Int J Adv Manuf Technol (2017) 91:79–90
DOI 10.1007/s00170-016-9701-2

ORIGINAL ARTICLE

Numerical simulation of the system “fixture–workpiece” for lever machining

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Received: 27 June 2016 / Accepted: 4 November 2016

Abstract In this article, the new configuration of fixture was proposed for ensuring the sufficient tool accessibility, which allows carrying out multiaxis machining of levers in one setup. The research based on numerical simulation was confirmed that the proposed fixture corresponds to all the accuracy parameters. Workpieces from steel, cast iron and aluminium alloy were investigated within the simulation. The values of displacements and stresses occurring during machining are less for proposed fixture in comparison with the existing fixtures that was confirmed by the deflected mode analysis. The modal analysis proved that the proposed fixture has much higher value of eigenfrequency than the other fixtures. To optimize the machining, the dependences for displacements and stresses on the cutting depth were determined. Oscillations of the system “fixture–workpiece” during machining were investigated for various manufacturing steps of levers machining of the fixtures from different fixture systems. The results of harmonic analysis showed that the dynamic stiffness of the proposed fixture was higher than that for the dedicated and modular fixtures. The oscillation amplitudes in the places of machined surfaces in the proposed fixture do not exceed the tolerance requirements for lever manufacturing.

Keywords Fixture · Modular adjustable fixture · Numerical simulation · Deflected mode · Amplitude-frequency characteristic

1 Introduction

Fixtures play the significant role for ensuring the competitive product manufacturing. They are an integral part of the closed-loop technological system “machine tool–fixture–cutting tool–workpiece”. This is proved by the fact that the portion of fixtures for machining is 70–80% of the total amount of tooling [1], the cost of fixtures is 10–20% of the total cost of manufacturing systems [2], 80–90% of the time required for production planning correspond to the design and manufacturing of fixtures [1], approximately 40% of the rejected parts are due to dimensioning errors that are attributed to poor fixture design [3] and 70% of new fixtures are a modification of the existing [4].

Up-to-date manufacturing engineering is characterized by multiproduct manufacturing of produced parts. Increasing of the part complexity requires complication of the design work for tooling manufacturing, particularly fixtures. It leads to

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raising the prime cost of the finished products. Such manufacturing conditions require frequent changeovers for machining of another batch of workpieces, which poses the question of the economic reasonability of design and manufacturing of dedicated fixtures for parts of specific size. Changeover of the modular fixtures implies their partial or complete reconfiguration within the transition to parts of another size range, which also requires time consuming. Furthermore, stiffness of the modular fixtures is often insufficient for productive machining with cutting conditions which are recommended by global manufacturers of cutting tools, due to a large number of connections and presence of T-slots. Another problem is the excessive steel intensity of the above-mentioned fixtures. Therefore, it is important to implement the flexible fixtures, which provide the changeover for another standard size of parts [5], have sufficient stiffness at the minimum possible weight and allow reducing of the fixture-related costs by 80% [6].

2 Literature review

The up-to-date trend of machining implementation provides the high intensification of manufacturing processes, such as reducing the machining time by decreasing the auxiliary time that is the actual problem nowadays due to the highly competitive market, multiproduct manufacturing and opportunities of the brand new metal cutting machine tools [1]. The development and implementation of the progressive fixtures, which have a high level of flexibility and allow machining in minimum number of setups, are one of the ways to improve the intensification of the machining due to increasing tool accessibility and provide the multiaxis machining. Striving for part machining in one setup is especially important for machine tools of drilling, milling and boring group, because the variety of the complex parts with surface relationship under different angles with small tolerances are machined by them. It usually requires a large number of setups and frequent changes of the locating charts, which directly affects to the manufacturing accuracy of the final product. Non-rotational parts, blocks, cylinders, straps, connecting rods, brackets, levers, etc. are usually machined on the above-mentioned machine tools. Milling the keyways and shaft flats and drilling the radial located holes in flanges and discs are also performed.

Increasing the flexibility and expanding the manufacturing capabilities of fixtures, as well as reducing the preparatory time for changeover, and therefore, raising the efficiency of using the machine tools are provided by the development and implementation of rapid-adjustable locating modules from the set of the modular adjustable fixtures [1, 5]. The developed design solutions for locating the non-rotational parts by plane [7, 8], plane and two holes [9, 10], and coordinate angle [11] and for locating the rotational parts by external [12] and internal [13–15] cylindrical surfaces confirmed the high efficiency in up-to-date engineering [1, 16, 17].

In engineering, particularly in the automotive industry, there is a quite common class of the complex parts, which includes levers, brackets, forks, connecting rods, rocker and traction parts, etc. that are included to the class 74 under the Unitary System of Design Documentation 1.79.100 OK 012-93. They are characterized by a large number of surfaces located in different planes under different angles to one another. Despite of their complex geometry, the elementary surfaces (cylindrical and taper holes, keyways, planes, ledges, etc.) are simple. These parts are also characterized by complexity of the locating charts and insufficient tool accessibility due to a complicated spatial relationship of the surfaces. Therefore, it is quite difficult to provide multiaxis machining of parts, as well as to intensify the manufacturing process of their production. Currently, machining of the complex parts is performed using the dedicated and modular fixtures, which either exclude the adjustment possibility or allow carrying out the adjustment in a short size range.

Thus, it can be concluded that using the flexible fixtures for machining of the complex parts is an inevitable way to improve the competitiveness of the finished products. However, at the initial stages of the design, numerical simulation of the system “fixture–workpiece”must be performed to assure that the flexible fixtures provide the sufficient machining accuracy and absence of vibrations under optimal cutting conditions.

Research of the system “fixture–workpiece” focuses on analysis of the contact interaction between the workpiece and locating-and-clamping elements. In the work [18], the friction between the workpiece and fixture elements was investigated, as well as deformations occurring in the contact surfaces were determined.

The simplified analytical and corresponding finite element models of contact deformations between the workpiece and clamping elements were developed and represented by Cioata and Kiss [19].

The finite element model for determining the stability of the equilibrium state of the fixture with functional elements was developed by Zheng [20] for solving the contact problems of workpiece clamping in fixture. In the optimization model, the system “fixture–workpiece” was considered as a system of rigid bodies with Coulomb’s friction in joints with applying the estimated external forces. The non-stationary components of cutting forces and moments were not considered.

Investigation of the sliding and microsliding occurring under the clamping forces was realized by Motlagh et al. [21] by means of the developed model “Armstrong”. It has allowed carrying out preliminary research for determining the above-mentioned processes for high values of clamping forces that was impossible in previous research.

Oscillations of the system “fixture–workpiece” under the action of dynamic components of cutting forces by using the equations of motion without the stiffness of the functional elements were investigated by Li and Melkote [22]. Thus, the equations of motion, which describe the dynamics of the system “fixture–workpiece” while machining, were obtained by the method of Newton-Euler. There is no taking into account material removing as an essential part of machining [23].

The feature of Deng’s research [24] is that the system “fixture–workpiece” was considered as quasi-static due to the effect of material removing but excluding the dynamic components of cutting forces and moments occurring during machining.

To take into account, the mass change of the workpiece during machining the matrixes of inertia and stiffness changing were used by Zhang et al. [25].

However, in all the above-mentioned works, the impact of the clamping elements is considered on the axiom of coupling with the constant values of corresponding reactions. Due to adventing the active control methods, it is insufficient to use the above-mentioned approaches for fixture design for obtaining the time-variable cutting forces, moments and displacements of elements of the system “fixture–workpiece”.

Using the hydraulic actuator with the feedback system for clamping the workpiece was firstly proposed by Bakker et al. [26–29] for automatic control of the clamping forces depending on the cutting forces. This methodology has been tested for various machining strategies. Investigation of the grinding process for the thin-walled parts of low stiffness was also represented in works [30, 31] by using the piezoelectric feedback sensors for electromechanic clamping and ability to control the clamping force taking into account the oscillation amplitudes of the workpiece.

Evaluation of the dynamic errors of the fixture as a result of changing the parameters during machining was researched by Mykytianskiy [32, 33]. The high complexity of calculations limits the use of this technique in a production environment in the implementation of the rapid design and optimization of the wide range of the fixture configurations.

Investigation of the fixture dynamics impact on the characteristics of the whole technological system was highlighted by Zaripov [34]. This research focuses on the fixture stiffness and determination of the required fixture accuracy for machining of the parts with different accuracy parameters. Experimental research of the dynamic state of the workpiece in the fixture is shown that the fixture has the greatest impact on the oscillation amplitude and frequency of the machining workpiece. The resonance zones were detected for the different fixture configurations. The impact of changes of the cutting forces on the oscillation amplitude during machining was investigated. It leads to deterioration of the accuracy and roughness of the machining surface and causes the damage of the cutting tool. The disadvantage of this work is the absence of the reliable mathematical model, which is confirmed by experimental data. It makes impossible to carry out calculations for other initial conditions, such as workpiece material, cutting tool and fixture configuration.

The aim of the research is substantiation of reasonability of developing the fixture, which provides the ability to adjust the fixture elements for lever setup in a certain size range, increases the tool accessibility and allows to carry out the multiaxis machining, as well as to prove that the proposed fixture ensures the specified accuracy parameters for part machining by comparison with the similar parameters of the dedicated and modular fixtures. To achieve this aim, the research problems are formulated:

- investigation of the deflected mode for elements of the system “fixture–workpiece”;
- investigation of the eigenfrequencies of the system “fixture–workpiece”;
- investigation of the dynamic state of the system “fixture–workpiece”.

3 Research materials

3.1 Manufacturing process development

Part “levers” were chosen as the object of the research (Fig. 1) because levers are components of many aggregates and units of engineering products, especially in the automotive industry. Although, a variety of automobile models is so large today, their main mechanisms with levers are not significantly differing. Due to the fact that the difference may be only in changing a standard size range or locations of certain surfaces, it is appropriate to develop the fixture, which provides the ability to install levers in a certain size-and-shape range, unlike dedicated fixtures, which allow to set up one-size parts only.

The adjustable locating-and-clamping module from the set of modular adjustable fixtures [1, 5] is developed for levers multiaxis machining [35]. It is assigned for the setup of the levers of different technical characteristics and allows to reduce the changeover time, as well as to ensure the tool accessibility of the machining surfaces. Proposed configuration is assigned for the setup of the levers in the range of central boss diameters 26–42 mm and arm thickness 13–21 mm. It is achieved by adjusting the screw mechanisms, which provides changing the distance between locating-and-clamping elements (Fig. 2a). The adjustable locating-and-clamping module may be installed either on the machine tool’s table or on the base plate from the set of modular fixture system. Such engineering solution in the total with power-driven rotary table allows carrying out the all drilling, milling and boring manufacturing operations at one setup computer numerical

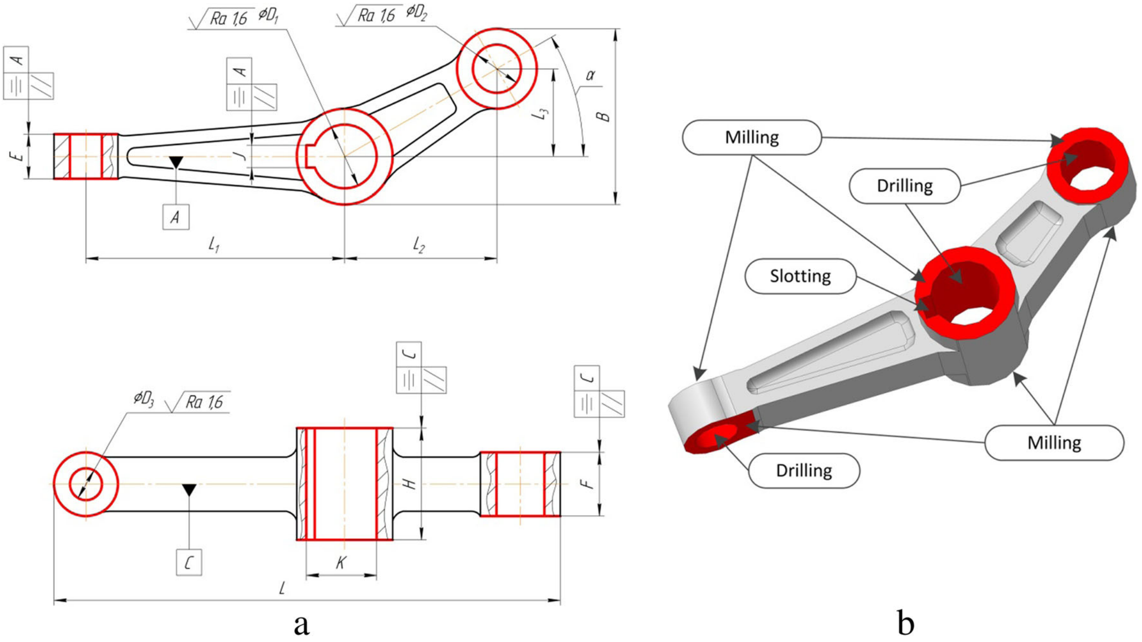


Fig. 1 Lever (**a**) and machining surfaces (**b**)

control (CNC) multiaxis machining operation (Fig. 2b), which is realized on the CNC machining centre. Thereby, the manufacturing process is reduced by five operations (Fig. 3).

3.2 Investigation of the deflected mode for elements of the system “fixture–workpiece”

Investigation of the deflected mode is carried out and displacements of the elements of the system “fixture–workpiece” under the external loads (clamping and cutting forces and their moments) are calculated for determining the possibility of achieving the dimension, form and spacing accuracy during the lever machining. The fixture strength is investigated by determining the equivalent stress taking into account the model of contact interaction between the workpiece and functional elements. The stress concentrators are identified. The maximum equivalent stress von Mises was compared with the acceptable value for the specific material. The dependence of stresses and displacements on the forces and moments are determined for predicting deviations from the nominal dimension, which will directly affect to the machining accuracy. Investigation of the loading changes on manufacturing steps for milling the boss faces is conducted due to possible varying of the cutting depth.

The model considers the Coulomb’s friction between contact surfaces, which are approximately similar roughness (1.6 μm by the Ra criterion) with friction coefficient 0.1

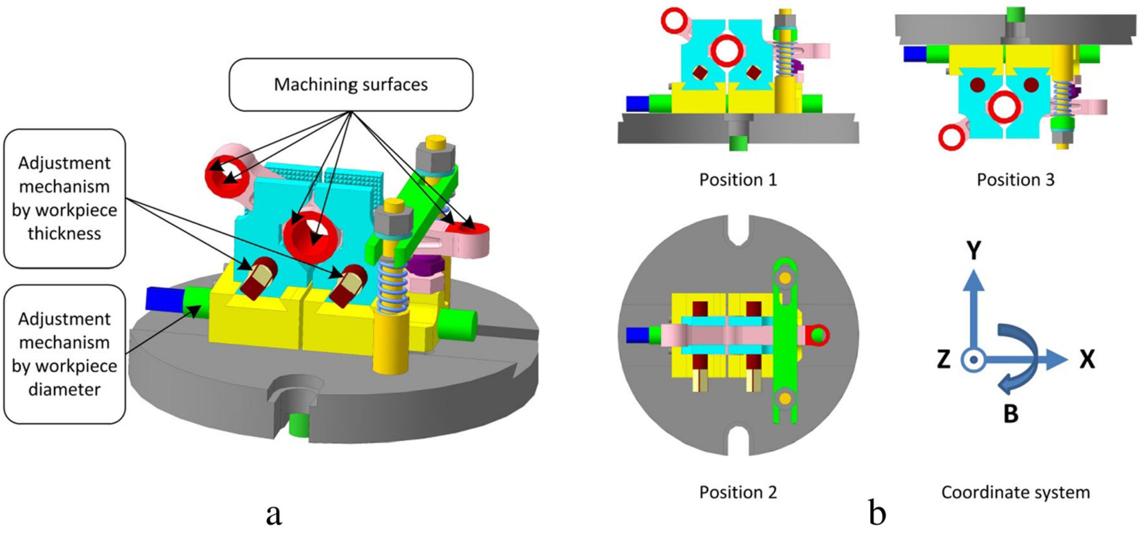


Fig. 2 Adjustable locating-and-clamping module (**a**) and cut-map for lever machining on the CNC multiaxis machining operation (**b**)

[36]. Friction coefficients for contacting pairs between the workpiece and fixture elements and the boundary conditions for numerical simulation are represented in Table 1. Mechanical properties of the fixture and workpiece are tabulated in Table 2.

Numerical simulation was accompanied by applying loads (cutting forces 134–5494 N and torques 16–29.8 N·m) for machined surfaces of the workpiece (Fig. 4). The load values depend on workpiece material and machining method. The clamping forces 1000–3000 N were applied to clamping elements depending on the fixture configuration. The combination of these boundary conditions allowed performing numerical simulation corresponding to the real machining process for static formulation.

The design models were created by using the ANSYS Workbench. The values of displacements and stresses occurring in the workpiece, fixture elements and contact points were determined. The results of numerical simulation for workpieces from different materials (structural alloy steel 40CrNi6, grey cast iron GG-20m aluminium alloy G-AlSi10Mg) such as determined values of the maximum displacement and equivalent stress von Mises [27] for the type and proposed fixtures are represented in Table 3. Illustrated simulation results for milling the main hole's boss face (manufacturing step 1) are shown in Figs. 5 and 6 and for milling the auxiliary hole's boss face located perpendicularly to the main hole (manufacturing step 5) are shown in Figs. 7 and 8.

Simulation the milling of the auxiliary hole's boss face located perpendicularly to the main hole (manufacturing step 5) is conducted by identifying the dependence of displacements on the depth of cut. Diagrams illustrated the dependences of displacements and stresses on the cutting depth are shown in Figs. 9 and 10.

Displacements occurring on all the manufacturing steps in the dedicated and modular fixtures are higher than in the proposed fixture. It suggests that the dimension, form and spacing deflections of the machined part in the proposed fixture are

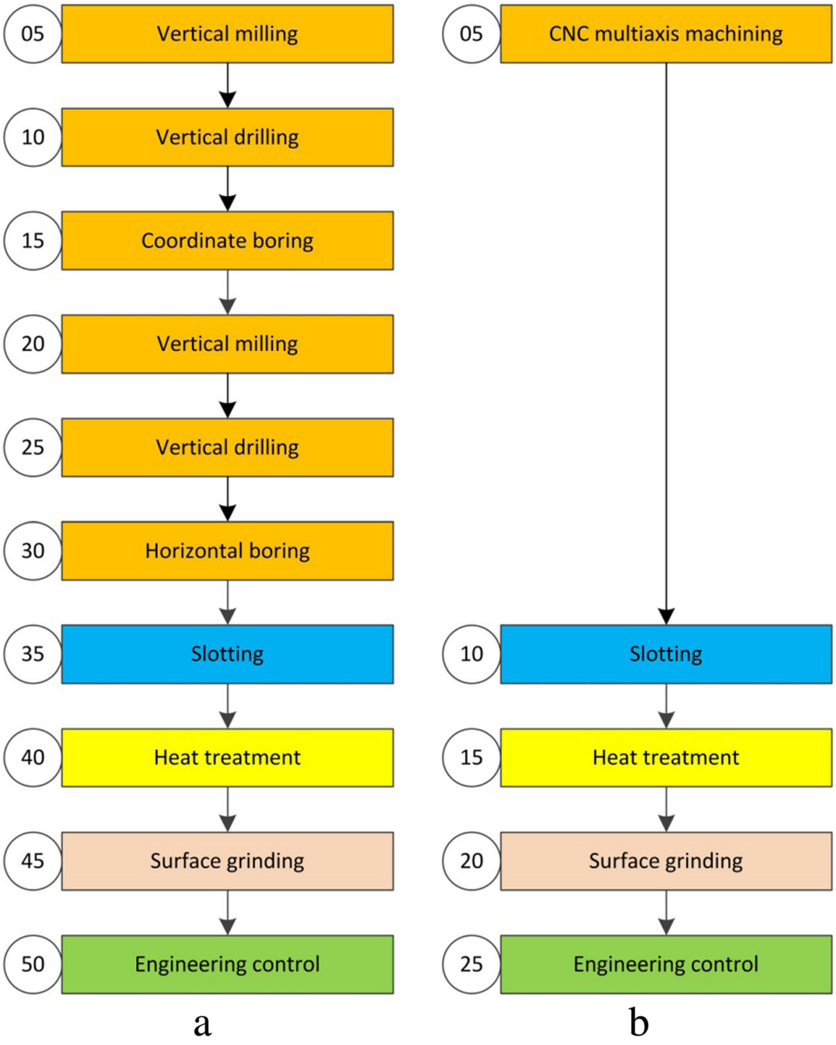
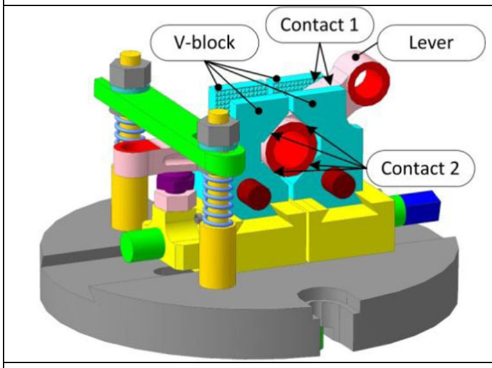
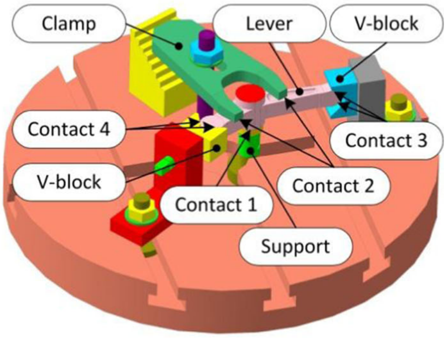
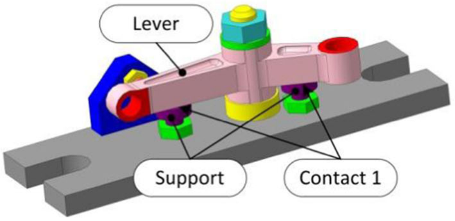


Fig. 3 Comparison of the process flow for the lever machining. **a** Type manufacturing process. **b** Proposed manufacturing process

Table 1 Boundary conditions for numerical simulation of the system “fixture–workpiece”

Fixture and contact layout	Reference surface / fixing type	Parameters of the bonding groups			
		Contact	Contact surfaces	Types of the contact surfaces	Friction coefficient f
	Bottom surface of the plate / fixture support	1	Side surfaces of the V-blocks / side surfaces of the lever	Serrated/ unmachined	0.7
		2	Working surfaces of the V-blocks / cylindrical surfaces of the lever	Smooth / unmachined	0.2
	Bottom surface of the plate / fixture support	1	Support / lever butt	Serrated / unmachined	0.7
		2	Clamping surfaces of the clamp / side surfaces of the lever	Smooth / unmachined	0.2
		3	Working surfaces of the V-blocks / cylindrical surfaces of the lever	Smooth / unmachined	0.2
		4	Working surfaces of the V-blocks / cylindrical surfaces of the lever	Smooth / unmachined	0.2
	Bottom surface of the plate / fixture support	1	Supports / side surfaces of the lever	Serrated / unmachined	0.7

lower and, therefore, the machining accuracy is increasing. Stresses on manufacturing steps for machining in the proposed fixture are higher than in the existing fixtures. This is explained by different areas of contact interaction between the workpiece and fixture elements, which are particularly caused by the nature of applying forces for different fixture configurations. The acceptable cutting depths for finishing steps can be determined by condition that machining displacements will not exceed the geometry fidelity (Fig. 9). It allows to predict the machining accuracy on a specific manufacturing operation or step. The acceptable cutting depths (without residual deformations) can be determined by Fig. 10. It allows increasing the machining productivity by using the maximum capabilities of machine and cutting tools.

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

Material (DIN standard)	Modulus of elasticity E, GPa	Poisson's ratio μ	Density ρ, kg/m^3	Tensile strength [σ_t], GPa	Ultimate strength of compression [σ_c], GPa	Yield strength σ_y, GPa
Structural alloy steel 40CrNi6	200	0.3	7850	0.980	0.980	0.785
Grey cast iron GG-20	110	0.28	7200	0.245	0.451	–
Aluminium alloy G-AlSi10Mg	100	0.27	2700	0.420	0.420	0.360
Structural steel C45 (after heat treatment)	200	0.3	7850	0.950	0.950	0.726

3.3 Investigation of the eigenfrequencies of the system "fixture–workpiece"

To prevent the resonance phenomenon during lever machining, it is necessary that the eigenfrequencies of the fixture elements have not matched the cutting frequency. One of the way for solving this problem is to assign other cutting conditions. For this purpose, the eigenfrequencies are determined by using the integrated module "modal analysis" of the computer aided engineering (CAE) system "ANSYS Workbench". The first eigenfrequency was compared with the frequency of the reversed components of cutting forces and moments on the all steps of drilling, milling and boring manufacturing operations. The results of the analysis allow determining required deturning from resonance (Table 4). While calculating all the fixture elements was bounded together by nodes joining, the possibility of relative friction movement is provided for certain surfaces of the fixture elements [37]. The contact types and characteristics of the contact pairs between surfaces are tabulated in Table 1.

As Table 4 shows, the resonance phenomenon does not occur for the considered fixtures, because the first eigenfrequency is significantly higher than the cutting frequency. But it is possible to make a preliminary conclusion that the designed fixture has higher stiffness to implement the proposed manufacturing process than the fixture for the type one. It indicates the expected increase in the dynamic stiffness of the developed fixture, which must be chequed by using the harmonic analysis.

3.4 Investigation of the dynamic state of the system "fixture–workpiece"

The harmonic analysis is performed by the integrated module "harmonic analysis" of the CAE system "ANSYS Workbench". The eigenfrequencies of the system "fixture–workpiece" were determined on the base of the modal analysis. Amplitudes of the dynamic components of cutting forces and moments were chosen within 20% of the nominal values [36]. Preliminary research has shown that operating frequency range for lever machining does not exceed 100 Hz. It allows limiting by the range 0–100 Hz on the amplitude-frequency characteristic for determining the values of displacements. The comparative analysis of displacements is conducted at the maximum machining frequency 100 Hz to ensure the equal conditions for the all fixtures. The values of oscillation amplitudes are determined as a result of numerical simulation of the dynamic of the system "fixture–workpiece" caused by the cutting process. The values of displacements in the machining zone are calculated for the type and proposed fixtures (Table 5, Figs. 11 and 12).

Oscillation amplitudes occurring at all the machining steps in the dedicated and modular fixtures are higher than in the proposed fixture. It suggests that in the other equal conditions, the dimension, form and spacing deflections of the machined part in the proposed fixture are lower, which increases the machining accuracy. The results of the investigation and comparison of the dynamic stiffness of the fixtures for certain steps are stated in Table 6. The dynamic stiffness of the proposed fixture is higher by 5% than in the dedicated fixture and 15 times higher than in the modular fixture, which ensures increasing accuracy indicators while lever machining.

4 Conclusions

1. It is proved that developed engineering solutions contribute to the intensification of the manufacturing process of machining and do not lead to deterioration of the accuracy indicators. The research of the deflected mode has shown that the developed fixture for lever machining provides

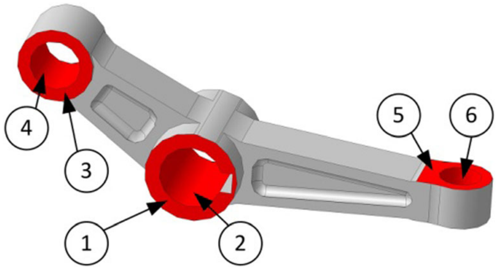


Fig. 4 Manufacturing steps during lever machining on the CNC multiaxis machining operation (fragment)

Table 3 Numerical simulation results for machining the levers from different materials

Number of manufacturing step in Fig. 4	Manufacturing step with maximum loading	Workpiece material	Maximum displacement, μm		Maximum equivalent stress von Mises, MPa	
			Type manufacturing process	Proposed manufacturing process	Type manufacturing process	Proposed manufacturing process
1	Milling	40CrNi6	0.08	0.017	132	174
		GG-20	0.03	0.015	78	122
		G-AlSi10Mg	0.03	0.015	74	121
2	Drilling	40CrNi6	0.02	0.019	72	101
		GG-20	0.01	0.017	44	73
		G-AlSi10Mg	0.01	0.019	38	61
3	Milling	40CrNi6	0.18	0.11	604	589
		GG-20	0.18	0.12	372	364
		G-AlSi10Mg	0.17	0.14	299	288
4	Drilling	40CrNi6	0.15	0.14	446	620
		GG-20	0.15	0.13	295	420
		G-AlSi10Mg	0.13	0.13	238	342
5	Milling	40CrNi6	0.05	0.046	208	134
		GG-20	0.05	0.05	143	91
		G-AlSi10Mg	0.05	0.05	130	83
6	Drilling	40CrNi6	0.19	0.12	348	307
		GG-20	0.23	0.16	302	243
		G-AlSi10Mg	0.21	0.18	235	199

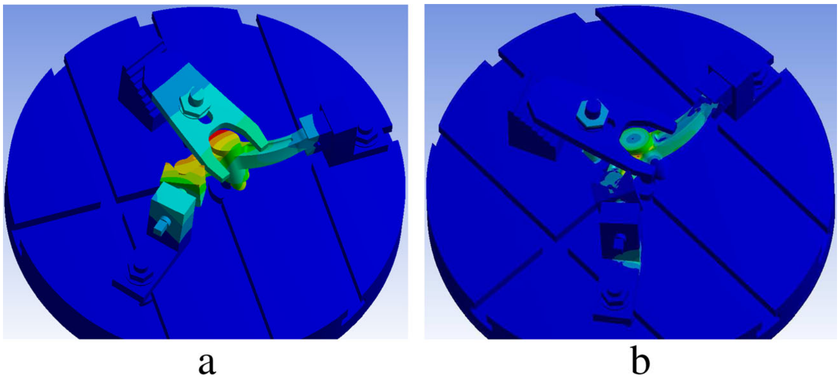


Fig. 5 Illustrated simulation results for modular fixture. **a** Equivalent stress von Mises. **b** Displacements

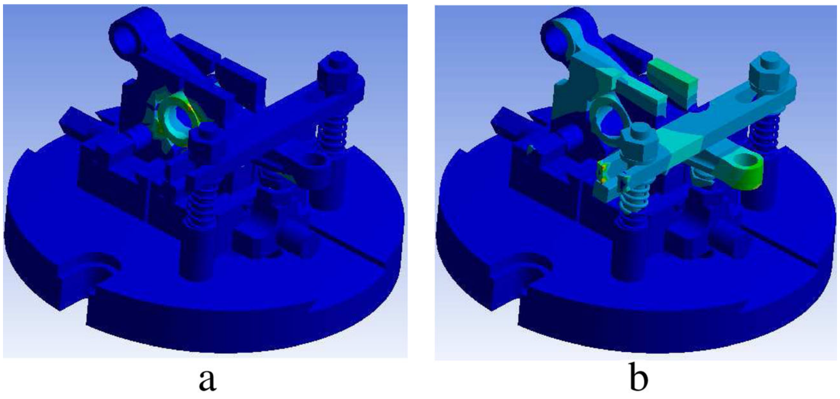


Fig. 6 Illustrated simulation results for proposed fixture. **a** Equivalent stress von Mises. **b** Displacements

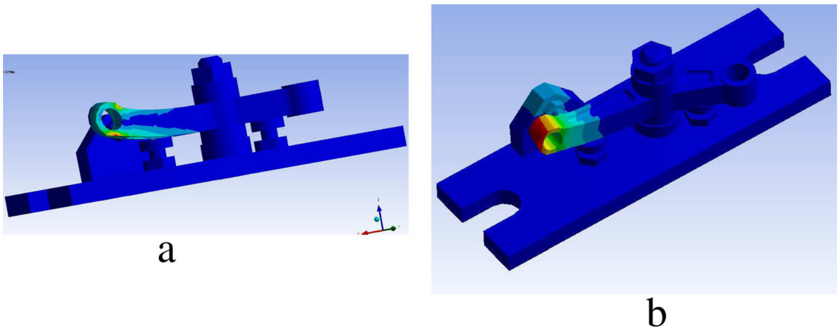


Fig. 7 Illustrated simulation results for dedicated fixture. **a** Equivalent stress von Mises. **b** Displacements

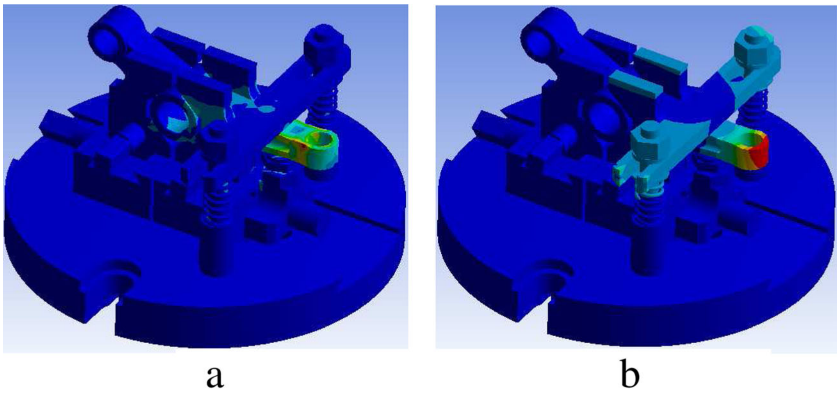


Fig. 8 Illustrated simulation results for proposed fixture. **a** Equivalent stress von Mises. **b** Displacements

multiaxis machining and corresponds the strength conditions, as well as significantly reduces the auxiliary and preparatory time. The results of numerical simulation of the deflected mode for the manufacturing process of lever machining in the different fixtures have shown that machining in the proposed fixture has higher accuracy indicators in comparison with the dedicated and modular fixtures due to the lower values of displacements, which are 0.01–0.05 mm on average. Stresses that occur between the fixture elements and in contact places with the workpiece during machining are insignificantly different within 10–50 MPa and do not exceed the ultimate strength for the workpiece and fixture elements. The essential difference (over 100 MPa) between the values of the manufacturing step for drilling

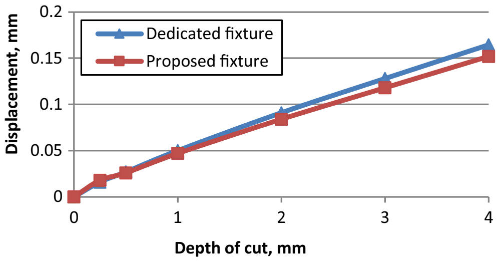


Fig. 9 Diagram of the dependence of displacements on the depth of cut

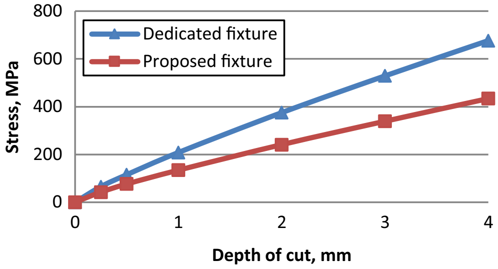


Fig. 10 Diagram of the dependence of equivalent stress von Mises on the depth of cut

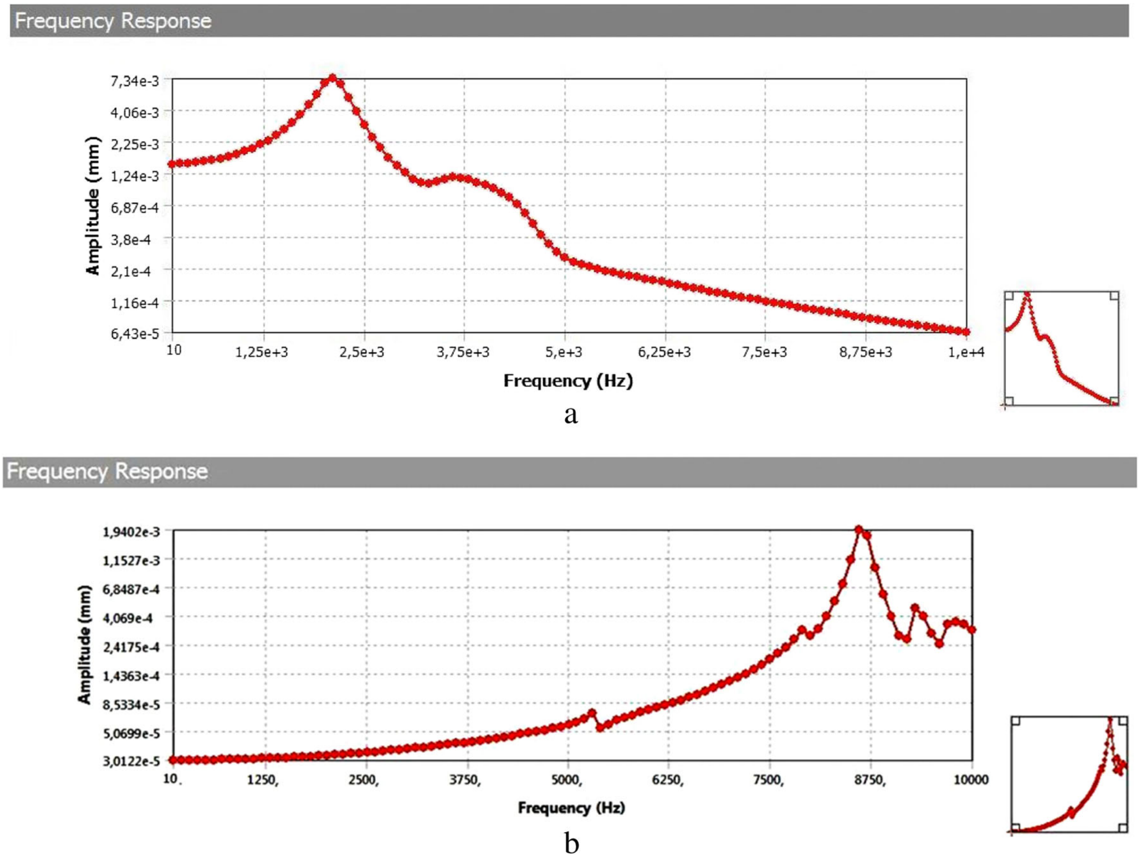
Table 4 The results of fixture eigenfrequencies investigation

Fixture	Critical frequency, Hz			Machining frequency, Hz
	1st	2nd	3rd	
Modular fixture	2186	2595	2835	96
Dedicated fixture	5888	7268	8250	96
Proposed fixture	6125	7830	8915	96

Table 5 The results of the harmonic analysis

Number of manufacturing step in Fig. 4	Manufacturing step with maximum loading	Workpiece material	Maximum amplitude, μm	
			Type manufacturing process	Proposed manufacturing process
1	Milling	40CrNi6	1.4	0.03
		GG-20	1.1	0.024
		G-AlSi10Mg	1.4	0.022
2	Drilling	40CrNi6	24	1.7
		GG-20	20	1.2
		G-AlSi10Mg	21	1.2
3	Milling	40CrNi6	1.2	0.89
		GG-20	1.2	0.77
		G-AlSi10Mg	1.1	0.74
4	Drilling	40CrNi6	12	11.5
		GG-20	11	9.4
		G-AlSi10Mg	12	11.4
5	Milling	40CrNi6	1.4	1.3
		GG-20	1.5	1.4
		G-AlSi10Mg	3	1.9
6	Drilling	40CrNi6	16.1	15.3
		GG-20	18.2	17.9
		G-AlSi10Mg	15.1	14.5

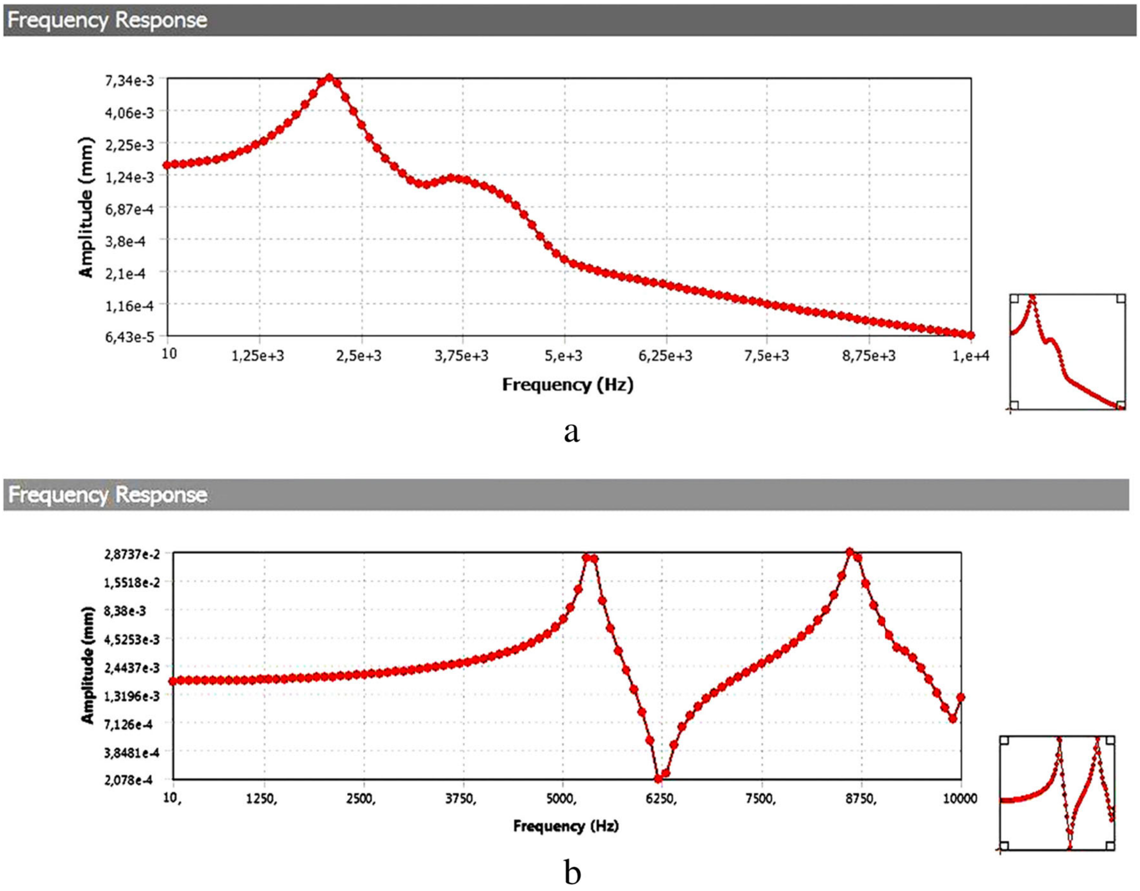
the boss of the auxiliary hole located perpendicularly to the main one can be explained by nature of loading perception due to differences between the fixtures. However, it is not critical because the minimum load factor is 1.5, and the maximum stress at this step does not exceed the ultimate strength.



a

b

Fig. 11 Amplitude-frequency characteristic for main hole's boss milling (manufacturing step 1) of the lever from the structural alloy steel 40CrNi6. **a** Modular fixture. **b** Proposed fixture



a

b

Fig. 12 Amplitude-frequency characteristic for main hole's boss drilling (manufacturing step 2) of the lever from the structural alloy steel 40CrNi6. **a** Modular fixture. **b** Proposed fixture

2. The first eigenfrequencies for the proposed fixture on manufacturing operations 05–015 and 20–30 of the type manufacturing process are higher in 1.04 and 2.8 times than the corresponding values for the other fixture systems. Moreover, comparison of the amplitudes of forced oscillations in the operating mode indicates increasing the dynamic stiffness of the proposed fixture in the range of 1.005–1.17 times for manufacturing operations 05–15 and 14.1–17.5 times for operations 20–30 relative to the other fixture systems. The presence of ranges explains the different modes and loads during lever machining for different materials.
3. Dynamic analysis of the elements of the system "fixture–workpiece" in case of lever machining of the proposed manufacturing process and cutting conditions suggests that the resonance does not occur. Oscillation amplitudes

Table 6 The results of the dynamic stiffness calculation

Number of manufacturing step in Fig. 4	Manufacturing step	Workpiece material	Amplitude of the dynamic component of the cutting force, N	Estimated dynamic stiffness, 10^7 N/m		Stiffness increasing, times
				Type manufacturing process	Proposed manufacturing process	
2	Drilling	40CrNi6	1099	0.46	6.46	14.1
		GG-20	704	0.35	5.87	16.6
		G-AlSi10Mg	597	0.28	4.98	17.5
4	Drilling	40CrNi6	993	0.83	0.86	1.04
		GG-20	650	0.59	0.69	1.17
		G-AlSi10Mg	520	0.43	0.46	1.05
6	Drilling	40CrNi6	705	0.44	0.46	1.05
		GG-20	597	0.33	0.33	1.02
		G-AlSi10Mg	463	0.31	0.32	1.04

during workpiece machining in the proposed fixture do not exceed the processing tolerances on the corresponding steps. Dynamic stiffness of the proposed fixture is higher than for the dedicated and modular fixtures on average in 1.05 and 15 times. Values of the oscillation amplitudes in the proposed fixture are less on average by 0.01–0.02 mm than for the dedicated and modular fixtures.

4. Further research focuses on experimental verification of the results of numerical simulation for determining the displacements under static loading, as well as oscillation amplitudes during machining taking into account the dynamic components of cutting forces and moments. Also, it is expedient to investigate the stability of equilibrium state of the elements of the system “fixture–workpiece” under external forces. Above-mentioned allows to evaluate the efficiency of the developed engineering solution and also promotes to development the fixtures for setup other complex parts.

Acknowledgements The presented article was supported by framework projects VEGA 1/0492/16, KEGA 042TUKE-4/2015 and VEGA 1/0619/15.

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