Technological Assurance and Features of Fork-Type Parts Machining

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Abstract. To provide the machining accuracy of parts on metal-cutting machine-tools fixtures appointed for accurately locating and reliable workpiece clamping are used. The expansion of technological capabilities of modern CNC machine tools necessitates the improvement of design procedures in production planning is needed. The variety of parts and the tendency to increase their complexity, as well as the desire to reduce the cost of time, makes it necessary to find new approaches to the design of tooling. The article proposes the design of a flexible fixture, which provides sufficient tool availability and allows multiaxis machining of fork-type parts at one setup. The ways of intensification and manufacturing process of fork-type parts machining with a significant reduction of auxiliary and preparatory time are offered. Studies performed by numerical simulation methods confirmed that the proposed design meets all the accuracy parameters. The results of static structural, modal, and harmonic analyses confirmed that the proposed fixture had sufficient strength and dynamic stiffness, which allows it to be used with intensive cutting modes that are characteristic of modern machines and cutting tools. The oscillation amplitudes in places of the work surfaces in the proposed device do not exceed the tolerances for the manufacturing of these surfaces.

Keywords: Flexible fixture · Manufacturing process · Numerical simulation · Stiffness · Accuracy

1 Introduction

Fixtures play an important role in ensuring the production of competitive products. They are an integral part of the closed technological system "machine tool—fixture—cutting tool—workpiece". This is confirmed by the fact that the part of the fixtures are up 70–80% of the total volume of tooling [1]; 10–20% of the total cost of production systems is the cost of fixtures [2]; 80–90% of time spent on production planning is spent on design and manufacturing of fixture [1, 3, 4]; up to 40% of defective parts in manufacturing engineering arises due to imperfections of the fixtures [5]; 70% of new fixtures are a modification of existing ones [6].

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Modern manufacturing is characterized by a variety of manufactured parts. The increase in the range of products requires complicated design and development tasks on tooling manufacturing, especially fixtures, and leads to an increase in the cost of finished products. Such production conditions require frequent adjustments to the machining of another batch of parts, which raises the question of the economic feasibility of design and manufacturing dedicated fixtures for parts of a specific size. Adjustability of modular fixtures involves their partial or complete re-arrangement in the transition to the machining of parts of another size, which also requires time-consuming tasks. In addition, the stiffness of the modular fixtures due to a large number of joints and presence of T-grooves is often insufficient for efficient machining with the cutting modes recommended by the world manufacturers of the cutting tool [7, 8]. The problem is also unreasonable steel intensity of the above-mentioned fixtures. Therefore, it is important to implement flexible fixtures, which provide adjustability of another dimension of parts [9], have sufficient stiffness with the minimum mass and allow reducing costs associated with fixtures by 80% [10].

The aim of this work is confirmation of the working capacity of the developed flexible fixture for fork-type parts machining in multiproduct manufacturing by means of research of the system “fixture—workpiece”.

2 Literature Review

Current trends are aimed at product varieties rising and lifecycles shortening [11]. Therefore, not only product design processes need to be adapted but also the development of manufacturing processes and equipment, to solve the dissonance of reduced time to market and increased product variety [12–14]. Flexible fixtures allow reducing the manufacturing cost, improving production efficiency, and ensure machining accuracy [15, 16]. Flexible fixtures must be designed to locate a group of parts in a single fixture that can be efficiently adjusted to different production conditions [17]. Fixture considers as a structure of a number of functional units and consists of locating, clamping, and supporting units. The clamping efficiency of the fixture and its adaptability to irregular workpieces is a hot-spot in manufacturing efficiency [18]. The paper [19] describes the design of workpiece clamping and system for automatic workpiece exchange implementing interchangeable technological pallets. A novel workpiece clamping method for increased machining performance is presented, which investigates fixture-workpiece interface proved by theoretically and experimentally [20]. Fixture design is a complicated and time-consuming process, there are various requirements which influence the efficiency and quality of fixture design [21–23]. Paper [24] proposes a comparative design procedure for flexible fixtures that can adapt to manufacturing system characteristics by using efficiency metrics, which theoretically justified and experimentally verified. The paper [25] identifies the components of the design process of flexible systems and suggests an overview of the components and relations between them in the design processes. The requirements for machining quality are very high in manufacturing engineering, therefore the combined effect of clamping and the milling on machined surface errors prediction is taken into account, and finite element analysis is developed to analyze the workpiece deformation for predicting the machined surface errors in “fixture—workpiece” [26]. Numerical simulation studies [27] and the experimental investigations [28] confirmed that the flexible fixture design allows multiaxis machining of levers with one set up and meets all accuracy parameters. The theoretical approach for the assessment of product efficiency while assembling is proposed in paper [29]. The fundamental approaches of using the computational intelligence systems for ensuring the reliability of complicated mechanical systems are presented in papers [30–32].

3 Research Methodology

3.1 Analysis of Fork-Type Parts

The object of the study is the fork-type parts (Fig. 1), which are components of many units and aggregates, especially in the automotive and tractor industries. The feature of the fork-type parts is the presence of arms (symmetrical about the central axis of the part), coaxial holes of different diameters (with requirements for intercenter distances between them), parallel axes, and plane surfaces (with requirements to their mutual spatial position). The fork-type parts are characterized by the complicated geometric shape that causes difficulties in locating and clamping workpieces and leads to an increase in the complexity of machining due to the increasing number of technological operations.

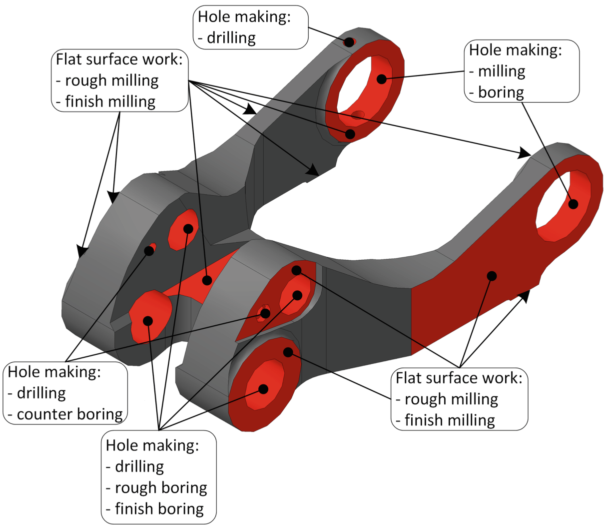


Fig. 1. Typical design and work surfaces of the fork-type part.

3.2 The Design of a Progressive Manufacturing Process

The typical manufacturing process of fork-type parts machining, which consists of 9 manufacturing operations and requires 7 setups of the workpiece during drilling-milling-boring operations (Fig. 2a), is investigated. Considering the technological capabilities of the modern machining centers and the tendency to the intensification of machining processes, it is proposed to manufacture parts of this type in one setup by combining manufacturing operations 15–35 of the typical manufacturing process into one—CNC multiaxis machining operation. This approach allows reducing the manufacturing process by 4 machining operations (Fig. 2b). Thus, the reduction of units of equipment from 5 machines to one machining center was achieved, and the number of fixtures is reduced from 5 dedicated fixtures to one flexible fixture.

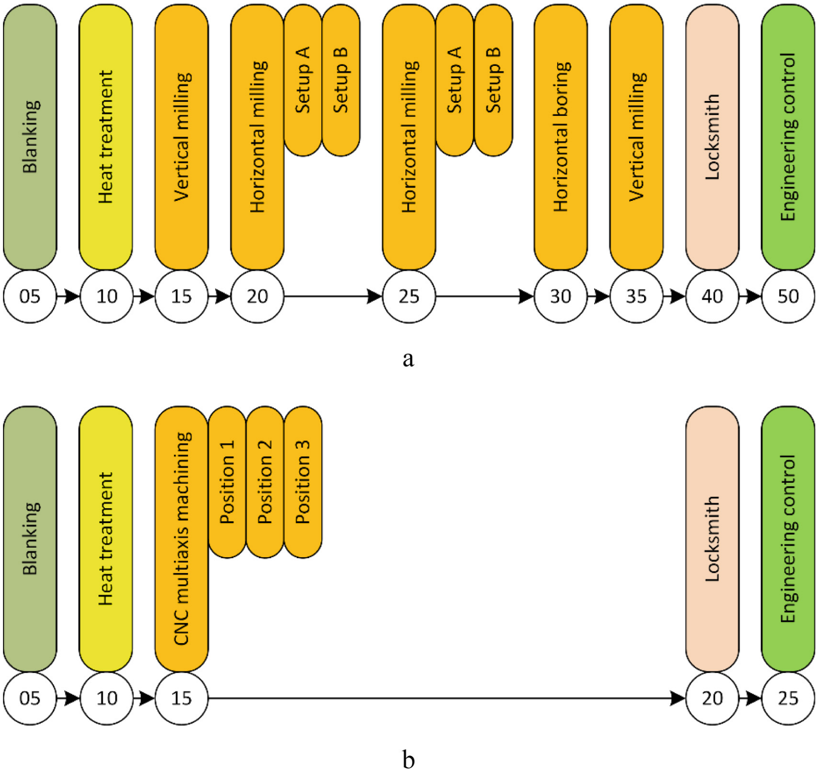


Fig. 2. Comparison of the manufacturing routes for the fork-type parts machining: **a** typical manufacturing process; **b** proposed manufacturing process.

The machining of all surfaces requiring drilling, milling, and boring machining is realized on a CNC multiaxis machining operation in three positions (Fig. 3).

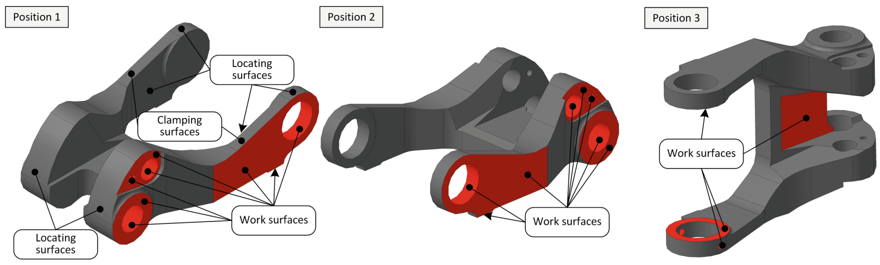


Fig. 3. Cut-map for fork-type parts machining on the CNC multiaxis machining operation.

3.3 Fixture Design for Fork-Type Parts

Although the variety of models of cars in our time is quite large, however, their main mechanisms, where the forks are present, almost do not differ. The difference can be only in changing the size or location of some of the surfaces to be machined, so it is necessary to develop a flexible fixture. This will enable the opportunity of the fixture elements adjustability to install forks in a certain range of sizes and shapes, expand tool availability and allow multiaxis machining, improve machining performance by reducing the auxiliary and preparatory time.

A flexible fixture is designed for the locating and clamping of forks of various sizes in the range of 215–250 mm in length, 135–150 mm in width, and 75–90 mm in height, which is carried out by adjusting screw mechanisms that provide a change in the distance between the locating elements (Fig. 4).

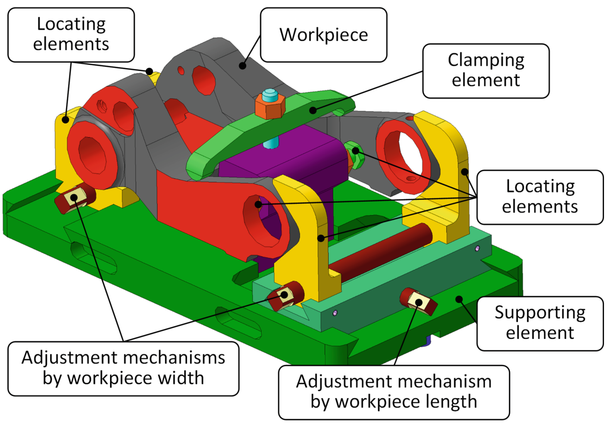


Fig. 4. Flexible fixture for fork-type parts machining on the CNC multiaxis machining operation.

Flexible fixture can be installed both on the table of the machine tool and on the base plates, which are included in the various sets of modular fixtures. This technical solution, combined with the rotating table of the machine tool, allows performing all drilling, milling, and boring operations with the constant clamping of the workpiece on one multiaxis machining operation performed at the horizontal CNC machining center. However, the machining can be carried out on the vertical machining center.

4 Results

4.1 Comparative Analysis of the Structures of Manufacturing Processes

The comparative analysis of the structures of the manufacturing processes for labor-intensiveness confirmed that the proposed manufacturing process provides a significant reduction in non-productive time for drilling and milling operations (Fig. 5), in particular: 232% at the auxiliary time; in additional time—116%; time to personal needs—131%; at the preparatory time—408%; machining time—130%; at the machining-calculation time—133%. For the proposed manufacturing process in the structure of machining time, there is a decrease in the share of auxiliary time by 16% compared with the typical manufacturing process.

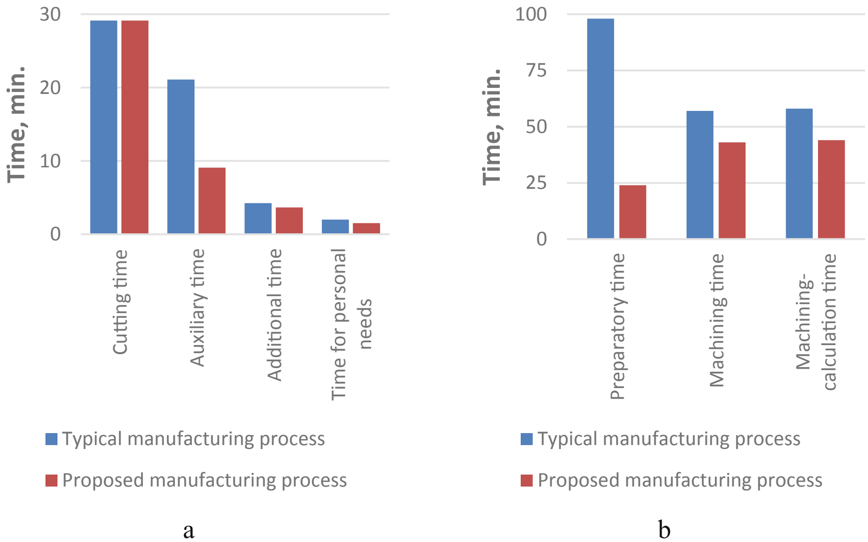


Fig. 5. Comparative analysis of the structures of manufacturing processes by labor-intensiveness.

In the conditions of multiproduct manufacturing, it is important to ensure the efficiency of manufacturing processes production of parts for different batches of machining. The study of the batch of parts change showed that the proposed manufacturing process is effective. Sharp reduction of time expenditures is observed when the quantity of batch of parts varies from 1 to 25 pcs., which is related to the norm of the preparatory time. For batches of parts up to 100 pcs., the proposed manufacturing process of multi-axis machining are more efficient than the typical manufacturing process. On average, this fact allows providing a reduction of the machining-calculation time of about 11–14 min for drilling, milling, and boring operations.

4.2 Static Structural Analysis of the System "Fixture—Workpiece"

The determination of the possibility of achieving the accuracy of the sizes, forms and the relative positioning of the surfaces during machining made a study of the static structural analysis and determined the displacements of the elements of the system "fixture—workpiece" under the influence of external loads (clamping forces and cutting forces, as well as cutting moments). The strength of the fixture is investigated by determining the equivalent stresses taking into account the model of contact interaction between the workpiece and the functional elements, and the stress concentrators have been identified. The maximum magnitude of the equivalent stresses determined by von Mises hypothesis was compared with the permissible value for a particular material. The dependence of the magnitude of stresses and displacements on forces and moments is established for forecasting deviations from nominal sizes, which will directly affect the accuracy of machining.

During the simulation, the following boundary conditions and the properties of the material of fixture and workpiece were set. The following contact surfaces were identified (Fig. 6): contact 1—working surfaces of the v-blocks/cylindrical surfaces of the workpiece; contact 2—working surfaces of the supports/internal side surfaces of the workpiece; contact 3—clamping working surfaces/upper surfaces of the workpiece. Reference surface/fixing type is the bottom surface of the plate/fixture support. For all

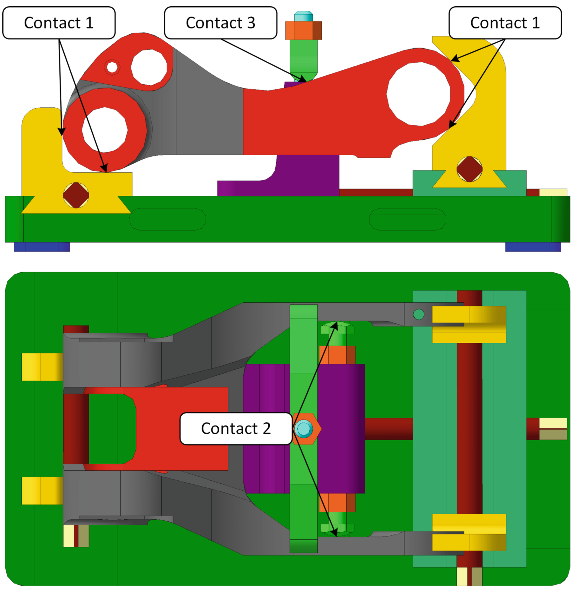


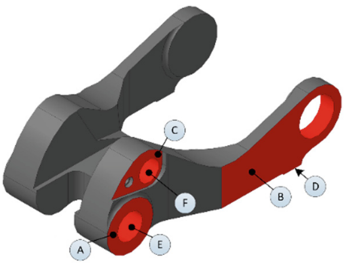
Fig. 6. Contact surfaces.

described contacts the type of contact surfaces is smooth/unmachined with friction coefficient 0.2. The model takes into account the Coulomb friction between the contact surfaces of the fixture, which have approximately the same roughness (1.6 μm for the Ra criterion) with a coefficient of 0.1.

The material of the workpiece is Structural Alloy Steel 40CrNi6 with the following mechanical properties: Young's modulus 200 GPa, Poisson's ratio 0.3, Density 7850 kg/m^3, Tensile strength 0.98 GPa, Ultimate strength of compression 0.98 GPa, Yield strength 0.785 GPa. The material of fixture elements is Structural Steel 45 (after heat treatment) with the following mechanical properties: Young's modulus 200 GPa, Poisson's ratio 0.3, Density 7850 kg/m^3, Tensile strength 0.95 GPa, Ultimate strength of compression 0.95 GPa, Yield strength 0.726 GPa.

During the simulation, the workpieces were applied in the form of cutting forces in 4375–13,060 N and torque 33–694 N m, depending on the method of machining, the constant clamping force of 30,000 N applied to the champ. On the basis of the set of boundary conditions, the simulation of the real process in the static was carried out. On the basis of the finite element method, the value of the maximum equivalent stress according to the IV Huber–Mises hypothesis of strength, and the maximum displacements that arose during the modeling of the machining process of the fork in the proposed fixture were obtained (Table 1).

Table 1. Numerical simulation results.

Figure	Surface	Manufacturing step with maximum loading	Maximum displacement (mm)	Maximum equivalent stress (MPa)
	A	Milling	0.062	348
	B	Milling	0.071	566
	C	Milling	0.082	373
	D	Milling	0.051	542
	E	Drilling	0.056	589
	F	Drilling	0.052	560

4.3 Modal Analysis of the System "Fixture—Workpiece"

To prevent the occurrence of the resonance phenomenon in the process of machining the fork, it is necessary that the frequency of the proper oscillations of the elements of the fixture does not coincide with the frequency of the cutting process. One of the ways to solve this problem is to assign other cutting modes. To do this, using the built-in Modal Analysis module in the ANSYS Workbench calculation complex, the frequency of the self-oscillation of the fixtures is determined, which is comparable to the frequencies of the alternating components of the forces and moments of cutting at all junctions of drilling-milling-boring operations. The results of the analysis allow determining the necessary resolution from the resonance (Table 2). In the calculations, all elements of the fixture were interconnected by combining the units. For some surfaces of the elements of the fixture, there is a possibility of relative movement with a coefficient of friction. Types of contacts and characteristics of the contact pairs between the surfaces of the elements are given in Sect. 4.2.

Table 2. Results of the fixture eigenfrequency investigation.

Critical frequency (Hz)			Machining frequency (Hz)
1	2	3	
1752	2250	2392	68

From Table 2 it can be seen that for the proposed fixture phenomenon resonance does not arise since the first critical frequency significantly exceeds the frequency of the cutting process. But one can make an intermediate conclusion that the developed fixture for the implementation of the proposed manufacturing process will have sufficient dynamic rigidity, which should be checked using harmonic analysis.

4.4 Harmonic Analysis of the System "Fixture—Workpiece"

The amplitudes of the dynamic components and cutting torques were selected within the range of 20% of the nominal value of their values. Previous studies have shown that the operating frequency range of the cutting process when machining the part does not exceed 100 Hz, which allows limiting the range of 0–100 Hz on the charts of the frequency response in determining the value of displacement. As a result of numerical modeling of the dynamics of the system "fixture—workpiece", amplitudes of oscillations and resonance frequencies caused by the cutting process are obtained. The parameters of the point's movements in the machining zone for the fixture of the proposed manufacturing process are determined. Maximum amplitude for described surfaces are: A (milling)—12 µm; B (milling)—15 µm; C (milling)—18 µm; D (milling)—66 µm; E (drilling)—8 µm; F (drilling)—13 µm. An example of the frequency response when milling the surface B of the part is shown in Fig. 7.

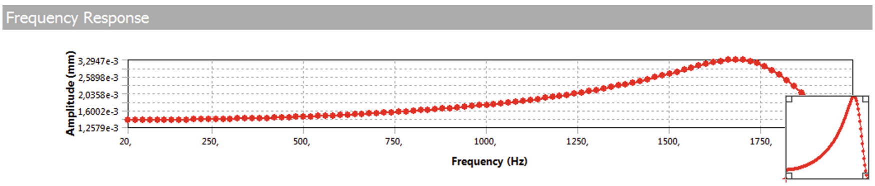


Fig. 7. Amplitude-frequency characteristic for milling surface B of the fork.

The amplitudes of oscillations that arise at all manufacturing steps are smaller than the tolerances on the respective machined surfaces, hence accuracy will be achieved. To determine the reserves of the proposed fixture, dynamic rigidity was calculated for several manufacturing steps. The amplitude of the dynamic component of the cutting force is for described surfaces: E (drilling)—1175 N; F (drilling)—1125 N. Maximum amplitude displacements are 12.8 μm for surface E (drilling) and 8.5 μm for surface F (drilling). Therefore, the estimated dynamic stiffness is calculated for surfaces: E (drilling)—0.92×10^5 N/mm; F (drilling)—1.32×10^5 N/mm.

5 Conclusions

1. It is proved that the developed technical solutions contribute to the intensification of the manufacturing process of machining and do not lead to deterioration of accuracy indicators. The conducted studies of the stress-strain state have shown that the design of the fixture for machining the fork-type parts provides multiaxis machining and meets the conditions of strength, as well as significantly reduces the costs of the auxiliary and preparatory time. The results of the numerical simulation showed that the machining in the proposed fixture has sufficiently high accuracy due to the small size of displacement up to 82 μm. The strength of the elements of the fixture is also sufficient since the maximum stresses at the factor of the strength of the system 1.5 do not exceed the permissible values.
2. The proposed fixture has sufficient stiffness, which implies no resonance since the first resonance frequency for the proposed fixture is 25 times higher the value of the maximum cutting frequency of the operation where the given fixture is applied. In addition, the analysis of the dynamic state of the elements of the system "fixture—workpiece" the proposed fixture showed that the amplitudes of oscillations that occur when machining the workpiece do not exceed the tolerances for machining at the appropriate manufacturing steps. The dynamic stiffness of the proposed fixture is $(0.92–1.32) \times 10^5$ N/mm, which is a rather high indicator for the fixtures, which perform machining of parts of similar configuration and standard sizes. The magnitudes of the oscillation amplitudes in the proposed fixture do not exceed 13 μm.
3. Further research is aimed at experimental verification of the results of numerical simulation for determining the values of displacements under the action of static load and amplitudes of oscillations in the process of machining taking into account the dynamic component of forces and cutting moments. It is also advisable to carry out studies on the stability of the equilibrium position of the elements of the system "fixture—workpiece" under the influence of external forces. This will allow evaluating the effectiveness of the developed technical solution, as well as facilitate the development of the fixture for the establishment of other parts of a complex form.

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