Serbian Tribology Society

SERBIATRIB '15

14th International Conference on Tribology

University of Belgrade, Faculty of Mechanical Engineering

Belgrade, Serbia, 13 – 15 May 2015

THE COMPILANCE AND LOAD CAPACITY OF CONTACTS BASED ON FRICTION

Vladimir KOČOVIĆ[1], Marija JEREMIĆ[1,*], Petar TODOROVIĆ[1], Branko TADIĆ[1], Djordje VUKELIĆ[2]

[1]Faculty of Engineering, Kragujevac, Serbia

[2]Faculty of Technical Sciences, Novi Sad, Serbia

*Corresponding author: marija.jeremic@kg.ac.rs

Abstract: *In the fixture/workpiece system, compliance and load capacity of the contact surface under dynamic conditions have a significant impact on the quality of machining process. The conducted experimental investigations aimed to evaluate the size of the compliance that occurs between the clamping/locating fixture elements and workpiece during machining processes. The experiment was performed on samples of different diameter d = 22 mm and d = 16 mm, which simulate clamping/locating fixture elements, while the prismatic sample simulates the workpiece. Based on the above, the authors of this paper have experimentally determined the compliance and load capacity flat contact surfaces of the same surface roughness of Ra = 0.8 μm. The results indicate a significant reduction of compliance, respectively, increase the load capacity of the contact surface with diameter of the clamping/locating fixture elements d = 22 mm. According to the obtained experimental results and theoretical considerations, the authors confirm the fact, that at significantly greater contact surface and at a lower specific pressure, there is a reduction of the compliance of contact elements.*

Keywords: *compliance, load capacity, contacts surface, friction, fixturing.*

1. INTRODUCTION

The compliance between clamping/locating fixture elements and workpiece under dynamic conditions has a significant impact on the quality of machining process. The theme of dynamic modelling contact compliance between clamping/locating fixture elements and workpiece is especially actual in conditions of limited value clamping force and demands for increased load capacity under tangential dynamic loads [1-9]. Tadić et al. [5] presented experimental and numerical research of the tangential load capacity and compilance between the clamping/locating fixture elements and workpiece. In order to increase the load capacity, and reduce compilance on contact surfaces, the authors have proposed a method based on the intending of the clamping element in the form of conical indenter into the material of the workpiece, using a surface of the workpiece that are not machined. Results of numerical analysis and experimental research indicate on considerable impact microgeometry of contact surfaces on the load capacity and the compilance of the fixture/workpiece system. Authors of the paper are based on the obtained results show that for the same values of compilance contact surfaces, conical indenter relative to the spherical shape provides greater load capacity.

The problem of compilance contact surfaces between the clamping/locating fixture elements and workpiece in dynamic conditions during machining process, were investigated by Tadic et al. [6]. For the purposes of experimental research, the authors of this paper have developed a special device that represents the physical models of clamping/locating fixture elements and workpiece. Experimental results show that under certain conditions the clamping/locating fixture elements with larger radii provide significantly less compilance contact surfaces. Todorovic et al. [8] have conducted a comparative analysis of the compilance of the two types of clamping elements in dynamic conditions. One type of the clamping element is a standard element with a flat surface at the top, while the second clamping element is specifically designed with round cutting insert in the top. Analyzed the case of workpiece clamping forces of small size, with the deformation of the contact surface of the workpiece and the clamping element mainly on the order of the height of surface roughness. Compared with standard clamping element, specially designed clamping element with round cutting plate on top has a much better performance in terms of tangential load capacity and compilance contact surfaces. Theoretical and experimental investigations of the compilance of the contact surface between the clamping elements and workpiece in dynamic conditions, taking into account the stiffness and damping coefficient were analyzed Todorovic et al. [7]. The theoretical model of behaviour of the contact surface between the clamping elements and workpiece in dynamic conditions, as well as the relative displacement of the clamping element is determined by using the differential equations of motion Lagrange. Lui et al. [9] have formulated a multi-modal function in which defines the geometric constraints related to the workpiece. Based on the constraints genetic algorithm searches the space of possible solutions and define the optimal position of the clamping force for prismatic workpieces. Liao and Hu [4] developed a methodology that aims to detect the compilance and stiffness of the contact element fixture/workpiece based on finite element method. Their model also describes the theory of vibration of the workpiece during the machining process. Asante [1] presented a methodology that combines the elasticity of contact with the finite element method in order to predict the contact load and distribution of compressive stress at the contact points of the workpiece and fixture elements. Asante [2] investigated the effects of fixture compilance and conditions of the machining process (cutting mode) on the stability of the workpiece. In the simple consideration, formulated the matrix stiffness of fixture, which represents the minimum displacements of contact points workpiece relative to fixture elements, as well as large displacements workpiece under the influence of cutting forces. Chaar et al. [3] describe a methodology for modelling of geometric deviations under the influence of elements for positioning. Displacements occurred under the influence of clamping force and cutting force is determined by the finite element method.

The issue of compilance and load capacity contact surfaces generated by friction in dynamic conditions was investigated in this paper. In contrast to previous investigations [6], the authors used in experimental investigation elements of flat contact surfaces and different shapes that simulate clamping/locating fixture elements and workpiece.

2. COMPILANCE AND LOAD CAPACITY OF CONTACTS BASED ON FRICTION

The fixture, especially in cases of processing complex contour cutting forces and torques equilibrate the through frictional force that occur at the contact surfaces of clamping/locating fixture elements and workpiece (Fig. 1).

Figure 1 schematically illustrated example milling machining process workpiece with prismatic shape. Tangential F_t and radial cutting force F_r changes direction under machining process the workpiece.

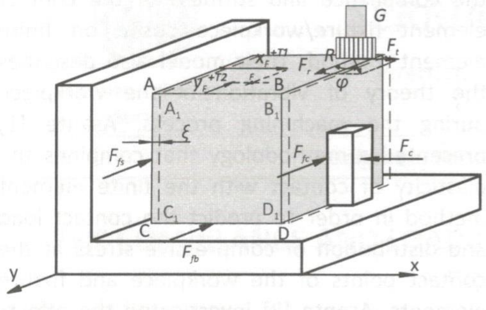

Figure 1. Example of equilibrium cutting forces by frictional forces

The static equilibrium equations of workpiece at *y* direction as follows:

$$F_{fc} + F_{fS} + F_{fb} \geq F_t \cdot \cos\phi - F_r \cdot \sin\phi. \quad (1)$$

where is: F_{fc} - friction force that occure between the clamping element (near point F) and the workpiece; F_{fS} -friction force between the workpiece and element positioning along the line AC; F_{fb} - friction force between the workpiece and the support element; F_t - tangential component of cutting force; F_r - radial component of the cutting force; ϕ - the current angle.

In the general case, the value of point R is:

$$F_t \cdot \cos\phi - F_r \cdot \sin\phi = F_y. \quad (2)$$

equilibrium of forces will be established only with the proper displacement of the workpiece in the zones of contact with the element of the clamping and positioning. This means that occure displacement the workpiece from position ABCD to position $A_1B_1C_1D_1$. Displacement which occurred as a consequence of the compilance of the above mentioned contacts zone are in direct connection with workpiece machining error. Compilance in the contact zones of the clamping and supporting elements and workpiece occurs due to action of force of the contacts in the environment the point F, which causes tangential stresses in the direction of the axis *y*. Each stress inevitably causes a deformation. The sum of local deformations precisely represents compilance and directly affects to the workpiece machining error. Laws change in the tangential and radial cutting forces in time are known and can be found in literature sources. Friction forces are complex functions of macro and micro-geometry of contact, the material characteristics of contact pairs, the clamping force F_c and displacements ξ_1. For each connection, can write the dependency type:

$$F_f = f(G, M, F_n, \xi_1). \quad (3)$$

where is: *G* – a set of parameters which define macro- and micro-geometry of locating element and workpiece interface surface; *M* – a set of parameters which definemechanical and thermal properties of locating elements material; F_n – normal reactions on locating elements and ξ_1 – compilace of contact. Given the large number of influential parameters that define microgeometry contact (a large number of surface roughness parameters of univariate) and the parameters that define the characteristics of the material contact pairs (hardness, strength, chemical composition), and in fact very complex processes and mechanisms of friction and wear, in terms of reliability is very is debatable each analytical dependence type. For that reason, compliance can be precisely determined only by experimental methods.

If the friction force F_{fC}, F_{fS}, F_{fB}, for certain investigate conditions, determine experimentally, for a wide interval clamping force, then it is possible that on the basis of a large number of experimental data form a certain type of regression equation $F_f = f(G, M, F_n, \xi_1)$. Thus, it is possible to establish a regression equation, respectively, depending on the friction force of the normal load and tangential contact compilance contact or tangential contact stiffness. In that way creates the key prerequisites for determining the machining error of the workpiece. The experimental function of this type allow modelling the behaviour of the workpiece in the fixture before performing the machining process and realistically anticipate machining error of the workpiece at certain elevations.

3. EXPERIMENTAL METODOLOGY

Experimental investigations were carried out in order to estimate compilance and load capacity of contact clamping/locating fixture elements and workpiece in dynamic conditions, taking into account the effect of frictional force. For research purposes, the authors have developed a special device that allows optimization of a large number of inputparameters which are critical to interface compliance.

3.1 Conditions of experimental investigations

The purpose of the research were used the causes of flat surfaces that simulate clamping/locating fixture elements and workpiece. Cause of circular shape which simulates a clamping/locating fixture element, is made from steel EN 10083-1, hardness 56 HRC. Cause of prismatic shape which simulates the workpiece, is made from steel C45E, tensile strength 710 MPa, hardness 208 HB, chemical composition: 0.44 % C, 0.18 % Si, 0.27 % Mn, < 0.01 P. Clamping forces, F_n, were varied within 278–631.2 N interval.

For each particular value of clamping force, a twist drill, Ø12, was used at n = 2000RPM and varied feeds, *f*, to simulate various tangential forces. These forces and their corresponding feeds, *f*, were monitored and recorded using the discussed measuring instrumentation. Experimental investigations involve the determination of compilance contact pair in dynamic conditions, on various forms of surface contact.

(a) (b)

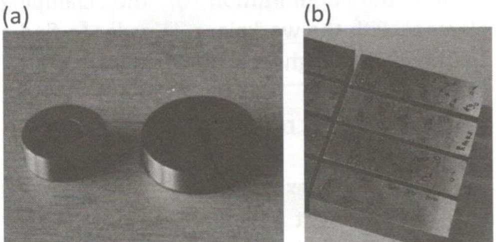

Figure 2. Photo images: (a) clamping/locating elements, and (b) workpiece material specimens

Contact surface is changed by changing the diameter of clamping/locating fixture elements (Fig. 2), where all other parameters remain the same.

3.2 Measuring instrumentation

Developed a special device allows investigation behaviour of contact clamping/locating fixture elements and workpiece in dynamic loads, whereby effects of the other characteristics of the fixture elements such as stiffness of the workpiece and fixturing elements were eliminated. The conceptual model of special devices intended for examining compilance between clamping/locating fixture elements and workpiece under dynamic loading conditions is shown in Figure 3.

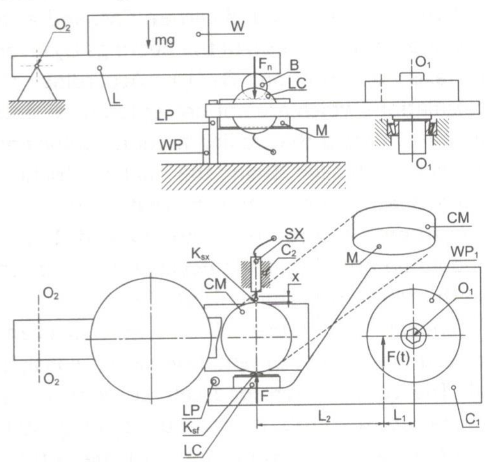

Figure 3. Experimental model

A sample of the clamping M, which was previously fastened in support CM is mounted on WP, that simulates the workpiece. Contact between samples is achieved through surface roughness of the contact pairs. Element in three points provides uniform distribution of loads between the individual elements. Exchangeable clamping/locating element, M, which was previously attached to its carrier, CM, is attached to workpiece material specimen, WP, which plays the role of the workpiece. Normal load (i.e. clamping force), F_n, is applied by the lever mechanism, L, which freely rotates about O_2–O_2 axis, and with calibrated weights, *W*. Tangential load, *F*, i.e., component of cutting force, F(t), is applied by the compression load cell, LC, mounted on the carrier, C1, to which a workpiece material specimen, WP1, is affixed. The carrier C_1 is pivoted about point O_1, i.e., axis O_1–O_1. Depending on the attack point of cutting force, F(t), i.e., distances L_1 and L_2, a component of the cutting force $F(t)$ is transmitted by LC onto the carrier, CM, at point K_{sf}. Displacement of carrier CM, i.e., the exchangeable clamping/locating element, M, is registered by a displacement sensor, SX, which is mounted on the fixed carrier C_2. During displacement of exchangeable clamping/locating element, M, relative to workpiece material specimen, WP, the ball, R, is rolling along the carrier CM. Measurement error is the result of unregistered rollingfriction force which occurs between the ball, R, and carrier, CM. and as a result of rolling friction in the bearings O_2 lever L (axis of rotation O_2-O_2). According to calculations which are not presented here, and bearing in mind that rolling friction coefficient is much smaller than the sliding friction coefficient, there follows that the total measurement error does not exceed 1%. It should be noted that the device was designed so that this error is minimized.

Shown in Figure 3 is the auxiliary measurement instrumentation which consists of: The compression load cell, LC, with force range up to 1100 N, measuring tangential force, F, which is proportional to the cutting force, $F(t)$; The inductive displacement transducer, W1T, The 2 channel HBM signal conditioner which processes the signals from sensors LC and SX; The PC which controls DAQ module and stores the results of measurement for further processing.

As the main advantage of the device should emphasize the fact that allows a deeper dynamic analysis of a specific type of contact elements for clamping the workpiece, wherein eliminate effects of the other fixture elements. This allows comparison of certain types of contact, their optimization and opens the way towards finding reliable solutions to mentioned elements in terms of reducing the compilance of contact.

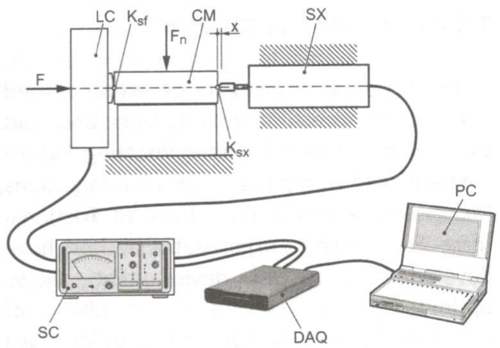

Figure 4. The auxiliary measurement instrumentation

A model show in Figure 5 represents the special device in terms of dynamic tests compilance of clamping/locating fixture elements.

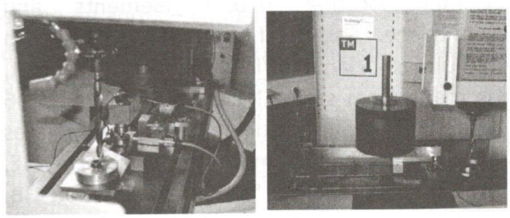

Figure 5. Experimental setup of the device for model testing of dynamic behaviour of clamping/locating fixture elements

The research can be performed on the elements of different forms of macro and micro geometry of the contact. For example contact of the two flat surfaces of different sizes, contact spheres of different radii and flat surfaces, the contact of different materials and different characteristics of the micro-geometry of contact pairs as well as other types of contact. In this way is possible to further discuss the optimization of the clamping element with the workpiece, in order to find a solution with a high level of reliability.

3.3 Measurement results

Results of experimental investigations involving different values of normal load for each of the tested contact pairs. Table 1 show the corresponding mean values of dynamic tangential force, $\overline{F}$, maximum dynamic tangential force, Fmax, as well as the mean values of displacement, $\bar{\xi}$, and maximum displacement, ξ_{max}, depending on the normal load, F_n, and feed, f. The values of the normal load and the corresponding feed were observed using the previously described measured by instrumentation.

4. ANALYSIS OF RESULTS AND DISCUSSION

Results of experimental investigations of compilance and load capacity of flat contact surfaces under dynamic conditions are shown in Table 1. The goal of experimental investigations is to show the effect of different values of diameter clamping / locating fixture elements in dynamic conditions, on compilance and load capacity of prismatic shape of the workpiece. Based on the Figure 6 can be observed displacements clamping/locating fixture elements, in relation to the workpiece, respectively, lead to the deformation and slipping contacts surface under the influence of various values of tangential loads. Based on the received signal tangential force and the corresponding displacements can be concluded that there are two types of compilance:

- contact type A, when the system after the fact the tangential force returns to its original state when the displacements is relatively small, on the order of two micrometers.
- contact type B arises when completely slipping contact is greater than 40 microns.

Table 1. Results of measurements of tangential forces, F, and corresponding displacements ξ

No	F_n [N]	f [mm/min]	d = 16 mm				d = 22 mm			
			$\bar{F}$ [N]	F_{max} [N]	$\bar{\xi}$ [µm]	ξ_{max} [µm]	$\bar{F}$ [N]	F_{max} [N]	$\bar{\xi}$ [µm]	ξ_{max} [µm]
1	631.2	30	31.82	43.87	0.25	0.64	27.69	38.62	0.59	0.86
4	513.5	30	28.11	38.79	3.71	3.91	30.37	43.09	0.31	0.33
5	513.5	60	53.23	67.34	39.29	43.28	54.93	70.25	3.17	7.33
7	395.8	30	28.76	41.37	8.03	8.92	25.02	33.65	0.46	0.66
8	278.0	30	26.78	35.85	252.90	316.75	28.01	42.79	3.25	3.99

Table 2. Basic statistical parameters for the experimental data

Element	$\bar{\bar{F}}$ [N]	$SD(\bar{\bar{F}})$ [N]	$(\bar{\bar{\xi}})$ [µm]	$SD(\bar{\bar{\xi}})$ [µm]
d = 16 mm	33.74	9.89	60.83	97.03
d = 22 mm	33.20	10.99	1.55	1.35

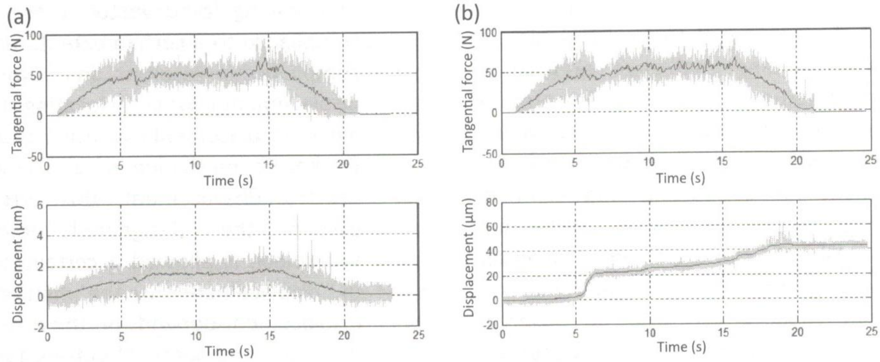

Figure 6. The tangential force F and the corresponding displacement for clamping / locating element: (a) d = 22 mm and (b) d = 16 mm

It is obvious that in the case of compilance type A and deformation of materials in contact, in fact the tangential force F, mainly carried out in the field of elastic deformation. In the case of leniency connection type b there is a significant proportion of plastic deformation of the material in the contact zone. Based on the theoretical analysis and experimental results it can be concluded that the load capacity and compilance, whether the loads transmitted by frictional forces or otherwise is a very complex problem. It is very difficult to define a general analytical model that in order for wider the load interval and different macro and micro geometry of contact reliably describe the dependency load capacity as a function of compilance. Research of the dynamic behaviour performed by a contact type flat surface on a flat surface. The goal of the experimental research was to determine the influence of the size of the surface clamping / locating fixture elements on compilance and load capacity of contact. It can be pointed that the research carried out in the framework of relatively lower value of clamping force F_n.

Processing of measurement results was performed using the mean values of compilance, regardless of the type of compilance, because these values, in terms of measurement errors of the workpiece can be comparable and authoritative. For the same reason, analysis of results was performed with the mean values of tangential force. Based on the results in Table 2 it can be concluded that the experimental investigations of compilance performed in approximately the same mean values of the tangential force. Dispersion of mean values of tangential force, also has an approximate value of 10 μm in diameter for both elements for supporting and clamping. Despite the mean value of the displacement in the element for supporting and clamping diameter d = 22 mm to 97.45 % smaller than the mean value of the displacement element for supporting and clamping diameter d = 16 mm. From Table 2 can also be observed dispersion of mean amount of displacement elements for supporting and clamping, where the dispersion element in diameter d = 16 mm larger than the element in diameter d = 22 mm to 98.61 %.

The authors considered that the theoretical clarification of this phenomenon is contained in the different values of contact pressures and different values of the contact surface resulting in clamping or supporting flat surface on a flat surface. Contact achieved with a diameter d = 22 mm with flat surface, and with the same the normal load is achieved by significantly larger contact surface and at a lower specific pressure. It should be emphasized that due to the small value of the clamping force, which were selected in the experiment, with respect to the actuality of the problem of clamping thin-walled workpieces it was not possible to precisely quantify the real value of the contact surface. Theoretically, it is evident that greater contact surface achieves lower values of specific pressure. In this regard, many of tribological research results indicate a trend increase in the coefficient of friction to reduce the contact pressure and an increase in real contact area. For these reasons compilance of contact follows this trend, which precisely shows the results in this paper.

5. 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.

ACKNOWLEDGEMENT

Research presented in this paper was supported by Ministry of Science and Technological Development of Republic of Serbia, Grant TR-35021, Title: *Razvoj triboloških makro/nano dvokomponentnih i hibridnih samopodmazajućih kompozita*.

REFERENCE

[1] J. Asante: A combined contact elasticity and finite element-based model for contact load and pressure distribution calculation in a frictional workpiece-fixture system, International Journal of Advanced Manufacturing Technology, Vol. 39, pp. 578-588, 2008.

[2] J. Asante: Effect of fixture compliance and cutting conditions on workpiece stability, International Journal of Advanced Manufacturing Technology, Vol. 48, pp. 33-43, 2010.

[3] R. Chaari, M. Abdennadher, J. Louati, M. Haddar: Modelling of the 3D machining geometric defects accounting for workpiece vibratory behaviour, International Journal of Simulation Modelling, Vol. 10, pp. 66-77, 2010.

[4] Y. Liao, S. Hu: An integrated model of a fixture-workpiece system for surface quality prediction, International Journal of Advanced Manufacturing Technology, Vol. 17, pp. 810-818, 2001.

[5] B. Tadic, B. Jeremic, P. Todorovic, D. Vukelic, U. Proso, V. Mandic, et al.: Efficient workpiece clamping by indenting cone-shaped elements, International Journal of Precision Engineering

and Manufacturing, Vol. 13, pp. 1725-1735, 2012.

[6] B. Tadic, D. Vukelic, D. Miljanic, B. Bogdanovic, I. Macuzic, I. Budak, et al.: Model testing of fixture-workpiece interface compliance in dynamic conditions, Journal of Manufacturing Systems, Vol. 33, pp. 76-83, 2014.

[7] P. Todorovic, D. Vukelic, B. Tadic, D. Veljkovic: Modelling of dynamic compliance of fixture/workpiece interface, International Journal of Simulation Modelling, Vol. 13, pp. 54-65, 2014.

[8] P.M. Todorovic, B. Buchmeister, M.J. Djapan, D. Vukelic, M.D. Milosevic, B. Tadic, et al.: Comparative model analysis of two types of clamping elements in dynamic conditions, Tehnicki vjesnik-Technical Gazette, Vol. 21, No. 6, pp. 1273-1279, 2014.

[9] Z. Liu, Y. Wang, K. Wang, X. Mei: Multi-objective optimization design of a fixture layout considering locator displacement and force-deformation, International Journal of Advanced Manufacturing Technology, Vol. 67, pp. 1267-1279, 2013.