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## **INVESTIGATION OF THE EFFECT OF FEED ERROR IN TAPPING OPERATION USING FINITE ELEMENT METHOD**

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**Abstract.** *Tapping is a very complex machining process, and yet, is widely used to produce internal threads. One of the most common problems in this operation is the feed error, in which the machine has problems to synchronize the tap feed rate and its spindle speed. To investigate this phenomenon, this paper proposes a 3D simplified model of the tapping process and use the finite element method to solve it. The simulations were done only altering the feed in each test, and the maximum thrust force was the output variable analyzed. The results showed that the thrust force changed, even for the smallest variation in the feed. The axial force increases with the feed change, and the maximum thrust force increased 92% when the feed increased 10%.*

**Keywords:** *Tapping, Feed error, Finite Element, 3D model.*

### **1. INTRODUCTION**

Mechanisms and machine components requiring screw threads have a long history of application to technology. The use of screw threads as fastener components is one of the most common methods of joining parts into assemblies (Henderer, 1977). The threaded joint has many advantages, as it possesses high strength and high rigidity, and the use of threads allows disassembly for maintenance and recycling (Fromentin et al., 2005). It is therefore of great interest to study and investigate the manufacturing process most commonly used to produce internal threads: tapping.

Tapping is a process for producing internal helical threads using a tool, called a tap, that has threads on its periphery to cut the required threads in existing holes. This operation involves relative axial and rotational motions between the tap and the workpiece. The feed per revolution must be the same as the pitch of the required thread (Drozda, 1983).

Tapping is one of the most complex operations in metal cutting (Lorenz, 1980). One of the reasons for that is because of the precise synchronization required for the feed rate, the spindle speed and the thread pitch to make a quality thread. There are several undesirable effects of a lack of synchronization in this operation, as the so-called feed error, can lead to unusually high magnitudes of thrust force (Dogra et al., 2002) and that may cause tap breakage due to the abrupt increase of cutting torque, or damage the thread accuracy by overcutting the already machined threads (Ahn et al., 2003).

The implementation of other techniques to aid the study of internal thread tapping is necessary. There is an industrial urgent need to use 3D models for specific operations and the finite element method (FEM) plays an important role in the improvement and optimization of processes and can be used to solve a tridimensional tapping model. By using this method of analyses, efficient predictions on various basic values such as process forces, pressure, strains, temperatures, wear and surface properties can be made (Oezkaya and Biermann, 2017).

Knowing that the synchronizing error is present in most of the tapping operation, this paper focus on the study of this phenomenon through a 3D FEM model.

### **2. METHODOLOGY**

The primary aim in simulating is to make efficient predictions within calculation time as short as possible and therefore 2D models are generally used. But in some cases, such as tapping, a 2D modeling and simulation are insufficient because the torque results from the whole chamfer length. So, this paper proposes a simplified tridimensional model of a tapping process to study the synchronization problem in the operation. In order to do this, the commercial software AdvantEdge (Advantedge User's manual, 2017) was used.

#### **2.1 The AdvantEdge software**

AdvantEdge is an explicit dynamic, thermo-mechanically coupled finite element model specialized for metal cutting. Features necessary to model metal cutting accurately include adaptive remeshing capabilities for resolution of multiple length scales such as cutting-edge radius, secondary shear zone and chip load; multiple body deformable contact for tool-workpiece interaction, and transient thermal analysis (Marusich, 2001).

This software uses the Lagrangian approach as your numerical formulation, which means that the elements are attached to the material. The material is deformed due to the action of the cutting tool, as its mesh, so, this way, there is formation of the chip due to deformation caused by the tool (Markopoulos, 2013). This type of equation can simulate large unconstrained plastic flows, provided that the solid is continuously remeshed.

Continuous remeshing and adaptive meshing in the workpiece are the main tools which the software employs for sidestepping the difficulties associated with deformation-induced element distortion, and for resolving fine-scale features in solution. This adaptive mesh also helps in the propagation of cracks along arbitrary paths through the chip formation.

AdvantEdge uses an explicit time integration strategy to solve the equations of motion through time. This approach determines the solution of the set of finite element equations by using a central difference rule to perform the integration. The equations are reformulated and they can be solved directly to determine the solution at the end of the increment, without integration (Markopoulos, 2013). Explicit algorithms are more attractive to solve problems that involve complicated contact situations, such as in machining. This type of integration is better for tridimensional calculations and is better when using concurrent computing (Marusich and Ortiz, 1995), like in this research.

## 2.2 The Power Law model

One of the most important factors in a finite element analysis in machining is the material model utilized. In order to describe the material behavior, this paper resorted to a Power Law model developed by Marusich and Ortiz (1995). The strain hardening ( $g(\epsilon^p)$ ), strain rate sensitivity ( $\Gamma(\dot{\epsilon})$ ) and thermal softening ( $\Theta(T)$ ) are included in this formulation, and it can be seen in Eq. (1).

$$\sigma(\epsilon^p, \dot{\epsilon}, T) = g(\epsilon^p) \times \Gamma(\dot{\epsilon}) \times \Theta(T) \quad (1)$$

Equation (1) is the main expression for the calculations performed by the software. But, each of those three terms can be better explained in the equations that follows:

$$g(\epsilon^p) = \sigma_0 \left( 1 + \frac{\epsilon^p}{\epsilon_0^p} \right)^{\frac{1}{n}}, \text{ if } \epsilon^p < \epsilon_{cut}^p \quad (2)$$

$$g(\epsilon^p) = \sigma_0 \left( 1 + \frac{\epsilon_{cut}^p}{\epsilon_0^p} \right)^{\frac{1}{n}}, \text{ if } \epsilon^p \geq \epsilon_{cut}^p \quad (3)$$

$$\Theta(T) = c_0 + c_1 T + c_2 T^2 + c_3 T^3 + c_4 T^4 + c_5 T^5, \text{ if } T < T_{cut} \quad (4)$$

$$\Theta(T) = \Theta(T_{cut}) \left( 1 - \frac{T - T_{cut}}{T_{melt} - T_{cut}} \right), \text{ if } T \geq T_{cut} \quad (5)$$

$$\Gamma(\dot{\epsilon}) = \left( 1 + \frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right)^{\frac{1}{m_1}}, \text{ if } \dot{\epsilon} \leq \dot{\epsilon}_t \quad (6)$$

$$\Gamma(\dot{\epsilon}) = \left( 1 + \frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right)^{\frac{1}{m_2}} \left( 1 + \frac{\dot{\epsilon}_t}{\dot{\epsilon}_0} \right)^{\frac{1}{m_1} - \frac{1}{m_2}}, \text{ if } \dot{\epsilon} > \dot{\epsilon}_t \quad (7)$$

The Strain hardening equations, Eq. (2) and Eq. (3), can be calculated using the yield stress ( $\sigma_0$ ), the plastic strain ( $\epsilon^p$ ), the reference plastic strain ( $\epsilon_0^p$ ), the cut off strain ( $\epsilon_{cut}^p$ ) and  $\frac{1}{n}$ , which stands for the strain hardening exponent.

The Thermal Softening can be calculated through the equations Eq. (4) and Eq. (5).  $c_0$  through  $c_5$  are coefficients for the polynomial fit of the material thermal softening curve,  $T$  is the temperature,  $T_{cut}$  is the linear cut off temperature, and  $T_{melt}$  is the melting temperature.

The rate sensitivity calculation equations can be described by equations Eq. (6) and Eq. (7). To perform the calculations, several information are needed:  $\dot{\epsilon}$ , which is the strain rate;  $\dot{\epsilon}_0$ , the reference plastic strain rate;  $\dot{\epsilon}_t$ , which is the strain rate where the transition between low and high strain rate sensitivity occurs;  $m_1$ , the low strain rate sensitivity coefficient and  $m_2$ , the high strain rate sensitivity coefficient.

This research modeled the problem as if the tool was only elastic deformable, so, the only information needed for the tool material were its Young's Modulus and the Poisson's ratio. The workpiece was modeled as being plastic and elastic

deformable, and all the information needed to describe the material behavior for the cast iron employed on the simulations were already in the software library, ready to be inputted in the equations two through seven. The tool and the workpiece materials will be better described in the following sections.

### 2.3 Experimental design

The idealized model can be seen in Fig. 1. The software allows that several steps of the simulation pre-processing can be made on the program itself: the mesh and remesh parameters, for instance. It is well known that the decisions made in this step will influence the quality of the simulation results.

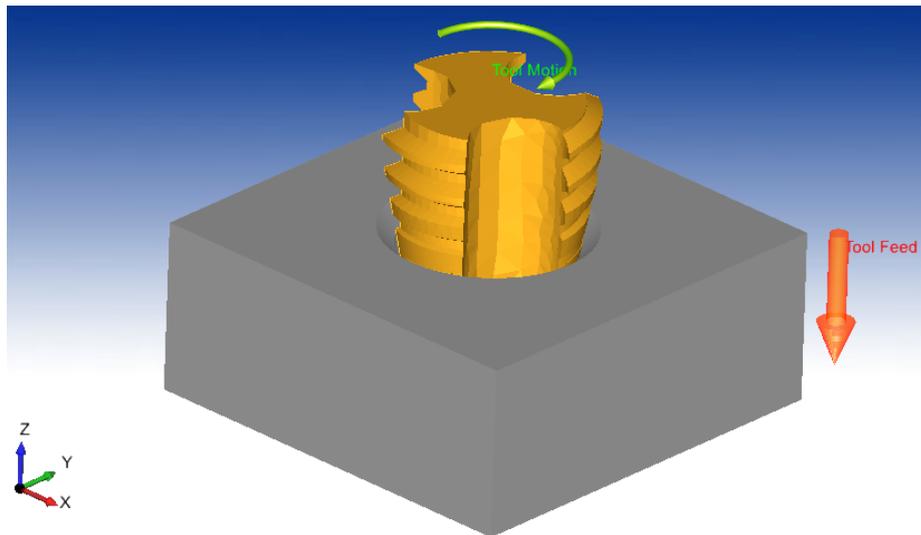


Figure 1. Idealized simplified model of a tapping process

The tool was modeled on a CAD software, based on an OSG Tap M6x1 166 GGMS (OSG, 2012). This tap has 3 straight flutes, with 1 mm pitch, 3 teeth in the chamfered length and it is made of uncoated high-speed steel HSS-M2, and all the information needed for the simulation, for this material, can be found in the software material library. This tap was simplified in the model, as shown in Fig. 2, as the tool was cut after the second row of teeth in the cylindrical part of the tap. This simplification was made to ensure a lesser time of simulation.

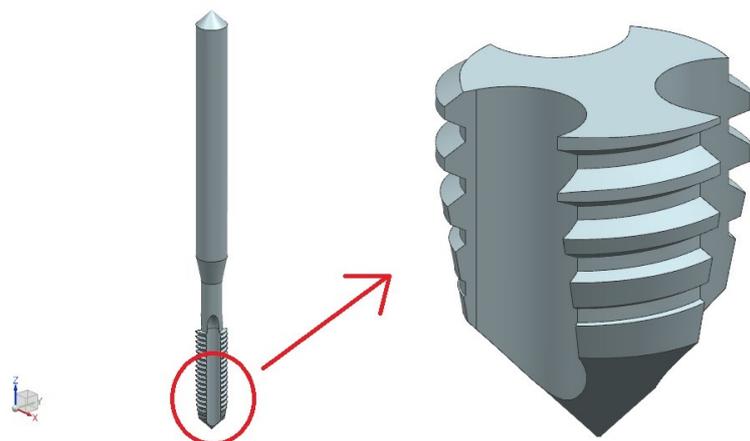


Figure 2. Simplification of the tool model

The workpiece has dimensions of 12 mm in width, 12 mm in length and 5 mm of height and a 5 mm hole in its center, as shown in Fig. 1. This pilot hole size was made as indicated in the tool manufacturing catalog. The workpiece material is a ductile iron “Nodular 4040”, selected from the software database, and its chemical composition is detailed in the Tab. 1.

Table 1. Chemical composition of the ductile iron “Nodular 4040”

Chemical composition	C	Cr	Mn	Ni	P	S	Si
Weight [%]	3.7	0.1	0.5	0.05	0.02	0.014	2.5

The mesh parameters were carefully chosen to each simulation, trying to balance the quality of the mesh and the computational time to perform the tests. The AdvantEdge software uses three-dimensional tetrahedral elements in the mesh, as can be seeing in the Fig. 3. The tool mesh has a minimum element size of 0.1 mm and a maximum element size of 1.0 mm, with a total of 9690 elements. The workpiece has a minimum element size of 0.1 mm and a maximum element size of 2.5 mm. The final average number of elements in the workpiece for all tests, knowing that, for each one, the mesh readapts uniquely, were 133,361.

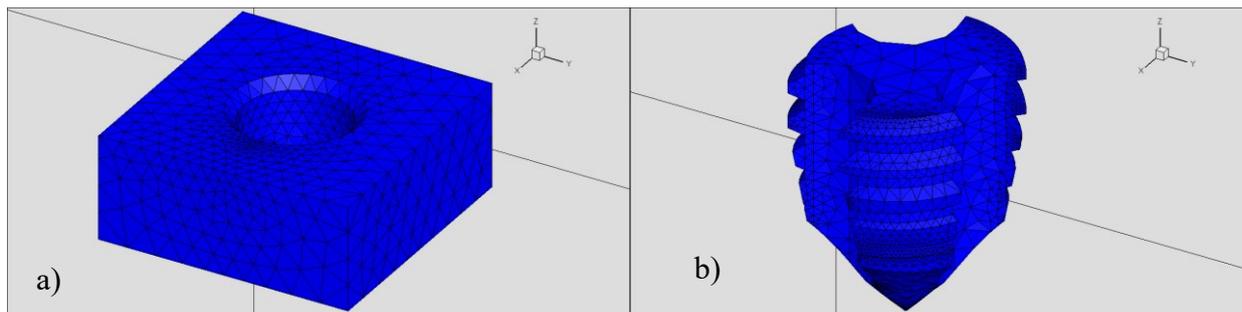


Figure 3. Tetrahedral mesh in the a) workpiece and b) toll

The process parameters were established as: a cutting speed of 14 meters per minute, as the tool manufacturer suggests for this kind of workpiece material, and three tool rotations. This last parameter was adopted because it is the amount of spins necessary to produce the first complete thread inside the hole, and therefore, reaching its maximum torque and forces.

The friction model used by the software is the Coulomb’s Law of friction. The contact between the tool and the workpiece is an important simulation criterion and it affects greatly in the simulation. This friction model considers a constant friction in the cutting zone and its coefficient of friction ( $\mu$ ) was set as 0.5, the software standard.

In an ideal tapping process, the spindle should travel a distance of one pitch once the tap has a full revolution. However, feed error may exist, which is defined as the deviation between the actual axial feed per revolution and the pitch of the thread. This phenomenon will lead to that the tap feeds less or more than one pitch in each revolution (Wan et al., 2017). To simulate that kind of error, the feed was changed in each test. The tool that was used required an input of a 1 mm pitch, so, the pitch was altered around that value. 15 different pitches were used and can be seen in Tab. 2.

Table 2. Pitch values utilized in the simulations

Test number	Pitch value (mm)
1	0.900
2	0.950
3	0.995
4	0.996
5	0.997
6	0.998
7	0.999
8	1.000
9	1.001
10	1.002
11	1.003
12	1.004
13	1.005
14	1.050
15	1.100

An Intel core i7-7700 processor with 3.6 GHz and 32 Gb of RAM memory was used for all the simulations.

### 3. RESULTS AND DISCUSSION

The variable of interest for this paper is the force in the z axis, the thrust force. According to Da Mota (2009) and Pereira (2014), this force is the most affected by the feed error, since is the force in the feed direction. The behavior of this force can be seen in Fig. 4, where the raw data for the test with the right amount of pitch, 1.000 mm, is show.

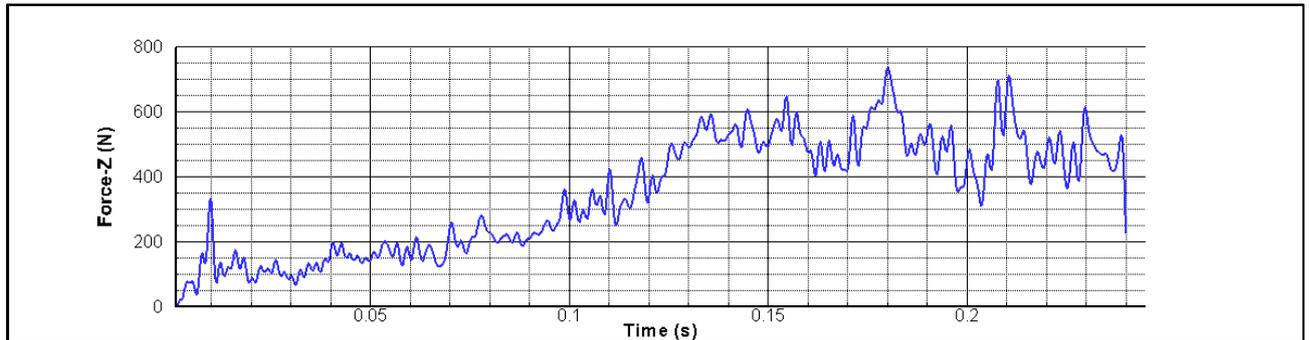


Figure 4. Raw data for the thrust force in the simulation of 1.000 mm pitch

The simulation raw data presented in Fig. 4 was, then, treated with the aid of a tenth-degree polynomial for better visualization of the results. This curve presented a 0.891873 goodness of fit and can be analyzed through Fig. 5.

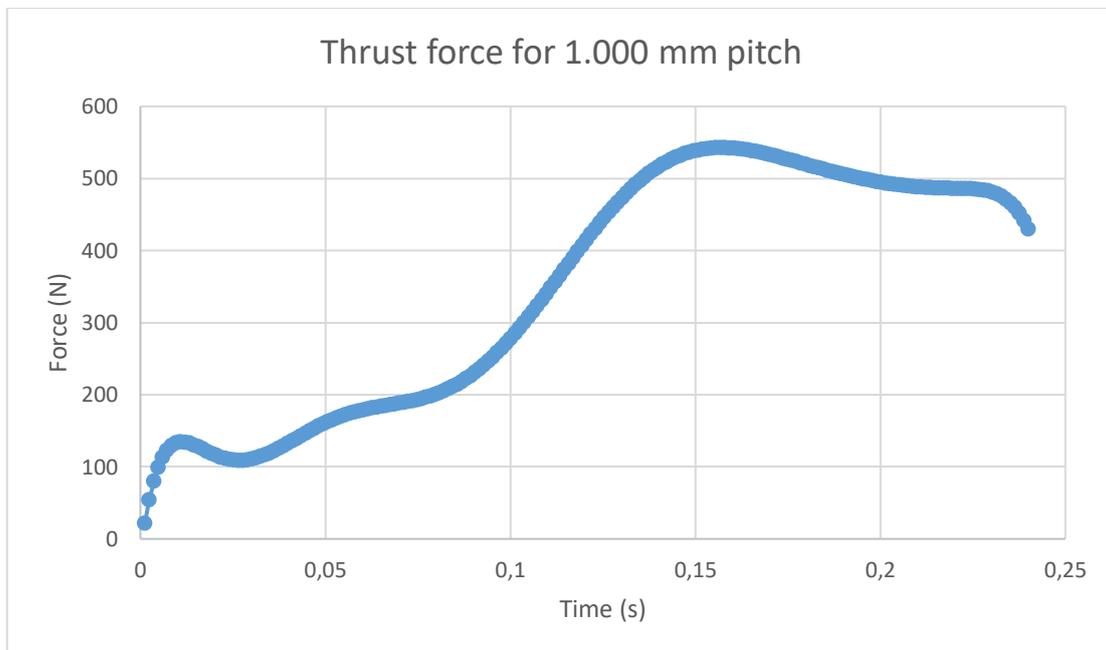


Figure 5. Polynomial fit for the thrust force results in the simulation for 1.000 mm pitch.

The maximum axial force in the tapping process is, theoretically, reached after the conical part of the tap fully entered the hole, cutting its first complete thread. Figure 5 shows that the maximum force was reached before the last cutting edge of the tool has entered the hole. Since this curve is a polynomial fit, it tries to fit as many points of the raw data as possible to show a tendency. With a good goodness of fit, this curve represents the tendency of the z axis force in this test and is a good way to visualize and analyze the result, without an excessive amount of points and yet, producing good results.

The rest of the simulations were treated with the same process. All of them had their raw thrust force data simplified with a tenth-degree polynomial curve. Then, the maximum thrust force was obtained for each of those tests and is shown in Fig. 6.

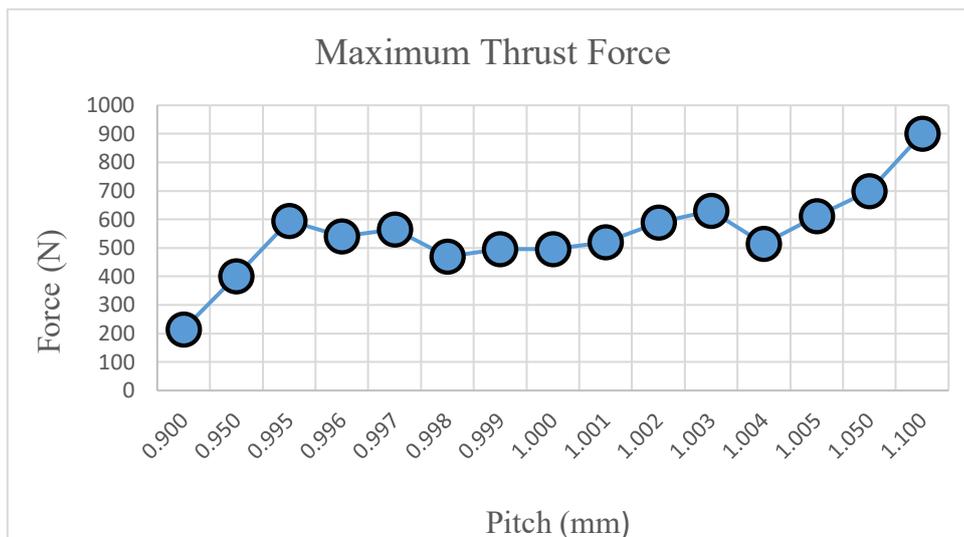


Figure 6. Maximum thrust force, for each pitch utilized

Analyzing the graphic in Fig. 6, it is possible to perceive that the maximum force in the feed direction changes when the pitch moves away from the ideal one.

In the range between 0.995 mm and 1.005 mm, the further the pitch goes away from the right value (1 mm), higher is the maximum thrust force. When the pitch is higher than the expected, the tool moves more than it is necessary, causing an excessive contact with the superior part of the thread being formed; When the pitch is lower than the expected, the excessive contact happens with the lower part of the newly formed thread. In both cases, the excessive pressure in the contact between cutting tool and workpiece causes the thrust force to increase.

When the tests were performed with higher values of pitch (1.050 mm and 1.100 mm), the maximum thrust force increased substantially. That boost follows the raise in the pressure and friction in the cutting zone.

When smaller pitches were used (0.950 mm e 0.900 mm), the maximum thrust force decreased quite much. According to Da Mota (2009) and Pereira (2014), that is the natural behavior of the axial force when the pitch is smaller than the correct one, since the tool is moving less than it is necessary, causing a force to appear in the same direction of the feed.

As the feed decreases, this force should become negative, but the AdvantEdge makes use of the Coulomb friction law, which supplies regardless of the magnitude of interface pressure a frictional stress that is proportional to this pressure (Bil et al., 2004). That phenomenon causes a very positive force in the z direction, greater than the one provided by the feed error, and that is why even for smaller pitch values the force remains positive.

For the 0.900 mm pitch, though, there were negative forces in the end of the test, when the thrust force tends to be the greatest. This may mean that the forces from the synchronism error began to outgrow the forces originated from the frictional stress as the axial force has become negative by the end of the formation of the first thread inside the hole. The graphic of this force is represented in Fig. 7.

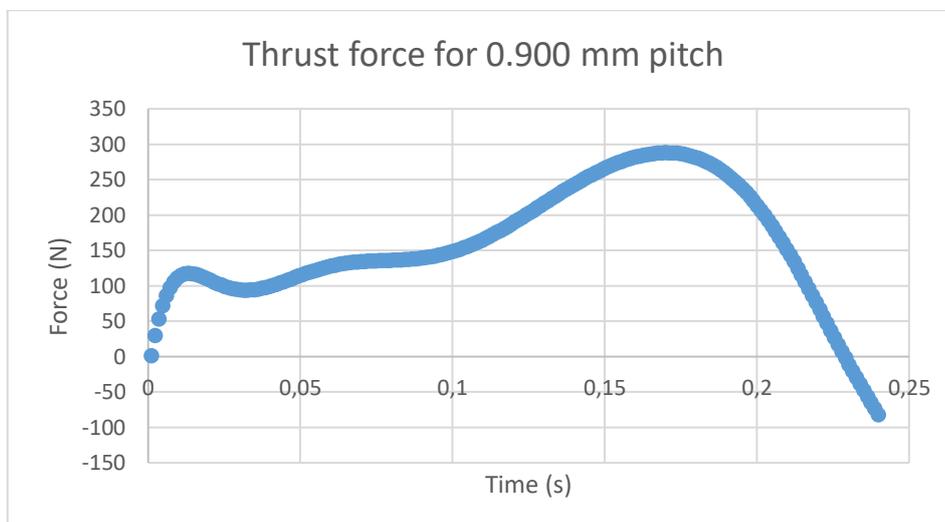


Figure 7. Thrust force for 0.900 mm pitch

#### 4. CONCLUSIONS

The feed error is an obnoxious problem for the tapping process. It is present, basically, every time this operation is performed, as the tapping is a very fast process and it's hard to accelerate and decelerate the machine spindle in a short period of time. This study showed that even for smaller errors in the pitch (0.995 mm through 1.005 mm), the maximum thrust force increases by up to 24.5%.

This paper, also, shows that small changes in the pitch (feed) can cause variations on the maximum axial force, since the formation of the first thread in the workpiece. This excessive force can cause the breakage of the tool and, likewise, contributes to a malformation in the thread, both, serious problems in a production line.

The 3D simplified model proposed in this paper, using the finite element method, displayed solid results. The behavior of the thrust force has shown to be very similar to what occurs in practice, proving that this methodology is a reliable method to study the tapping process.

#### 5. ACKNOWLEDGEMENTS

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