The optimization of the position and the magnitude of the clamping forces in machining fixtures

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Abstract. This paper presents a method which allows the optimization of the position and magnitude of the clamping forces for a specific case of processing: milling of a canal in a prismatic workpiece, using a multi-objective method, implemented with ANSYS software. The design variables are location dimensions of clamping elements, whose range of variation is determined by constructive and dimensional considerations of the workpiece-fixture assembly and the magnitude of the clamping forces. The objective functions of optimization are to minimize the maximum total displacement of the selected edge and to minimize the maximum equivalent stress in workpiece. The constraint is the magnitude of the contact forces between locators and the piece’s surfaces to be greater than zero. Values of the design variables which meet the objective functions were obtained after the simulation was performed.

1. Introduction
In order to make a workpiece by chip removal processes, it is necessary that the workpiece is installed in the machining fixture or directly on the table of the machine tool in a strictly determined position against the trajectory of the cutting tool. The installation of the workpiece has two functional phases: orientation and clamping.

A strictly determined position of the workpiece against the cutting edges and the trajectory of the cutting tool is determined by orientation, this position being maintained during the chip removal process by clamping. In order to achieve the clamping, it is necessary to apply a system of clamping forces which will make the contact of the workpieces with the locators and maintain this contact during processing, while also ensuring a maximum rigidity to the workpiece-fixture assembly, leading to the reduction or elimination of vibrations.

In the practice of designing machining fixtures, the stage of calculation and choosing the points for applying clamping forces is very important because it determines, largely, the accuracy of the processing of the workpiece. Determination of the clamping forces must be made by taking into account the least favorable situations, even if these situations are very unlikely to occur.

Also, the evaluation of the contact forces between the elements of the workpiece-fixture system (locators, workpiece, clamping elements) is very important because their magnitude is not constant during the processing of the workpiece, depending on the cutting forces and moments, which have position and direction which vary during the processing.

The extreme values of the contact forces are very important. The maximum and minimum values of the contact forces are determined according to [1], [2].
The maximum value of the contact force for locators with a plane contact surface, must not exceed:

\[ f_{c_{\text{max}}} = p_{\text{max}} \cdot \pi a^2 = 1.5\sigma_y \cdot \pi a^2 \]  

(1)

in order to avoid the deterioration of the surface of the workpiece (indentation will appear). In relation (1), \( p_{\text{max}} \) is the maximum value of the contact pressure, \( \sigma_y \) is the yield stress of the workpiece material and \( a \) is the radius of the contact area.

At the same time, the minimum contact force, \( f_{c_{\text{min}}} \), must prevent the loss of contact between the workpiece and the locators, and must also prevent the workpiece to slipping from the locators.

The conditions can be written as follows:

\[ f_{c_{\text{min}}} > 0, \]
\[ f_{c_{\text{min}}} \geq \frac{\sqrt{q_x^2 + q_y^2}}{\mu} \]  

(2)

where \( q_x \) and \( q_y \) are components on the x and y directions of the tangential forces which act in the contact area and \( \mu \) is the static friction coefficient between the workpiece and the locators.

2. Literature review

Within the activity of designing the fixtures used at chip removal processes of the workpiece, the optimization of the orientation layout and the optimization of the fixture layout represent a very important phase, as highlighted in various studies and researches.

Therefore, in [3], the authors optimized the clamping forces in order to minimize the elastic deformations in the workpiece-fixture assembly, using an analysis compatible with the ANSYS software, taking into account the material removal effect. They used the balancing force-moment method and Coulomb friction law in order to determine the clamping forces in 5 positions of the machining tool.

In [4], the authors presented a clamping force optimization method, where the locators were assumed as deformable bodies, and the workpiece as a rigid body. They determined the optimal clamping force for which the location error due to the machining forces is minimum.

W. Chen et al., in paper [5], presented an optimization method for minimizing the maximum deformation of the machined surfaces and maximizing the uniformity of the deformation. The optimization method used in this paper is a multi-objective one, implemented using the ANSYS software package.

An optimization method based on genetic algorithm which is used for the optimization of the orientation layout, is presented in paper [6]. The goal of the study is the identification of such orientation layout for which the maximum elastic deformation in various parts of the workpiece is minimum.

In [7], Qin G H et al. lays down the model of the relation between the clamping deformations and the position error. Based on this model, the optimal design of clamping scheme is obtained, which allows the minimization of the position error of the workpiece.

Paper [8] studies the workpiece-fixture interface compliance when the clamping is made using a standard clamping element and respectively, one which is specially designed. The advantages of using a specially designed clamping element, relative to a standard homologue clamping element, are demonstrated by experiments.

In paper [9], authors presents an optimization orientation layout problem of the clamping forces and the number of clamping elements with the goal of minimizing the elastic deformation of the workpiece due to chip removal processes. The workpiece is assumed as elastic body and the fixture elements are assumed as rigid body. The finite element analysis implemented with ANSYS software is
used in order to determine the elastic deformation of the workpiece, caused by chip removing processes, and the clamping forces.

Paper [10] presents an optimization method of the fixture layout for peripheral milling of the low rigidity workpieces. The study is focused on optimizing the number and the positions of the locators on the secondary locating surface. In the first stage, the initial number and the position of the locators are determined by adding locators in the position with maximum deformation. In the second stage, the number and positions of the locators are optimized, so as the precision of the machining to be maintained.

3. Model development for FEA analysis

A situation which is encountered in practice is assumed, namely the chip removal process (milling is performed using a frontal cylindrical mill with a 25 mm diameter) of a canal in a prismatic workpiece having 225x122x122 mm in dimension (Figure 1).

The workpiece is oriented and fixed in a working fixture of type 3-2-1, which can take over 6 degrees of freedom. The 6 locators – L1, L2,…, L6 – are disposed in three mutual perpendicular planes, which intersect in the point 0, this being the origin of the coordinates system attached to the workpiece – fixture assembly. Their shape is cylindrical, with a 18 mm diameter and a plane contact surface.

![Figure 1. 3D model of the workpiece – fixture system](image)

![Figure 2. Cutting toll positions considered for analysis](image)

In Figures 1 and 2, is used the next notation: L1,…L6 – locators, C1 and C2 – clamping elements, Y_C1, Z_C1 – position dimensions of the C1 and X_C2, Z_C2 – position dimensions of the C2.

The Clamping Forces 1 and Clamping Force 2 are applied on the side surfaces of the workpiece through the clamping elements C1 and C1, which are cylindrical shape, with a 25 mm diameter. The material of the workpiece is an aluminium alloy and the locators and clamping elements are made of structural steel. The properties of the materials used in the simulation are presented in Table 1.

| Properties                  | Aluminum Alloy | Structural Steel |
|-----------------------------|----------------|------------------|
| Density [kg/m³]             | 2770           | 7850             |
| Young’s Modulus [MPa]       | 71000          | 200000           |
| Poisson’s Ratio [-]         | 0.33           | 0.3              |
Tensile Yield Strength [MPa]  & 280 & 250 \\
Tensile Ultimate Strength [MPa]  & 310 & 460 \\

The components of the chip removal force and the chip removal moment are calculated according to [11], and their values are: F_x=131 N, F_y=232 N, F_z=55 N and M=2.77 N·m. Total force is:

\[ F = \sqrt{F_x^2 + F_y^2 + F_z^2} = 272 \text{ [N]} \]

For the simulation of the process, the forces and the moment of the chip removal were applied in 9 equidistant points on the top surface of the workpiece, at a distance of 24.5 mm from the evaluated edge (Figure 2).

The solid model of the system chosen to be analyzed was realized in Ansys Design Modeler and then transferred in Ansys Workbench for structural analysis. All the elements of the system have been modeled as isotropic elastic bodies. The locators and the clamping elements have cylindrical shape, the contact surface is plane. Friction is considered at the contact between the locators and the workpiece. A constant static coefficient of friction (0.1) was used to establish contact properties at the interfaces.

To simulate the locators being rigidly fixed in place, the surface of each locator opposite to the contact was restrained in all three translational degrees of freedom. In order to simulate the clamping force, there have been applied single forces over the surface of both fixture elements, in opposite contact.

4. FEA preliminary analysis

In order to have a term of comparison, a preliminary analysis of the workpiece – fixture system is performed, where the clamping elements are situated as follows: Y_{C1} = 112.5 mm, Z_{C1} = 56 mm, X_{C2} = 61 mm and Z_{C2} = 56 mm, and the magnitude of the clamping forces, 640 N and 690 N.

After the analysis, the following results are of interest: the contact forces between locators L1, L2 and L3 and the workpiece, the maximum total deformation of the evaluated edge and the maximum equivalent stress (von Mises stress) in the workpiece. These are presented in the following figures, based on the position of the cutting tool (points 1, ..., 9).

![Figure 3. Contact forces between locators L1, L2 and L3 and the workpiece](image)

By analyzing Figure 3, we can observe that the magnitude of the contact forces between locators L1, L2, L3 and the workpiece varies based on the position of the cutting tool. The three forces are
larger than zero, and the maximum values do not exceed the critical value which would lead to permanent plastic deformations.

![Figure 4. Maximum Equivalent Stress in workpiece](image)

![Figure 5. Maximum Total Deformation of the evaluated edge](image)

As regards the maximum equivalent stress which appears in the workpiece, this too varies depending on the position of the cutting tool, a minimum being observed when the cutting tool is between L1 and L2 (Figure 4).

The maximum total deformation of the evaluated edge presents the same bearing of evolution as the equivalent stress (Figure 5).

5. **Optimization of the magnitude of the clamping forces and their position**

Optimization is made with the goal of determining the optimal magnitude of the clamping forces and their position, so as the stability conditions of the used orientation layout to be accomplished, as well as the precision of the process.

Screening and Response Surface method are used for optimization study. The Screening optimization method uses a simple approach based on sampling and sorting. It supports multiple objectives and constraints as well as all types of input parameters [12].

For this purpose, the following design variables are proposed:
(1) location dimensions of clamping elements and
(2) magnitude of the clamping forces.

The position dimensions of the two clamping elements are specified relative to the origin of the coordinates system: \( Y_{C1}, Z_{C1} \) – position dimensions of the C1 and \( X_{C2}, Z_{C2} \) – position dimensions of the C2.

The variation ranges of the variables are presented in Table 2. The variation ranges of the position quotas are determined based on constructive and dimensional considerations of the workpiece – fixture assembly, and the variation ranges of the clamping forces are determined based on technical specifications of the clamping system of the fixture.

| Design variables | Initial value | Min  | Max  |
|------------------|--------------|------|------|
| \( Y_{C1} \) [mm] | 112,5        | 62,5 | 162,5|
| \( Z_{C1} \) [mm] | 56           | 21   | 81   |
| \( X_{C2} \) [mm] | 61           | 31   | 91   |
| \( Z_{C2} \) [mm] | 56           | 21   | 81   |
| Clamping Force 1 | 640          | 540  | 740  |
| Magnitude [N]    |              |      |      |
| Clamping Force 2 | 690          | 590  | 790  |
| Magnitude [N]    |              |      |      |

The optimization method allows multiple objective functions and constraints. In this case, two objective functions are chosen:

- minimize \( \text{Maximum Total Displacement} \) of the selected edge;
- minimize \( \text{Maximum Equivalent Stress} \) in workpiece;

and three constraints:

- minimum \( \text{Values of the Contact Forces} \) between locators L1, L2, L3 and workpiece must be greater than 0 (zero).

After performing the analysis, optimal values of the design variables were obtained, for which the objective functions and imposed constraints are accomplished. These are presented in Table 3.

The values of the objective functions for the optimal design variables are presented in Table 4.

| Design variables | Initial value | Optimized values |
|------------------|--------------|-----------------|
| \( Y_{C1} \) [mm] | 112,5        | 101,26          |
| \( Z_{C1} \) [mm] | 56           | 50,40           |
| \( X_{C2} \) [mm] | 61           | 54,90           |
| \( Z_{C2} \) [mm] | 56           | 50,40           |
| Clamping Force 1 | 640          | 576             |
| Magnitude [N]    |              |                 |
| Clamping Force 2 | 690          | 621             |
| Magnitude [N]    |              |                 |

The graphical representations from below present a few of the dependences of the objective functions on the design variables, which are useful representations for the stage of orientation and clamping layout, allowing the study of the influence of the variation of the design variables’ values on the objective functions.
Table 4. Objective functions for optimal values of design variables

| Objective functions                                      | Preliminary values | Optimized values |
|----------------------------------------------------------|--------------------|------------------|
| Total deformation maximum maximum value over time [mm]    | 0.012              | 0.0075           |
| Equivalent stress maximum maximum value over time [MPa]   | 1.275              | 1.1620           |
| Contact force L1 minimum total [N]                       | 9.997              | 41.4670          |
| Contact force L2 minimum total [N]                       | 56.678             | 1.0824           |
| Contact force L3 minimum total [N]                       | 2.395e-09          | 0.1857           |

Therefore, the group of figures 6…8 displays the influence of the position of the clamping element C2 on the minimum contact force between the locators (L1, L2, L3) and the workpiece.

Figure 6. Dependence of the minimum contact force between locator L1 and the workpiece on the variables X_C2 and Z_C2

Figure 7. Dependence of the minimum contact force between locator L2 and the workpiece on the variables X_C2 și Z_C2

Figure 8. Dependence of the minimum contact force between locator L3 and the workpiece on the variables X_C2 și Z_C2

Figure 9. Dependence of the minimum contact force between locator L1 and the workpiece on the variables Y_C1 și Z_C1
Figure 10. Dependence of the minimum contact force between locator L2 and the workpiece on the variables $Y_{C1}$ și $Z_{C1}$

Figure 11. Dependence of the minimum contact force between locator L1 and the workpiece on the variables $Y_{C1}$ și $Z_{C1}$

Figure 12. Dependence of the minimum contact force between locator L1 and the workpiece on the magnitude of the clamping forces

Figure 13. Dependence of the minimum contact force between locator L2 and the workpiece on the magnitude of the clamping forces

Figure 14. Dependence of the minimum contact force between locator L3 and the workpiece on

Figure 15. Dependence of the maximum total deformation of the evaluated edge on the
the magnitude of the clamping forces

![Figure 16. Dependence of the maximum equivalent stress on the magnitude of the clamping forces](image)

The group of figures 9…11 displays the influence of the position of the clamping element C1 on the minimum contact force between the locators (L1, L2, L3) and the workpiece.

The influence that the magnitude of the clamping forces has on the minimum contact force between the locators (L1, L2 and L3) and the workpiece is presented in figures 12…14. Figure 15 displays the influence of the magnitude of the clamping forces on the maximum total deformation of the evaluated edge, and Figure 16 displays the dependence of the maximum equivalent stress – magnitude of the clamping force.

6. Conclusions

It is observed that the values of the objective functions are smaller than those resulted in the preliminary analysis, and the constraints are accomplished, in the sense that the contact forces between the locators and the workpiece are larger than zero, which means that during the processing, the workpiece doesn’t lose the contact with the locators, thus the orientation layout is preserved and the process is performed in adequate conditions of precision.

At the same time, comparing the values of the objective functions for the initial values and the optimal ones of the design variables, it is observed that smaller values were obtained for the total maximum deformation of the evaluated edge and the equivalent maximum stress in the workpiece. Also, the optimal values of the clamping forces are smaller, which implies a reduced energy consumption, and the contact forces are bigger than zero, which means that the integrity of the orientation layout is maintained.

By studying the graphical representations in figures 6…16, it can be noticed that for certain values of the position dimensions of the clamping elements, the magnitude of the contact forces is close to zero, which would lead to the compromising of the orientation layout. These representations are useful in order to avoid those areas for applying clamping forces by using clamping elements.

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