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Development of Flexible Fixtures with Incomplete Locating: Connecting Rods Machining Case Study

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Abstract: The rapid development of manufacturing in recent years has led to a significant expansion of the technological capabilities of modern metal-cutting equipment. Therefore, the modern approach to intensifying production requires an advanced fixture design. Design and manufacture of flexible fixtures capable of machining similar shapes and sizes of complex geometry parts reduce setup time. The article aims to design flexible fixtures for parts such as one-piece connecting rods under incomplete locating conditions. The advantages are the minimum number of parts and tool availability for multi-axis machining connecting rods in one setup. This approach, combined with up-to-date machining centers and industrial robots, can increase the production efficiency of manufacturing non-removable connecting rods. This effectiveness is in a decrease in the number of operations by 5–7 times, fixtures—by 3–4 times, and machine tools—by 3–5 times, depending on the type of a non-removable connecting rod and its design features. The numerical simulation results of the proposed fixture design confirmed the comprehensive technological capabilities and dynamic characteristics. Particularly, a decrease in displacements and oscillation amplitudes up to 7% compared to the full-basing locating chart was provided. It is determined that the system "fixture–workpiece" entirely meets all the strength, accuracy, and rigidity parameters, which allows you to perform machining with intensive cutting modes. The amplitudes of oscillations do not exceed the tolerances on the dimensions of these surfaces, established by requirements for non-removable connecting rods, and all displacements are elastic. During numerical simulation, the workpiece position remained stable at all machining steps.

Keywords: fixture design; machining; sustainable manufacturing; process innovation; complex-shape part

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1. Introduction

At present, in the conditions of active development of the concept of Industry 4.0, manufacturers of spare parts for the automotive industry and other equipment face a rather complicated problem, namely, to ensure rapid production of products of various nomenclature in the shortest possible time in discrete batches [1]. The quality of the finished part/product should meet both the requirements set by the designer in the drawing and international quality standards [2]. Due to the mentioned above, it is necessary to constantly update the equipment and manufacturing technologies and approaches to the production process [3]. Various equipment, including internal combustion engines, is constantly growing in automotive, agricultural, shipbuilding, and military industries. Simultaneously, the time of product entry on the market is reduced, models are updated, and technical characteristics are changed.

In current conditions, the approach to manufacturing spare parts for the above equipment has changed. First, manufacturers are trying to make their products lighter and more efficient. This applies to massive body parts (for example, engine cylinder blocks) [4], and other essential parts of the engine are trying to optimize the weight. In the last 10 years, the technology of manufacturing highly loaded parts from composite materials has been actively developed in the automotive industry [5], but their use has some limitations due to their physical and mechanical properties. For example, parts of the cylinder-piston group cannot be made of composite materials because composites cannot withstand high temperatures without destruction and changes in shape. Secondly, at the enterprises to produce spare parts, much attention is paid to the intensification of production [6,7], which aims to reduce the time of manufacture of the finished part/product and reduce costs. Simultaneously, enterprises are ready to spend money on purchasing advanced metal-cutting machines and other equipment, which allows to reduce the share of manual labor of the worker to a minimum or exclude it altogether. This requires introducing new technical solutions to change the manufacturing process towards the concentration of machining operations of the part.

The work also aims to theoretically prove the hypothesis of achieving the required machining accuracy and approach to fixture design based on numerical modeling of the developed flexible fixtures for one-piece machining rods with an incomplete locating for multiproduct production.

The connecting rod is the main element of a crank mechanism used in all classic configurations of internal combustion engines. Simultaneously, automakers try to make their products as light and durable as possible. This leads to the need to accurately calculate the connecting rods using numerical simulation methods.

In this regard, Shanmugasundar et al. [8] performed a topological optimization of the connecting rod design using the Autodesk software, considering calculations performed using the finite element analysis method using the ANSYS software. Xiao et al. [9] numerically determined the optimal thickness of the smaller connecting rod head to ensure sufficient rigidity when fitting the sleeve and the optimal amount of tension in the joint. Basavaraj et al. [10] determined that the optimal material for rods subjected to high cyclic loads is carbon steel alloyed with chromium and molybdenum.

Optimizing the mass of the connecting rods of large diesel internal combustion engines is an urgent task. Seyedzavvar et al. [11] performed parametric optimization of the connecting rod design using the CATIA software. As a result, the weight was reduced, and the resulting model was tested for strength using the ABAQUS software. Muhammad et al. [12] carried out the topological optimization of the connecting rod design using the ANSYS software. As a result, the total mass was reduced by 60% under the same constant static load.

The analysis confirmed that incorrect calculations lead to accidents during the failure of the connecting rods precisely. Chao [13] and Strozzi et al. [14] gave the main design errors and methods of avoiding them. Jia et al. [15] proved that the marking of connecting rods during stamping should be clearly defined in shape and size and be positioned in specific places not to violate the strength of the whole part.

Balamurugan et al. [16] analyzed the time of manufacture of the connecting rod in each manufacturing process operation and suggested ways to intensify production by combining some operations. Liu et al. [17] also studied the manufacturing process of connecting rod production and proposed a new method for evaluating the manufacturing process that responds to the state of machining in real-time based on digital twins.

In mass production, the connecting rods are manufactured using special multipart fixtures to reduce the machining time [18]. However, connecting rods can be manufactured using universal re-adjustable fixtures in single and small-scale production conditions and sports and special-purpose machines [19].

Many scientists are involved in improving the manufacturing process of machining parts, such as connecting rods. In particular, the manufacturing process of the detachable connecting rod machining was investigated by Kar [20]. Simultaneously, a special expanding mandrel was proposed as a fixture for the operation of machining holes for screws. Raijada and Dudhatra [21] designed a fixture for boring holes in a connecting rod.

Cui et al. [22] proposed a methodology to develop fixtures based on the computer-aided design (CAD) approach. Raja et al. [23] also designed, modeled, and tested fixtures for milling machines based on the CAD software.

Litrop et al. [24] developed an approach to design and optimize fixtures with their consequent testing under cyclic loading. In addition, Lu et al. [25] proposed a multi-objective optimization algorithm for the locating chart in fixture design.

Corrado et al. [26] considered the system "fixture–workpiece" as a separate assembly unit and predicted the accuracy of processing depending on the errors in the connections of the assembly elements.

Parvaz et al. [27] proposed an analytical and algorithmic procedure for designing fixtures for workpieces with free-form geometry of the NURBS type. Wu et al. [28] proposed an algorithm for designing fixtures for automated machining of complex shape parts and software in cases of changes in the shape and number of jet engine blades.

Luo et al. [29] developed geometric theorems and applied DOF workpiece analysis based on a normal constraint line to avoid repositioning when a complex workpiece is installed on many different surfaces.

Kamble and Mathew [30] integrated a segmented fixture design approach into a single methodology for complex design in four stages: installation planning, fixture layout development, detailing, and verification.

Thus, based on the recent advancements in the design, modeling, manufacturing, and intensification of rods production and development of fixtures for their machining, the actual research direction in the development and numerical modeling of fixtures for one-piece machining rods for one step has proposed to be studied.

The scientific novelty is in the fact that the method of numerical modeling theoretically proves the workability of the proposed concept of machining parts such as connecting rods in a fixture with an incomplete location and the possibility of applying this approach to other types of parts of complex shapes, such as forks and brackets.

The practical importance is highlighted by developing a ready-made technical solution that can be used in enterprises where parts such as connecting rods of different designs in small batches with a particular frequency can be processed. Of course, to implement this approach, the company must have a multi-coordinate machine with the function of automatic binding and transfer of the coordinates of the workpiece in the machine's coordinate system.

2. Materials and Methods

2.1. Assignment

The object of study was selected parts such as connecting rods. The connecting rods have a very different design depending on the purpose of the product/machine where the connecting rod works. However, of all the designs of connecting rods, there are four main ones: detachable connecting rods, detachable clip connection rods, one-piece connecting rods, and one-piece clip connecting rods (Figure 1).

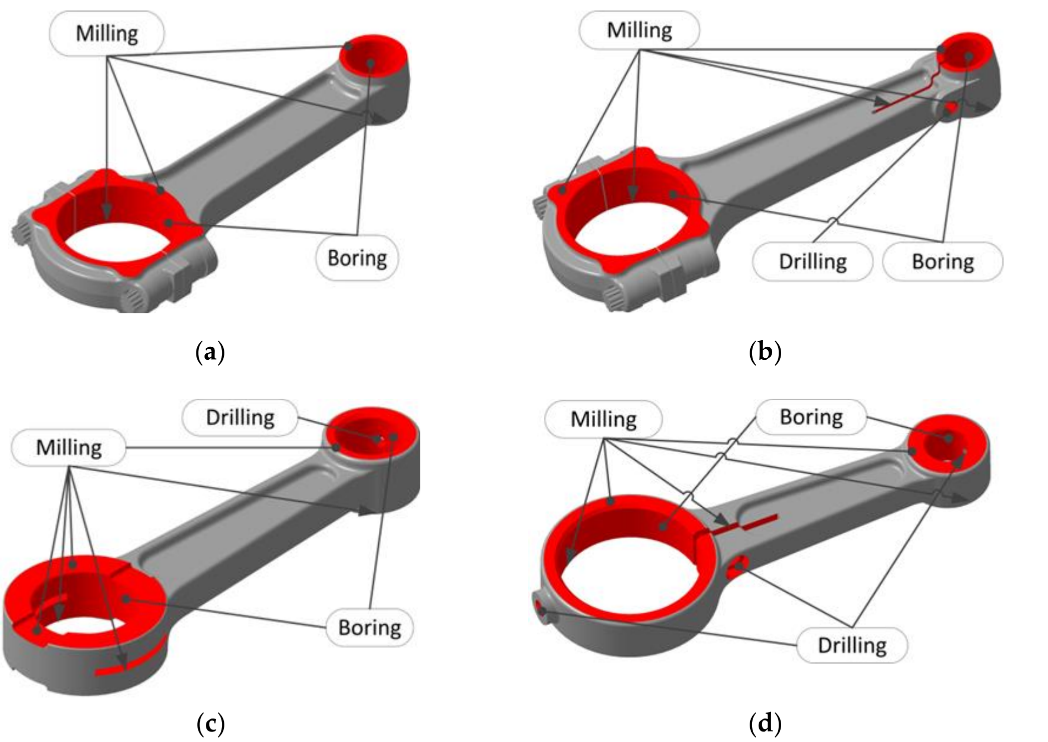


Figure 1. The designs of connecting rods with machined surfaces: (**a**) Detachable connecting rods; (**b**) Detachable clip connecting rods; (**c**) One-piece connecting rods; (**d**) One-piece clip connecting rods.

Detachable connecting rods (Figure 1a) are mainly used in automobile engines and high-power compressors. The connecting rods shown in Figure 1b have an incision in the small head of the connecting rod to allow rigid fixation of the piston pin and prevent its rotation. This design is used for manufacturing large connection rods for low-speed marine engines. One-piece connecting rods (Figure 1c) are usually used in motorcycle engines. One-piece connecting rods (Figure 1d) have a cut in the large head of the connecting rod and are used in reciprocating compressors of low and medium power. The cut is designed to securely lock the rolling bearing in the large connecting rod head by tightening the clip screw.

All the holes and planes of a connecting rod are interconnected by the requirements of center-to-center distances, the axes' parallelism, and the spatial position of the flat surfaces relative to each other.

Due to the widespread application of one-piece connection rods in oversized internal combustion engines (Figure 1c) and compressors, an increase in machining productivity of one-piece clip connection rods (Figure 1d) is an urgent problem. One-piece connecting rods, unlike detachable ones, are one part during the whole manufacturing process of their production, so they were chosen as an object for analysis and further development of the fixture design.

One-piece connecting rods are characterized by many untreated surfaces and complicated spatial geometric shapes. These features cause difficulties in locating and clamping workpieces. They also lead to the increased complexity of machining due to several manufacturing operations.

According to the sequence and principles in designing a progressive manufacturing process, it was established that the number of operations machining for a one-piece connection rod (Figure 1c) is five drilling-milling-boring operations for which you need to perform ten reinstallations of the workpiece. To machine a one-piece clip connection rod (Figure 1d), the manufacturing process consists of seven drilling-milling-boring operations, which require eleven reinstallations of the workpiece.

2.2. Design Requirements

An analysis of typical drawings of non-removable connecting rods and the literature sources, in particular, showed in [31] that the hole and end surfaces of the large connecting rod head are its main design bases in contact with the crankshaft surfaces. Accordingly, the hole and the end surfaces of the small connecting rod head are auxiliary design bases in contact with the ends of the piston lugs and the piston pin sleeve. The hole of the large connecting rod head is made according to the tolerances of IT6–IT7 qualities, which for most non-removable connecting rods is 0.03–0.07 mm. The end surfaces of the large connecting rod head are made according to the tolerances of IT10–IT11 qualities, which for most non-removable connecting rods is 0.15–0.20 mm. The accuracy of the holes of the small connecting rod head is not so high and is limited by IT10–IT11 qualities and the accuracy of the ends of the small connecting rod head IT11–IT12, respectively. Precision requirements for oil channel holes are limited to IT14 tolerances. The deviation of the center-to-center distances should not exceed 0.05–0.1 mm, depending on the dimensions of the connecting rod. The axes of the holes of the large and small connecting rod heads must be parallel with a tolerance of 0.05:100 to 0.15:100, and their ends must be perpendicular to the axes of these holes in the range from 0.1:100 to 0.3:100. The roughness of the upper hole in the large head of the connecting rod should be Ra = 0.32–0.63 µm, and in the small head—Ra = 1.6–3.2 µm. The roughness of the ends of both heads is in the range of Ra = 1.6–3.2 µm. The hardness of the connecting rods is regulated by their official purpose and is within the HRC 50–55.

2.3. Manufacturing Process

Given the technological capabilities of up-to-date multi-purpose machines and design approaches successfully used in developing fixtures for fork-type parts, it is proposed for machine parts such as one-piece connection rods (Figure 1c). This allows carrying out one replacement by combining four drilling-milling-boring operations of a typical manufacturing process into one—at the CNC multi-purpose machining center. For parts such as one-piece clip connection rods (Figure 1d), it is proposed to carry out machining for one institution by combining five operations of a typical manufacturing process into one at the CNC multi-purpose machining center. This approach allows you to intensify the production process, clearly shown in Figure 2.

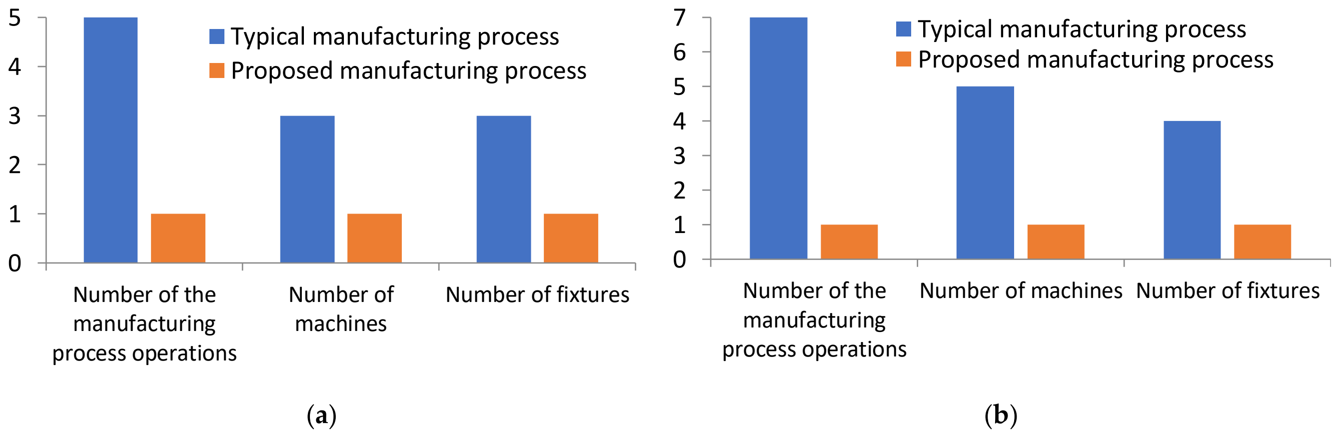


Figure 2. Diagram comparing manufacturing process indicators: (**a**) One-piece connection rods; (**b**) One-piece clip connection rods.

For one-piece connection rods, it was possible to reduce the manufacturing process by four machining operations, the number of machines from three units to a single CNC multi-purpose machine, and the number of special fixtures from three units to one flexible fixture. For one-piece clip rods, it is possible to reduce the manufacturing process by six machining operations, the number of machines from five units to the CNC multi-purpose machine, and the number of special fixtures from four units to one flexible fixture.

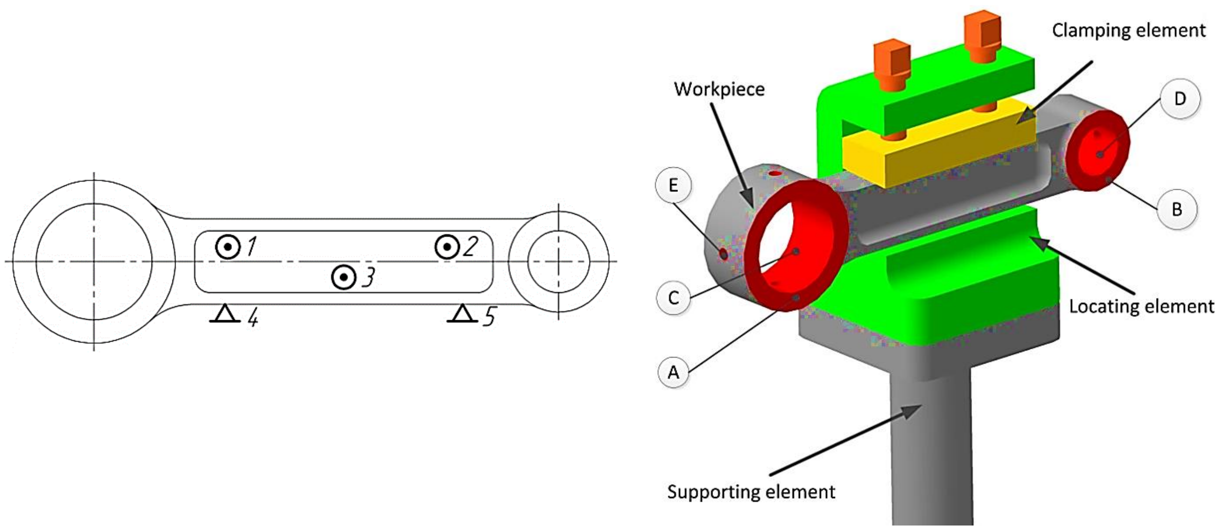
When using a modern machine with automated positioning of the part, pre-machining of base surfaces is not required. This fact simplifies the fixture design and reduces the manufacturing process by one operation compared to the manufacturing process.

The proposed manufacturing process of machining all surfaces of the one-piece connection rod that requires drilling, milling, or boring can be implemented in the machining center with CNC, and vertical and horizontal layouts in six positions.

2.4. Fixture Design

Despite various machines containing connecting rods in a global market, the design of one-piece connecting rods is almost indistinguishable. Their difference can only be in changing the type-size of the configuration of machined surfaces and their characteristics (accuracy, roughness) depending on the purpose of the machine/unit, so it is advisable to develop a flexible fixture that installs one-piece connection rods in a specific range of sizes and shapes. This fixture should ensure full tool accessibility and allow multi-axis machining of all surfaces needed in a single step. Simultaneously, the standard dimensions and design parameters of non-removable connecting rods and one-piece clip rods are relatively similar, and several types of connecting rods can be processed in one fixture. The use of modern progressive machines allows us to depart from the principle of the orientation of the workpiece in the fixture and requires only a secure fastening to ensure the invariability of the position of the workpiece during machining.

As a result, a flexible fixture was developed for the installation of one-piece connection rods of various sizes in the range of 140–200 mm in length, 35–50 mm in width, and 17–24 mm in height, which is carried out by adjusting the screw mechanisms that change the distance between the locating-clamping elements (Figure 3) Machined surfaces are shown in Figure 3 by letters A, B, C, D, E.



(**a**) (**b**)

Figure 3. Flexible fixture for machining a one-piece connecting rod with machined surfaces in a CNC multi-purpose operation: (**a**) Locating chart; (**b**) 3D visualization.

This fixture is modular, i.e., it can be installed due to standardized mounting and clamping elements in the base modules or a three-jaw chuck or machine vise with prismatic jaws. The proposed fixture has a relatively simple design with a minimum of parts and connections and, therefore, is expected to have high rigidity for machining with the maximum allowable cutting modes. This technical solution will allow you to perform machining on a three-coordinate milling machine with CNC, equipped with only a two-coordinate rotating table. The only condition is the presence of a system of a preliminary determination of the position of the workpiece relative to the machine's coordinate system.

3. Results

3.1. Stress-Strain Analysis of the System "Fixture–Workpiece"

At the initial stage of the study, the proposed design of the fixture was tested for a non-removable connecting rod of a simpler design that does not contain a terminal connection. Since this concept was developed for the first time, to minimize time from the potential risks of unsatisfactory modeling results, it was performed for the design of the connecting-rod, which contains fewer machining transitions and, accordingly, the number of operations for numerical simulation of these transitions.

Since the principle of operation of the proposed fixture is based on the need to ensure absolute reliability of fastening, to determine the possibility of achieving an accuracy of size, shape, and relative position of surfaces during machining, it is necessary to perform a stress-strain analysis of the system "fixture–workpiece". The displacement of the "fixture–workpiece" elements under the action of external loads (clamping forces, cutting forces, and cutting moments) in the proposed fixture for one-piece connection rods is determined. The fixture's strength was determined by obtaining values of equivalent stresses. The contact interaction models between the workpiece and functional fixture elements are considered, and stress concentrators are identified. The maximum values of equivalent stresses determined in the ANSYS Workbench software according to von Mises equivalent strength were compared with the permissible value for the specific material from which the fixture parts are made and the material of the machining workpiece.

The fixture model considers the Coulomb friction coefficient of 0.1 between the contact surfaces of the fixture, which have approximately the same roughness Ra = 1.6 µm.

The boundary conditions are presented in Figure 4 and Table 1.

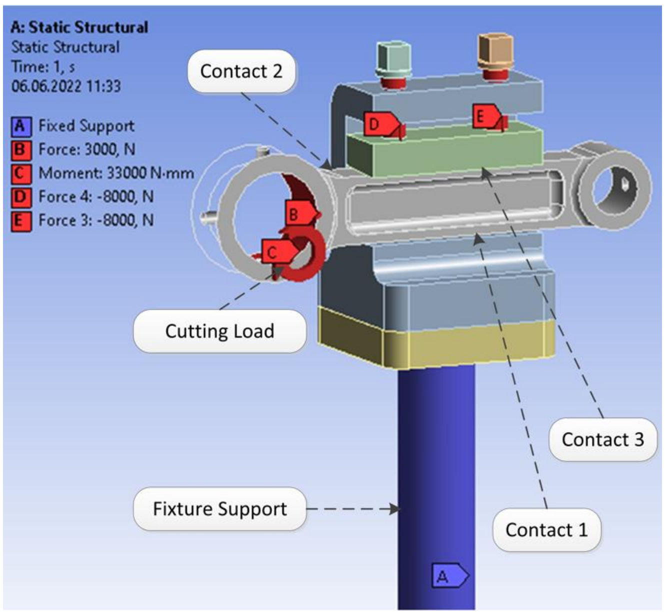


Figure 4. Boundary conditions and contact layers for the fixture.

In the process of modeling, the forces and torques of cutting were applied to each of the machined surfaces in turn, as the technological capabilities of the machine can perform only one-tool machining. The value of forces at different machining steps varied between 0.51–2.94 kN and torques 45–142 N·m depending on the method and stage of machining. Simultaneously, on a pressure plate from screws, the constant clamping force 8.0 kN applied to each of them acted.

Table 1. Boundary conditions for numerical simulation of the system "fixture–workpiece".

Reference Surface/Fixing Type	Parameters of the Bonding Groups			
	Contact	Contact Surfaces	Types of the Contact Surfaces	Friction Coefficient
The cylindrical surface of the fixture/fixture support	1	The lower plane of the support/the lower surface of the connecting rod neck	smooth/non-machining	0.2
	2	the end surface of the support/the end plane of the connecting rod neck	smooth/non-machining	0.2
	3	the surface of the pressure plate/the upper surface of the connecting rod neck	grooving/non-machining	0.7

The material properties of the fixture and the workpiece are summarized in Table 2.

Table 2. Mechanical properties of the materials for the workpiece and fixture elements.

Material (DIN Standard)	Young's Modulus, GPa	Poisson's Ratio	Density, kg/m^3	Tensile Strength, GPa	The Ultimate Strength of the Compression, GPa	Yield Strength, GPa
Structural alloy steel 40Cr	200	0.3	7850	0.960	0.960	0.765
Structural steel C45 (after heat treatment)	200	0.3	7850	0.950	0.950	0.726

To evaluate the results of numerical modeling and theoretical performance of the structure, we compare them with the results of similar indicators obtained in previous studies [32] and the allowable values of the permissible parameters for the connecting rod from the average values of its dimensions: length–170 mm, width–40 mm, and height–20 mm.

These boundary conditions allowed simulating the process under static loads. The values of the maximum equivalent stress according to the von Mises hypothesis and the maximum displacements of the elements and surfaces of the system "fixture–workpiece" are presented in Table 3.

Table 3. Numerical simulation results.

Surface (Figure 3)	Manufacturing Step with a Maximum Loading	Maximum Displacement, mm		Permissible Values of Displacements, mm	Maximum Equivalent Stress, MPa		Permissible Values of Stresses, MPa
		Fixture with Incomplete Locating	Fixture with Complete Locating		Fixture with Incomplete Locating	Fixture with Complete Locating	
A	Milling	0.039	0.048	0.15	297	315	726
B	Milling	0.082	0.095	0.20	419	427	726
C	Drilling	0.092	0.107	0.25	329	361	726
D	Drilling	0.085	0.097	0.20	314	338	726
E	Drilling	0.006	0.006	0.25	112	94	726

The results show that the proposed fixture design provides the specified accuracy. The corresponding indicators do not exceed the values for a flexible fixture with a complete workpiece locating.

3.2. *Eigenfrequencies of the System "Fixture–Workpiece"*

Vibrations inevitably occur in the technological system during machining. Technological parameters of machining modes cause them (e.g., cutting depth, feed, speed, dimensions, number of tools, etc.). Eigenfrequencies for these oscillations depend on the design parameters and the material of parts.

The eigenfrequencies have been determined using the built-in module "Modal Analysis" of the ANSYS Workbench software to prevent the resonant modes during the machining of one-piece connection rods in the developed fixture. The corresponding comparison with the machining frequencies at all steps of drilling-milling-boring operations for the studied fixture has been performed.

The analysis results determine the required detuning from the resonance (Table 4).

Table 4. The results of fixture eigenfrequencies investigation.

Fixture	Eigenfrequency, Hz			The Maximum Frequency of the Machining, Hz	Manufacturing Step with the Maximum Frequency of the Cutting Process
	1st	2nd	3rd		
Incomplete locating	1729	1817	2231	100	Drilling of the hole (diameter 4 mm, speed 3000 rpm)
Complete locating	1425	1427	2073		

The mode shape examples for the first two eigenfrequencies are shown in Figure 5.

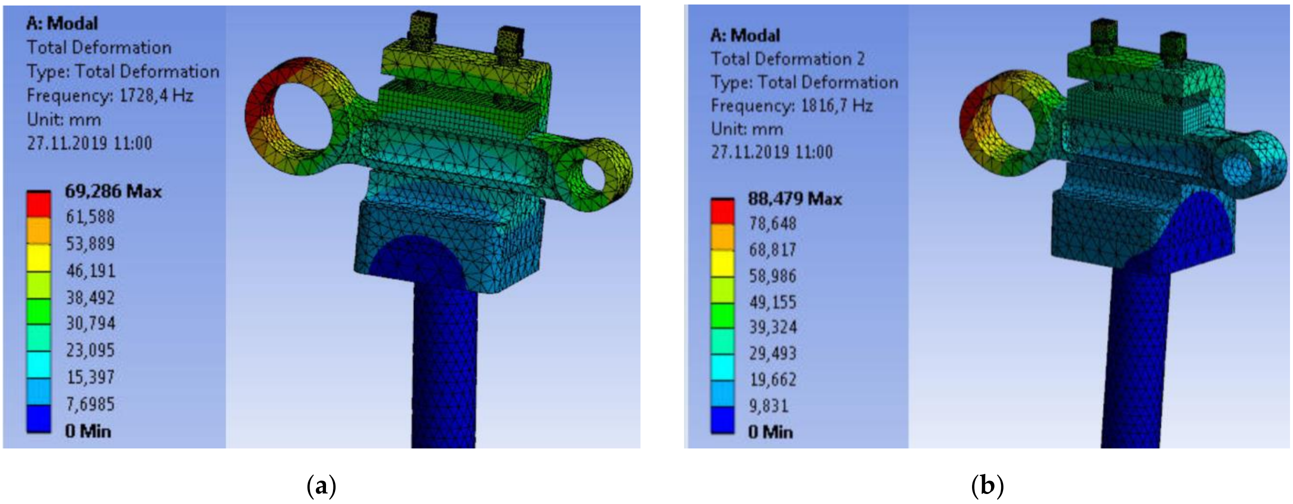


Figure 5. An example of the proposed fixture's oscillation frequencies: (**a**) The 1st eigenfrequency; (**b**) The 2nd eigenfrequency.

Remarkably, at the first eigenfrequency, oscillations occur in the XY plane and the second one in the YZ plane. Since the first eigenfrequency significantly exceeds the operating frequency of the cutting process (1729 Hz >> 100 Hz), resonance does not occur.

Nevertheless, after comparing the values for the complete and incomplete locating fixture, it should be noted that the oscillation frequencies for the incomplete locating fixture are higher, which can be explained by fewer parts and connections between them, respectively.

3.3. Forced Oscillations of the System "Fixture–Workpiece"

To check the oscillation amplitudes of of the system "fixture–workpiece", the amplitude of dynamic forces and torques during cutting was chosen as 20% of the nominal values. Therefore, the amplitude of cutting forces at the machining steps of one-piece connection rod surfaces varied from 101 N to 587 N, and the amplitude of cutting torques was in the range of 9.0–28.4 N·m.

Previous studies have shown that the range of operating frequencies of the cutting process when machining one-piece connection rods does not exceed 100 Hz. This fact allows limiting the range 0–100 Hz on the frequency response charts when determining the amount of displacement.

To establish the possibility of fixture operation in a wider range and review the amplitude-frequency characteristics of fixture, it was decided to set the range 0–2 kHz, which corresponds to 30,000 rpm for single-blade tools, and 15,000 rpm–for two-blade tools such as drills. This may be relevant for the treatment of small diameter holes that are intended for lubrication. Therefore, to increase the efficiency of processing such holes, it is possible to use tools made of hard alloy that allow high cutting speeds and, accordingly, to ensure optimal operating conditions of these tools, it is necessary to provide them with high speeds. Therefore, the study of the amplitude of oscillations in the range 0–2 kHz is relevant information for further research.

The numerical simulation of forced oscillations for the system "fixture–workpiece" allowed for obtaining the amplitudes of displacements at points in the machining zone during the cutting process (Table 5).

Table 5. The results of the dynamic analysis.

Surface (Figure 3)	Manufacturing Step with a Maximum Loading	The Resulting Force at the Transition, N	Force's Amplitude, N	Torque, N·m	Torque's Amplitude, N·m	Maximum Displacement for the Fixture, µm	
						Incomplete Locating	Complete Locating
A	Milling	895	179	68	13.6	4.8	5.1
B	Milling	1070	214	83	16.6	6.4	6.6
C	Drilling (Ø 29.5 mm)	2937	587	142	28.4	9.6	10.3
D	Drilling (Ø 15.5 mm)	1706	341	107	21.4	7.1	7.3
E	Drilling	505	101	45	9.0	2.1	2.1

An example of the frequency response when drilling a hole with a diameter of 29.5 mm in the large head of the one-piece connecting rod is shown in Figure 6.

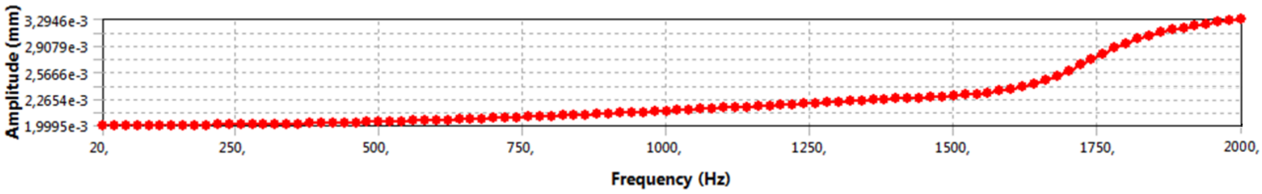


Figure 6. The amplitude-frequency response of the fixture with incomplete locating when machining the surface of a one-piece connection rod.

The amplitudes of oscillations that occur at all machining steps are less than the tolerances on the corresponding machined surfaces. Therefore, the needed accuracy is achieved.

For determining the reserve of the proposed fixture, the dynamic response has been evaluated for the machining step of drilling a hole with a diameter of 29.5 mm in the large head of the connecting rod (Table 6).

Table 6. The results for the calculation of the dynamic stiffness of the fixture.

Fixture	Manufacturing Step	The Amplitude of the Dynamic Component of the Cutting Force, N	The Maximum Amplitude of Displacements, µm
Incomplete locating	Drilling a hole (Ø 29.5 mm)	587	9.6
Complete locating		587	10.3

4. Discussion

Thus, the theoretically hypothesis of achieving the accuracy parameters of machining in a fixture with incomplete locating of workpiece on the example of the developed design of a flexible fixture installing one-piece connection rods for multi-nomenclature production is proved. Thus, the proposed approach to the fixture design based on the reliable clamping of the workpiece and the use of modern CNC machine tools with the functions of automatic determination of the coordinates of the workpiece has shown its effectiveness.

According to the results of the numerical simulation of the stress-strain state of the proposed design of a flexible fixture for one-piece connection rods, it is established that the values of the accuracy parameters specified by the designer during machining will be provided. After all, the maximum displacement of the fixture elements during machining of a one-piece connection rod was 0.092 mm when drilling and 0.082 mm when milling, not exceeding the tolerances according to the requirements of the drawing 0.25 mm and

0.2 mm, respectively, for this connecting rod design. The displacement data are also elastic, as the values of the maximum stresses at the most loaded step do not exceed the strength limits of the material of the fixture parts and the workpiece material.

The developed fixture design also meets the strength conditions. The safety factor for this system at maximum stresses of 419 MPa equals 1.8. As a result of comparing fixtures with complete and incomplete locations, it was found that the displacements and stresses are smaller by 7% and 9%, respectively, in the fixture with an incomplete location. This fact is explained by the smaller number of parts and connections in such a fixture.

The results of harmonic analysis of the proposed design indicate the high rigidity of the developed technical solution and the lack of resonance due to design shortcomings of the fixture because the first eigenfrequency of the fixture is more than 14 times higher than the maximum frequency of the cutting process. Analysis of the dynamic state of the elements of the system "fixture–workpiece" of the proposed fixture showed that the amplitudes of oscillations that occur during removal of the allowance during cutting in places of machined surfaces do not exceed tolerances for machining at the appropriate steps. The maximum value of the oscillation amplitude for the operating step of drilling a hole with a diameter of 29.5 mm in the large head of the connecting rod is 0.096 mm.

Analyses of free and forced oscillations also confirm the higher performance of the proposed fixture design for connecting rods machining. Overall, it was established that the proposed fixture with an incomplete location for one-piece connection rods at the theoretical stage provides the necessary indicators of machining accuracy.

Overall, the proposed methodology continues recent strategies in the development of flexible fixtures [33], increases the reliability of the automated flexible fixture systems for mass production [34], improves methods for flexible fixture design in the automotive industry [35], extends recent developments in reconfigurable fixture design [36], and improves simulation approaches in fixture design [37].

Further research will evaluate the magnitudes of displacements under static and dynamic loads during machining, considering time-varying dynamic components of cutting forces and torques.

5. Conclusions

1. The efficiency of the developed flexible fixture for machining of rods with incomplete basing based on comparison of the maximum stresses, movements, and frequencies of oscillations with their admissible values for a rod of the concrete size is theoretically proved. Actual performance will be tested in further experimental studies.
2. The proposed approach to the machining of connecting rods with incomplete location allowed for reducing the number of technological operations by 4 and 6, the number of units of equipment by 2 and 4, and the number of special fixtures by 2 and 3, depending on the type of one-piece connecting rods.
3. A comprehensive approach to the numerical modeling of the stress-strain state and free and forced oscillations of the "workpiece-fixture" system is proposed. The reliability of the proposed fixture is justified in terms of strength, rigidity, and vibration safety.
4. It is established that the values of displacements, frequencies of oscillations, and amplitudes of oscillations in the fixture with incomplete locating are 3–7% less than in fixtures with full locating, which was developed and studied earlier.

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