the profile of the face of the part, in order to obtain shape variations.

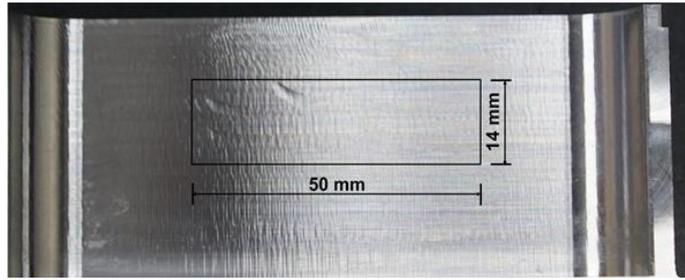


Figure 6: Inspection area

To evaluate the defects correlated to shape variations in the part, using the optical profilometer, a map was generated in the form of level curves, which correlated the difference of removal of material in different regions of the face of the thin wall for each analysis.

3. RESULTS AND DISCUSSIONS

Figure 7 shows the manufacturing of the part from the removal of the Waterline structure. Throughout the process, it was found that the structure had sufficient stiffness to withstand the shear forces, with acceptable texture levels.

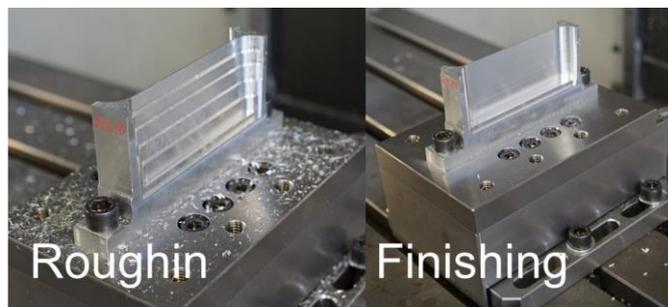


Figure 7: Fabrication of the thin wall from the Waterline sacrificial structure

Figure 8 shown the cutting forces in the time domain and frequency domain of the step structure. From the frequency spectrum, it was found that the frequencies reached correspond to the frequencies of passage of the teeth, their harmonics and instabilities throughout the finishing phase. From Fig. 8, it was noted that dynamic instability occurred generating higher amplitudes in the force signal at frequencies near 1800 Hz, corresponding to a resonant condition. However, the vibration modes of the part with the addition of the sacrificial structure do not meet the tool during milling, without compromising the surface quality of the part with the resonant conditions.

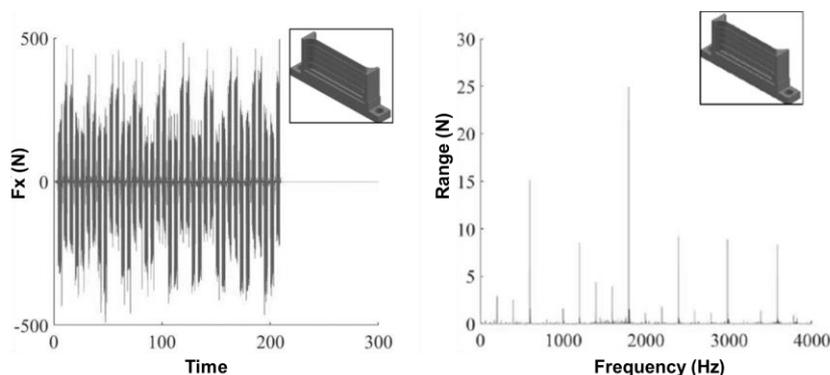


Figure 8: Cutting forces in Waterline structure

Figure 9 shows the geometric profile of the thin wall after the removal of the Waterline structure. In the machining of the Waterline type structure a perceived surface defect occurred at the end of the cut, consisting of a horizontal trace in the direction of the feed, possibly caused by the contact between tool and part, outside the programmed cutting region. From the modal simulation, it was noticed that at a frequency of excitation near 2200 Hz and 3080 Hz, a

vibrating mode was given which is attributed to the type of fault that is identified in the part at its lower part. This mark can be a consequence of the way of vibrating in the last machining passes, making the tool, with a cut height of 11 mm, touch the face of the part, causing the marks presented. The observed defect does not compromise the quality of the component. The highest roughness values were observed on the face opposite from the shoulder with $R_a = 0.81 \pm 0.13 \mu\text{m}$, $R_z = 6.33 \pm 0.66 \mu\text{m}$ and $R_t = 6.26 \pm 1.47 \mu\text{m}$.

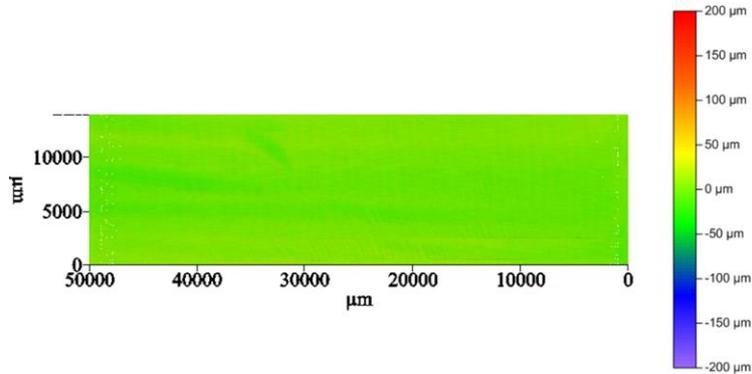


Figure 9: Topographic profile of Waterline structure after milling

Figure 10 shows the manufacturing of the part from the removal of the Column Ribs structure. Throughout the process, it was found that the structure presented sufficient stiffness to resist the shearing forces in the thinning operation, without presenting superficial defects resulting from this process. In the finishing operation (removal of the reinforcement), dynamic instabilities were observed at the beginning of the removal to a height of 25 mm depth, which resulted in superficial defects due to vibration and fine-wall contact with the tool.

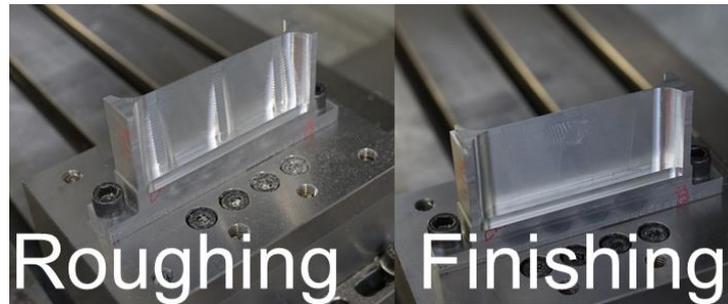


Figure 10: Fabrication of the thin wall from the Column Ribs sacrificial structure

The instability was correlated to the fact that certain harmonics of the excitation force (corresponding to the harmonics of the pitch frequency of the teeth) coincide with the natural frequencies of the part along the cut. In Fig. 11, the shear forces and the frequency spectrum are shown along the cut-off time of the Column Ribs structure. From this analysis, it was noticed that the instability predominated at the beginning of the cut with frequencies near 2000 and 3600 Hz, having a high amplitude at the beginning of the cut at frequencies close to 3600 Hz.

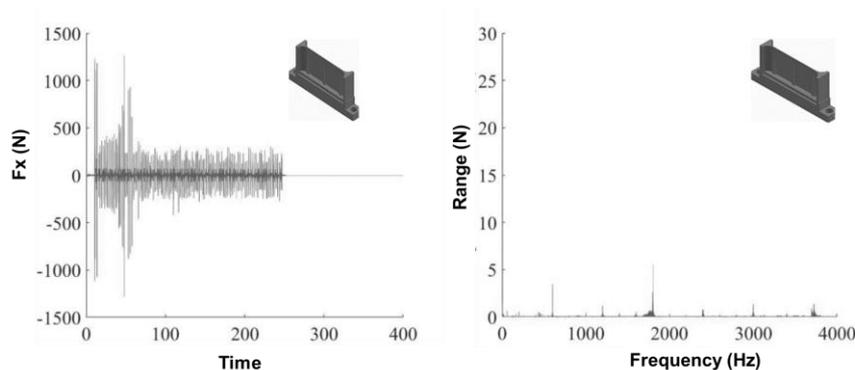


Figure 11: Cutting Forces of Column Ribs

In the part produced from the removal of the Column Ribs structure, it was observed that the highest roughness was obtained on the opposite side from the shoulder, with $Ra = 4.0 \pm 1.73 \mu\text{m}$, $Rz = 35.33 \pm 9.9 \mu\text{m}$ and $Rt = 33.25 \pm 2.45 \mu\text{m}$. From this analysis, it was noted that the deviation from the mean is extremely high, indicative of localized faults due to instability in some regions during cutting. Figure 12 shows the relief shown by the part after removal of the Column Ribs type sacrificial structure. From the Fig. 12, it was noticed the difference of form generated by the milling and points of defects related to instabilities along the cut.

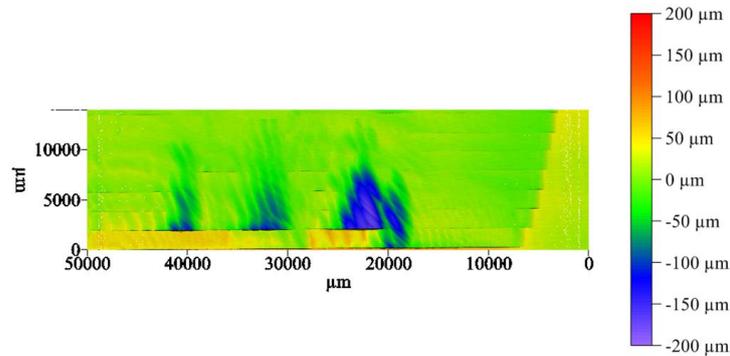


Figure 12: Topographic profile of Column Ribs structure after milling

Figure 13 shows the fabrication of the part from the removal of the Polyomino B structure. Throughout the process, it was noticed that the structure did not present sufficient stiffness to resist the cutting forces in the thinning operation, presenting surface defects correlated with the deflection of the part. In the finishing operation (removal of the reinforcement), dynamic instabilities were observed at the beginning of the removal up to a height of 30 mm depth. This instability may be a consequence of the resonance of the system.

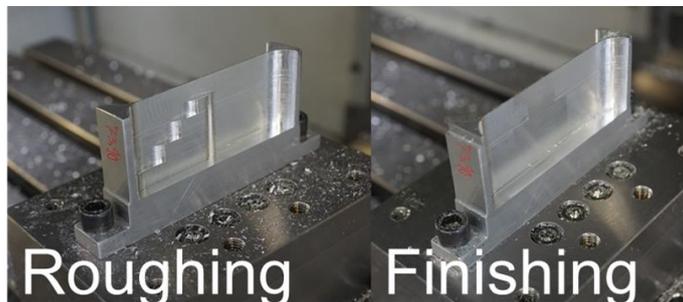


Figure 13: Fabrication of the thin wall from the Polyomino B sacrificial structure

Figure 14 shows the shear forces in the time domain and in the frequency domain in the removal of the Polyomino B structure. From the frequency spectrum, it can be seen that the greatest instabilities occur at the beginning of the cut at frequencies near 1800 Hz.

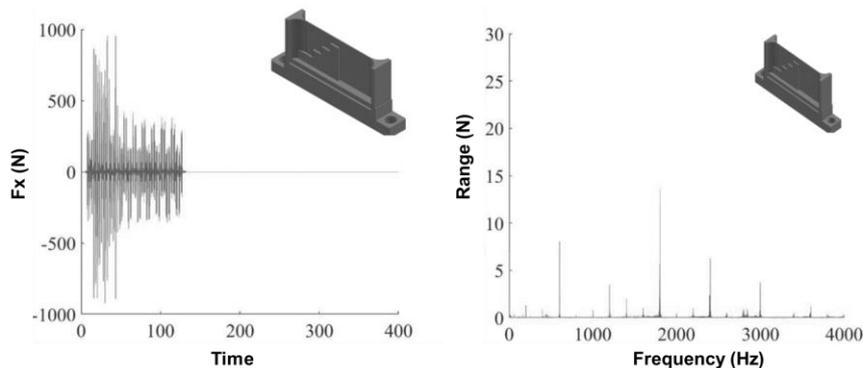


Figure 14: Cutting forces of Polyomino B structure

In a similar manner to the previous structure, the Polyomino B structure did not have sufficient stiffness to withstand the shear forces. This fact was proven when the thickness of the thin wall was compared in parts supported by the reinforcement and in regions where the reinforcement was not present. It was observed that the highest roughness was obtained on the opposite side from the shoulder, with $R_a = 11.67 \pm 1.03 \mu\text{m}$, $R_z = 36.67 \pm 2.39 \mu\text{m}$ and $R_t = 37.46 \pm 5.45 \mu\text{m}$. A high value for the maximum valley depth (R_v), attributed to the shape deviation shown in the workpiece finish, was also noted. Figure 15 shows the geometric profile of the part after the removal of the structure Polyomino B. In a similar way, the level differences related to shape errors along the milling and defects related to instabilities along the cut are visualized.

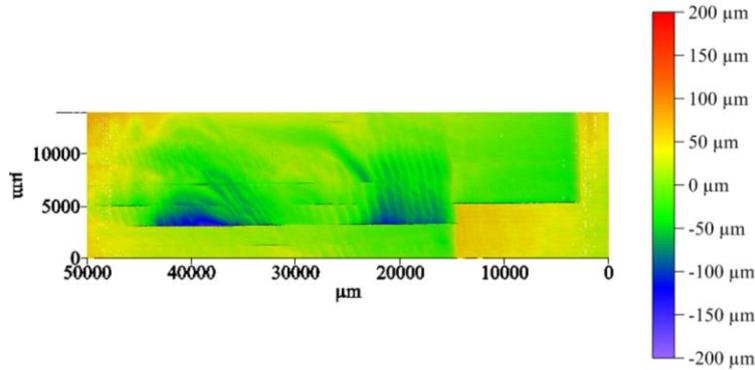


Figure 15: Topographic profile of Polyomino B structure after milling

For all the machining operations, the vertical roughness parameters (R_a , R_z and R_t) were measured on the two faces of the part using the shoulder in one of the faces to assist in the identification of the analyzed region. The parameters correspond to the roughness average collected in six different regions of the area analyzed by the optical scanning equipment, with the standard error related to the mean in a 95% confidence interval. In order to compare the surface roughness of the strategies performed, Fig. 16 graphically shows the vertical roughness parameters evaluated in the face of the part that presented the highest values.

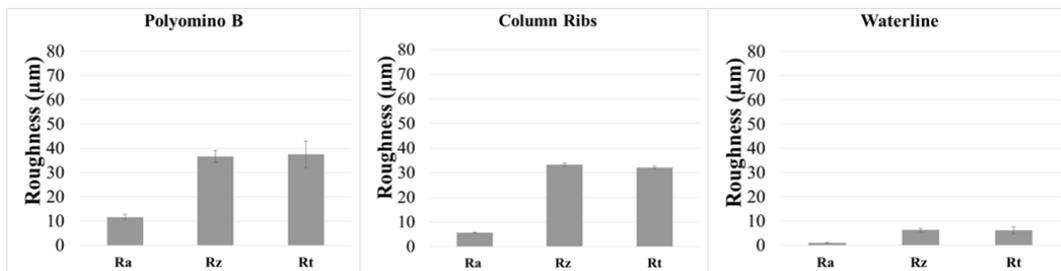


Figure 16: Vertical roughness parameters for the analyzed structures

The waves consist of surface irregularities or geometric errors whose spacings are on a larger dimensional scale than irregularities considered as roughness. Figure 17 shows the profile of the waves along the central region of the parts with the proposed strategies. From Fig. 17 it is possible to infer about the more regular behavior of the part with the Waterline sacrificial structure.

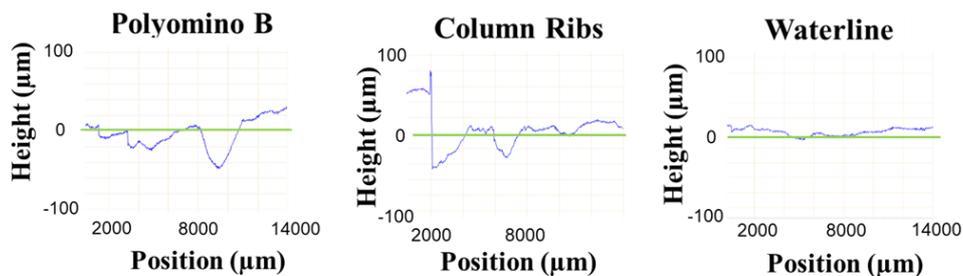


Figure 17: Profile of roughness along the central section

4. CONCLUSIONS

The Waterline and Column Ribs structures showed ability to withstand cutting efforts in roughing operations, and no surface markings were observed due to this operation. In the finishing operations, the Column Ribs and Polyomino B structures showed typical surface defects of deformations and instabilities along the cut.

These instabilities can be controlled by altering the frequency of tooth passage, through changes in the cutting parameters, seeking to escape from resonant conditions.

The Waterline structure was the selected structure that presented better surface finish, with the cutting parameters presented in the work, obtaining low vertical values of roughness. This occurrence can be attributed to the fact that its stiffness is superior than at the other reinforcements analyzed and the geometric form of the structure minimizes the amplitude of the modes of vibration. Another advantage of this structure is related to its symmetry, making it possible to predict the behavior of the part along the milling.

Therefore, for the tools adopted and the cutting parameters defined, the structure that presented the greatest efficiency in terms of surface finish was the Waterline structure.

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