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Abstract

Purpose – The purpose of this paper is to propose a general model for locating and clamping workpieces of complex geometry with two skewed holes under multiple constraints.

Design/methodology/approach – Numerous constraints related to application of the proposed model are discussed as prerequisite to design of fixture solution. Based on theoretical model, a fixture was designed and successfully tested in experimental investigation. Experimental results were also verified using FEM simulations.

Findings – This study showed that, opposed to conventional approach, novel solution results in significantly smaller fixture dimensions, while providing greater stability. Insertion of mandrels and supports element sub-assemblies into the workpiece holes significantly increases workpiece stiffness through an increased moment of inertia, while the internal support elements largely diminish the problem of thin wall deformation in the workpiece.

Practical implications – The fixture designed in this case was actually used in industrial application to accommodate a thin-walled casting of gearbox housing, where it proved to be a very stable framework. It can be used in industry without any major readjustments.

Originality/value – According to available literature, this work is the first successful implementation of a fixture solution in which the problem of multiple constraints is solved by attaching centering elements, support sub-assemblies, and other fixture elements to the internal workpiece walls, and then locating them in the second part of the fixture.

Keywords Fixture, Layout optimization, Stability, Skewed holes, Plant layout, Machine tools

Paper type Case study

Introduction

In order to machine surfaces on a workpiece using the desired cutting tools, it is necessary to set up the workpiece and tools on a selected machine tool and give them appropriate primary and auxiliary motions. Moreover, the workpiece and tools must be positioned relative to each other and relative to particular machine tool elements, while the workpiece must be properly located and clamped. Fixtures are devices used for quick and reliable workpiece locating and clamping, to guarantee machining within required tolerance. They are also used for any other operation, e.g. welding, assembly, inspection, etc. (McKeown and Webb, 2011).

Fixtures directly influence machining quality, material removal rate, and manufacturing costs. Costs related to fixture design and manufacture amount to 10-20 percent of the total manufacturing costs (Bi and Zhang, 2001). These costs are also related to fixture design (Vukelic *et al.*, 2011). Thus, fixture design plays an important role at the planning stage before shop floor production. Optimization of fixture layout is a critical aspect of machining fixture design, defining the types, number, and material of fixture elements, and their position relative to workpiece. It is considered optimal if minimizing workpiece deformation.

Literature review

Numerous approaches have been used to determine optimal fixture layout, such as: the finite element approach, mathematical approach, geometrical approach, etc. Also, various computational techniques have been used for optimization of fixture design: genetic algorithms (GA), artificial neural networks (ANN), as well as the combination of methods: finite element analysis (FEA) and GA, GA and ant colony algorithm (ACA), ACA and FEA, etc.

Deng and Melkote (2006) presented a model-based framework for determining the minimum required clamping force that ensures dynamic stability of a fixtured workpiece during machining. Siebenaler and Melkote (2006) presented a FEA fixture-workpiece model to investigate influence of various parameters on workpiece deformation, including the

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compliance of the fixture body, contact friction, and mesh density. Tian *et al.* (2006) presented optimal selection of workpiece locating positions and identified feasible clamping regions that meet the requirements of the form-closure principle for fixture layout. Qin *et al.* (2006) proposed analysis and optimal design of fixture locating scheme. Liu *et al.* (2007) optimized the number and positions of locators, however, only on the secondary locating surface. Ratchev *et al.* (2007) addressed this knowledge gap by proposing a fixture-workpiece behaviour prediction methodology using FEA to predict complex fixture-workpiece behaviour during machining processes. Asante (2010) investigated the effect of fixture compliance and cutting conditions on workpiece stability. He used the minimum eigenvalue of the fixture stiffness matrix – which represents minimum displacements at the contact points – locating and clamping elements, as well as the largest displacement of the workpiece due to the cutting forces to assess the stability of the workpiece. Hazarika *et al.* (2010) developed setup planning methodology for prismatic parts generating optimal layout of locating and clamping elements, and providing their sizes. The objective was to minimize the maximum of locating elements reaction forces during machining. Layout was optimized as constrained optimization problem and solved using nonlinear optimization. Vishnupriyan *et al.* (2011) determined optimal fixture layout to minimize the machining error considering locator geometric error and workpiece elastic deformation. Chaari *et al.* (2011) presented a modelling methodology for geometrical machining defect. The kinematical deviation due to part locating and relocating is modelled by homogeneous transformation. Dynamic displacements caused by clamping and machining force are determined by FEA. Tadic *et al.* (2012) proposed an approach to workpiece clamping based on plastic deformation of workpiece in predefined narrow zones, and analyzed load capacity and interface compliance. Vishnupriyan (2012) investigated significance of system compliance and workpiece dynamics as the two critical sources of machining error. Components of machining error were computed for different layouts and various clamping forces.

Contributions involving application of artificial intelligence can be found in a number of additional papers (Krishnakumar and Melkote, 2008; Kaya, 2006; Siebenaler and Melkote, 2006; Prabhaharan *et al.*, 2007; Chen *et al.*, 2008; Padmanaban and Prabhaharan, 2008; Lu *et al.*, 2011; Zuperl *et al.*, 2011; Selvakumar *et al.*, 2012).

Other examples of fixture design and optimization can be found in review papers (Kang and Peng, 2008; Pehlivan and Summers, 2008; Leopold and Hong, 2009; Wang *et al.*, 2010; Boyle *et al.*, 2011).

The presented investigations considered optimal location for certain fixture elements – predominantly locating and/or clamping elements. Most frequently, goal function was minimization of workpiece deformation under the influence of forces. In this way, it is possible to define all suitable locations for particular fixture elements.

Also, majority of investigations dealt with workpieces of a relatively simple geometric form. They considered a single-operation context, typical of conventional machine tools where a single surface is machined with a single tool. The developed fixtures were highly specialized, designed for prismatic and rotational workpieces, and specific machining processes. Modern manufacturing requires fixtures capable of reliable locating and clamping of complex-geometry workpieces, which are machined in a single setup, with multiple tools in various cutting planes. Modern cutting tools yield the best manufacturing and economic effects when operated at maximum cutting regimes (Pokorny *et al.*, 2012). Advances in cutting tool materials, tool geometry, coatings, and wide selection of cutting tools, have enabled rigorous machining conditions which confront machining fixtures with serious theoretical and engineering problems. There are numerous industrial examples where fixtures cannot withstand cutting forces generated by most intensive cutting regimes.

Moreover, such fixtures must also meet additional constraints:

- Overall dimensions ratio between machine tool work table and workpiece is close to one.
- Numerous machining operations in a single setup, in several cutting planes.
- Very narrow tolerances on a large number of dimensions.
- Machining of castings with relatively thin walls in particular cross-sections.
- Machining of castings with relatively high form errors, large cone angle deviations in openings, and significant deviations of linear measures.
- Machining of castings with two skewed holes.
- High material removal rates.

This paper presents theoretical analysis of the problem, proposes a locating and clamping model for a general case of a complex-geometry workpiece, and provides an extensive case study of the fixture design which meets all the requirements and constraints. The design features a 0.84 table/workpiece length ratio, and functions reliably in practice as one of the fixtures used on a HURCO 500 horizontal machining center. A general case of locating and clamping of a complex-geometry workpiece is considered, under multiple constraint conditions. Fundamental problems are identified and arguments presented for the suggested locating and clamping solutions under multiple constraints. Within the case study, a concept fixture solution, detailed fixture design, and FEM analyses are presented. Parameters which define fixture stiffness in various cutting zones are defined. Considering the workpiece displacements in the fixture, which contribute to machining errors, this allowed the determination of maximum cutting forces within the limited (allowed) range of workpiece displacements in particular cutting zones. Thus, prerequisites were created for optimization of cutting tool selection, and selection of cutting parameters which provide maximum material removal rate. Special attention was placed on the determination of complex boundary conditions for FEM analysis.

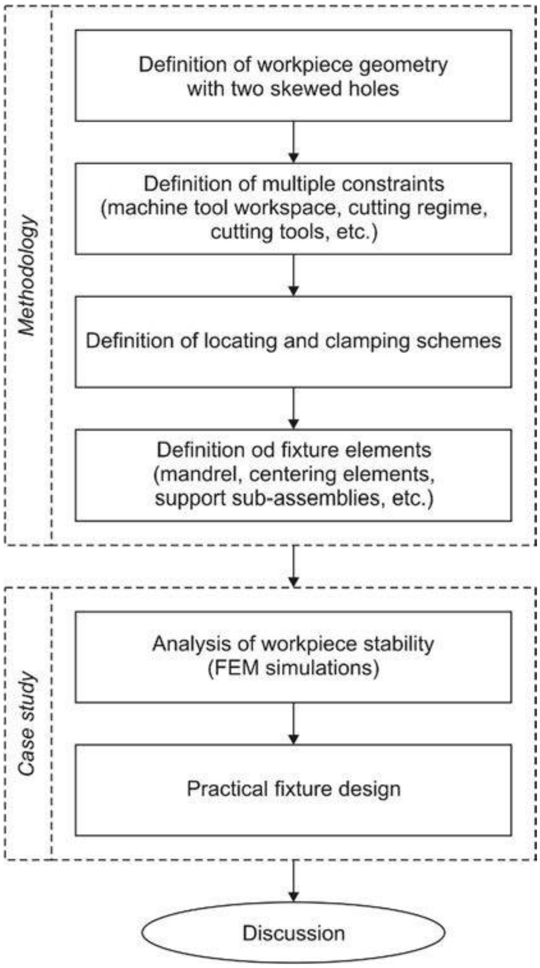
To allow readers to better grasp the basic idea behind this investigation, shown in Figure 1 is a flow chart which illustrates all basic steps.

Methodology

General model is presented for locating and clamping workpieces of complex geometry with two skewed holes under multiple constraints. In industrial practice, castings of such geometry (Figure 2) are most often used for gearbox housings, transmission housings, and housings of multiplicators for various machine types.

A general case of locating and clamping complex-geometry parts with two skewed holes is considered (Figures 3 and 4).

Figure 1 Flow chart showing all basic steps conducted in this investigation



Machining is performed on horizontal machining centers in two machining processes, and a large number of operations (cutting tool changes). The first machining process, which is considered in this paper, involves milling of surfaces P_1, $P_2, \ldots, P_i$ (Figure 3), which form the primary locating surface for the second machining process. Next, two auxiliary holes are drilled, O_1 and O_2, which also serve for workpiece locating in the second machining process. Finally, also required are all other machining operations in which the surfaces P_1, $P_2, \ldots,$ P_i either lie on the *Y-Z* plane or parallel to it. In the second process, the machining is performed in holes and on all other workpiece surfaces except the surface containing segments P_1, $P_2, \ldots, P_i$. As is common with complex-shape castings, present within the entire workpiece volume are significant external and internal geometric form deviations (circle, square, rectangle, etc.).

On the outer workpiece contour (Figure 3), only surface segments P_1, $P_2, \ldots, P_i$ are lying on an ABCD surface area with relatively small deviations, i.e. they are parallel to the *Y-Z* plane. As previously mentioned, the process plan requires that the surface segments P_1, $P_2, \ldots, P_i$ be brought into the plane by milling, and used as the primary locating surface in the second machining process. However, such choice of machining sequence – favourable for solving locating and clamping problems in the second process – leaves the first machining process (Figures 3-5) without the proper locating surfaces on the remaining outer surfaces.

The basic problem is related to complex workpiece geometry and the constraints related to overall dimensions of the machining center work table, which does not provide space for a stable fixture. Furthermore, it often occurs that hole walls get thinner at the ends, with complex geometry and wide casting tolerances. Even without the work table dimensions constraint, there remains the problem of reliable clamping, especially given the requirements for high removal rates.

Therefore, the authors based their work on the idea that locating and clamping of complex-geometry workpieces, under the discussed constraints, can be successfully realized by attaching particular centering elements, support sub-assemblies, and other fixture elements to the internal workpiece walls, and then locating this assembly in the second part of the fixture.

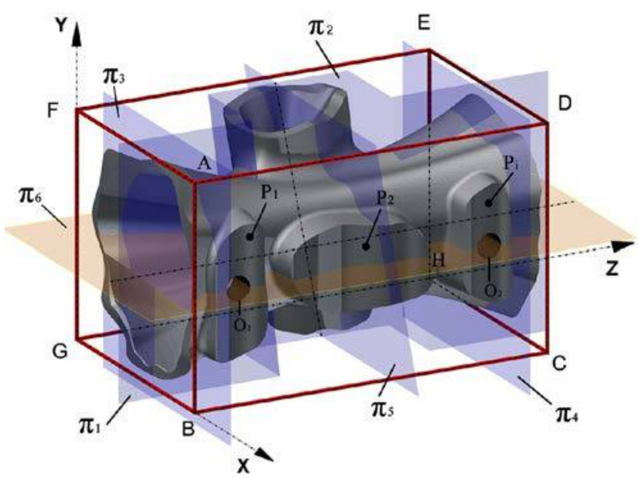
This concept of fixture design should result in significantly smaller overall fixture dimensions, while providing greater stability. It should have a positive effect on accuracy and surface quality in both the first and the second machining processes.

Shown in Figure 4 is a 2-D locating scheme of a complex-geometry workpiece whose 3-D model is shown in Figure 3. The locating scheme shown in Figure 4 corresponds to the staggered cross-section through π_1 and π_2 planes marked in Figure 3 (both hole axes are encompassed). The workpiece is centered along the longitudinal *Z*-axis and clamped from the internal rib contours, k_1 and k_2, in the zone formed by three points. Centering is also performed alongside the traverse skewed axis (Y_1-axis) and the workpiece is clamped from contours k_3 and k_4 in the zone formed by the three points. After inserting support elements in the cross-sections in planes π_3 and π_4 (Figures 3 and 4), the carriers of centering and clamping elements are fastened to the external part of the fixture, which is in the form of a closed frame. The longitudinal carrier is fastened to the closed carrying frame at points B_{xy1} and B_{xy2}. It is fastened in a way which prevents any displacement or rotation of the workpiece alongside the *X* and *Y*-axes. In other words, the workpiece has four degrees of freedom constrained. The traverse carrier of the centering and clamping element is fastened to the exterior carrier frame at point B_2, which prevents workpiece displacement in the *Z*-axis direction, thus constraining the fifth degree of freedom. Under forces F_{y1} and F_{y2} (Figure 4) the workpiece rotates around the *Z*-axis until surfaces P_1, $P_2, \ldots, P_i$ (Figure 3) approximately coincide with the surface bounded by points ABCD. The workpiece is blocked in that position by blocking the position of point B_2 on the traverse carrier of the centering and clamping elements in the Y_1-axis. Prior to blocking, support elements must be set in cross-sections defined by planes π_3 and π_4.

The support elements in the π_3 plane are located in the space constrained by contour k_{p3} (Figure 4) and provide contact with the internal workpiece contour, k_{u3}, for instance, in the zone formed by points A_3, B_3, and C_3. The support elements in the π_4 cross-section are located within the space constrained by contour k_{p4} (Figure 4) and provide contact with the internal workpiece contour, k_{u4}, for instance, in the zone formed by points A_4, B_4, C_4, D_4, E_4, and F_4. Once the formed sub-assemblies of internal support elements, the workpiece, and the centering and clamping elements are fixed

Figure 2 Castings of complex geometry with skewed holes

Figure 3 3-D model of complex-geometry workpiece with skewed holes



to the closed frame via their respective carriers, at points B_{xy3}, B_{xy4}, B_{xy5}, and B_{xy6}, the workpiece is supported by holes in the zone formed by many points. Supports at points B_3, D_4, E_4, and F_4 represent low stiffness spring supports, which allow contact with other contact points of the remaining rigid support elements within the internal contour segments k_{u3} and k_{u4} prior to attaching the support elements' sub-assemblies to the external part of the closed fixture frame. The support elements are not in contact with the carriers of centering and clamping elements. Instead, the support elements' sub-assemblies are distanced from these elements by clearances z_1 and z_2. This allows the contact between the support elements and internal workpiece walls to be maintained at several points and their attachment to the external closed fixture frame, without significant loads on the thin workpiece walls. The locating scheme (Figure 4) shows the support elements in π_3 and π_4 cross-sections. However, support elements sub-assemblies can be positioned elsewhere, for example, in plane π_y, and then attached to support elements in other planes, as well as to the external fixture framework in the form of a closed frame.

The following is analysis of loads on the fixture elements built into the internal workpiece section, considered in the *X-Z* plane. Shown in Figure 6 is load scheme for the considered workpiece. Figure 6 pertains to cross-section in plane π_6 (Figure 3). Based on the proposed locating and clamping scheme, the workpiece is generally supported in zones formed by S_1-S_{14}. Since, in the majority of cases, a closed-frame fixture framework can be rendered very stiff, the displacements of that particular section are disregarded during machining error assessment. The centering element (long mandrel) has clamped supports within the zones defined by points B_{xy1} and B_{xy2}, and provides workpiece support within the zone defined by points S_3-S_6. In other words, the long mandrel can be considered as a beam clamped at points B_{xy1} and B_{xy2} which are located in lateral, fixed walls. The stiffness of such workpiece support predominantly depends on dimensions L, l_2, d_1, and d_2 (Figure 6).

Support elements can be designed in a way which provides very stiff workpiece supports in the zone defined by points S_1, S_2, S_6, and S_7. It is also possible to design the short mandrel centered along the Y_1-axis (Figure 4) in a way which provides very stiff workpiece supports in the zone defined by points S_9-S_{14} (Figure 6). These points lie on the contours k_3 and k_4 (Figure 4).

Under the impact of the F_{xz} cutting force, which is acting in point C (Figure 6) in the *X-Z* plane, the workpiece and all other fixture elements are deformed. There is a complex stress

Figure 4 Locating scheme with mandrels and internal support elements

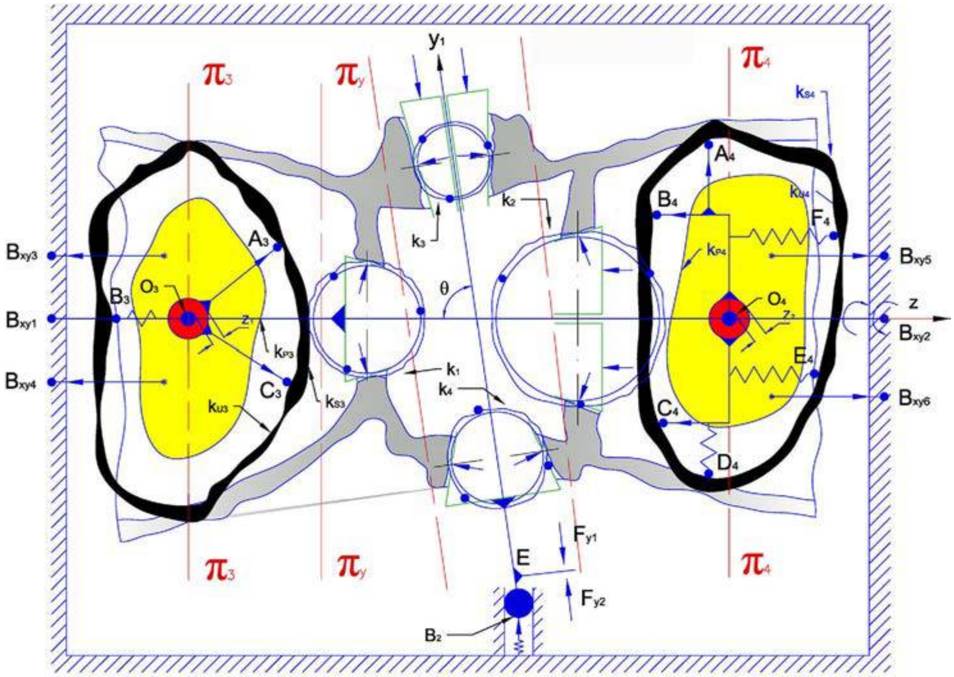


Figure 5 3-D model of workpiece with built-in mandrels on internal support elements

and strain state within the discussed support zones. Stresses are concentrated in the neighborhood of points S_1-S_{14}. The exact distribution of such stresses in real fixture systems is never known, especially for fixtures which accommodate complex-geometry castings. The most critical deformation from the workpiece centering aspect is the deformation of the long mandrel, which provides supports at points S_3-S_6.

In general, the most critical case of workpiece dimensional accuracy occurs when:

- Diameter d_3 (Figure 6) is small. This results in small stiffness of the short mandrel, causing high elasticity of supports S_9-S_{12}, which fail to contribute to the overall stiffness of the fixture.
- Workpiece length, L, is very large relative to dimension l_2, i.e.:

$$L >> l_2,\ \ l_2 \rightarrow \varepsilon \ \text{and}\ \ l_1 \approx \frac{L}{2} \tag{1}$$

where ε is a low-order value.

The equation of the elastic line e of the long mandrel (Figure 6) can be derived starting from the general form of the elastic line differential equation. This differential equation is of the following form:

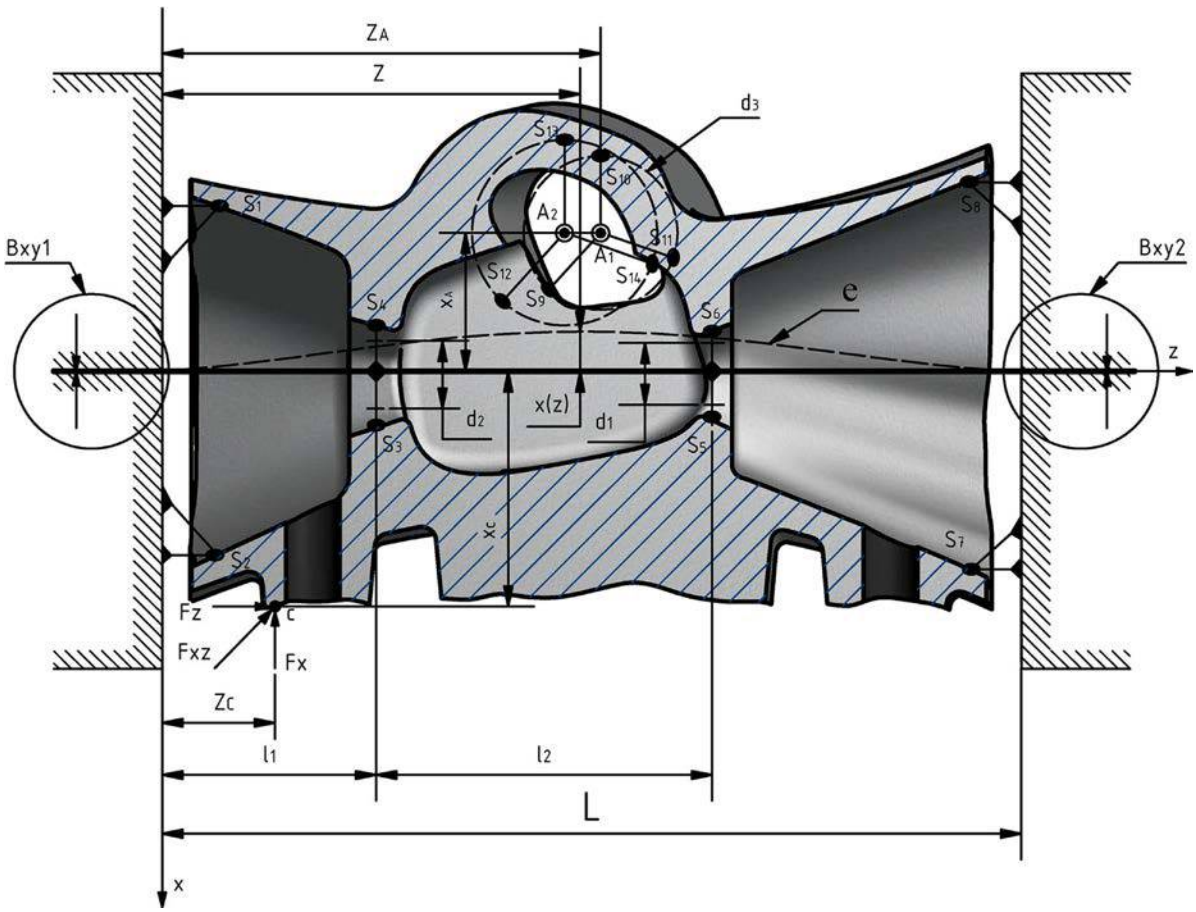
$$E \cdot I \frac{d^2x}{dz^2} = M(z) \tag{2}$$

where E – elasticity module of the long mandrel material; I – moment of inertia of the long mandrel cross-section; $M(Z)$ – function of moments about the Z-axis.

Considering the conditions stated under (a) and (b), the solution of this differential equation provides the elastic line of the following form:

$$x(z_c) = \frac{F_x \cdot L^3}{6 \cdot E \cdot I} \cdot \left(\frac{L - z_c}{L}\right)^2 \cdot \left(\frac{z_c}{L}\right)^2 \cdot \left[3 \cdot \frac{z_c}{L} - \left(\frac{L - z_c}{L} + 3 \cdot \frac{z_c}{L}\right) \cdot \frac{z_c}{L}\right] \tag{3}$$

Figure 6 Workpiece load scheme in the *X-Z* plane



Cutting force component along X-axis, F_x, in expression (3) is used to calculate the deflection of long mandrel. Maximum deflection was obtained for F_x acting at the middle of the long mandrel, i.e. $z_c = L/2$.

The second mandrel is also a cylinder with the radius of $d \leq \min(d_1, d_2)$ and the following moment of inertia:

$$I = \frac{d^4 \cdot \pi}{64}. \quad (4)$$

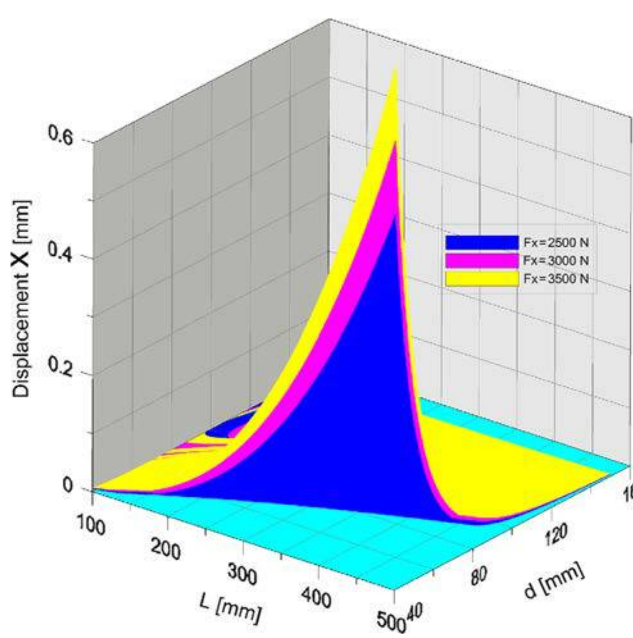
In this case, the equation for the maximum displacement along the X-axis reads:

$$x = \frac{64 \cdot F_x \cdot L^3}{192 \cdot d^4 \cdot \pi} \quad (5)$$

Shown in Figure 7 is a 3-D diagram of the dependence of displacement x on the mandrel diameter d, the distance between the clamped supports L, i.e. mandrel length, and the magnitude of force F_x. The diagram shows that, given the high simulated loads, the displacements are small, even in this most critical case with a wide range of parameter values. The displacements obtained by the simulation represent the maximum machining error, which is the result of the centering error along the X-axis.

This locating and clamping model can be combined with conventional methods, including the use of external

Figure 7 Dependence of maximum displacement of the long mandrel along the *X*-axis at the distance between full-moment supports, L, mandrel diameter, d, and force, Fx



supporting elements and the introduction of external forces to provide sufficient clamping force.

The proposed model is general, and its advantages over conventional methods can be summed up as follows:

- The overall fixture dimensions are reduced to fit the dimensions of the worktable, while at the same time allowing accommodation of large workpieces. Fixture elements attached to internal workpiece walls provide reliable locating from the closed fixture frame which is inherently compact.
- Considering machining allowances, the functions of internal holes (which most often accommodate bearings, shafts, gears, and similar), as well as the theoretical and practical aspects, locating should be performed from the holes, to avoid errors due to non-coincident datum and locating planes. Besides, the second machining process is focused on hole machining which can cause problems to cutting tools' stability and high material removal rates, especially in the case of long holes. In this respect, the proposed scheme of locating from holes provides optimum allowances for internal machining.
- The proposed system significantly increases workpiece stiffness in fixture. The built-in locating and clamping sub-assemblies and elements which support the thin-walled workpiece at several points, substantially diminish local deformations in the cutting zones, and greatly increase the overall stiffness of the entire fixture system due to increased inertia momentum. The inertia momentum is increased by attaching fixture elements to internal workpiece walls.

Case study

In this case study the problem of locating and clamping of a cast gearbox housing (Figure 8) in the first machining process is considered. Several details are worth noting:

1. The process plan schedules the machining on a horizontal machining center HURCO-500 in two machining processes. The first process (Figure 9) requires:
   - machining of surface P_1 which serves as the main locating surface for the second machining process;
   - drilling of two holes to allow workpiece centering in the second machining process using locating pins; and
   - a number of drilling and threading operations.

The second machining process requires machining with a number of cutting tools in various cutting planes. Figure 9 shows the workpiece and cutting tools used in both machining processes.

2. Maximum productivity is required. As discussed, the crucial point is the design of highly reliable fixtures which provide workpiece stability in high-productivity manufacturing, i.e. the fixture and workpiece must sustain extreme cutting forces.
3. In some workpiece cross-sections (Figure 8) wall thickness is relatively small, affecting workpiece stability due to extremely limited clamping forces. Preliminary FEM analysis showed that, if applied, the required clamping forces cause significant workpiece deformations. This, in turn, increases machining errors.
4. In the first machining process, complex workpiece geometry, casting drafts, and a number of dimensional deviations on cast gearbox housings with various tolerance ranges, complicate location from the aspect of cutting tool stability and machining allowances, hole operations are most demanding (Figure 9). There are also a number of functional workpiece dimensions which are tightly toleranced. Through a number of analyses it has been established that the general locating and clamping schemes shown in Figures 4 and 5 provide reliable workpiece locating and clamping, and satisfy all the discussed constraints.

Figure 8 Gearbox housing with two skewed holes used in the case study

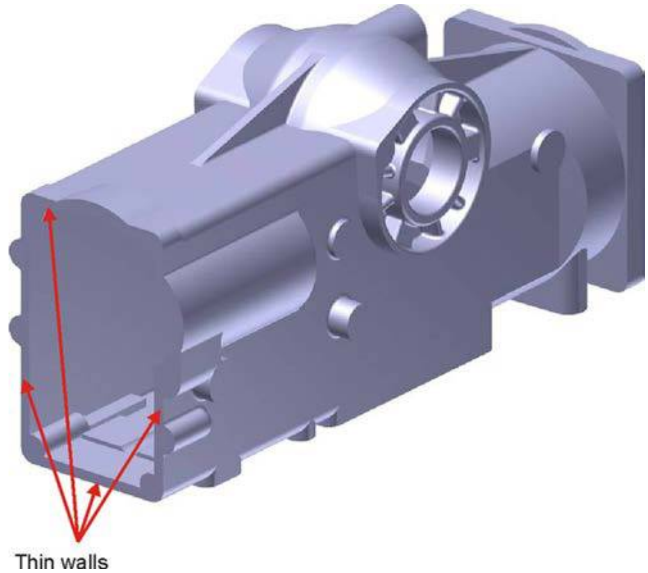
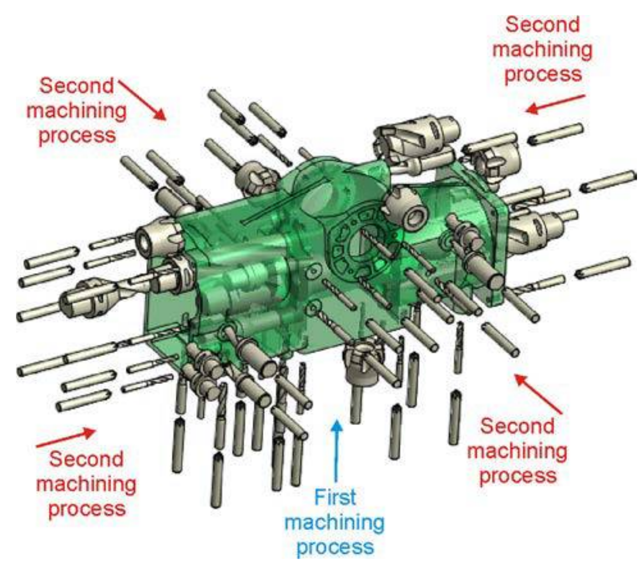
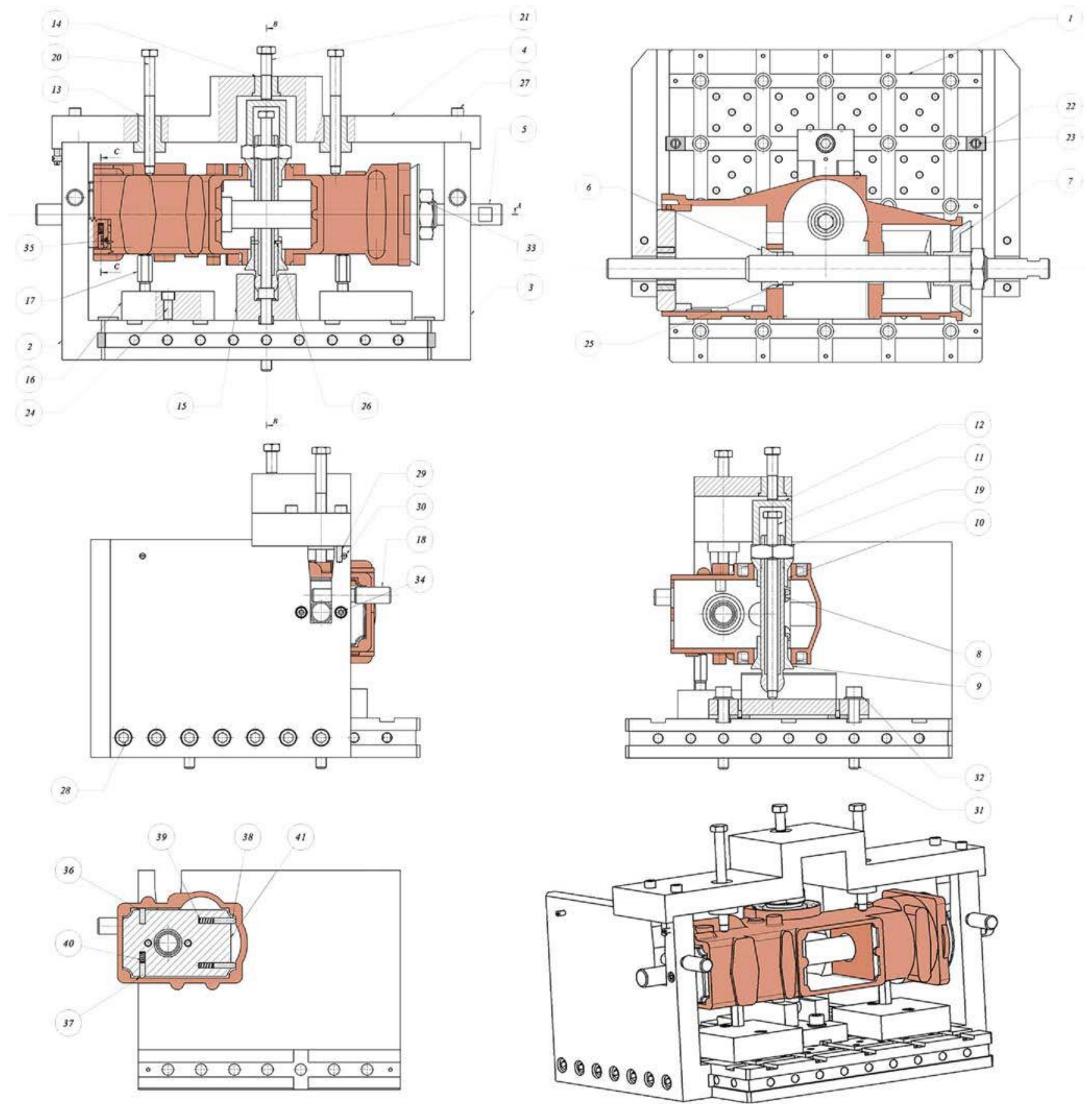


Figure 9 Gearbox housing and cutting tools required for the first and second machining processes



Fixture design for the first gearbox housing machining process is shown in Figure 10. The assembly, as well as the workpiece locating and clamping sequences are also shown in 3-D, in Figure 11 (a)-(e). Figure 12 shows a photo of the real fixture, designed and assembled for the first machining process on the gearbox housing.

Figure 10 Fixture design for the first machining process on the gearbox housing



The proposed fixture design meets the basic constraint regarding the small work table on a HURCO-500 machining center. Shown in Figure 13 are palette trajectories and fixture footprint diameter.

Fixture design shown in Figures 8-10 allows correct workpiece location in limited space, primarily due to locating from the two skewed holes. The workpiece also gets favourable orientation in the fixture, which is dedicated to the second machining process. The orientation also allows machining with minimum tool overhangs, which increases their stability, life, and productivity. Moreover, maximum material removal rate requires extreme cutting regimes, which, in turn, requires high workpiece stability in the fixture.

Workpiece stability in fixture was analyzed in FEMAP, using 15,496 tetrahedral finite elements, and a total of 29,737 nodes. The workpiece material was nodular cast iron GJS 500-7, elasticity module 169 GPa. Fixture elements were made of carburizing alloy steel and tempering steel. Special attention was given to boundary conditions which are best seen on the 3-D model given in Figure 14. Marked in red are the contact zones, blue denotes supports, clamped supports, and other boundary conditions.

Figure 11 Fixture assembly sequence, and workpiece locating and clamping shown in 3-D

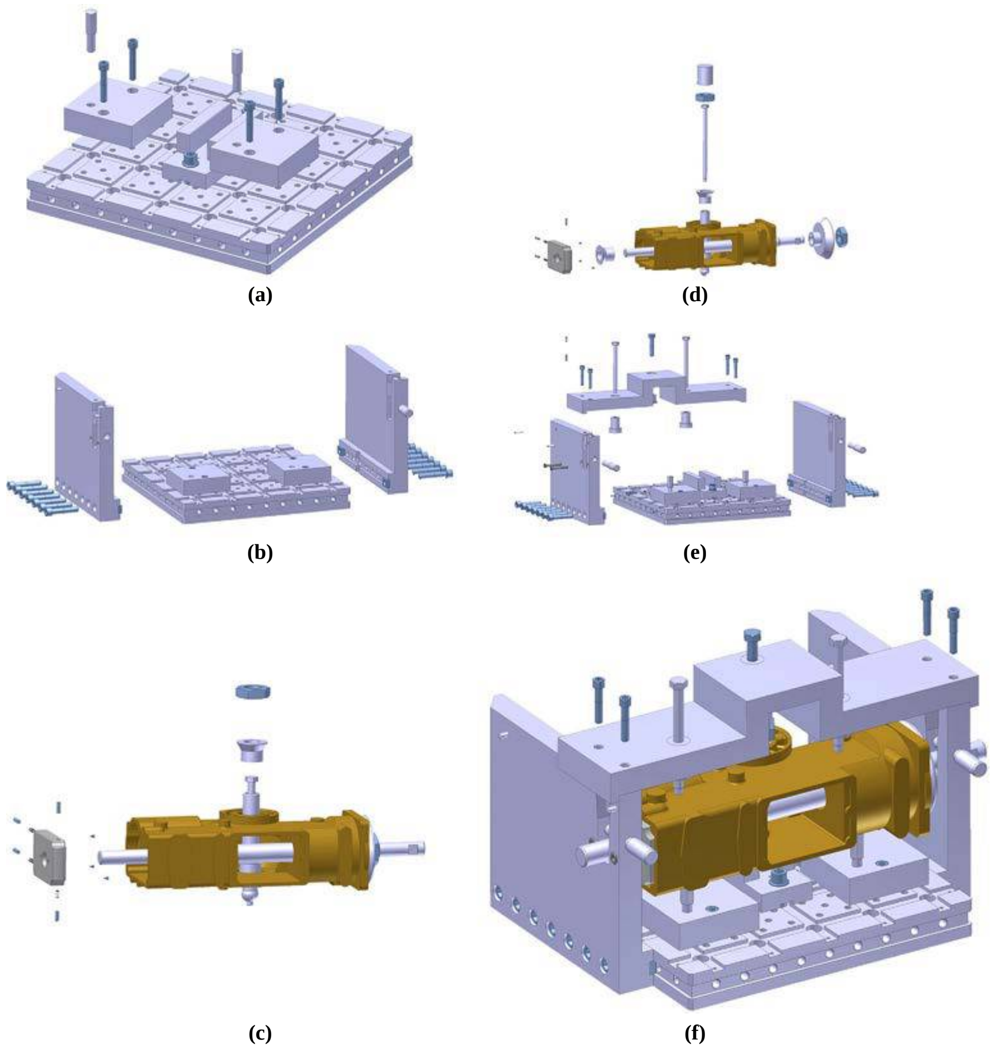


Figure 12 Photo image of the fixture used in the first machining process

Figure 13 Palette trajectories on the HURCO-500 and fixture footprint diameter

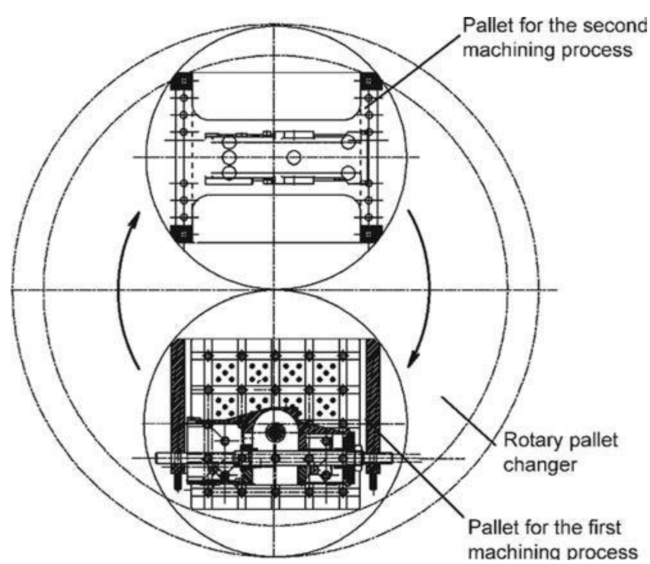
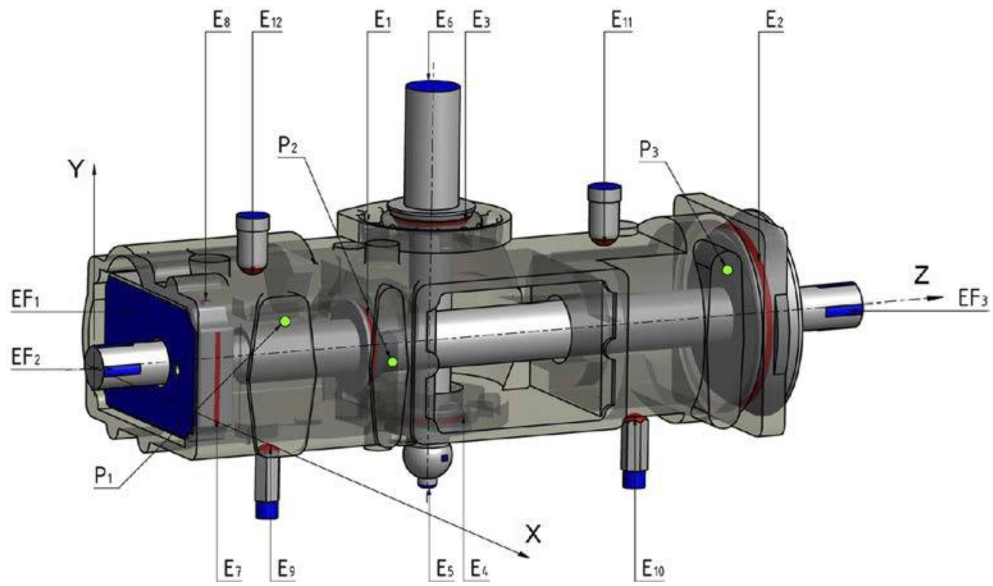


Figure 14 Workpiece with the marked locating and clamping zones – boundary conditions



The following holds regarding the boundary conditions:

- Within the contact zone between both cones of the long and short mandrel and internal workpiece walls (Zones E1 and E2, i.e. E3 and E4), the screw nut exerts high pressure. Thus, within the narrow zones in the shape of the cone ring, there are supports whose elasticity is defined by the stiffness of the long, i.e. short mandrel assembly.
- The screw, which runs through the short mandrel (Pos. 11 – Figure 10) is preloaded and can be considered as pressed against the base modular plate in the neighborhood of point E5 (Zone E5).
- The hollow cylinder (Pos. 12 – Figure 10) is tightened by the screw (Pos. 21 – Figure 10) placed on the top plate. Considering the top plate's high stiffness the contact between the screw and hollow cylinder (Zone E6) virtually represents another support element for the workpiece.
- The support element sub-assembly (Pos. 41 and 36-40 – Figure 10) provides workpiece support in zones E7 and E8 (Figure 14). The support element sub-assembly is attached to the closed fixture frame over EF1 and EF2 surfaces, which, given the stiffness of the thin-walled workpiece, can be considered a rigid body.
- Support elements placed on the base modular plate provide support over the contact surfaces defined by zones E9 and E10.
- The ends of the long mandrel are inserted into the grooves of lateral carrier plates (Pos. 2 and 3 – Figure 10) with an overlap of 0.01 mm. These grooves limit movements of the long mandrel along the *X*-axis. Lock pins (Pos. 18 – Figure 10) limit the movements of the long mandrel along the *Y*-axis. For these reasons, the ends of the long mandrel are considered clamped along the *X*- and *Y*-axes (Zones EF1 and EF2).
- Clamping zones (Zones E11 and E12) are the result of contact between the screws and the workpiece. This, in part, balances the cutting forces. Presumably, clamping forces applied by the screws (Pos. 20 – Figure 10) provide enough friction to prevent slipping at the clamping screws/workpiece interface. The analysis took into consideration the elastic deformation (displacement) of the clamping screws, considering that they are attached to the top plate (Pos. 4 – Figure 10) of the closed fixture frame while being located at some distance from the clamping zone (Zones E11, and E12).

Generally, contact areas cannot be exactly determined, primarily because the workpiece is a casting with rough surfaces and significant geometric form errors. However, considering the values of elastic modulus of the support elements and workpiece materials, the shape of contact surfaces, the possible magnitudes of loads, as well as the results of contact stress analyses, the contact surface areas in the neighborhood of particular points and lines are small. Therefore, the FEM analyses assumptions regarding items (a)-(g), were following: the workpiece is supported by fixture support elements whose area sizes range from 0.2 to 5 mm^2, depending on the type of particular contact. In the repeated FEM analyses, contact area sizes of particular contacts were varied in a relatively wide interval of 0.1-10 mm^2 without noticeable changes in results.

FEM analysis of workpiece and fixture loading was conducted in order to establish maximum loads in the cutting zones for which displacements in respective axes do not exceed 0.03 mm. This boundary displacement was based on allowed machining error and an appropriate safety factor which compensates for miscellaneous influences (errors of fixture manufacture and assembly, uneven machining allowances, increase of cutting forces due to sand inclusions in castings, etc.). Simulated loads were equivalent to maximum cutting forces allowed for the particular workpiece. These forces were used for analysis of the maximum cutting regime, cutting tools geometry, and process plan optimization. Thus, boundary conditions were set for the selection of cutting tools (selection of cutting tool geometry) to allow maximum material removal rates considering workpiece stability in the fixture and optimum process plan.

FEM analyses were conducted for all cutting zones. Intensities, directions, and senses of cutting force vectors were varied (Figure 15). As a result, most critical directions, senses and intensities which yield maximum displacements were identified, which is crucial for analysis of the proposed model.

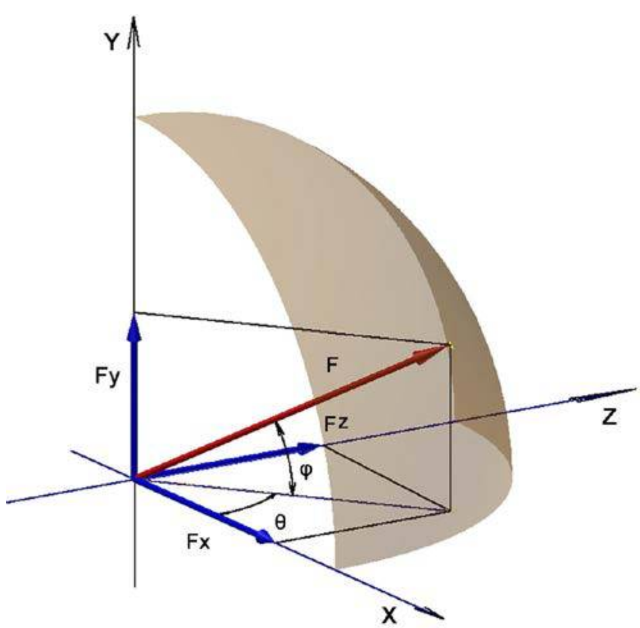
Shown in Figure 14 is a selection of just three cutting zones (operations: milling, drilling, reaming, countersinking, and threading). The zones are marked P_1, P_2, and P_3 and they are located at various distances relative to the coordinate system shown in Figure 14. Figures 16 and 17 show total workpiece displacement and workpiece displacements in X-axis direction, respectively, as the function of cutting force F, and angles of inclination, φ, and θ. Cutting force was set to $F = 1{,}000\,\text{N}$. Based on the diagrams shown in Figures 16 and 17, and a number of other diagrams omitted for brevity, the selection of cutting tool geometry and regime parameters was optimized.

The diagrams show that the deformations of workpiece and fixture elements built into the workpiece holes depend mostly on the cutting force direction and cutting zone location. Consequently, these parameters were used to optimize the selection of cutting tools and parameter regimes in the particular cutting zones.

Figure 18 shows a 3-D model of a meshed workpiece and displacements in X-axis direction in zone P_1 (Figure 14). The figure indicates that the largest displacements are located in the narrow cutting zone, which is due to a concentrated force (in this particular case $F = 1{,}000\,\text{N}$, $\varphi = 30^\circ$ and $\theta = 20^\circ$) and a thin wall in that zone.

The role of the internal support element is best shown in Figures 19 and 20. Figure 19 shows displacements in X-axis direction without the internal support element, all other parameters being identical. Shown in Figure 20 is a 3-D diagram which illustrates total workpiece displacements in zone P_1, as the function of cutting force direction and angles φ, and θ, for both cases – with and without the use of the internal support element. Figures 19 and 20 show that the deformations are not only significantly larger, but have also lost their local character.

Figure 15 Varied direction of the resulting cutting force in the polar coordinate system



FEM analysis results for stress fields distribution was also examined, but proved insignificant from the aspect of this investigation and were therefore omitted.

Discussion

Through theoretic analysis and a comprehensive case study, the authors presented a method for locating and clamping of complex-geometry workpieces in conditions of a large number of constraints. Locating from holes proved favourable for following reasons:

- In the majority of cases, the hole axes of housings of gearboxes, transmissions, multipliers, etc. coincide with the geometric locations of spindles which carry gear trains and other functional elements, demanding tight tolerance fields and high surface quality.
- Holes for bearings are typically located in zones with normal wall thickness which, given the insertion of additional elements (pins), allows correct workpiece location from such holes, with increased stiffness.
- To allow high quality machining of internal surfaces of the considered complex-geometry casting at high material removal rates, the following should be minimized: fixture instability, large tool overhangs, uneven machining allowances, and interrupted cutting.
- Due to liberal dimensional tolerances for castings, failing to locate the workpiece from these holes in the first machining process leads to uneven machining allowances in the second process which requires the machining of holes. This significantly affects the workpiece stability, effective material removal rate and machining errors.
- In extreme cases, due to small machining allowances, failure to locate from the holes in the first machining process can lead to errors in hole machining.

Considering the constraints, the locating and clamping of complex-geometry workpieces featuring thin walls in some cross-sections can be efficiently realized by the proposed method. From a practical point of view, the process of operating the fixture is complex and time consuming. However, due to a large number of tool changes on the machining center (Figure 7), and the fact that the second machining process lasts upwards of 30 minutes, the fixture operator has enough time to complete all setup operations on the first palette.

The fixture was designed to accommodate a typical complex-geometry workpiece (a thin-walled casting of gearbox housing) and provides a very stable framework. This was confirmed by the conducted FEM analyses, as well as in practical application, on the HURCO-500 horizontal machining center. Comprehensive FEM analyses revealed very small displacements in virtually all cutting zones (displacements on the order of 0.01 mm), under significant cutting forces of 1,000 N. This indicates high workpiece stability, allowing intensive cutting regimes. Small workpiece displacements in cutting zones are primarily due to thin workpiece walls in particular radial cross-sections, and are therefore of local character. Also contributing to local character were the concentrated forces, which were simulated in particular cutting zones. Importantly, the sizes

Figure 16 Total workpiece displacement depending on the cutting zone and direction of cutting force

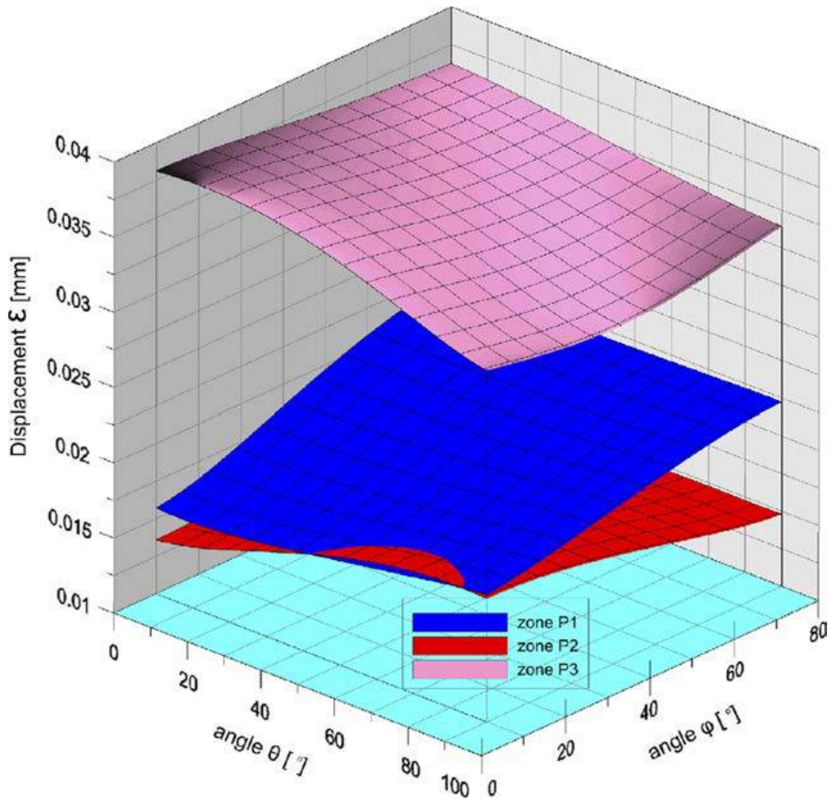


Figure 17 Workpiece displacement in *X*-axis direction depending on the cutting zone and direction of cutting force

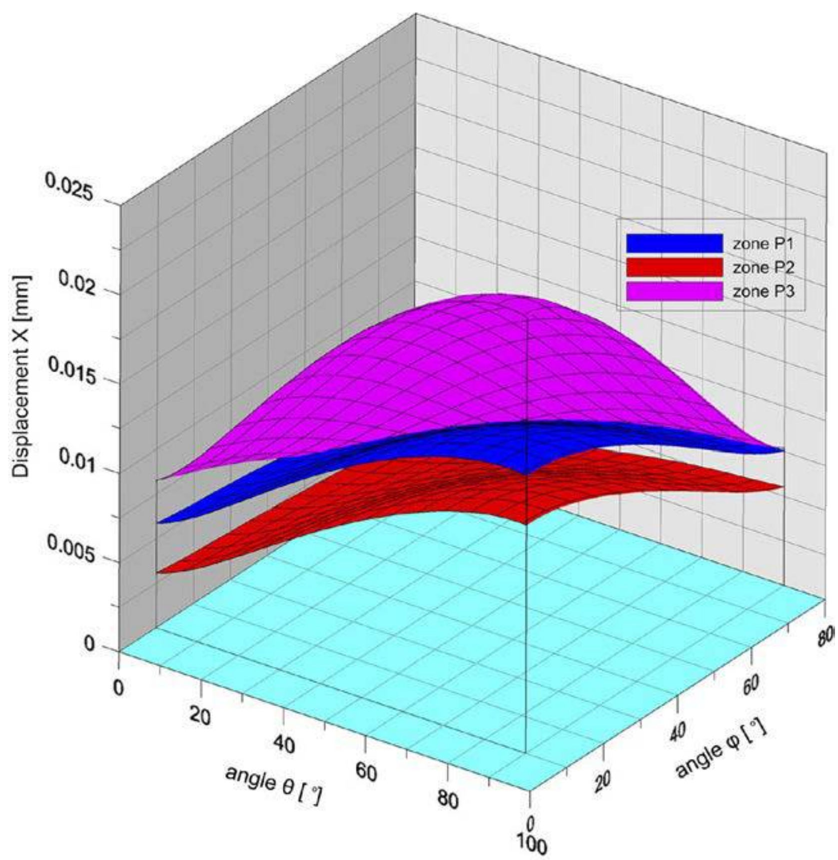


Figure 18 3-D model of a meshed workpiece showing displacements in *X*-axis direction for a milling operation in zone P1 – with the use of an internal support element

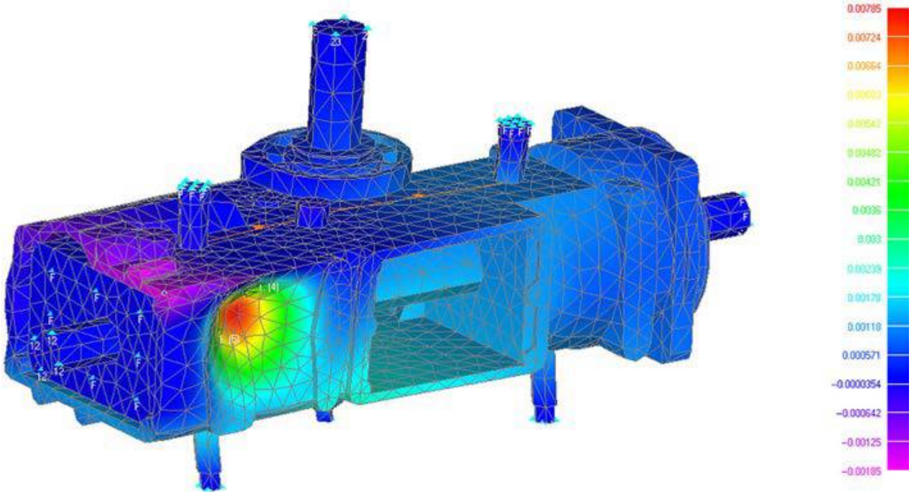
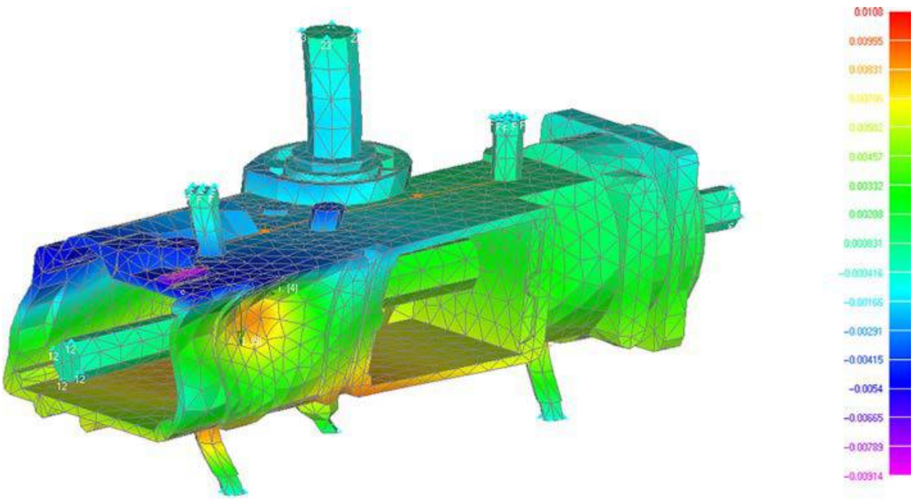


Figure 19 3-D model of a meshed workpiece showing displacements in an *X*-axis direction for a milling operation in zone P1 – without the use of internal support element



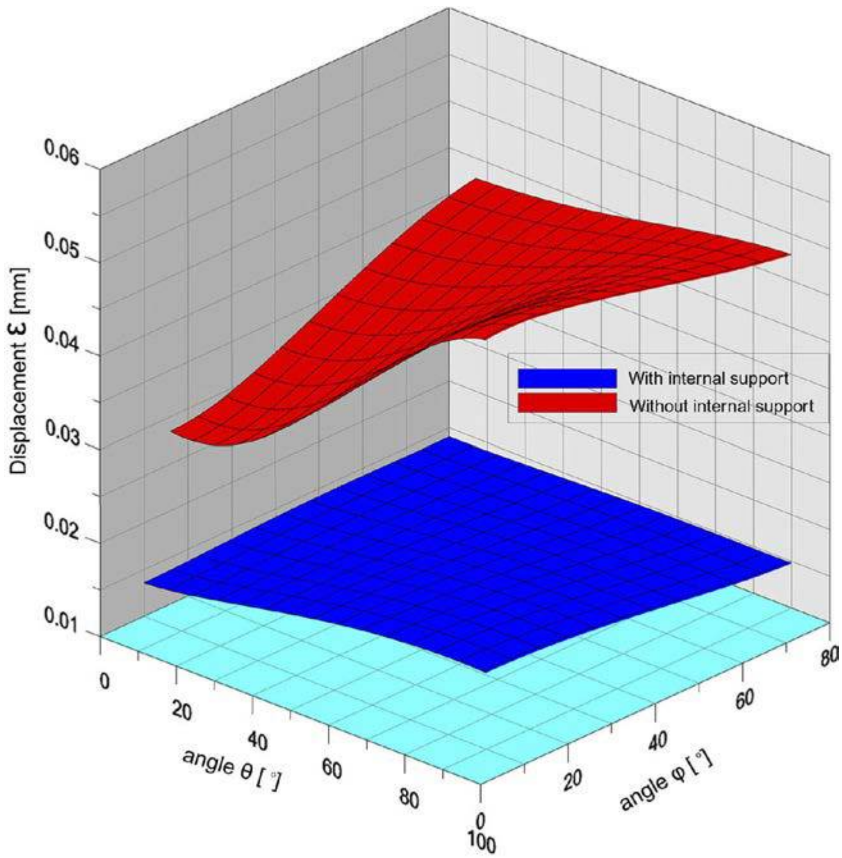
of areas affected by the cutting forces also depend on the type of cutting tool. However, tool optimization was beyond the scope of this work and was therefore omitted. Finally, the maximum allowed loads determined by the simulation of concentrated cutting forces in various directions, under the maximum allowed displacement constraint, allowed introduction of a safety factor which compensates for various influences.

Conclusions

Based on the presented investigation, following conclusions can be drawn:

- Locating of complex-geometry workpieces with two skewed holes, in a constrained space, is efficiently performed using mandrels which are positioned and fixed in workpiece holes and are located, together with the workpiece, on the other part of the fixture which provides the basic framework.
- Insertion of mandrels and support element sub-assemblies into the workpiece holes significantly increases workpiece stiffness through an increased moment of inertia, while the internal support elements largely diminish the problem of thin wall deformations in the workpiece.
- FEM simulations included variations of intensity, direction, and sense of loads, under limited displacement constraint, which allowed maximum cutting forces to be determined in particular cutting zones. This is a prerequisite for optimization of tools (tool geometry) and cutting regime parameters to maximize material removal rate.
- The designed and manufactured fixture based on the proposed model of locating and clamping of complex-geometry workpieces under multiple constraints, was successfully tested in the first machining process required

Figure 20 Total workpiece displacements in the fixture depending on cutting force direction – with and without the use of internal support element



for the manufacture of gearbox housing on a HURCO-500 machining center. The cutting regimes were kept at the maximum for the given set of tools, while the fixture proved stable and reliable.

The proposed model can be considered universal. Moreover, it allows further theoretical and experimental investigations regarding optimization of the selection of cutting tools and cutting regime parameters from the aspect of machining error.

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Further reading

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