

Study of the influence of the cutting temperature on the magnitude of the contact forces in the machining fixtures

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Abstract. In the machining process, the workpieces are installed in machining fixtures in order to establish a strictly determined position with the cutting tool or its trajectory. During the cutting process, the weight of the workpiece, the forces and moments of inertia, cutting forces and moments, clamping forces, the heat released during the cutting process determine the contact forces between the locators and the workpiece. The magnitude of these forces is important because too large value can destroy the surface of the workpiece, and a too small value can cause the workpiece to slip on the locators or even the loss of the contact with the workpiece. Both situations must be avoided. The paper presents a study, realized with CAE software, regarding the influence of the cutting temperature on the magnitude of the contact forces in a machining fixture for the milling a rectangular workpiece.

1. Introduction

The great variety of workpieces found in the industry stimulates the designers to find new solutions for machining fixtures, which meet the requirements of precision and productivity imposed by the users.

This is done shortly and at low costs if CAE type numerical simulation software, as in [1], [2], and CAD type three dimensional modeling, as in [3], are used to validate the fixtures configuration and if modern control techniques of the processes are used for the processing of their component parts, to eliminate human errors [4].

In the practice of designing machining fixtures, the designers should consider the influence of the cutting process parameters on the machining precision of the workpiece installed in the fixture. Among these, we list the cutting forces and moments, parameters of the cutting regime (cutting depth, feed, cutting speed), material of the workpiece, material of the tool, cooling-lubrication during the process, geometry and kinematic precision of the machine-tool etc.

At the same time, the chosen orientation layout, the type of locators, the nature of the contact between the locator and the workpiece and the clamping elements and the workpiece [5], the size and location of the clamping forces [6] must be taken into account.

It is a known fact that the thermal phenomena have an influence both on the behavior of the workpieces during operation [7], [8] and during machining by cutting. During cutting, the thermal phenomena influence the nature and the dynamic of some characteristic phenomena as well as the results of the process, in terms of precision and quality of the machined surface, the wear of the cutting tool, the process of the forming of the chip, vibration, etc.



The heat developed during the cutting results from the almost complete transformation of the mechanical work consumed for the cutting process. It is largely due to the plastic deformations of the material during the chip formation (Q_1), frictions at tool/chip interfaces (Q_2) and tool/cut surface (Q_3) and to a lesser extent, to additional deformation of the chips (twisting, crushing).

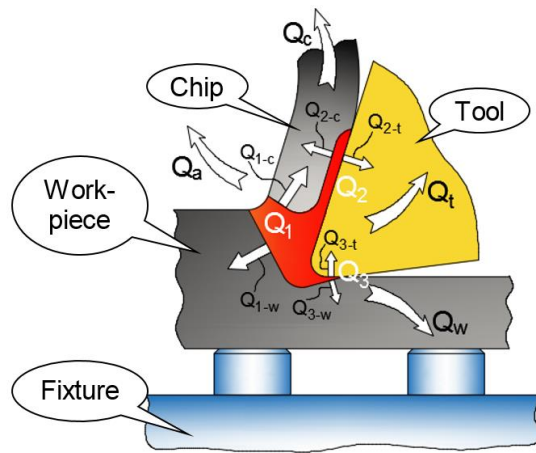


Figure 1. Main sources and distribution mode of the heat during cutting

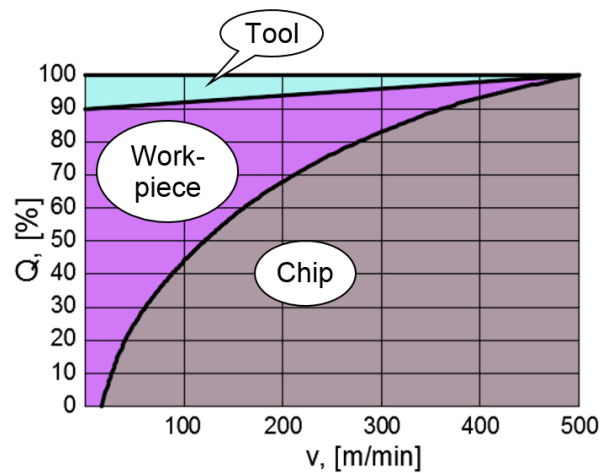


Figure 2. Percentage distribution of the heat (Q) according to the cutting speed (v)

The heat developed during the cutting process spreads from the sources where it was formed towards the cooler areas, distributing in the chip (Q_c), the tool (Q_t), the workpiece (Q_w) and the cutting environment (Q_a). Each source transmits, according to Figure 1, a certain amount of heat towards the neighboring areas.

Heat flows go in opposite directions towards cooler areas. Thus, from the source developed in the shear plane due to the deformation of the cut material (Q_1) a flow goes towards the chip (Q_{1-c}) and a much smaller flow (Q_{1-w}) goes towards the workpiece. The heat developed by the tool – chip friction (Q_2) goes towards the chip through the Q_{2-c} flow and to the tool through the Q_{2-t} flow, and the heat from the friction on the back edge (Q_3) goes towards the tool (Q_{3-t}) and towards the workpiece Q_{3-w} .

This way, the heat absorbed by the chip (Q_c) can be expressed as:

$$Q_c = Q_{1-c} + Q_{2-c} \quad (1)$$

the one absorbed by the tool (Q_t) will be:

$$Q_t = Q_{2-t} + Q_{3-t} \quad (2)$$

and the one absorbed by the workpiece (Q_w) will be:

$$Q_w = Q_{1-w} + Q_{3-w} \quad (3)$$

The percentage distribution of heat flows depends largely on the cutting conditions, especially on the type of operation and the cutting regime. Figure 2 shows that, in general, most of the heat is absorbed by the chip, followed by the workpiece and the smallest part by the tool.

The machining precision is negatively influenced especially by the amount of heat absorbed by the workpiece and the tool, which remain in contact during the entire machining process and it is manifested especially in the field of small cutting speeds (Figure 2).

The heat absorbed by the workpiece or the cutting tool can be determined using various methods, as shown in [9], [11].

Analytically, the heat absorbed by the piece can be roughly estimated using the relationship [12]:

$$Q_w = \frac{1}{3} \cdot \lambda \cdot \frac{bl^2}{v} \nabla \theta_{max} [J] \quad (4)$$

in which:

λ – the thermal conductivity of the material of the workpiece, W/mK;

b – is the width of the chip, in m;

l – the tool path length, in m;

v – the cutting speed, in m/s;

$\nabla\theta_{\max}$ – the maximum value of the temperature gradient (K/m).

It is a known fact that the installation of the workpiece in the fixture has two functional phases: orientation and clamping. It is necessary for this system of forces to ensure the contact of the workpieces with the locators and to maintain it during machining, while also ensuring maximum rigidity of the workpiece-fixture assembly, which leads to the decrease or removal of vibrations.

At the same time, the size of the clamping forces, together with the other influences (forces and moments of cutting, weight, forces and moments of inertia, centrifugal forces, mass forces, etc.) must not cause contact deformations destroying the surfaces of the workpiece.

The heat absorbed by the workpiece is inevitably transmitted to the fixture in which it is installed, generating the expansion of its component parts, which influences the machining accuracy and the size of the contact forces between the workpiece and the locators.

The extreme values of the contact forces are very important. The maximum ($f_{c_{\max}}$) and minimum ($f_{c_{\min}}$) values of the contact forces are determined according to [13], [14].

The contact force must not exceed the maximum value $f_{c_{\max}}$ as there is a risk of damage to the surfaces of the workpiece (indentation will appear) and the minimum contact force ($f_{c_{\min}}$) must prevent the loss of contact between the workpiece and the locators, and must also prevent the workpiece to slipping from the locators.

2. Model development

This paper presents a study on the influence of the heat generated during the cutting process on the size of the contact forces between the workpiece and the locators of the fixture in which the piece is installed.

For this purpose it is considered a situation in which a parallelepiped shaped workpiece (size 225x122x112 mm) is subjected to cylindrical-frontal milling. A canal, with 2 mm depth, is formed, positioned at a distance of 12 mm from the evaluated edge, which is the reference element for measuring (Figure 3). This situation has been chosen so that there are no considerable changes of rigidity in the workpiece caused by the machined canal, affecting the results of the analysis. The diameter of the cutting tool is 25 mm and has two teeth ($z=2$ teeth).

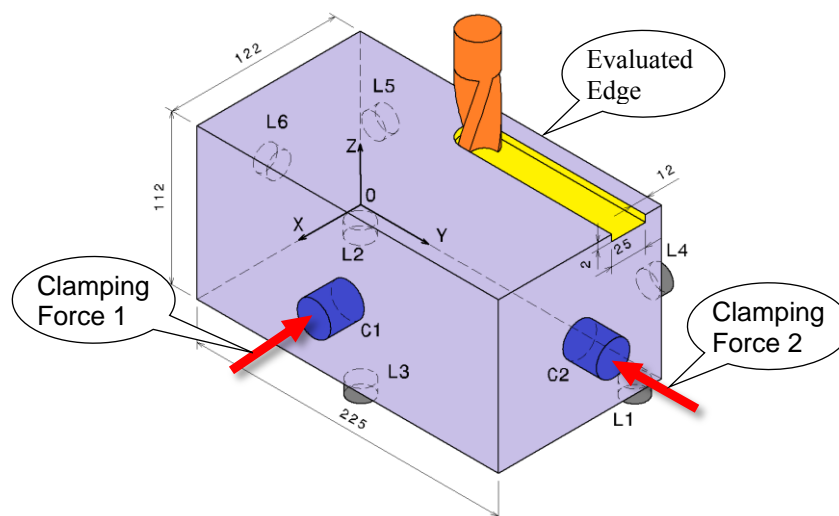


Figure 3. 3D model of the workpiece – fixture system

Table 1. Coordinates of locators and clamping elements

Coordinates	Locators						Clamps	
	L1	L2	L3	L4	L5	L6	C1	C2
X [mm]	9	9	113	0	0	61	122	61
Y [mm]	216	9	112,5	216	9	0	112,5	225
Z [mm]	0	0	0	56	56	56	56	56

The orientation layout is of type 3-2-1, locators (L1,..., L6) have a cylindrical shape, 18 mm in diameter, with a flat contact surface and the clamping elements C1 and C2, also have a cylindrical shape with a diameter of 25 mm. The values of the clamping forces are 576 N and 621 N. The contacts forces between the workpiece and the locators and between the workpiece and the clamping elements are flat and the friction coefficient at sliding is 0,1.

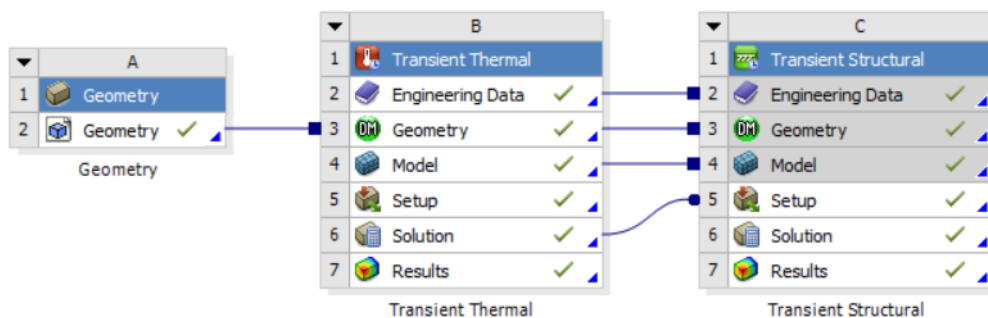
The locators and elements of applying clamping forces, relative to the system OXYZ, are positioned as in Figure 3 and Table 1.

The workpiece, the locators and clamping elements are made of structural steel. The properties of the material used in the simulation are presented in Table 2.

Table 2. Properties of the material

Properties	Structural Steel
Density [kg/m ³]	7850
Young's Modulus [MPa]	200000
Poisson's Ratio [-]	0,3
Tensile Yield Strength [MPa]	250
Tensile Ultimate Strength [MPa]	460

The 3D model of the workpiece-fixture system was made in Ansys Design Modeler and it was then transferred to Ansys Mechanical for the two analyzes.

**Figure 4.** Project layout in Ansys

Two analyzes were carried out: a transient thermal analysis to determine the temperature in the workpiece-fixture assembly during machining and then a transient structural analysis in which the temperature field from the thermal analysis was imported. Loads and constraints specific to the structural analysis were added to this analysis, namely: forces and moment of cutting, clamping forces, binding of the degrees of freedom of the locators and of clamping elements (Figure 4).

For both analyzes, the loads were applied in 9 equidistant circular areas, 25 mm in diameter, on the upper surface of the workpiece, their centers being located on a line parallel to the evaluated edge, at a distance of 24,5 mm (Figure 5).

For the thermal analysis, a thermal flow of 2 W/mm^2 acts in the 9 circular areas, and the heat transfer between the workpiece and the environment is made by convection, the convection heat transfer coefficient being $2 \cdot 10^{-5} \text{ W/mm}^2 \cdot ^\circ\text{C}$.

For the structural analysis, the forces and the moment of cutting are considered to have the following values: $F_x=131 \text{ N}$, $F_y=232 \text{ N}$, $F_z=55 \text{ N}$ and $M=2.77 \text{ N}\cdot\text{m}$, and they also act in the 9 circular areas on the upper surface of the workpiece.

Under a cutting speed of approximately 60 m/min and a feed per tooth of 0.012 mm/z , the cutting processing time of the workpiece over the entire length of 225 mm is of approximately 81 seconds . This will also be the time used in the analysis.

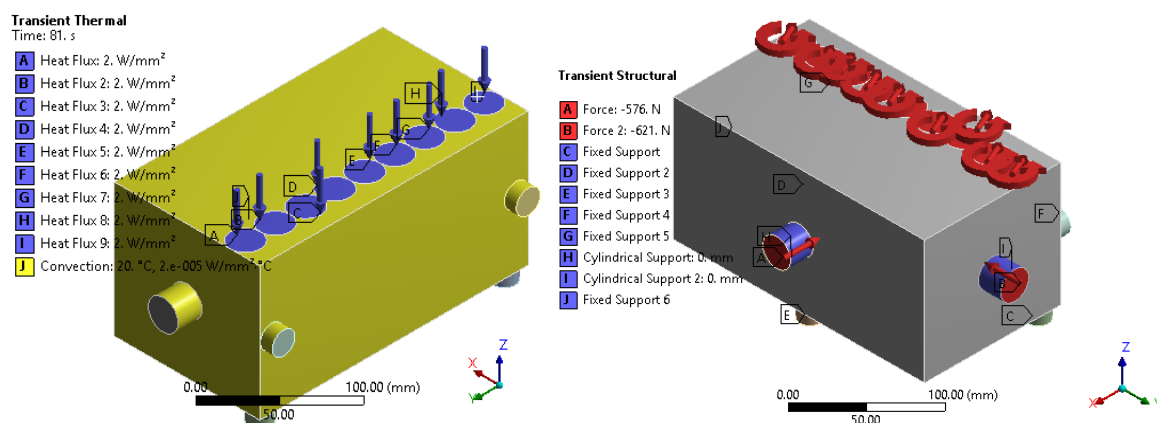


Figure 5. Loads and constraints for analyzes

3. Results

After running the thermal analysis, the field of temperatures in the workpiece is displayed for two of its surfaces: the upper and the right side of the canal, at time points 42 s and 81 s (Figure 6).

It can be seen that the contact areas between the locators and the surfaces of the workpiece get warm due to the heat released during cutting, which results in expansion of the workpiece-fixture assembly, with possible consequences on the machining precision as well as on the size of the contact forces between the locators and the surfaces of the workpiece.

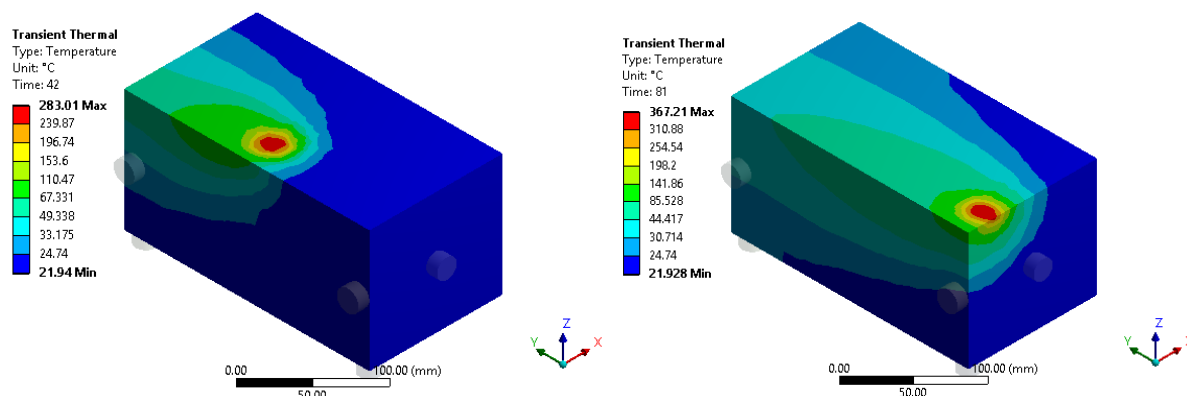


Figure 6. Temperature in workpiece at moments 42 s and 81 s

Four cases of workpiece-fixture assembly loading were considered for the study of these consequences, as follows:

- Case I: when only the clamping forces act (No T, No F);

- Case II: when only the forces and moment of cutting act (No T, With F);
- Case III: when only the cutting temperature acts (With T, No F);
- Case IV: when both forces and moment of cutting as well as cutting temperature act (With T, With F).

For each of the four considered cases, the contact forces and total deformation of the evaluated edge were determined.

As such, Figures 7...10 present the variation of the contact forces between the locators (L1,..., L6) and the workpiece in the 4 cases considered above. In Figure 7, the contact forces have constant values throughout the machining because neither the temperature which results from the cutting, nor the forces nor the moment which result from the cutting process act on the workpiece.

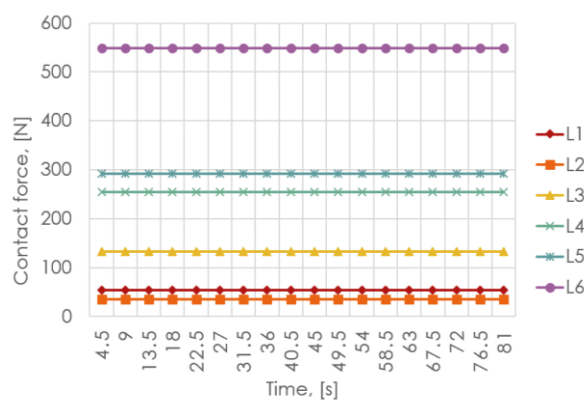


Figure 7. Contact forces for Case I (No T, No F)

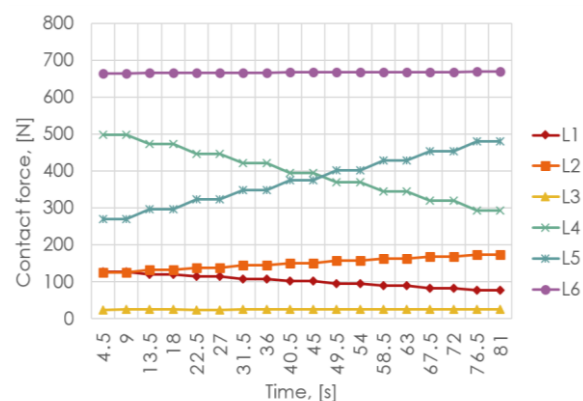


Figure 8. Contact forces for Case II (No T, With F)

For case II, when only the influence of forces and moment of cutting is taken into account, the variation of the contact forces during machining is shown in Figure 8. This is consistent with the results published in the specialty literature.

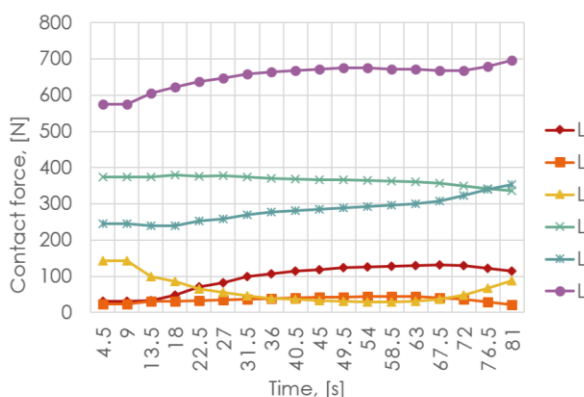


Figure 9. Contact forces for Case III (With T, No F)

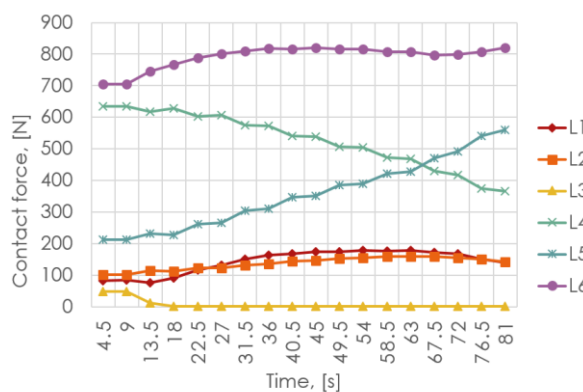


Figure 10. Contact forces for Case IV (With T, With F)

For case III, only the influence of the clamping forces and the cutting temperature on the size of the contact forces is considered. It can be seen, by comparison to the graphic in Figure 8 that the allure of the curves is changing, indicating a certain influence of the cutting temperature on the values of the contact forces.

Case IV is the one in which both loads are considered. The variation of the contact forces during machining is shown in Figure 10.

In order to highlight the variation of the contact forces in the four loading situations, for each of the locators L1,..., L6, the representations in Figures 11...16 were realized.

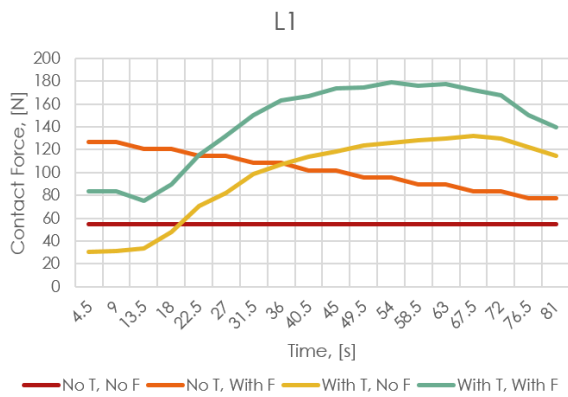


Figure 11. Contact forces for locator L1

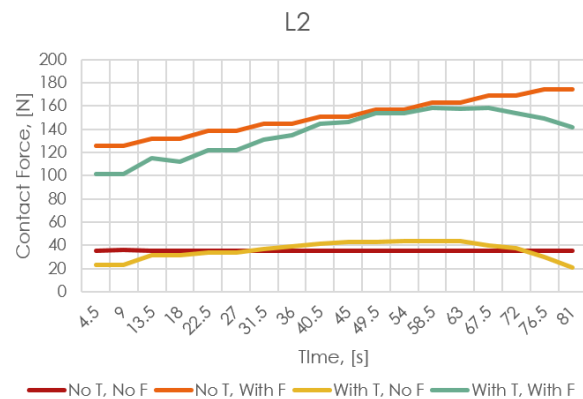


Figure 12. Contact forces for locator L2

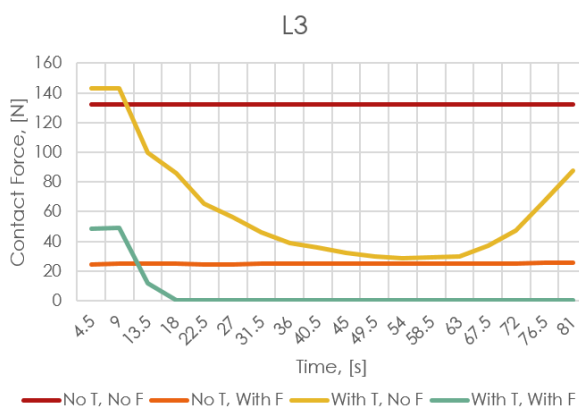


Figure 13. Contact forces for locator L3

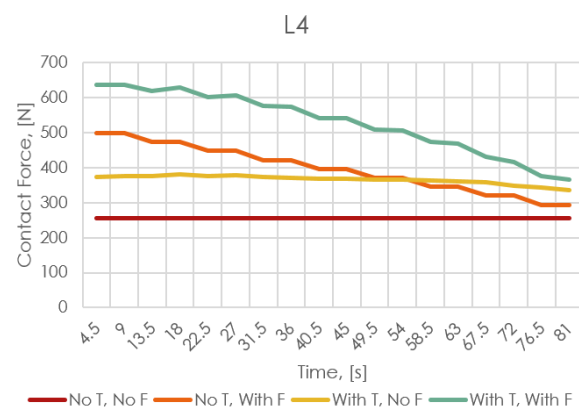


Figure 14. Contact forces for locator L4

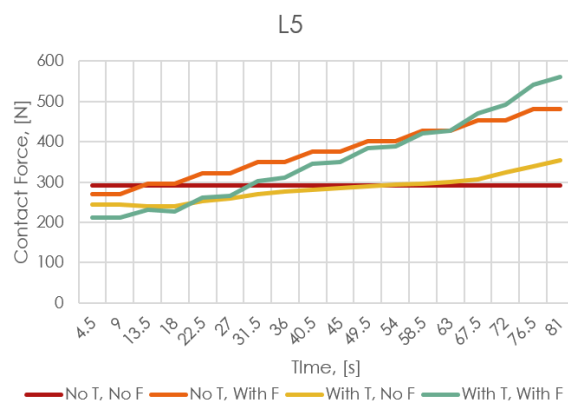


Figure 15. Contact forces for locator L5

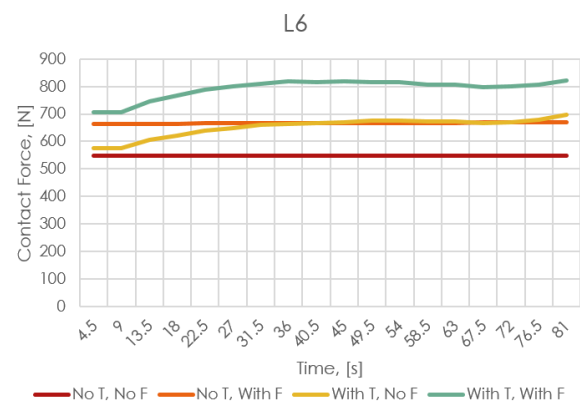


Figure 16. Contact forces for locator L6

Figure 17 shows the variation of the maximum deformation of the evaluated edge for the four loading cases, and Figure 18 for case I and II. It is important to take into account the maximum deformation of the evaluated edge because the edge is the reference element for measuring for the position dimension of the canal.

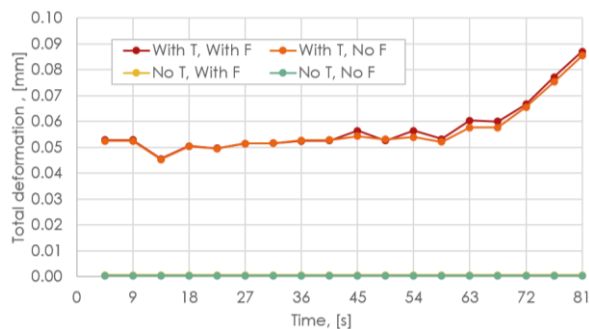


Figure 17. The maximum total deformation of the evaluated edge for Case I, II, III and IV

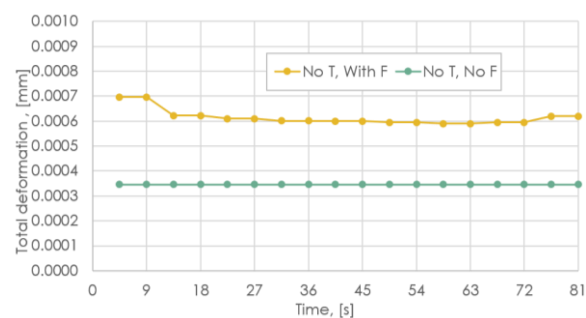


Figure 18. The maximum total deformation of the evaluated edge for Case I and II

4. Conclusions

From the graphical representations from above, it can certainly be inferred that the heat generated during cutting influences the size of the contact forces between the locators of the fixture and the workpiece subjected to machining.

This influence can be manifested in two ways:

- To determine an increase in the contact forces, leading to the destruction of the surfaces of the workpiece by the occurrence of permanent plastic deformations, especially in the case of locators with point and linear contact. This can be seen in Figures 11, 14, 16, when the contact forces between locators L1, L4 and L6 and the workpiece have higher values by approximately 25-30% than those obtained without taking into account the influence of the cutting temperature.
- To determine a decrease of the contact forces, resulting in the slipping of the workpiece on the locators or even in the loss of contact of the workpiece with the locators, which would lead to a compromise of the orientation scheme, with negative consequences on the machining precision. This situation can be seen in Figure 13, when the contact force corresponding to the locator L3 is almost equal to zero.

Clearly, both situations must be avoided.

It can be seen from Figures 17 and 18 that the total maximum deformation increases in the situation when the influence of the cutting temperature is taken into consideration, compared to the situations when it is ignored. If the deformation exceeds the size of the tolerance field of the quota, this could lead to the rejection of the workpiece.

In conclusion, following the simulation it was found that the heat released during the cutting process influences both the size of the contact forces between the locators of the fixture and the workpiece subjected to machining, as well as the machining precision. This is especially important when machining materials with a high conductivity coefficient (aluminium alloys, for example), with cutting regimes which can cause high cutting temperatures.

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