DRILL-THREADING PROCESS PERFORMANCE WHEN MACHINING AISI Al-Si-Cu$_4$ ALLOY: DYNAMIC BEHAVIOUR ANALYSES USING MATHEMATICAL AND EXPERIMENTAL METHODS

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Abstract. *Conventional threading operations involves two distinct machining processes: drilling followed by threading. To make the thread machining, just after concluded the drilling step, some time need to be spendingin in order to change the tools or for move the work piece to another machine. This paper presents an analysis of the combined process (drilling followed by threading) using a single tool for both operations. A dynamic model of the machining centre was developed and experimental measurements using accelerometers were caried out. In addition to this, a numerical model based on finite element method (FEM) was developed and the operating deflection shapes (ODS) method was also applied. This FEM model allowed us to determine the displacements of the machining centre. Furthermore, the fixture system was optimised using experimental data and the mathematic methods (FEM and ODS). The results showed that there are excellent correlation between the dynamic stability of the machining centre-tool holder and the tool life.*

Keywords*: Tap-milling, Numerical methods, FEM, ODS, AlSiCu$_4$ alloy.*

1. INTRODUCTION

Drilling and tapping processes are commonly and widely applied in metal cutting operations. According to Ertunc and Oysu (2004), drilling process represents nearly 40% of all the metal removal procedures in the aerospace industry. It is possible to measure the importance of these processes, taking into account the study of Furness et al. (1999). They reported that the drilling process was responsible for up to 50% of all machining in the U.S.A. in the end of 1990s. If in one hand the tapping and drilling processes are widely applied, on the other hand they are difficult to control. The full control in these processes is challenging due to workpiece materials, depths and tolerances of the final piece and others details that difficult the machining processes. If an error occurs while selecting or controlling the machining parameters and the machine and tool stiffness, these operations can cause irreparable damages in the workpiece that can result on its discharge. Undoubtedly this would represent significant losses because the tapping process is commonly applied in the final step of the machining process. Therefore, tool and cutting conditions must have a standard of excellent reliability.

In the conventional method, the machining of inner thread involves two different operations: firstly the drill is responsible for machining the hole and then, the taper machines the thread. As a result of this, the conventional method requires the use of two different tools (drill and taper) resulting in expending time (idle time) for changing the tools (if both operations can be carried out in the same machine) or even in moving the workpiece to another machine.

Nowadays, the majority of the machines in line of serial production are equipped with automatic tool change. The tool change spend approximately five seconds in mean and this time could seem insignificant. Nevertheless, when it comes to machining thousands of workpieces, this time becomes relevant and can reduce drastically the machining efficiency. To avoid the excessive tool change quantity, today it is available on market a new technology of manufacturing tools and machines. In the conventional procedure the whole operation is carried out in two machines (each one is responsible for one part of the workpiece machining procedure). In other words, one machine makes the hole and second one manufactures the thread. The time necessary for changing the tools is eliminated by using this two-machine configuration. But, the installation of the workpiece in each machine continues to spend time. This procedure could be automated by using robots in a manufacturing cell configuration, however it would continue to spend time and new investments are required in the automation of the operation. In addition to this, in the conventional method it is necessary to use two different tools (drill and taper). Each one has its own cutting parameters (e.g.: cutting speed, feed rate, and depth of cut) and cutting fluids. These different tool characteristics mean different tool behaviors and, consequently, different tool life stages for the same quantity of produced workpieces. Due to this, it is extremely hard to manage this manufacturing process.

A promising alternative method is the use of an especial tool identified as a tap mill tool (Fig. 1). It makes the thread of a raw workpiece, in other words without the previous hole. Thus, this inner thread machining technology eliminates the need of tool change and the use of two machines. The drilling and tapping operation are realized by same tool in the same machine.

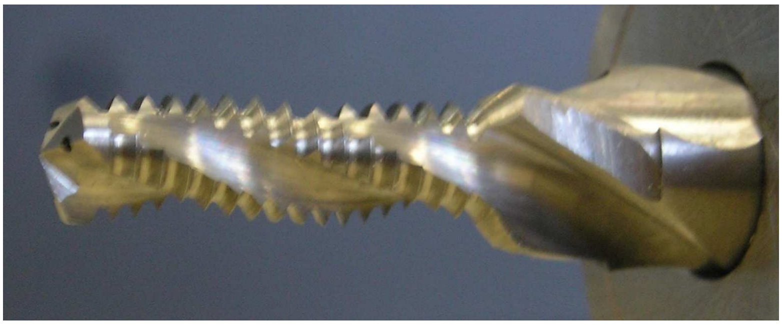


Figure 1. Tap mill tool (diameter of 5 mm and length of 65 mm).

Figure 2 shows the entire process. It starts when the tool approximates to the workpiece. In the following two steps (a and b), the tool acts as a drill, feeding against the workpiece and machining the hole – blind or through. At the end of the course, the chamfer is also made (one may observe that the tool presented in Fig. 1 has a reamer between the drill body and the shank). In the third step (c), the tool returns $^{1}/_{3}$ of the pitch, this way the drilling is complete. The threading process is started in the fourth step (d), in which the tool is moved from the centre line and approaches the hole wall with two relative movements: rotation and translation. In the following step (e), the ridges are milled with the same movements. The sixth step (f) occurs inversely to the fourth, with the tool returning to the centre line. In the last step (g), the tool is set back to the original position. Obviously, this technology eliminates the necessity to change tools or machines. Also, the tool specified to machine an M6 thread is capable to make an M7. Another operational advantage is the fact that the inversion of the spindle rotation is not necessary anymore (in the traditional methods, the taper feeds against the workpiece clockwise and returns anti-clockwise in synchronous movements, and the spindle have to be stopped before the reversion. what causes natural machine wears).

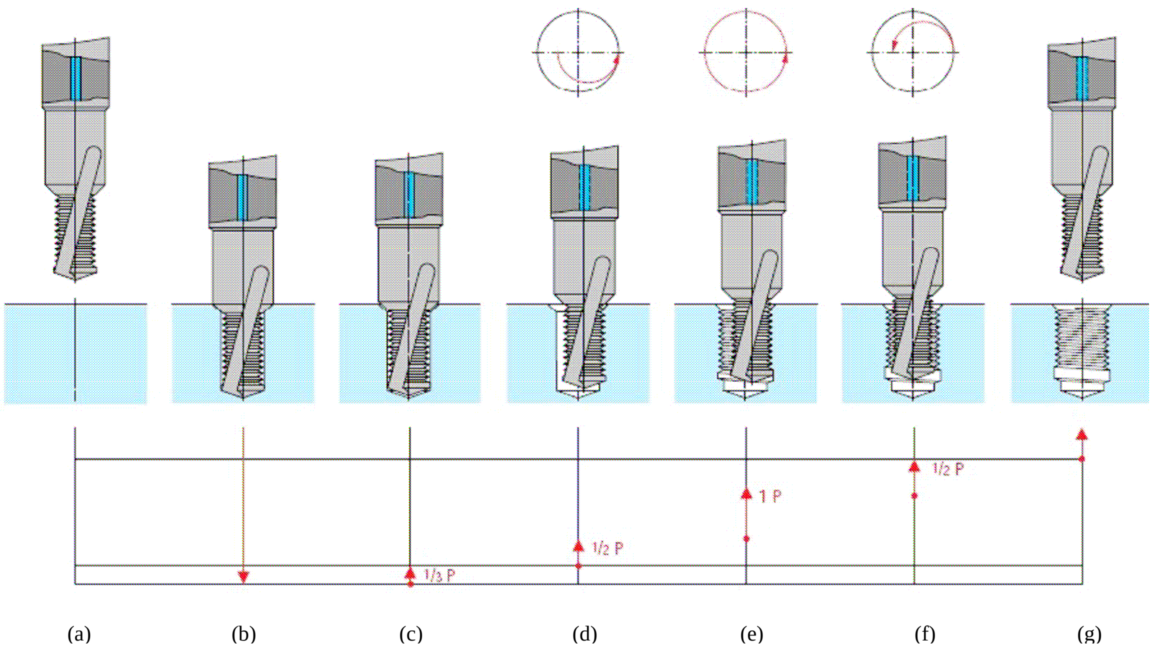


Figure 2. Tap Milling scheme (Gurgel, 2006).

The use of monitoring techniques is extremely important during the machining process because it provides information about the behavior of the whole process. According to Jantunen (2002) the wide use of automated production is possible only if there is a method available for tool wear monitoring and tool breakage detection. Tool wear influences the quality of the surface finish and the dimensions of the parts that are manufactured. Due to this, the economical tool life cannot be benefited without a reliable tool wear monitoring system. Today, tool changes are defined based on conservative estimations of tool life which does not take into account sudden failures and causes an unnecessarily high quantity of changes. This conservative estimation for tool life does not consider the tool full lifetime and, consequently, valuable production time is lost.

Therefore, the main objectives of this study are the evaluation of the machining evolution, the parameters related to the spindle and the dynamic stability of the process, the quality of the thread profile machined according to the dimensional tolerance, and the determination of the displacements of the machine centre based on the operating deflection shapes method (ODS). In addition to this, the fixture system was optimized based on mathematic methods (FEM and ODS). In the next section we present a short review of ODS method and equations. Then the methodology applied during the research is described. The fourth section shows the results obtained and the last section, the conclusions.

2. ODS - Operating Deflection Shapes

Vibration problems in structures, vehicles or operating machinery often involve the excitation of structural resonances, or modes of vibration. Many types of machinery and equipment can encounter severe resonance related vibration problems during operation. In order to diagnose these problems, an animated display of the machine, vehicle or structure's operating deflection shapes is often useful. In most cases, structural responses at or near a resonant (modal) frequency are "dominated" by the mode, and the ODS closely approximates the mode shape. Due to this, Richardson (1997) affirms that ODS and modes of vibration are closely related.

Experimental modal testing (performing a modal survey) is usually done under controlled stationary (non-time varying) conditions, using one or more exciters. Furthermore, the excitation forces and their corresponding responses are simultaneously measured. In many cases, especially with vehicles and operating equipment, the measurement signals may be non-stationary (time varying) and the excitation forces cannot be measured. In these cases, the use of a controlled sine force to excite the structure is common. Due to this, different post-processing is required aiming to display ODS's from a set of measurements. In order to obtain the modes of vibration, the excitation force is applied on a specific place that is not a vibration mode node (the structure point that has no displacements) and the excitation frequency should be close to one of the resonance frequencies. In this situation, the ODS presents one vibration mode and shows the related structure displacement.

ODS applications are usually divided into three categories: visualization of the vibration pattern of a structure under given operating conditions (Pai and Young, 2001), structural fault detection (Waldron et al., 2002), and modal parameters acquisition without the need of an experimental modal analysis (Margolis and T. Shim, 2001, Parloo et al., 2002, and Han and Feeny, 2003). ODS analysis can provide significant trouble-shooting and analysis advantages for vehicle manufacturers at much less expense than other methods, such as modal analysis. As advantages it is possible to cite: (a) The measurement of force inputs are not required for ODS, but must be measured to perform modal analysis (an expensive additional task); (b) ODS algorithms are straightforward and easy to execute, providing very quickly, an overall view of structural problem areas; and (c) ODS is not limited by a basic mathematical model.

Of course, modal analysis has its advantages as well, and one may elect to use one method to complement the other. The experimentally acquired vibration data are frequently displayed on time or frequency domain charts. Unfortunately, these representations produce a poor visualization of the correlation that exists between all structure acquisition points. As a result of this, the use of 3-D animation procedures is very common in ODS studies. In this work, the ODS tool was implemented together with a FEM tool, following the static equilibrium condition for each time step t_i as it is written on Eq. (1):

$$[K]\{u(t_i)\} = \{r(t_i)\},\ for\ i = 1,2,...,T \tag{1}$$

Where: K is the structural stiffness matrix; $u(t_i)$ is the structural displacement vector; $r(t_i)$ is the instantaneous force vector; and i is the i-th time step.

The instantaneous force and displacements vectors may be written as:

$$[R] = \begin{bmatrix} r_1(t_1) & r_1(t_2) & \cdots & r_1(t_T) \\ r_2(t_1) & r_2(t_2) & \cdots & r_2(t_T) \\ \vdots & \vdots & \vdots & \vdots \\ r_n(t_1) & r_n(t_2) & \cdots & r_n(t_T) \end{bmatrix} \tag{2}$$

$$[U] = \begin{bmatrix} u_1(t_1) & u_1(t_2) & \cdots & u_1(t_T) \\ u_2(t_1) & u_2(t_2) & \cdots & u_2(t_T) \\ \vdots & \vdots & \vdots & \vdots \\ u_n(t_1) & u_n(t_2) & \cdots & u_n(t_T) \end{bmatrix} \quad (3)$$

Where: n is the total acquisition point quantity.

Re-writing Eq. (1):

$$[K][U] = [R] \quad (4)$$

The degrees of freedom that matches the acquisition points present known displacements $[U]_b$, where: $[U]_b = [\{u(t_1)\}_b \quad \{u(t_2)\}_b \quad \cdots \quad \{u(t_T)\}_b]$ and T is the total quantity of time steps. The unknown displacements are represented by $[U]_a$, where $[U]_a = [\{u(t_1)\}_a \quad \{u(t_2)\}_a \quad \cdots \quad \{u(t_T)\}_a]$. The equilibrium equations can be divided as follows:

$$\begin{bmatrix} [K]_{aa} & [K]_{ab} \\ [K]_{ba} & [K]_{bb} \end{bmatrix} \begin{bmatrix} [U]_a \\ [U]_b \end{bmatrix} = \begin{bmatrix} [R]_a \\ [R]_b \end{bmatrix} \quad (5)$$

Considering that all external forces $[R]_a$ are null:

$$\begin{bmatrix} [K]_{aa} & [K]_{ab} \\ [K]_{ba} & [K]_{bb} \end{bmatrix} \begin{bmatrix} [U]_a \\ [U]_b \end{bmatrix} = \begin{bmatrix} [0] \\ [R]_b \end{bmatrix} \quad (6)$$

Taking the first equation set:

$$[K]_{aa}[U]_a + [K]_{ab}[U]_b = [0] \quad (7)$$

So:

$$[K]_{aa}[U]_a = -[K]_{ab}[U]_b = [\bar{R}]_a \quad (8)$$

The displacement matrix $[U]_a$ is calculated by an algorithm for static solution case (Saturnino, 2004).

3. METHODOLOGY

The work material was the aluminum alloy, ISO $AlSiCu_4$, which is largely applied on engine heads and sample bars that are manufactured by the cast process. Due to this, a micrographic analysis and hardness tests were carried out to observe the microstructure of the alloy and to obtain its properties. The knowledge of these properties is essential in order to obtain a better performance of the machining process. All tests were realized in a CNC machining centre, that has a 10,000rpm maximum rotation spindle, 12kW effective power, and cutting fluid flowing through the centre of the tool. Aiming to improve the stability of the tool we used a fixture system composed by a hydraulic chuck.

The cutting fluid is a mineral oil, soluble in water at 8% concentration, which was monitored daily by optic refractometer. The tap mill material was a K ISO grade uncoated cemented carbide. This tool is able to machine M6 and M7diameters and it has a 28º helix angle, 140º tip angle, 1mm thread pitch, maximum depth of 2.5xDiameter and three cutting edges.

The cutting conditions were chosen to avoid the natural frequencies and the introduction of other external phenomena that could influence the machining process. Thus, a rotation of 8,000 rpm was selected, that means a cutting speed of 150.8m/min and the feed rate of drilling is of 0.04mm/rev.z, where in z is the number of cutting edges. The tapping feed rate is of 0.05mm/rev.z and the depth of the hole is of 17.6mm.

In this evaluation was considered that the end of tool life occurs when the maximum flank wear reaches 0.05mm. The tool was measured using an optical microscope. Other way to affirm that the tool reached the end of life is a catastrophic fail. This 0.05mm threshold value was chosen taking into account a end of life conservative estimation due to the tool high costs and the required workpiece quality.

The dynamic stability of the process was evaluated by measuring the acceleration of the system (we installed accelerometers in the work material, near to the cutting tool -fixed part on the spindle and in the table of the machining centre). Then, the dynamics of the machining process can be represented in the frequency domain by calculating the fast Fourier transform (FFT) of the data. Aiming to evaluate the dynamic stability of the set composed by workpiece, tool and machining centre table, the ODS tool developed by Saturnino (2004) was used (Fig.3).

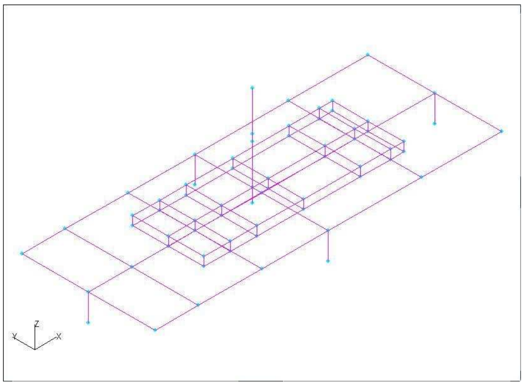


Figure 3. ODS model.

Aiming to optimise the work material fixture on the machine centre, three fixture configurations were evaluated using the FEM (Fig.4). The evaluation of the workpiece (threaded holes) was done using a geometric standard called calibrator gauge. This device is used to calibrate holes M6 x 1.0 with work quality 6H, thus its side not step correspond a limit of 6.0080 ± 0.00075mm; while its side new step is of 6.0015 ± 0.00075mm and the side damaged step is of 5.9990mm.

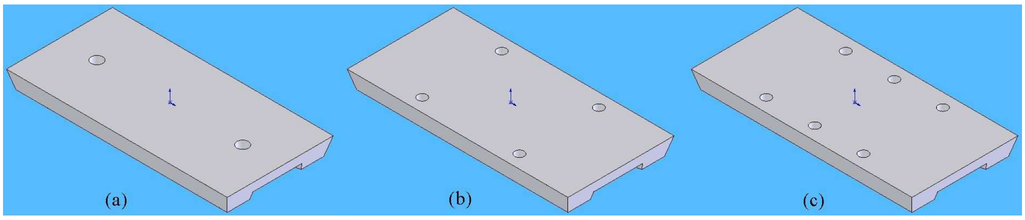
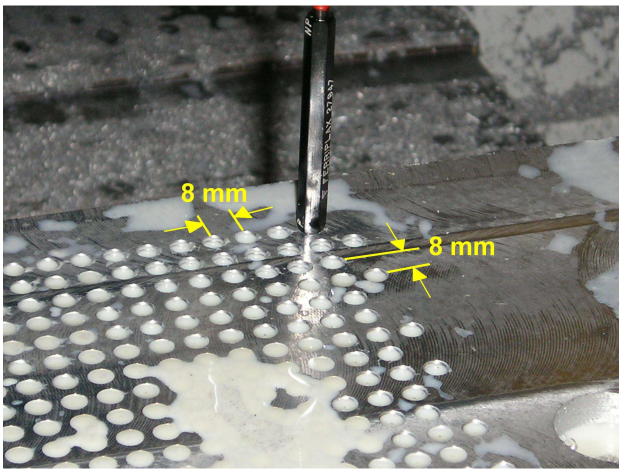
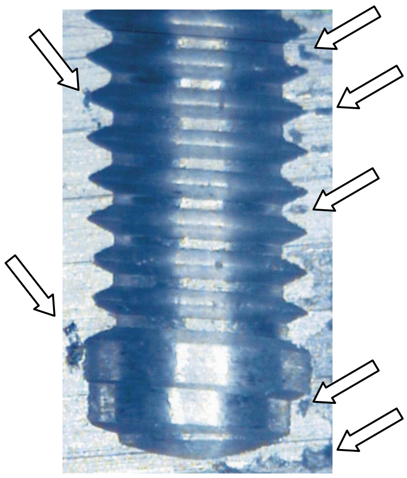


Figure 4. Models of fixture systems for FEM evaluation using: a) 2; b) 4; and c) 6 bolts.

4. RESULTS AND DISCUSSION

General view of the work material during the geometric evaluation using a thread calibration gauge is showed in Fig. 5-a. The distance between centres of the holes was adjusted on CNC program in 8mm.





(a) (b)

Figure 5. General view of the work material after machined some threaded holes (a) and transverse section of the machined work-piece after 5,691 threads holes (b). The details of the material porous are indicated by arrows.

Fig. 5-b shows the transverse section of the machined work material after 5,691 threads holes. Observing this figure one may observe the presence of some porous around the transverse section, that is attributed to a defects originated when the casting process took place. Due to the high sensitivity of the threading process, those porous are extremely undesirable for its dynamic behavior and consequently can promote the catastrophic failure of the tool if vibration levels reach some critical values. On the other hand, the high chemical affinity between the tool material (cemented carbide) and work material (Al-Si-Cu_4) promotes adhesion on the rake face and clearance face, as can be observed in Fig. 6, after machined 5,691 threaded holes. In the Fig. 6-a, the flank face is highlighted and low flank wear is observed. Figure 6-b shows the rake face and no crater wear can be observed. Then, based on the analysis of Fig. 6, was concluded that negligible wear was observed and the tool geometry remains like a fresh tool. However, the presence of adhered material should alter the tool geometry hence compromise the dynamic stability of the process.

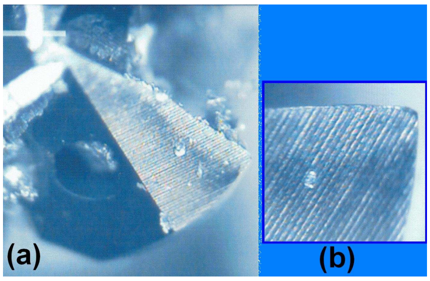
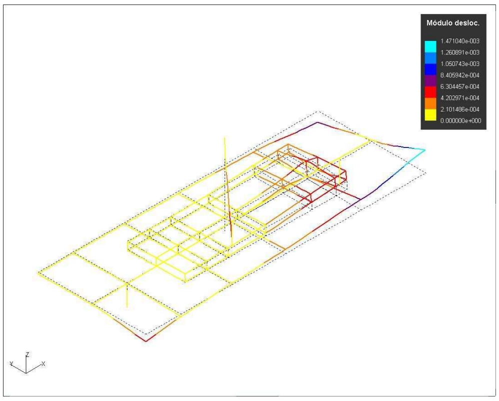


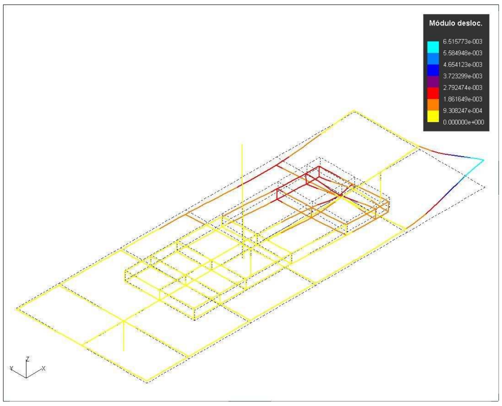
Figure 6. View of the tool after 5,691 thread holes were machined (a) and detail of the tool rake face (b).

3.1. Optimization of the displacements and fixture system by ODS

Figure 7 shows the displacement for the work material base, on the machine tool, when excited at three different spindle rotation and evaluated using the ODS tool. Largest displacements were observed when excited at 9,333rpm and concerning to machining process this was the poorest condition evaluate.



(a)



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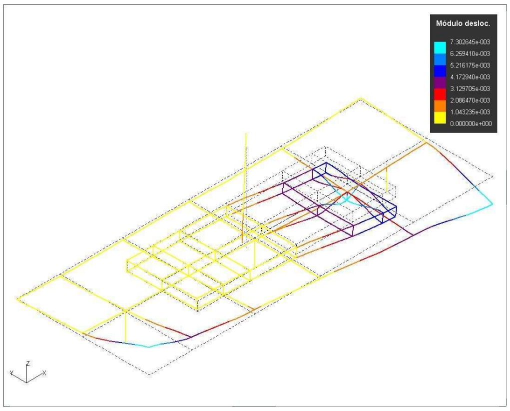
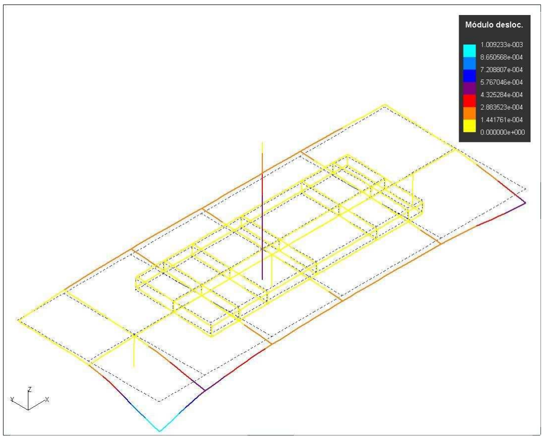


(c)

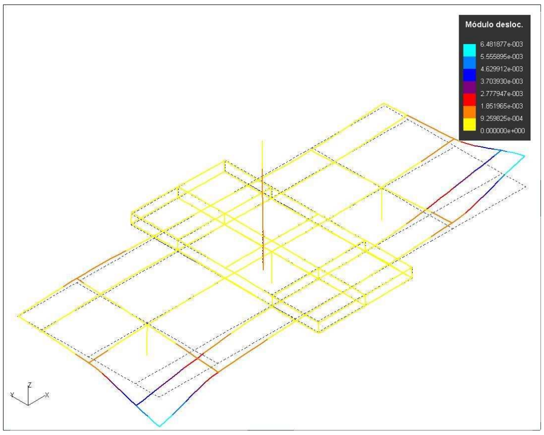
Figure 7. Maximum displacements for excitation of spindle: rotation of 7,333 rpm (a), 8,000 rpm (b), and 9,333 rpm (c).

3.2. Fixture system

Concerning the fixture system (for 2, 4 or 6 bolts), Fig. 8 present the results obtained using the ODS tool. One may observe in this figure the maximum displacements of the set workpiece and base of the machine tool. In addition to this, these fixture systems were also evaluated using a FEM, as shown in Fig. 9. We used the MSC Patran – Nastran software to model the system. We observed that the central area of the workpiece, that is the effective area for machining the thread holes, presented the worst fixture when only 2 bolts were used. In contrast, when 4 or 6 bolts were used, we achieved a higher stability, what facilitates one to obtain higher quality pieces while saving the tool life.



(a)



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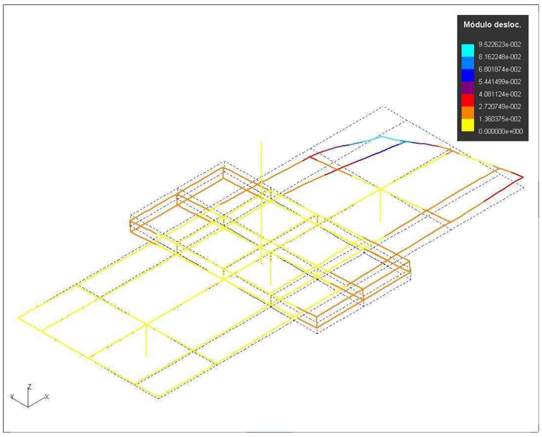


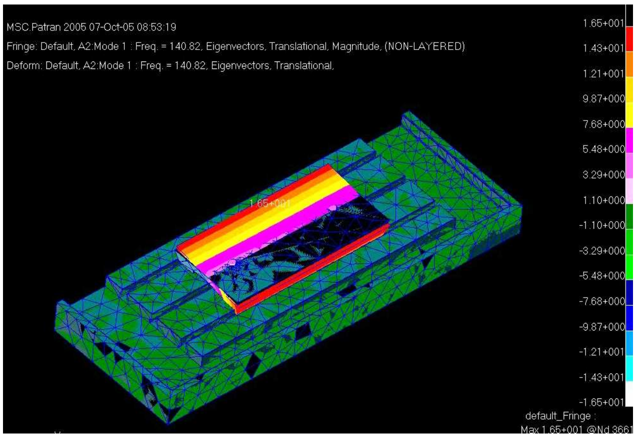
(c)

Figure 8. Maximum displacements for fixture system using 2 bolts (a), 4 bolts (b), and 6 bolts (c) – ODS analysis.

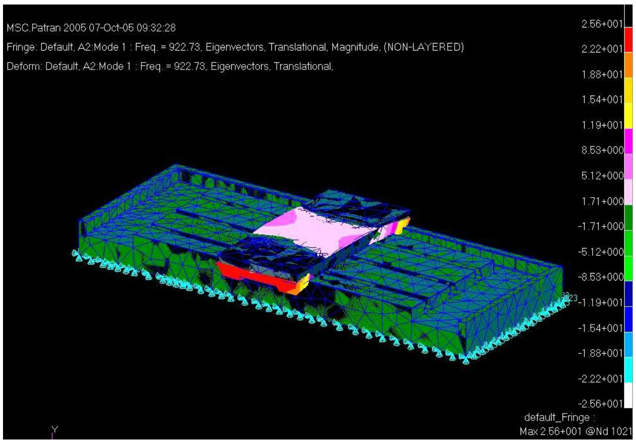
Table 1 presents the first natural frequencies for the set workpiece and base of the machine tool for three different fixture arrangements (2, 4, and 6 bolts). It is possible to observe that using 4 or 6 bolts the 1st natural frequency reaches a value almost five times higher than when only 2 bolts were used. This means that a fixture system with 4 or 6 bolts guarantees that the vibration amplitude of the set would be smaller if the machining parameters are exciting the set at low frequencies (100 – 200 Hz), common situations while machining workpieces in a standard CNC machining centres.

Table 1. 1st Natural Frequencies of the system.

Bolts Quantity	Natural Frequency [Hz]
2	140.82
4	922.73
6	857.48



(a)



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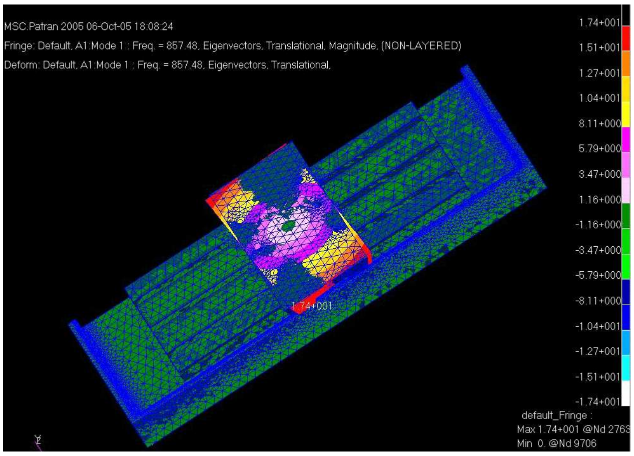


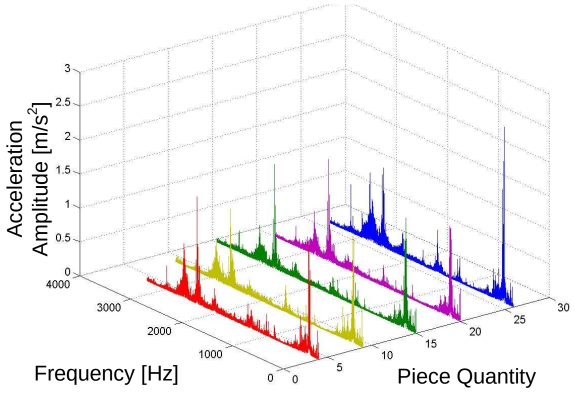
(c)

Figure 9. First vibration mode for fixture system using 2 bolts (a), 4 bolts (b), and 6 bolts (c) – FEM analysis.

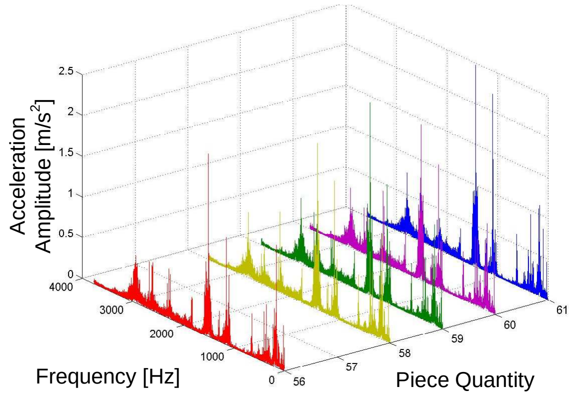
3.3. Vibration measurements for the optimized system up to 30,253 machined threads

The acceleration was evaluated at different time steps during the process of machining 30,253 threads. The corresponding results are presented in Fig. 10. These figures show the quantity of work materials, frequency (frequency domain using FFT) and acceleration amplitudes. In each work material 495 threads were machined. Based on these figures we can observe clearly that there is a tendency for increasing the acceleration amplitude when the machining time increases (and consequently the quantity of machined pieces). On the other hand, the spectra of the frequencies remain almost the same during the whole process. Therefore, we can conclude that extremely low wear as we observed, together with adhered material on the tool, was sufficient to increase the magnitude of the acceleration of vibration.

Figure 11 shows the quantity of threaded holes during this study. The first tool used machined exactly two threads before the catastrophic failure. The second one, working at optimized spindle rotation (8,000 rpm) machined more than 5,500 threads. However, after optimized the fixture system (we used 4 bolts instead of 6 to reduce the time spent to prepare the tests) the tool was able to machine more than 30,000 threaded holes (without the toll catastrophic fail).



(a)



(b)

Figure 10. Acceleration of vibration on frequency spectra – fixture system using four bolts in (a) from 1,980 to 12,870 threaded holes and in (b) from 27,720 to 30,253 threaded holes.

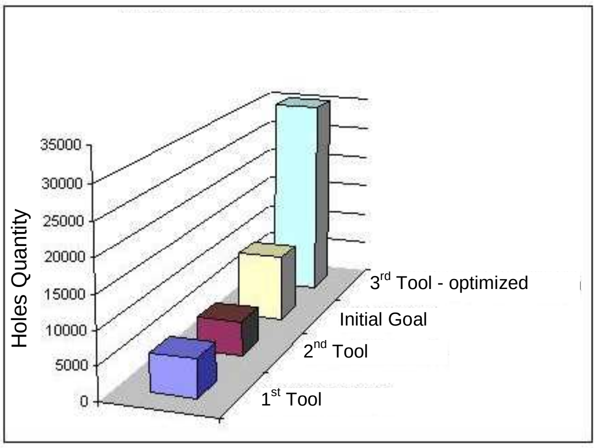


Figure 11. Machined threads versus cutting condition at different optimization stages.

4. CONCLUSIONS

In this paper we presented results on the use a unique tool developed for hybrid machining process involving drilling and threading. Initially we tried to understand and optimize the process by applying various methods and tools (such as: ODS, FEM, acceleration amplitude measurements, and optical analysis of the tool at different stages). Briefly, we can concluded that the ODS technique proved to be a powerful tool to evaluate the displacements of the work material and machine tool base. The ODS results helped us to choose the best machining parameters. In addition to this, the use of FEM could help us to optimize the fixture system, avoiding to work close to the natural frequencies. If in the beginning of this research we were able to machine only two threaded holes before the catastrophic failure of the tool, after the ODS and the FEM studies we could optimize the process and reach more than 30,000 threaded holes (without failure).

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