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NOVEL WORKPIECE CLAMPING METHOD FOR INCREASED MACHINING PERFORMANCE

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Original scientific paper

Fixtures which balance cutting forces and torques by the friction forces generated on contact surfaces of locating, clamping elements and workpiece surfaces are widespread in industrial practice. Among other things, these friction contacts are characterized by a certain amount of interface compliance which is a complex function of macro- and microgeometry of contact pairs in the workpiece-fixture system, as well as the clamping and cutting forces. Workpiece machining errors are mostly the consequence of that interface compliance. This paper investigates workpiece-fixture interface compliance in cases where clamping is performed using a standard, and specially designed clamping element. Theoretical considerations are presented, followed by results of experimental investigation. Considerable advantages of the specially designed clamping element compared to its standard counterpart are demonstrated by experiments. The results are a good starting point for a research into optimization of special fixture clamping elements and their wider industrial application.

Keywords: *fixture, clamping force, compliance, indenting*

Povećanje učinkovitosti strojne obrade novom metodom stezanja izradaka

Izvorni znanstveni članak

Naprave kod kojih se sile i momenti nastali u procesu rezanja uravnotežuju silama trenja, nastalim na kontaktima elemenata za baziranje i stezanje s izratkom, su vrlo zastupljene u industriji. Spomenute kontakte, pored ostalog, karakterizira određena popustljivost veza koja je složena funkcija makro i mikrogeometrije kontaktnih parova u sustavu izradak-naprava, sila stezanja i sila rezanja. Pogreške obrade uvelike su posljedica upravo popustljivosti spomenutih veza. U radu se razmatra popustljivost veza između elemenata za stezanje i izratka u slučajevima stezanja uređajem za stezanje s ravnim čelom i specijalno dizajniranog elementa za stezanje. Nakon teorijskih razmatranja izloženi su rezultati eksperimentalnih istraživanja. Rezultati ukazuju na značajne prednosti specijalno dizajniranog elementa za stezanje u odnosu na standardni oblik elementa za stezanje s ravnim čelom. Dobiveni rezultati otvaraju prostor za istraživanja u smislu optimizacije elemenata naprava za stezanje i mogućnosti njihove industrijske primjene.

Keywords: *naprava, sila stezanja, popustljivost, utiskivanje*

1
Introduction

Application of new scientific approaches to improve the level of knowledge and organization in production preparation sectors not only has a considerable impact upon the final product characteristics but also indirectly affect production costs and times of delivery. Manufacturing companies which primarily focus on technological and operational preparation of production, i.e. those that keep up to date with the technological parameters and the results of technological processes, stand the best chances of improving the activities in the observed sectors [1]. One of essential characteristics of modern production systems is the ability to manufacture a variety of high-quality products in the shortest possible time. Short time-to-market is a key instrument in providing market domination and higher profit margins. Job and small-batch production often take priority as dictated by the market demand for a variety of products. All this demands development of a flexible, agile, manufacturing system which is capable of meeting new production programs [2].

Owing to stringent market demands and intensive development of science, equipment, and novel technologies, the level and trend of further development of machining processes in the metal cutting industry depend on numerous factors. The factors which most influence the quality of machining process are: type of blank, machining technology, operations, sub-operations, machine tools, cutting tools, fixtures, measuring devices, etc. [3, 4, 5, 6, 7]. In order to bring the machining process to a higher level, all these elements must be optimized. Within a number of factors which influence output effects of manufacturing process, machining fixtures play a prominent role [8].

Fixture design optimization has been focused on by numerous investigations in previous years.

DeMeter [9] used a rigid body fixture-workpiece model and the min-max load criterion for synthesis of optimal fixture layout and minimum clamp actuation intensity. Nonlinear optimization methods were used while neglecting the elastic deformation of workpiece. Jeng et al. [10] presented a search algorithm for the instant center of motion, based on the correlation between the cutting forces and clamping moments. Based on the property of instant center of motion, minimum clamping force was estimated. Wu and Chan [11] used genetic algorithm (GA) to determine the most statically stable fixture layout. They used a rigid body fixture-workpiece model and ignored elastic deformation of the workpiece due to clamping and machining forces. Meyer and Liou [12] presented a methodology to generate the configuration of a fixture, which was under dynamic machining forces. Linear programming was used to determine optimal locator positions and clamping forces. Wang et al. [13] developed an intelligent fixturing system to adjust the clamping forces adaptively to achieve minimum deformation of the workpiece according to cutting forces. Linear static finite element analysis (FEA) was used to find the workpiece deformation. Krishnakumar and Melkote [14] presented a GA-based discrete fixture layout optimization method to minimize the deformation of the workpiece under static conditions.

They applied the GA to 2-D fixturing problems. Hurtado and Melkote [15] formulated a multi-objective optimization model that defines minimum clamping loads to achieve workpiece shape conformability and fixture stiffness goals for a workpiece subjected to quasi-static machining forces. Vallapuzha et al. [16] investigated the use of spatial coordinates to represent locations of fixture elements in their fixture layout optimization model solved by GA. Amaral et al. [17] employed 3-2-1 locating method and developed an algorithm to automatically optimize fixture support, clamp locations, and clamping forces, to minimize workpiece deformation, subsequently increasing machining accuracy. Hamedi [18] presented a fixture design system which integrated nonlinear FEA into the artificial neural network (ANN) and GA. The GA-based program is used to search for the optimal value of clamping forces with small deformation/stress in the component. Deng and Melkote [19] presented a model-based framework for determining the minimum required clamping force to ensure the dynamic stability of a fixtured workpiece during machining. Kaya [20] presented a GA-based continuous fixture layout optimization method. The optimization objective was to search for a 2-D fixture layout that minimized the maximum elastic deformation at different locations of the workpiece. Qin et al. [21] focused on the mathematical modelling and design optimization of clamping sequence for a deformable workpiece-fixture system to minimize the effect of clamping sequence on the workpiece machining quality. Sanchez et al. [22] calculated the contact load at the fixture-workpiece interface using a simple and direct mathematical tool along with the FEA, which simplified the deformation minimisation problem. They also ascertained the interpolating functions which related the clamping position with respect to the load contact in order to define valid clamping regions. Siebenaler and Melkote [23] presented a fixture-workpiece model using FEA to investigate the influence of various parameters on workpiece deformation, including the compliance of the fixture body, contact friction, and mesh density. Tian et al. [24] presented an approach to optimized selection of locating positions of workpieces and identifying feasible clamping regions that meet the requirements of the form-closure principle for fixture layout. Liu et al. [25] proposed a method to optimize the fixture layout in the peripheral milling of a low-rigidity workpiece. This paper dealt with the optimization of the number and positions of locating elements restricted to the secondary locating surface. Prabhaharan et al. [26] presented a fixture layout optimization method that used GA and ant colony algorithm (ACA) separately. The workpiece deformation was modelled using FEA for the problems of fixture layout optimization with the objective of minimizing the dimensional and form errors. Asante [27] presented a model that combines contact elasticity with FEA to predict contact loads and pressure distribution at the contact region in a workpiece-fixture system. Chen et al. [28] presented a fixture layout design and clamping force optimization procedure based on the GA and FEA. The optimization procedure was multi-objective: minimizing the maximum deformation of the machined surfaces and maximizing the uniformity of deformation. Prabhaharan et al. [29] optimized fixture layout for 2-D workpiece geometry with an objective of minimizing the workpiece elastic deformation using ACA-based discrete and continuous fixture layout optimization methods. Dou et al. [30] presented the application of particle swarm optimization (PSO) algorithm to minimize the workpiece deformation. A PSO based approach is developed to optimize fixture layout through integrating Ansys parametric design language (APDL) of FEA to compute the objective function for a given fixture layout. Lu et al. [31] created a cellular GA model of clamping force determination as a multimodal function with a set of geometric and performance constraints, to solve the global optimal clamping forces. Vishnupriyan et al. [32] optimized the fixture layout in order to minimize the machining error considering both geometric error of locating elements and elastic deformation of workpiece. Both of these parameters were simultaneously optimised using a GA. Elastic deformation of workpiece under machining loads was obtained by FEA. Zuperl et al. [33] developed an intelligent fixturing system, which adaptively adjusts variable clamping forces to achieve minimum elastic deformation of the workpiece according to the cutter position and the dynamic cutting forces.

Review of available literature leads to the conclusion that workpiece machining errors are mostly the result of inadequate fixture clamping. Unreliable clamping not only causes larger workpiece/clamping element interface compliance, but can ultimately lead to a complete detachment of workpiece from its locating elements with disastrous consequences. Optimization of locating and clamping schemes - including the number, type, and layout of locating and clamping elements, and clamping force magnitude – can significantly reduce workpiece deformations and increase machining accuracy, which is especially important in the case of thin-walled workpieces with complex geometry [34]. The clamping forces required to secure workpiece location within given tolerances often vary during machining process, being the function of tool path and cutting parameters. This is most typical of the machining of complex geometry workpieces on machining centres. With this in mind, fixture design optimization gains ever more relevance. Fixture design optimization boils down to finding such fixture layout which shall minimize the workpiece elastic deformation and contact deformations at points of contact between workpiece and various fixture elements (locating and clamping elements, supporting elements, and other fixture elements). Minimization of deformations directly reduces machining errors and increases surface quality.

However, a question is posed whether it would be possible to deform narrow zones on the workpiece in the process of clamping, in order to increase productivity while remaining within the set tolerances. The authors of this paper suggest that, considering modern cutting regimes (high cutting speeds, exceeding 1000 m/min, high feed rates, sometimes over 1000 mm/min, large chip cross sections and cutting forces) special attention should be paid to fixture design optimization which would allow minimization of workpiece-fixture interface compliance. Therefore, investigation should be aimed at theoretical and experimental solutions which allow reliable fixture designs. Reviewed in this paper are theoretical and experimental results of optimization of fixture clamping elements regarding the reduction of compliance and increase of tangential load capacity of workpiece-fixture interface. Tangential load capacity of workpiece-fixture interface is defined as the load capacity in the direction normal to the clamping force vector.

2
Theoretical background of the proposed clamping method

To balance cutting forces and torques during the machining process, fixtures most often employ friction forces effective at points of contact between workpiece and locating and clamping elements (Fig. 1).

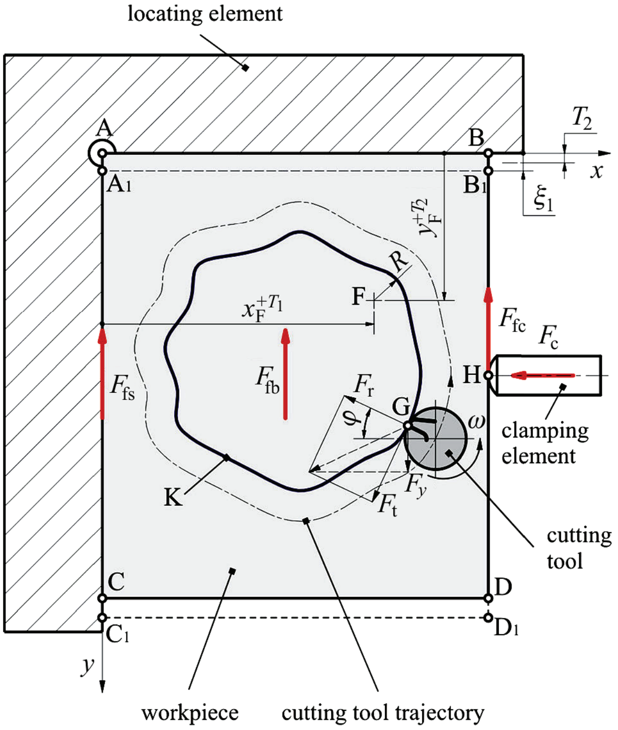


Figure 1 An example of balancing cutting forces with friction forces

Shown in Fig. 1 is an example of milling of a complex contour – K. The directions of tangential, F_t, and radial cutting force, F_r, vary during machining along the contour, K. Equation of static workpiece equilibrium in y axis direction is:

$$F_{fc} + F_{fs} + F_{fb} \geq F_t \cdot \cos\varphi - F_r \cdot \sin\varphi, \tag{1}$$

where: F_{fc} is friction force between clamping element (neighbourhood of point H) and workpiece; F_{fs} is friction force between workpiece and locating element in AC direction; F_{fb} is friction force between workpiece and base locating element; F_t is tangential component of cutting force; F_r is radial component of cutting force; φ is current angle of contour which defines tool path.

If, in the general case, at point G holds:

$$F_t \cdot \cos\varphi - F_r \cdot \sin\varphi = F_y. \tag{2}$$

The equilibrium shall be maintained only by allowing certain displacement of workpiece within the contact zones between workpiece and clamping and locating elements. This means that the workpiece shall be displaced from ABCD position into $A_1B_1C_1D_1$ position. Displacement ξ_1, which is the result of compliance of the contact zones, directly corresponds to workpiece machining error e.g., the machining error of y_F dimension ($\xi_1 > T_2$). The interface compliance is due to force, F_y, which causes tangential stresses in y axis direction at contacts in the neighbourhood of point H, along support AC, and on locating element (ABCD). The resulting deformation is directly proportional to stress magnitude. The sum of these local deformations equals interface compliance and directly influences the workpiece machining error.

Analytical description of the change of tangential, F_t, and radial, F_r, components of cutting force with time are well established and can be found in literature [35].

Friction forces, F_{fc}, F_{fs}, F_{fb}, are the complex functions of: contact surface macro - and microgeometry, material characteristics of contact pairs, clamping force, F_c, and interface compliance, ξ_1. For clamping and locating fixture elements there holds the following relationship:

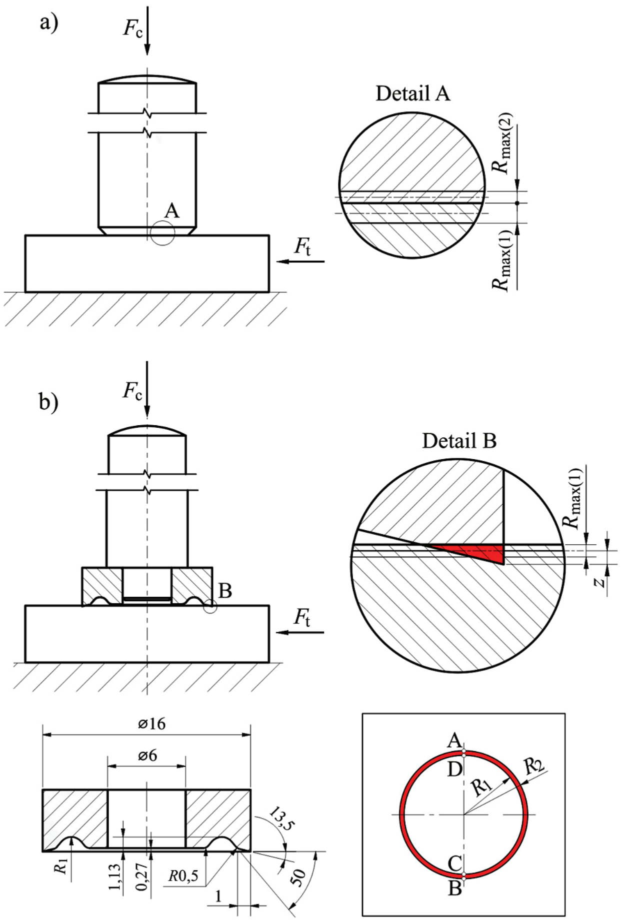
$$F_t = f(G, M, F_n, \xi_1). \tag{3}$$

where: G is the set of parameters which define the contact macro- and micro geometry; M is the set of parameters which define material characteristics of the contact pair; F_n is the normal interface load (as the function of clamping force) and ξ_1 is the interface compliance. Considering such large number of parameters which define the contact micro geometry (surface roughness) and parameters which define material properties of contact pairs (hardness, strength, chemical composition), as well as the complexity of friction and wear mechanisms, the authors maintain that analytical relationship, $F_t = f(G, M, F_n, \xi_1)$, is of little use for our purpose. For that reason, the relationships required by this investigation were established experimentally, as described in detail in the following section.

If the friction forces, F_{fc}, F_{fs}, F_{fb}, are experimentally determined under specified conditions for a wider interval of clamping force values, then, based on a large quantity of experimental data, it is possible to form regression equations in the form of $F_t = f(G, M, F_n, \xi_1)$. Therefore, it is possible to form regression equations which represent dependence of friction forces on the normal load and tangential compliance, i.e., tangential stiffness of contact. In this way, key prerequisites for determination of machining error are made available. In other words, experimentally obtained functions allow modelling of workpiece behaviour in fixture as well as realistic estimation of workpiece machining error for particular dimensions, prior to physical machining.

With this in mind, two types of elements were experimentally investigated which can be used for clamping as well as for locating purposes.

Shown in Fig. 2 are macro geometries of a standard clamping element and a specially designed clamping element. Standard clamping element was selected as representative of the conventional clamping method. On the other hand, the specially designed clamping element is a stepped cylinder with a round cutting tool insert mounted on its tip, and is used in this experiment to quantify the differences between tangential interface compliances using the standard and proposed clamping element.



F_c - clamping force
F_t - tangential force
$R_{max(1)}$ - maximum roughness depth of workpiece
$R_{max(2)}$ - maximum roughness depth of clamping element
z - depth of indent

Figure 2 Macro geometries of a standard clamping element and a specially designed, round insert clamping element.

The idea behind the proposed round insert clamping element (Fig. 2b) is that it should provide lower workpiece-fixture interface compliance compared to the standard clamping element (Fig. 2a). It is supposed that, while clamping force F_c is active (Fig. 2b) the round insert indents the workpiece. The hardness of the round insert is much higher than that of the workpiece, since it is made of hard metal. Thus, round insert is indented into the workpiece over a wedge-profiled ring with a relatively large circumference. The depth of indent largely depends on the magnitude of clamping force. Compliance of round insert/workpiece interface under tangential load is predominantly the function of the depth of indent of round insert into workpiece material. Depending on the clamping force, round insert shall penetrate workpiece material to the depth of z, relative to mean centre line roughness, over the entire circumference. The shear within the roughness profile height or regular material, under tangential force, F_t, occurs in the neighbourhood of contact arcs AB and CD. Bearing in mind that the depth of indent is relatively small, there follows $R_1 \approx R_2$, which implies that the shear within the roughness profile or, eventually, full material, takes place over the entire circumference of the wedge-profiled ring.

The clamping method proposed in this paper is based on the hypothesis that the load capacity of clamping element/workpiece interface can be significantly increased by allowing the clamping element to locally deform a narrow zone on the workpiece surface. Considering previous discussion, such small local deformations, in the vast majority of cases, do not compromise workpiece aesthetics. As proven by experiments in this investigation, local deformations are small even in the case of large clamping forces, and their order of magnitude is assessed at ten microns.

3
Experimental investigation

Experimental investigation included measurements of load capacity for tangential force, F_t, and interface compliance, ξ_1, between the clamping element and test inserts which represented workpiece material. Two types of clamping elements were used in experiment – a standard clamping element and a specially designed, round insert clamping element. The experiment encompassed:

- Variations of clamping force, F_c, within 400 N to 13 000 N interval,
- Variations of tangential load, F_t, on the clamping element/test insert interface, within 5 N to 2500 N interval,
- Monitoring of interface compliance, ξ_1, expressed as displacement in the contact zone.

Experiments were performed under static interface loads, using the following measurement equipment:

- Specially designed and manufactured device whose operating scheme is shown in Fig. 3. Photo image of the device is given in Fig. 4. The device is mechanical, using a lever mechanism and calibrated weights to clamp test inserts with the standard and round insert clamping elements, at specified values of clamping force, F_c. The device also allows users to simulate tangential load, F_t, while monitoring the corresponding interface compliance, ξ_1.
- Dial indicators of displacement with accuracy of 0,01 mm. In order to enhance the accuracy of measurement, these instruments were used to monitor displacements within the clamping element/test insert interface zone, amplified by 22,5 times. In this way, it was possible to monitor displacements as small as 10^{-4} mm, using geometric relations given in Fig. 3.
- Microscope and surface roughness measurement devices (Talysurf 6) were used to measure width and depth of indent marks left by the round insert clamping element (Fig. 7).

Test lever is supported by a tapered roller bearing, along the axis x, which runs through the centre of masses (Fig. 3). The tapered roller bearing allows rotation of the test lever about point O, in the x-y plane. Contact between either standard or round insert clamping element and test insert, representing workpiece material, is maintained by a constant force, F_c. The clamping is performed at point O_1, i.e., clamping force vector runs through O_1. Relative to the axis of revolution of test lever, point O_1 is displaced by e in the direction of y axis. Clamping force, F_c, is varied using a specially designed lever mechanism and calibrated weights. Once clamping is established, force F_{t1} is applied on the test lever at point A, at a distance y_o from the lever pivotal point, and the resulting displacement, ξ, is recorded. Force, F_{t1}, is also applied by a specially designed system of levers and calibrated weights, which allows its periodic, incremental increase from minimum to maximum.

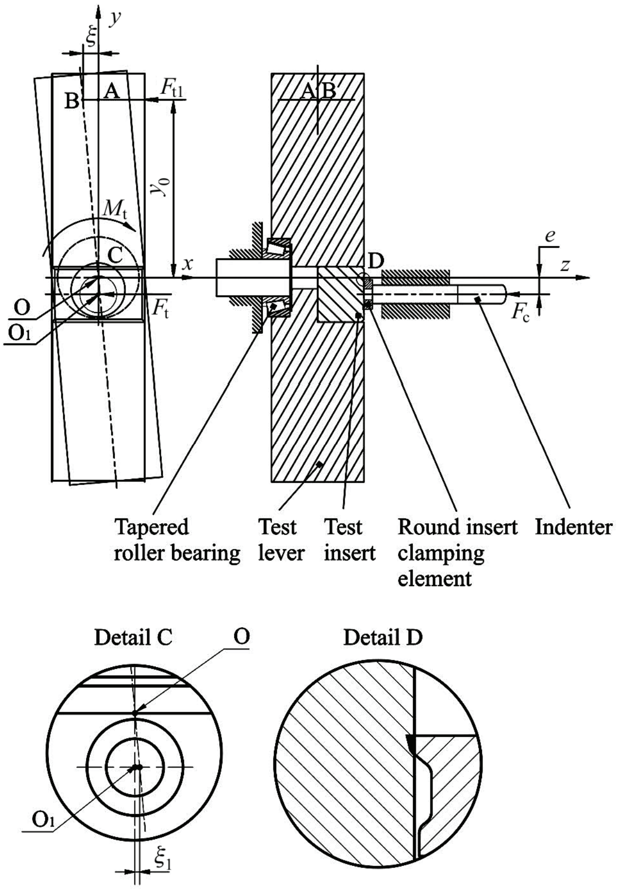


Figure 3 Operating scheme of the device for measurement of test insert/clamping element interface compliance and load capacity.

Based on geometric relationships (Fig. 3) and static equilibrium conditions for the test lever, there follow the values of interface load capacity, F_t, and compliance, ξ_1, at point O_1, that is, interface compliance, ξ_1, within the clamping zone. Based on this, follows:

$$F_t = (F_{t1} \cdot y_0 - M_t)/e, \tag{4}$$

$$\xi_1 = (e \cdot \xi)/y_0, \tag{5}$$

where: F_t – interface load capacity; F_{t1} – interface load at point A; M_t – friction torque in tapered roller bearing, e – distance from clamping point to test lever axis of revolution; y_0 – distance between point of attack of force F_{t1}, and axis of revolution; ξ_1 – interface compliance for test insert and clamping element at point O_1 (Fig. 3); ξ – displacement of test lever along x axis, at point A.

In this way, a series of data pairs for F_t and were obtained for both clamping element geometries and each value of simulated clamping force, F_c, and displacement ξ_1. Force F_c was used to simulate the clamping force, force F_t represents the tangential load capacity of test insert/clamping element interface, while the displacement, ξ, is indirectly indicative of interface compliance. Based on the displacement ξ, it is possible to calculate real interface compliance ξ_1.

Measuring device (Fig. 4) is designed for extreme stability. All deformations (deformations of test lever, and other levers of measuring system, as well as the deformations of clamping element) can be disregarded in comparison with test insert/interface compliance. In addition, the following should be noted regarding the measuring device used in this experiment:

- it provides clamping with various clamping forces;
- guiding accuracy of clamping element carrier (Fig. 4) is higher than 5×10^{-4} mm, which, considering interface compliance values, allows reliable measurements;
- bearing supports of test lever and other levers are high-accuracy roller bearings with small rolling friction factor;
- the tapered roller bearing supporting the test lever features small rolling friction factor. To calculate the friction torque for this bearing, experimental data provided by the manufacturer were used. Friction torques were calculated for all other bearings and included into load capacity budgets.

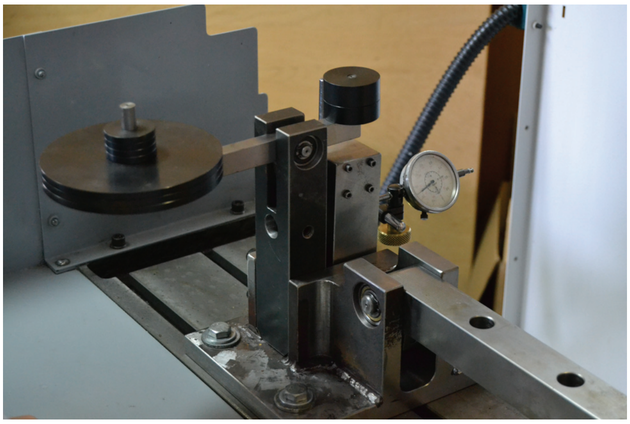


Figure 4 Photo image of the device used for measuring load capacity and compliance of test insert/clamping element interface.

4
Results

Experimental investigation was conducted on test inserts made of C45E annealed steel, with tensile strength of 710 MPa, hardness of 208 HB, and the following chemical composition: 0,44 %C, 0,18 %Si, 0,27 %Mn, 0,011 %Si, and <0,010 %P. Test inserts were of the following dimensions: 25 × 30 × 50 mm.

The standard clamping element was made of carburized steel 16MnCr5 with 56 HRC hardness, and chemical composition: 1,15 % Mn, 0,95 %Cr, 0,035 %P, 0,035 %S, 0,16 %C, and <0,4 %Si.

Specially designed round insert clamping element was made of hard steel, P20. Surface roughness of interface between test insert and clamping element featured the following parameters: R_a = 0,37 ÷ 0,39 μm, and $R_{\max}$ = 4,6 ÷ 5,3 μm.

Results of experimental investigation are presented in Tab. 1.

Statistical analysis of experimental data resulted in regression equations which describe the dependence of friction force (tangential force) F_t on clamping force, F_c and interface compliance, ξ_1, between clamping element and test insert (which simulates workpiece material). Those regression equations and the corresponding coefficients of correlation R are given in Tab. 2. Statistical analysis of experimental data presented in Tab. 1 was performed in Statistica 8.

Presented in Fig. 5a and Fig. 5b are diagrams which show dependence of friction force (tangential force), F_t on interface compliance, ξ_1, in case of various clamping forces, F_c, using standard and round insert clamping elements.

Table 1 Results of experimental investigation for round insert clamping element

F_c=400 N		F_c=640 N		F_c=1800 N		F_c=2900 N		F_c=4500 N		F_c=5700 N		F_c=7000 N		F_c=9000 N		F_c=11 000 N		F_c=13 000 N	
ξ_1 / mm	F_t / N	ξ_1 / mm	F_t / N	ξ_1 / mm	F_t / N	ξ_1 / mm	F_t / N	ξ_1 / mm	F_t / N	ξ_1 / mm	F_t / N	ξ_1 / mm	F_t / N	ξ_1 / mm	F_t / N	ξ_1 / mm	F_t / N	ξ_1 / mm	F_t / N
0	28,1	0	59,4	0	73,3	0	51,5	0	128,7	0	213,84	0	296,9	0	257,5	0	217,9	0	178,3
0,0006	46,1	0,0003	77,4	0,0011	127,7	0,0003	105,9	0,0003	183,1	0,0001	322,6	0,0001	405,8	0,0001	366,3	0,0001	326,7	0,0001	287,1
0,0011	64,2	0,0006	95,4	0,0057	182,1	0,0006	160,2	0,0006	237,6	0,0006	431,5	0,0006	514,5	0,0003	475,1	0,0003	435,5	0,0001	395,9
0,05	80,2	0,0009	113,4	0,0154	236,4	0,0017	214,6	0,0011	292,0	0,0011	540,2	0,0011	623,4	0,0009	583,9	0,0006	544,4	0,0003	504,8
/	/	0,0011	131,5	0,0296	290,9	0,0057	269,1	0,004	346,4	0,0034	649,1	0,0034	732,2	0,0028	692,7	0,0009	653,1	0,0011	613,5
/	/	0,0017	149,5	0,0483	345,3	0,0114	323,5	0,0097	400,7	0,0085	757,8	0,008	841,0	0,0046	801,6	0,001	761,9	0,0014	722,4
/	/	0,0034	167,5	0,05	346,2	0,0199	377,9	0,0148	455,2	0,0148	866,7	0,0131	949,9	0,008	910,4	0,0011	870,8	0,0023	831,3
/	/	0,0057	185,5	/	/	0,0296	432,2	0,0227	509,6	0,0227	975,6	0,0171	1058,6	0,0125	1019,2	0,0013	979,6	0,004	940,0
/	/	0,0097	203,6	/	/	0,0398	486,7	0,0313	564,0	0,0381	1084,3	0,0227	1167,5	0,0171	1128,1	0,0017	1088,5	0,0074	1048,9
/	/	0,0256	221,5	/	/	0,0511	541,1	0,0403	618,5	0,0539	1193,2	0,0267	1276,3	0,0222	1236,8	0,0023	1197,2	0,0108	1157,6
/	/	0,05	241,3	/	/	/		0,0511	672,8	/	/	0,033	1385,1	0,0284	1345,7	0,0051	1306,1	0,0137	1266,5
/	/	/	/	/	/	/	/	/	/	/	/	0,042	1493,9	0,0324	1454,5	0,0085	1414,9	0,0176	1375,3
/	/	/	/	/	/	/	/	/	/	/	/	/	/	0,0409	1563,3	0,0119	1523,7	0,0227	1484,1
/	/	/	/	/	/	/	/	/	/	/	/	/	/	0,0494	1672,1	0,0148	1632,5	0,025	1592,9
/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	0,0176	1741,3	0,0296	1701,7
/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	0,0216	1850,1	0,033	1810,5
/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	0,0273	1958,9	0,0369	1919,4
/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	0,0335	2067,8	0,0403	2028,2
/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	0,0392	2176,6	0,0454	2136,9
/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	0,0471	2285,5	0,0511	2245,9

Table 2 Regression equations describing dependency of friction force (tangential force) on the clamping force and test insert/clamping element interface compliance – for two types of clamping elements

Clamping element	Regression equation	Coefficients of correlation R
Round insert	$F_t = -94265{,}3\cdot\xi_1 + 0{,}042104\cdot F_c + 99435{,}53\cdot\xi_1^{1{,}052493} + 82{,}31460\cdot(\xi_1\cdot F_c)^{1/2}$	0,970
Standard	$F_t = -8245{,}90\cdot\xi_1 + 0{,}035662\cdot F_c - 52{,}9507\cdot\xi_1^{0{,}000872} + 63{,}77113\cdot(\xi_1\cdot F_c)^{1/2}$	0,946

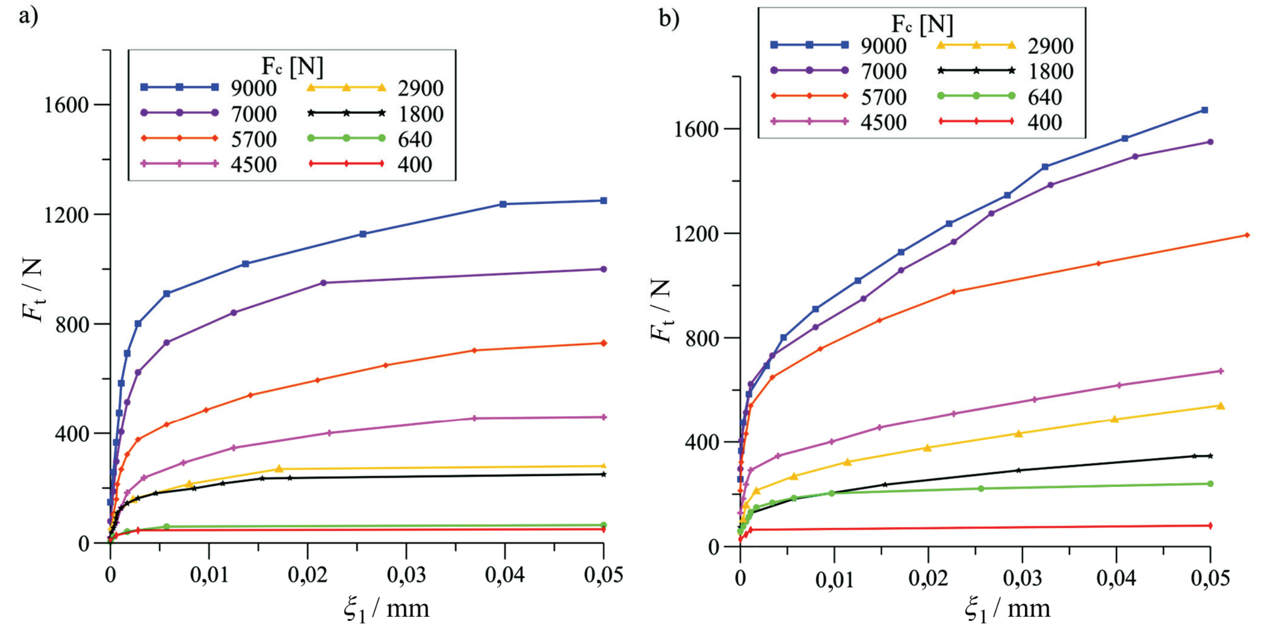


Figure 5 Dependence of friction force (tangential force) F_t, on interface compliance ξ_1, for various clamping forces – a) standard clamping element, and b) round insert clamping element

5
Disscusion

Based on theoretical considerations and results of experimental investigation, it is possible to conclude that load capacity and interface compliance of tangentially loaded contacts represent a very complex matter. Generally, experimental results indicate that clamping by specially designed, round insert clamping elements yields higher load capacity compared to the standard ones. Within the entire interval of load values (Fig. 5) round insert clamping element shows significantly higher load capacity and lower interface compliance compared to its standard counterpart. The advantage is noticeable at both lower and higher loads, as clearly shown in Fig. 6.

Integration of regression equations (Tab. 2) over a particular interval of clamping force values, yields the P indicator, which quantifies the advantage of round insert clamping element over its standard counterpart:

$$P=\frac{\int\limits_{F_{\mathrm{c}1}}^{F_{\mathrm{c}2}}\int\limits_{0}^{0,05} f_1(F_\mathrm{c},\xi_1)\mathrm{d}F_\mathrm{c}\mathrm{d}\xi_1 \int\limits_{F_{\mathrm{c}1}}^{F_{\mathrm{c}2}}\int\limits_{0}^{0,05} f_2(F_\mathrm{c},\xi_1)\mathrm{d}F_\mathrm{c}\mathrm{d}\xi_1}{\int\limits_{F_{\mathrm{c}1}}^{F_{\mathrm{c}2}}\int\limits_{\xi_1}^{\xi_2} f_2(F_\mathrm{c},\xi_1)\mathrm{d}F_\mathrm{c}\mathrm{d}\xi_1}\cdot 100\,\%, \quad (6)$$

where: $F_{\mathrm{c}1}$, $F_{\mathrm{c}2}$ – clamping force intervals for which P is determined; $f_1(F_\mathrm{c}, \xi_1)$ - regression function (Tab. 2) which defines the dependence of friction force (tangential interface load capacity) on the clamping force and interface compliance in the case of round insert clamping element; $f_2(F_\mathrm{c}, \xi_1)$ - regression function (Tab. 2) which defines the dependence of friction force (tangential interface load capacity) on the clamping force and interface compliance in the case of standard clamping element.

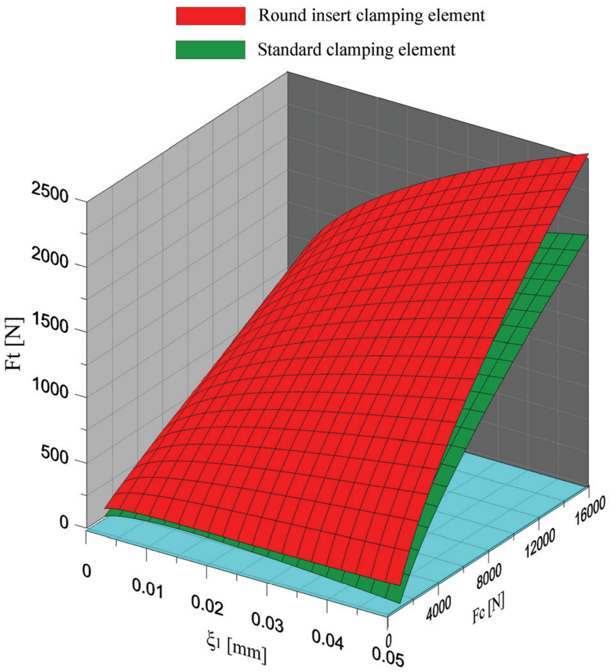


Figure 6 3D diagram showing dependence of friction force (tangential force) F_t, on interface compliance ξ_1, and clamping force F_c, for standard and round insert clamping elements, based on regression equations from Tab. 2

According to equation (6) there follows:

- For the clamping force range F_c = 400 ÷ 1800 N, the round insert clamping element provides an average load capacity increase of 43,5 %, due to larger friction force on the test insert. This is especially important bearing in mind that it is achieved with small clamping forces and small local deformations of workpiece.
- For the clamping force range F_c =9000 ÷ 13 000 N, the round insert clamping element provides an average load capacity increase of 22,8 %, due to larger friction force on the test insert. Again, this is important considering that the increase is achieved under large cutting forces.
- Over the entire clamping force interval, F_c = 400 ÷ 13 000 N, the round insert clamping element provides an average load capacity increase of 24,2 %, due to larger friction force on the test insert. These backs up the claim that the round insert clamping element can be efficiently used regardless of the clamping force order of magnitude.

Of special importance are indent marks left on the test insert by the round insert clamping element. Shown in Tab. 3 are depths of indent marks left by round insert clamping element for the appropriate clamping force. Photo image and topography with samples of depth of indent marks are shown in Fig. 7.

Table 3 Depths of indent marks produced by round insert clamping element and appropriate clamping force

Clamping force F_c / N	Depth of indent z / µm
400	3,1
640	3,0
1800	4,5
2900	5,1
4500	7,2
5700	8,5
7000	9,0
9000	10,7
11 000	12,3
13 000	14,0

Based on Table 3 and Fig. 7 it can be concluded that the depths of indent marks are low. For example, clamping force of 2900 N yields plastic deformation of just 5 µm, which approximately equals the maximum height of the roughness profile for that sample. Similarly, the depth of indent of approximately 12 µm corresponds to the clamping force of F_c = 11 000 N.

Based on this, one concludes that high load capacity can be achieved by allowing the round insert clamping element to penetrate workpiece approximately to the maximum depth of roughness profile. This confirms the initial hypotheses about the practical applicability of specially designed clamping or locating elements. In a majority of cases such elements do not compromise workpiece aesthetics, while providing much larger load capacity and smaller workpiece/fixture interface compliance.

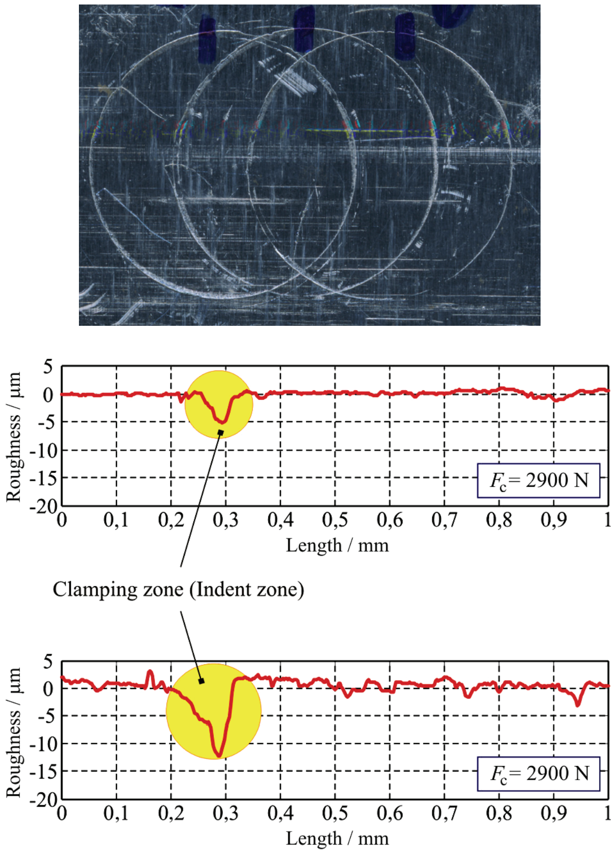


Figure 7 Photo image and samples of depths of indent marks left by round insert clamping element

There are numerous facts which underpin the claim that the proposed method of locating and clamping shall also perform satisfactorily under dynamic cutting forces. Specially designed locating and clamping elements can be made of high-quality tool materials (hard metal). It is common knowledge that, in real machining conditions, modern tools are exposed to far greater relative speeds, wear, and geometry change than the clamping and locating elements. Due to the effect of dynamic cutting forces, the workpiece oscillates at speeds the magnitude of 100 mm/min, relative to clamping and locating elements. From the tribological aspect – considering the possibility of a significant drop in friction factor, changes in material structure, heating, etc. – such small speeds of oscillation at the workpiece/fixture interface do not represent a problem. Namely, they are caused by low-frequency dynamic cutting forces. It is also worth noting that manufacturers of modular fixtures offer ready-made clamping and locating elements which are capable of sustaining similar dynamic loads and also function on the similar principle. Bearing in mind this fact, it is reasonable to suppose that – compared to the results obtained for testing under static conditions – the dynamic loads will not cause any significant compliance of the interface between workpiece and the specially designed locating and clamping elements. Notwithstanding certain deterioration of their load capacity, the results assure us that the proposed locating and clamping elements shall perform better than the standard clamping elements even under dynamic loads.

6
Conclusion

Based on the matter presented in this paper, the following conclusions can be drawn:

- Whenever a clamping element is used to balance the cutting force component which acts orthogonally to the direction of clamping force vector, there occurs compliance to a certain extent. Interface compliance results in workpiece displacement relative to locating surfaces. Such displacement is the cause of workpiece machining error. Depending on the displacement, this error can exceed the designated tolerance. Workpiece is allowed a certain amount of displacement in the fixture. The displacement depends on the magnitude, direction, and sense of cutting force, as well as on the compliance of interface between workpiece and workpiece clamping and locating elements. It means that, within the fixture, workpiece maintains only a virtual balance.
- In the majority of cases, standard fixture elements (screw clamps, strap clamps, etc.) used for clamping, balance cutting forces with friction forces. Friction forces are generated at contact surfaces - interfaces between clamping elements and workpiece. In this paper, clamping process was simulated using two types of clamping elements – the standard and the round insert clamping element. The investigation showed that the standard clamping element, which is universally present in practice, exhibits significantly lower load capacity compared to the specially designed, round insert clamping element.
- Based on experimental results, it follows that, over a wide range of clamping forces, the specially designed clamping element can increase workpiece/fixture load capacity and diminish interface compliance. This is especially true for smaller clamping forces which is essential for clamping workpieces of small stiffness.
- Considering small widths and depths of indent marks which are the result of clamping, the proposed method of workpiece clamping and locating can be efficiently applied in design of clamping and locating elements.
- Design of clamping elements based on the proposed principle, essentially employs hard metal inserts and standard clamping and locating elements (screw clamp, strap clamp, support element), which is simple and feasible from the technical point of view.

The authors think that the design and experimental testing of novel solutions of locating and clamping elements under dynamic loads represents an up-to-date topic. With this in mind, future work shall include development and design of a special device to allow measurement of loads and compliance of interface between workpiece and differently designed locating and clamping fixture elements under various dynamic loads. In this case, real workpiece would be replaced by a test insert designed either as stiff or thin-walled component and made of various materials. This should provide us with the testing platform required for further investigation.

Finally, the authors maintain that there is a wide area of improvement in fixture design regarding the interface compliance of contact surfaces loaded orthogonally relative to clamping force. In that respect, this paper represents a small step towards the goal.

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