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COMPARATIVE MODEL ANALYSIS OF TWO TYPES OF CLAMPING ELEMENTS IN DYNAMIC CONDITIONS

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Original scientific paper

This paper studies the compliance of the fixture-workpiece system. Workpiece clamping case with two types of clamping elements is considered. The first type of clamping element is standard, with flat top, while the second one is specially designed, with round cutting insert. Analyzed was the case of workpiece clamping using small forces, whereby the deformations in the workpiece/clamping element interface are predominantly on the order of magnitude of roughness height. A comparative analysis of dynamic behaviour of both types of clamping elements is also presented. In comparison with its standard counterpart, the specially designed clamping element with round cutting insert has superior clamping performance regarding both tangential load capacity and compliance.

Keywords: *clamping, compliance, fixture, roughness*

Usporedna analiza modela dva tipa elemenata za stezanje u dinamičkim uvjetima

Izvorni znanstveni članak

U radu se razmatra popustljivost sustava naprava-izradak. Razmatra se slučaj stezanja izratka s dva tipa elemenata za stezanje. Prvi tip elementa za stezanje je sa standardnim ravnim čelom. Drugi tip elementa za stezanje je specijalne izvedbe s čelom u obliku kružnog klina. Analiziran je slučaj stezanja malim vrijednostima sila stezanja pri čemu se deformacije u zonama kontakta između elemenata za stezanje i izratka pretežno odvijaju u zonama visine neravnina. Također je prikazana komparativna analiza, predhodno spomenuta, dva načina stezanja izradaka u uvjetima dinamičkih opterećenja. Specijalno dizajnirani element za stezanje s čelom oblika kružnog klina u odnosu na standardni element za stezanje s ravnim čelom ima izrazito veću steznu učinkovitost po pitanju tangencijalne nosivosti i popustljivosti.

Ključne riječi: *hrapavost, naprava, popustljivost, stezanje*

1 Introduction

Key aspects of product development are conceptual and detailed design stages in which new ideas emerge and are being evaluated. This can be a long, complex and often iterative process, which encompasses following stages: identification of the need for some product, creation of initial ideas for the design, evaluation and improvement of such ideas, detailed design, testing of the solution for further improvements, generation of complete documentation for the adopted solution, such as the engineering drawings, bills of materials, etc. [1, 2]. All this implies that it is not only necessary to design a product, but also to select the most adequate manufacturing equipment [3]. Locating and clamping of workpiece and cutting tools in their working position is performed using special equipment, generally termed fixtures. Fixtures significantly influence the output effects of manufacturing process. For that reason fixture design is very important and demands great attention since it directly influences the total cost of manufacture, productivity, machining quality, etc. [4, 5].

In order to reduce the costs of fixture design and optimization, and increase the efficiency of machining system, and accuracy, precision and quality of machining, over the years a number of methodologies which aide fixture designers have been proposed.

Choudhuri and De Meter [6] presented a methodology for analyzing the impact of a locator tolerance scheme on the geometric errors of a workpiece. Wang et al. [7] focused on the fixture performance of the workpiece locating accuracy and developed different algorithms for force closure fixturing with the D-optimality criterion to minimize the workpiece positioning errors. Estrems et al. [8] determined the uncertainty in a cutter hole within a rotational workpiece. The workpiece was located by means of two V-blocks to determine the uncertainty when the dimensional values are influenced by the accuracy of the fixtures. Xiong et al. [9] introduced a geometric constraint into the elastic contact model to calculate the passive force of a fixture-workpiece system. Qin et al. [10] formulated an elastic contact model to optimize the fixture layout. Zhu and Ding [11] transformed the form-closure fixture layout design into a linear program and solved it using the simplex method in discrete domain. Asante [12] predicted the contact load and pressure distribution at the contact points in a workpiece-fixture system by combining contact elasticity and FEM. Wang et al. [13] proposed a systematic method to identify the surface errors, location error and machining error through FEA and coordinate measurement machine measurements, respectively. The evaluation of profile tolerance was done through the analysis of error sources by assuming an absolute precise surface. Chaiprapat and Rujikietgumjorn [14] developed a mathematical model that is able to predict the geometric variation in a resultant-machined surface when the tolerance of a datum feature is given. Vukelic et al. [15] used a combination feature-based, knowledge-based and geometry-based methodology for development complex system for fixture selection, modification, and design. Zheng and Chew [16] presented a method to select optimal locations for 4/7 fixels automatically. They used Gilbert-Johnson-Keerthi distance algorithm and the Gram-Schmidt process to yield the fixel locations. Fan and Kumar [17] studied the fixture locating layout with the help of robust design approach. To increase the quality of the machining workpieces and for robust layout which is insensitive to errors, they combined the Taguchi method and the Monte Carlo statistical method. Asante [18] investigated the effect of fixture compliance and cutting conditions on workpiece stability. He used the minimum eigenvalue of the fixture stiffness matrix and the largest displacement of the workpiece due to the cutting forces to assess the stability of the workpiece. Chaari et al. [19] presented a modeling methodology for geometrical machining defect. Dynamic displacements caused by clamping and machining force were determined by FEA. Sun et al. [20] used FEM to analyze the clamping forces by considering cutting forces and frictions and applied genetic algorithm (GA) to optimize the fixture layout and clamping force. Vishnupriyan et al. [21] determined optimal fixture layout to minimize the machining error considering locator geometric error and workpiece elastic deformation. Papastathis et al. [22] presented a modelling approach that captures the dynamic response of fixture elements and thin-walled workpieces subjected to dynamic moving loads. Vishnupriyan et al. [23] proposed a method of using an artificial neural network (ANN) for the prediction of dynamic workpiece motion. They optimized parameters of the ANN using a GA to achieve better prediction capability of the ANN and minimize different forms of errors in training and generalization. Maracekova et al. [24] investigated effect of clamping pressure on workpiece inaccuracy in turning operations. They found that the chucks clamping pressure induces elastic deformations and roundness deviation of workipiece. Tadic et al. [25] proposed an approach to workpiece clamping based on plastic deformation of workpiece in predefined narrow zones, and analyzed load capacity and interface compliance. Liu et al. [26] developed geometric model considering the shape of a locator and a FEA-based force–deformation model. Based on these two models, multiple objects of fixture layout optimization problems were proposed, and a multi objective GA-based optimization method was constructed. Jiang et al. [27] described a locator layout multi-objective continuous searching optimization and decision algorithm for automatic design of the locator layout in checking fixture design. Xiong et al. [28] presented a self-reconfigurable intelligent fixture system. They proposed new fixturing principle "N-2-1-1". Fixture layout optimization procedure combined GA and FEA.

Previous investigations have been directed towards the development of methodologies which provide more efficient fixture design and optimization. However, a methodology to aide fixture designer with fixture elements is still to be developed, with the key task to identify the adequate structure and geometry of fixture elements, especially the elements for clamping and locating which interface the workpiece. Considering the modern trends in machining (more stringent requirements regarding quality and productivity) special focus is placed on optimization of fixture design in terms of compliance minimization in all workpiece/fixture interface areas. This requires current investigations to focus not only on the identification of inadequate fixture behaviour during machining, but also on the theoretical and experimental contributions to novel solutions of fixture elements which feature higher reliability.

Shown in this paper is a part of theoretical and experimental results related to design solutions of fixture elements which increase the tangential load and decrease the workpiece/fixture interface compliance using small clamping forces, which is specially important for the machining of thin-walled workpieces.

2 Methodology

In order to perform the machining on a particular workpiece surface(s) using appropriate cutting tools, it is necessary to first set up workpiece and tools on an adequate machine tool which provides the desired motions and feeds. In this process, it is important for both the cutting tool(s) and workpiece to assume particular positions relative to each other and the machine tool elements, in order to allow the machining of the desired surfaces. Once assumed, the relative positions must be maintained by adequate clamping to counteract the forces active during machining.

In fixtures, it is most common to balance the cutting forces and torques through friction forces which are present between the fixture elements (locating and clamping elements) and workpiece. Such forces balance the tangential workpiece/fixture interface load. With this in mind, the following two types of contact interfaces are considered:

- the contact interface between workpiece and a clamping element with a flat top (standard clamping element) (Fig. 1),
- the contact interface between workpiece and a clamping element with round cutting insert (Fig. 2).

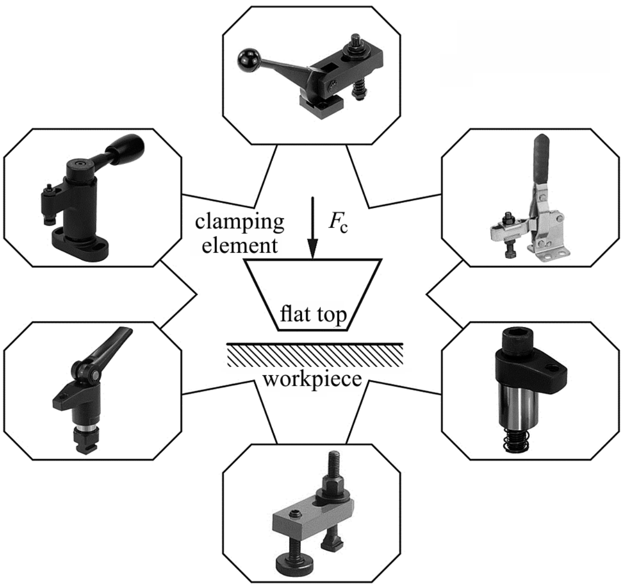

Figure 1 Standard clamping element (clamping element with a flat top)

Clamping force F_c, acts upon the clamping element with round cutting insert (Fig. 2). In the case of small clamping forces, the sharp circumference of the clamping element penetrates the workpiece surface at the depth y.

Bearing in mind the fact that the surface roughness values of both the clamping element and workpiece fall in the area of $P_{ce}=(R_p+R_v)_{ce}$ (in the case of clamping element) and $P_{wp}=(R_p+R_v)_{wp}$ (in the case of workpiece) it is logical to assume that, at small clamping forces, the depth of penetration y, shall fall within the surface roughness height. Realistically assuming that the surface roughness of the clamping element is much smaller than that of workpiece, one concludes that the depth of penetration of the clamping element into workpiece surface largely depends on the wedge angle. There are two boundary values of the wedge angle:

- $\beta\rightarrow\varepsilon$, where ε is a small wedge angle, which corresponds to an ideally sharp wegde tip,
- $\beta\rightarrow180°$, which is, in fact, equall to the flat top.

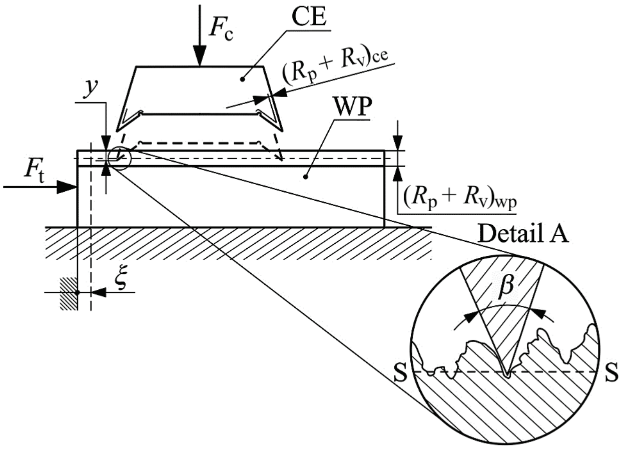

Figure 2 Schematic interpretation of the contact interface between the clamping element with round cutting insert and workpiece.

According to the investigation of static load capacity for such clamping elements [29, 30] it has been shown that smaller wedge angles of clamping element tips provide greater tangential load capacities within the same contact interface compliance, i.e. displacement ξ. Within the mentioned investigations, numerical simulations and practical experiments were performed at high values of clamping force. With this in mind, it is supposed that the clamping element with round cutting insert, featuring the wedge tip angle β, shall be able to provide higher tangential interface load capacity than its counterpart with flat tip (β=180°), even for smaller clamping forces. The stated hypothesis is argumented as follows:

- Larger penetration depth of this type of clamping element into the workpiece surface roughness profile shall provide less sliding of the surface roughness profile (section S-S, Fig. 2, Detail A), which also lowers the interface compliance and increases the tangential interface load capacity. More specifically, when the tangential force acts upon the clamping element with round cutting insert, the load is largely distributed along the directions which are close to the root of the workpiece surface roughness profile (Fig. 2, Detail A). For this reason, it is logical to expect lower interface tangential stresses, which consequently results in less material flow, i.e. higher stiffness and lower interface compliance.
- When using clamping element with flat top, at small clamping forces the workpiece/fixture contact interface is established predominantly over the surface roughness profile tips, while the tangential interface load is balanced with the friction force. Due to the micro geometry of the contact interface, one should expect higher interface compliance. Using flat top clamping element with small clamping forces, causes the tangential loads to be distributed along the directions which are closer to surface roughness profile tips. For this reason, it is logical to expect higher values of tangential loads at the roots of the surface roughness profile, which incurs more intensive material flows, i.e. lower stiffness and higher contact interface compliance.

With this in mind, it is assumed that the clamping element with round cutting insert provides contact interface which has superior stability compared to that of its flat-tip counterpart. It is also assumed that the stifness of this type of workpiece/fixture interface can be experimentally related to the clamping force under dynamic tangential loads.

3 Experimental procedure and measuring equipment

Experiments were performed on prismatic specimens made of steel, C 45 E, annealed, tensile strength 710 MPa and hardness 208 HB. Chemical composition of this steel is: 0,44 % C; 0,18 % Si; 0,27 % Mn; 0,011 % Si and <0,010 % P. Dimensions of the specimens which substitute the workpiece in this experiment, are 25×30×50 mm. Contact surface roughness ranged within Ra = 0,8 ÷ 1,0 μm.

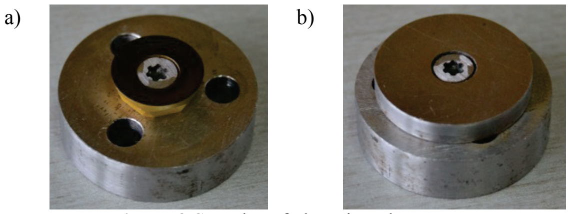

Figure 3 Samples of clamping elements.
a) with round cutting insert, b) with flat top.

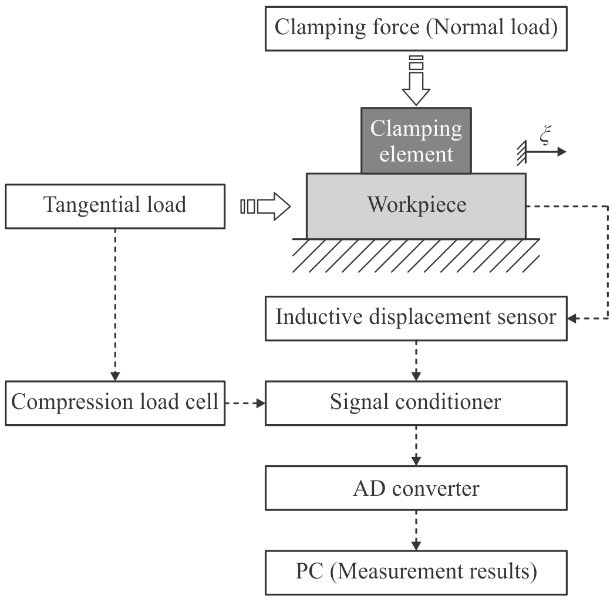

Figure 4 Experimental procedure

Shown in Fig. 3a is a specially designed clamping element with round cutting insert, made of hard metal, designation P20. The disc-shaped clamping element (Fig. 3.b) with flat top was made of steel EN 10083-1, hardness 56 HRc. Its surface roughness was Ra = 0,8 ÷ 1,0 µm.

Shown in Fig. 4 is an experimental procedure, while a segment of experimental set up is shown in Fig. 5.

A general case of contact is considered between the clamping element and workpiece. The workpiece is clamped using a specified clamping force. Workpiece is tangentially loaded by the real cutting force. This tangential load caused by the cutting force results in a workpiece displacement relative to the clamping element, which is defined by the displacement ξ. The magnitude of ξ represents the contact interface compliance. During this experiment, tangential force F_t, and contact interface compliance ξ, were measured.

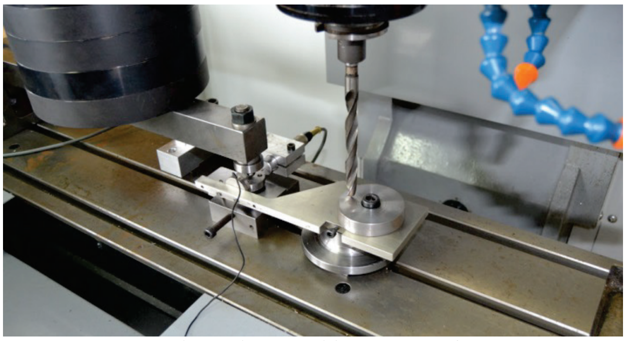

Figure 5 Experimental set up with a segment of measurement instrumentation

Experimental investigations were conducted on a specially designed device for the measurement of model dynamic compliance. Complete instrumentation consists of [25, 31]:

- The compression load cell FC2311-0000-0250, with force range up to 1100 N, which measures tangential force F_t, proportional to the cutting force;
- The inductive displacement sensor W1T, with nominal displacement of ±1 mm, and deviation from normal sensitivity less than ±1 %;
- The 2 channel HBM signal conditioner for load cell and inductive displacement sensor;
- The 8 analog input channels simultaneous sampling AD convertor with a 16-bit resolution, which was used for signal sampling from the load cell and inductive displacement sensor;
- The PC which controls the AD converter and stores the results of measurement for further processing.

4 Results

Clamping force F_c, was varied within the interval of 278.0-631.2 N. For each increment of the clamping force, a ∅12 mm twist drill was used at n=600 rpm, and variable feed rates, to simulate several values of dynamic tangential force F_t. The forces and their corresponding displacements were monitored through previously described instrumentation. Shown in Fig. 6 is an example of the tangential force F_t, and the corresponding displacements ξ, within a single experiment run.

The processed results of experimental investigations are presented in Tab. 1. The table shows values of the clamping force F_c, feed rate f, mean tangential force $\overline{F}_t$, measured in dynamic regime, and mean contact interface displacement $\overline{\xi}$. Examined were the segments of experimental results which pertained to approximately constant cutting force (mark as considered zone in Fig. 6). Moreover, in order to review the experimental results more clearly, Tab. 1 also shows the non-dimensional ratio:

$$\overline{F}_t / F_c, \qquad (1)$$

i.e., the ratio between the mean dynamic tangential force $\overline{F}_t$, and the static clamping force F_c. This rendered it possible to use the 2D diagram in Fig. 7. to represent the relationship given by (1) as the function of displacement, $\overline{\xi}$, that is, to show on a single diagram the dependence of contact interface displacement on the various values of clamping force F_c, and mean tangential force $\overline{F}_t$.

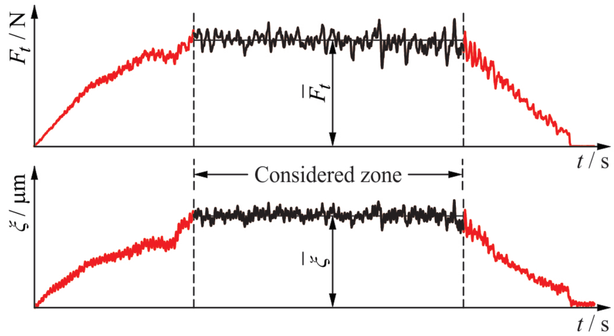

Figure 6 Diagram showing the relationship between cutting force F_t, and the corresponding displacement ξ

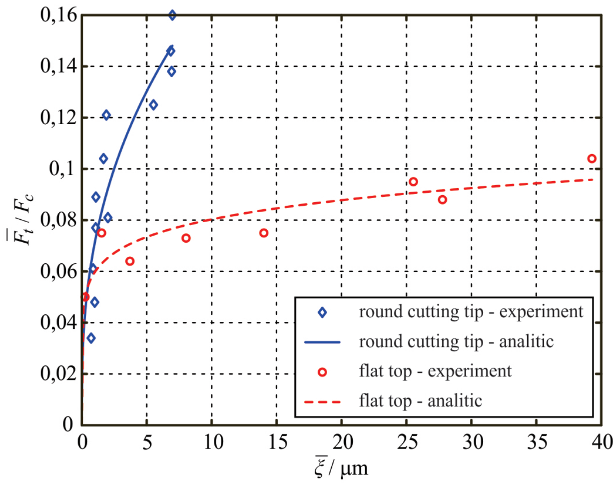

Figure 7 Experimental and analytical diagrams of the dependence of ratio $\overline{F}_t / F_c$ on the contact interface displacement $\overline{\xi}$

Based on the results shown in Tab. 1, i.e., Fig. 7, the ratio between the mean tangential force, $\overline{F}_t$, and clamping force F_c, can be related to the mean displacement of the contact interface, $\overline{\xi}$, using the following regression equation:

$$\frac{\overline{F}_t}{F_c} = A + C \cdot \overline{\xi}^N, \qquad (2)$$

where A, C and N are coefficients which are constant for the given experimental conditions. For both types of clamping elements, regression analysis yielded coefficients A, C and N with high coefficients of correlation R, as shown in Tab. 2.

Table 1 Results of measurements

No.	F_c / N	f / mm/min	Clamping element with round cutting insert			Clamping element with flat top		
			$\overline{F}_t$ / N	$\overline{F}_t / F_c$	$\overline{\xi}$ / µm	$\overline{F}_t$ / N	$\overline{F}_t / F_c$	$\overline{\xi}$ / µm
1	631,2	20	21,38	0,034	0,72	31,82	0,050	0,25
2	631,2	40	38,59	0,061	0,88	47,34	0,075	1,53
3	631,2	60	65,39	0,104	1,68	58,25	0,095	25,54
4	631,2	80	91,94	0,146	6,85	/	/	/
5	513,5	20	24,76	0,048	1,00	32,86	0,064	3,71
6	513,5	40	39,72	0,077	1,07	45,19	0,088	27,78
7	513,5	60	62,13	0,121	1,89	/	/	/
8	395,8	20	32,06	0,081	2,01	28,76	0,073	8,03
9	395,8	40	49,36	0,125	5,52	41,16	0,104	39,29
10	395,8	60	63,15	0,160	6,98	/	/	/
11	278,0	20	24,82	0,089	1,09	20,85	0,075	14,02
12	278,0	40	38,41	0,138	6,92	/	/	/

Table 2 Coefficients

Clamping element	A	C	N	R
Round cutting insert	$6{,}10\times10^{-3}$	0,0651	0,4013	0,923
Flat top	$3{,}98\times10^{-4}$	0,0593	0,1294	0,974

Equation (2) can be written as:

$$F_c = \frac{\overline{F}_t}{A + C \cdot \overline{\xi}^N}. \tag{3}$$

Expression (3) allows the calculation of the clamping force F_c, which keeps the displacements below the set value of mean displacement in the contact interface zone $\overline{\xi}$, provided the mean tangential cutting force $\overline{F}_t$, is known. In other words, the real minimal clamping force, F_{cr}, can be determined from:

$$F_c \geq s \cdot F_{cr}. \tag{4}$$

where $s>1$ is a factor of safety.

5 Discussion

The results obtained by experiment fully support the theoretical assumptions which predict that the specially designed clamping element with round cutting insert yields higher tangential load capacity and lower contact interface compliance compared to the clamping element with flat top. Within the entire loading interval, the specially designed clamping element shows superiority which is clearly evident from the diagram in Fig. 7. The same diagram shows that, until reaching the ratio $\overline{F}_t/F_c \leq 0{,}06$, both types of clamping elements yield approximately the same displacement, i.e. sliding. However, once the ratio exceeds 0,06 the difference in contact interface displacements becomes obvious.

If we denote by $\mu_{\overline{\xi}}$ the ratio:

$$\mu_{\overline{\xi}} = \frac{(\overline{F}_t / F_c)_{rci}}{(\overline{F}_t / F_c)_{ft}} = \frac{6{,}10\times10^{-3} + 0{,}00651 \cdot \overline{\xi}^{0{,}4103}}{3{,}98\times10^{-4} + 0{,}0593 \cdot \overline{\xi}^{0{,}1294}}, \tag{5}$$

then the function shown in Fig. 8 illustrates the advantage of the clamping element with round cutting insert within a wide area of mean compliance values, i.e. contact interface displacements.

More precisely, within the entire domain of displacement values, $\mu_{\overline{\xi}}$ is greater than one, and - depending on the mean displacement value - reaches high values in the contact interface zone. For example, displacement of 5 µm, yields $\mu_{\overline{\xi}} \approx 1{,}8$. In the physical sense, that means that the specially designed clamping element yields significantly smaller compliance compared to its conventional counterpart which is widely used in everyday practice.

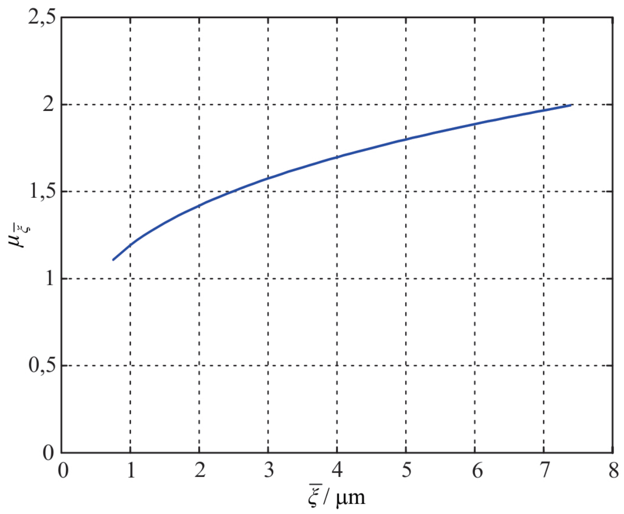

Figure 8 Graphical interpretation of the $\mu_{\overline{\xi}}$ ratio.

6 Conclusion

Previous discussion yields the conclusion that workpiece machining errors directly depend on the magnitude of displacements within the workpiece-fixture contact interface zone. Therefore, error reduction requires minimization of displacements within the contact interface zone which are the result of the cutting forces. Consequently, the design of macro geometry of clamping elements requires special emphasis. This study has shown that macro geometry of clamping elements strongly affects the magnitude of displacements within the workpiece-fixture contact interface zone. Advantages of the clamping element with round cutting insert have been confirmed by experiment. Experiments have shown that, given the identical displacements, the specially designed clamping element provides almost double load capacities in comparison with its conventional counterpart. Bearing in mind that the cutting force loads used in this experiment were dynamic, one can conclude that the proposed clamping element has a potentially significant industrial application, especially where small clamping forces are to be used (machining of thin-walled workpieces). Using the proposed clamping element with small clamping force, results in the zone of local workpiece deformations being located near the roots of the surface roughness profile, which yields small and barely visible clamping marks. With this in mind, the potential area of application of the proposed type of clamping element is fairly large. Its design demands a hard metal insert tip to be placed into a standard clamping element, which is undemanding from an engineering point of view as well as cost-efficient.

Further investigations shall be focused on finding an optimal macro- and micro geometry of the clamping element tip (i.e. the segment which penetrates workpiece) as well as the selection of tip material. Furthermore, additional effort shall be placed on experimental investigations of the workpiece-fixture interface compliance when using coolants, considering the fact that conventional clamping elements with flat top, exhibit a significant reduction of friction due to application of coolant. In such conditions, workpiece-penetrating clamping elements can substantially reduce the fixture/workpiece interface compliance.

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