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EQUIPMENT AND PROCEDURE FOR EXPERIMENTAL DETERMINATION OF STATIC RIGIDITY OF ENGINE LATHES

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Abstract: *As machining precision and productivity in a technological manufacturing system (TMS) depend on system rigidity, it is necessary to establish TMS rigidity accurately. This can be done with rigid test bars that do not influence TMS rigidity measurements. The test bars can be used for measuring rigidity of any machine tool or subassembly of a machine. This paper presents experimental equipment and procedure for determination of static rigidity of an engine lathe. Planar and spatial test forces were applied and corresponding deformations of different lathe's subassemblies were measured. Obtained data can be used afterwards to assess the suitability of TMS for machining steps of different quality and to estimate the influence of TMS deformations on the accuracy of machined parts.*

Key words: *engine lathe, rigidity measurement, experimental equipment, test bar.*

1. INTRODUCTION

Manufacturing precision and productivity in a technological manufacturing system (TMS) depend on its rigidity [1].

Generally, size and shape alterations of the manufactured parts are influenced by the static or quasi-static deformations of TMS, while deformations produced by various dynamic loads directly influence the roughness of the manufactured surfaces [1].

Forces applied to TMS may be static [1], quasi-static [2], or dynamic [1], while deformations of TMS elements under these forces may be static or dynamic.

Deformations of TMS elements are estimated through analytical calculations or through numerical techniques like finite element method (FEM) and their results are validated through experimental work [3].

Experimental determination of deformations in TMS implies a controlled loading of TMS with known forces and measurement of resulting deformations with adequate equipment [3], [4], and [12].

Quasi-static forces are applied by special equipment used frequently for modal analysis [2]. In this case, onto TMS being in static state is applied a sinusoidal, low frequency force. The advantage of this procedure is the accurate determination of static rigidity of TMS, permitted by reduced influence of friction forces on TMS deformations. However, the procedure is costly to apply because extensive experimental work and expensive equipment are implied.

Within all TMS, rigidity of main spindle assembly (MSA) is crucial. Reference [5] shows a static and dynamic optimization of MSA, taking into account geometrical characteristics of spindle and bearings, and assembly characteristics like the number of bearings and distance between them.

Deformation of MSA is firstly determined through analytical calculations and results are validated experimentally. However, within this study were not taken into account loads on several directions on MSA. Also, no information is provided on specific equipment that is used for applying forces on MSA.

Reference [6] presents a complex rigidity-based optimization of MSA design considerring several constructive and functional design parameters. Its geometric model is constructed parametrically for an easier modification according to utilization needs. The optimization of MSA design is performed only by FEM.

Static rigidity of TMS elements consisting in boring bars is studied by [7]. Three types of boring bars with different shapes are loaded with spatial forces. Their deformations are stated by analytical calculations, by FEM and experimentally. However, paper does not present the experimental equipment that was used for experiments.

Static rigidity of turning tools with different holders was determined experimentally by reference [8] and best holder in terms of rigidity was selected.

Different measurement and test techniques that may be used for determining interactions between manufacturing processes and TMS structures (including deformations) are described by [9].

Other experimental tests for determining the rigidity of lathes and lathes' components are presented in [11] and [13].

2. THEORETICAL CONSIDERATIONS

A technological manufacturing system is a group of elements consisting in: machine-tool, tool and its fastening device, workpiece, device for fastening workpiece, all these elements working together in the manufacturing process [3] and [4]. TMS is generally considered as an elastic system [3].

In order to determine the rigidity of TMS, the basic elements regarding TMS structure, references, states, stresses and deformations must be known [3] and [4].

A TMS is a combination of physical elements, E_k, that are interdependent constructive and functionally [3] and [4]. An element E_k of TMS may be simple, like a tool, or complex (an assembly or subassembly of TMS).

Deformations of TMS depend on material and geometrical characteristics of its components and on characteristics of the joints between components with respect to couple of materials, roughness of contact surfaces, type of contact (dry or wet), contact pressure, fits between components, etc [3].

To define certain features of the TMS load or deformation, an appropriate geometrical three-orthogonal Cartesian reference system Oxyz must be used (Fig. 1).

A geometrical reference system can be attached to physical references (RF). A physical reference may be absolute, if it is exterior to TMS, or may be relative, if it is a part of TMS [3]. A geometrical reference system that is parallel to functional work directions of machine-tool in TMS is commonly used.

A TMS can be in one of the following four states: "rest", "passive functioning (idle)", "stable active functioning (machining)" or "unstable active functioning (machining)", as stated in [3] and [4].

The static load F in TMS (Fig. 1) appears mainly between physical elements with direct contact, in a state of "rest", "passive functioning (idle)", or "stable active (manufacturing) functioning" of TMS. Static force is applied to a loaded element E_F of TMS (Fig. 1).

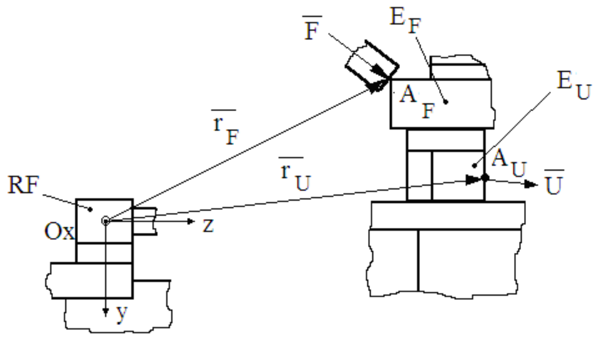

Fig. 1. A generic load scheme of TMS [3] and [4].

In Fig. 1, the static load F (force) has the components Fx, Fy, Fz along X, Y, and Z axes of reference system Oxyz. A_F is a point belonging to the element E_F, identical to the application point of load F. r_F is the position vector of point A_F in relation to the origin of the reference system Oxyz.

The components of TMS are deformed (U) when the load F acts upon them. Direction and measuring point associated with deformation U are established according to each particular case.

Similar to the load, the deformation U has three components Ux, Uy, Uz along the X, Y, Z axes of reference system Oxyz (Fig. 2). To simplify, we will denote Ux as X, Uy as Y and Uz as Z.

Deformation U is measured on component E_U, which can be identical or different compared to element E_F: $E_U \equiv E_F$ or $E_U \neq E_F$.

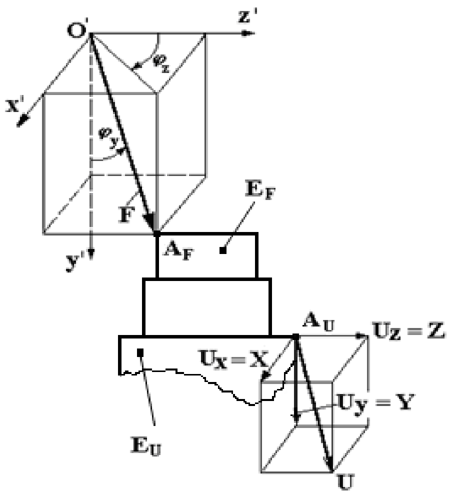

Fig. 2. Schemes for measuring the TMS loads and deformations [3] and [4].

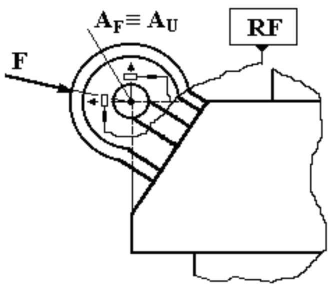

Fig. 3. A particular load scheme of TMS [3] and [4].

If A_U is the measuring point of deformation, U and $\overline{r_U}$ is the position vector of A_U in relation to the origin of the referential Oxyz (Fig.1), then: if $E_U \equiv E_F$, then $A_U \neq A_F$ (Fig. 1, Fig. 2), or $A_U \equiv A_F$ (Fig. 3).

Fig. 4 presents three schemes for measuring TMS planar loads and deformations: a) on main spindle assembly (MSA) without intermediary test bar; b) on MSA with intermediary test bar 1; c) on MSA with clamping chuck 2 that holds the test bar 1.

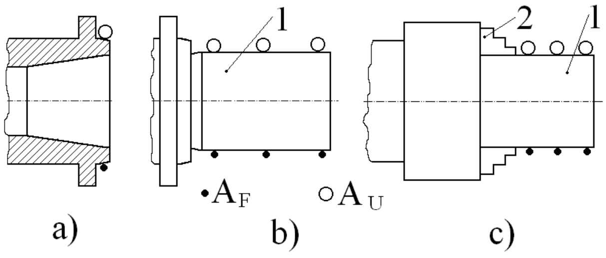

Fig. 4. Schemes for measuring planar loads and deformations of TMS: a) direct on MSA; b) on MSA with test bar; c) on MSA with test bar in clamping chuck [3] and [4].

To measure spatial loads and deformations, a test bar 1 with element 2 of spherical shape “a”, is mounted in MSA (Fig. 5). This bar is the axis of MSA. The deformation is measured in the force application point ($A_U \equiv A_F$) with spherical head “b” connected to a deformation transducer.

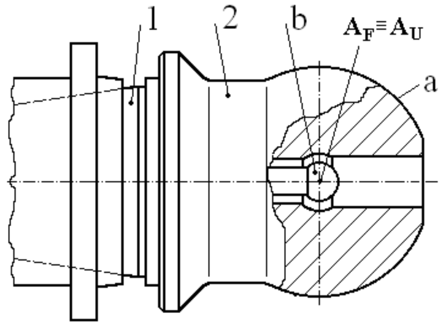

Fig. 5. Test bar for measuring spatial loads and deformations of TMS [3].

Fig. 6 presents a measuring scheme for the carriage of a lathe. In tool holding turret of the lathe is mounted a prismatic part 1 with conical hole, in which is held the test bar 2. Carriage can be loaded on different directions through spherical element 3. The deformations are measured in the application force point.

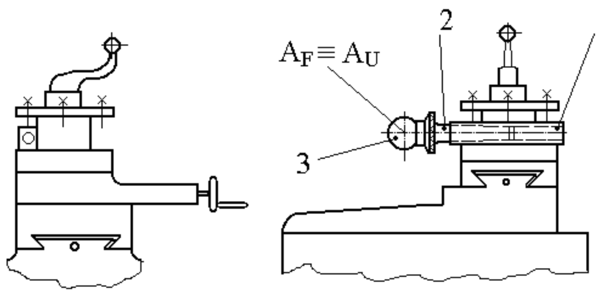

Fig. 6. Scheme for measuring loads and deformations of lathe’s carriage [3].

For experimental determination of static rigidity for a TMS element, it will be subject to a progressive increasing load, whose value is measured at each level. The corresponding deformation is measured with an adequate instrument [3].

Controlled loading of TMS elements is performed with a dynamometric device, which measures spatial forces applied onto the test bar. Test bar materializes the application points for force, A_F and for deformation, A_U.

3. EXPERIMENTAL RESEARCHES

3.1 Equipment for rigidity measurement

Different test bars were previously used for creating spatial forces on lathe spindles [10]. Test bar in Fig. 7 was used first in [3]. The assembly of spherical head 2 with the body 1 of the test bar is realized through a cylindrical fit “d” and thread “e”. Body 1 is provided with a conical or cylindrical shank. The load applied onto spherical feature “b” of part 2 is transmitted and measured onto feature “a” of part 1 through hole “c”. The main disadvantage of this solution is the low accuracy caused by the clearance fit between parts 1 and 2 on feature “d” and by the short distance existing between the threaded assembly feature “e” and the spherical feature “b” onto which loads are applied. These design weaknesses caused deformations of measured spherical feature “a” unrelated to real deformations of the axis of tapered body 1.

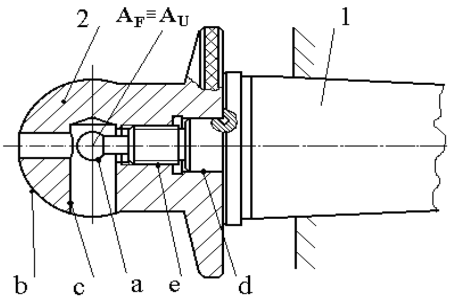

Fig. 7. Initial design of the test bar [3] and [10].

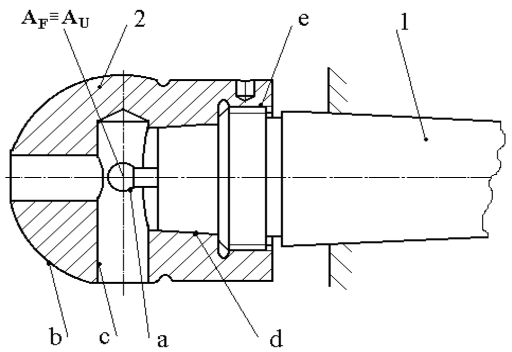

Fig. 8. Improved design of the test bar [10].

To increase the accuracy of the test bar, initial design was improved as shown in Fig. 8. Test bar in Fig. 8 consists of two elements: body 1 and spherical head 2. Assembly of the spherical head 2 with the body 1 is performed through the pressed conical fit “d” and the thread “e”. Body 1 is provided with the spherical head “a” and hole “c” for the access of strain measuring transducers. Due to the pressed conical fit between parts 1 and 2 and the increased distance between the threaded assembly feature “e” and the spherical feature “a”, measuring accuracy of the test bar increases.

A second improvement of the test bar in terms of measuring accuracy and manufacturability is presented in Fig. 9. This consists of body 1 and pin 2 with spherical head “a”. This design ensures that deformation of measured spherical feature “a” isn’t influenced at all by deformation of loaded feature “b”, but only by real deformation of the axis of tapered body 1 (of the machine-tool spindle). Furthermore, compared to previous designs, the test bar in Fig. 9 is simpler and easier to manufacture.

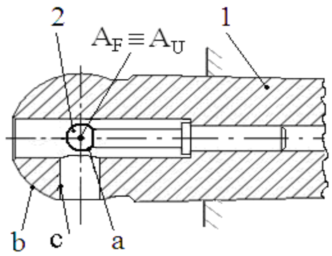

Fig. 9. Extra improved design of the test bar [10].

Test bars in Fig. 7, Fig. 8 and Fig. 9 were experimentally tested by using FEM modules of Autodesk Inventor 2013 and Ansys 14 and by using experimental stand in Fig. 10. Performed experiments proved the superiority of test bar in Fig. 9 in terms of accuracy ensured for rigidity measurement of MSA. Test bar in Fig. 9 was integrated within measuring system in Fig. 10 for testing the rigidity of MSA of engine lathe SNA 500. Force F may be applied in a linear manner or spatially onto the test bar 2 provided with spherical element 3.

Deformations are measured with three inductive transducers 4, which are held on the bed of lathe (relative physical reference) by rods 5 (components of magnetic supports). The force is applied by screw 10 on dynamometer 9, which is mounted on cross slide of lathe 8 by using support 11 and prismatic part 6. For adjusting the position of the dynamometric device on y-axis, adjusting screw 7 is used. Deformations of MSA 1 are measured in the forces' application points ($A_F = A_U$).

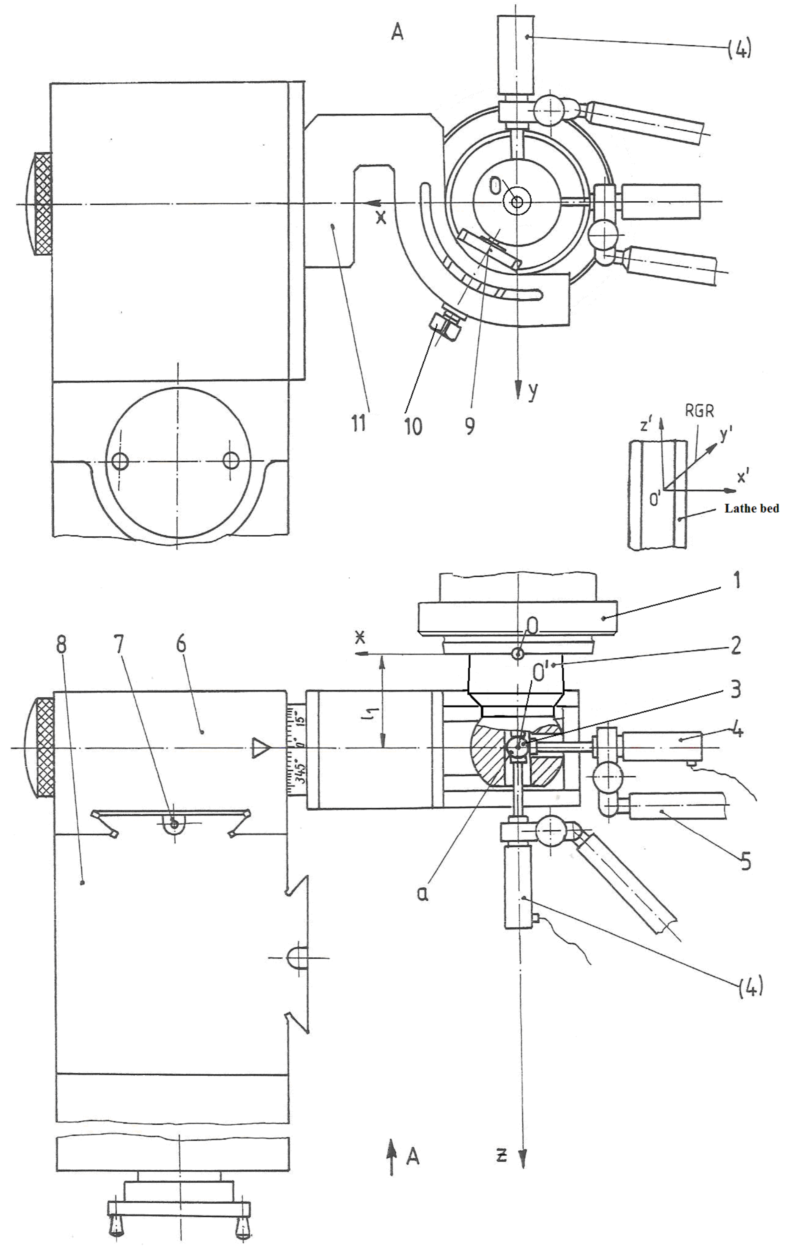

Fig. 10. Experimental equipment for measuring static rigidity of MSA for engine lathe SNA 500.

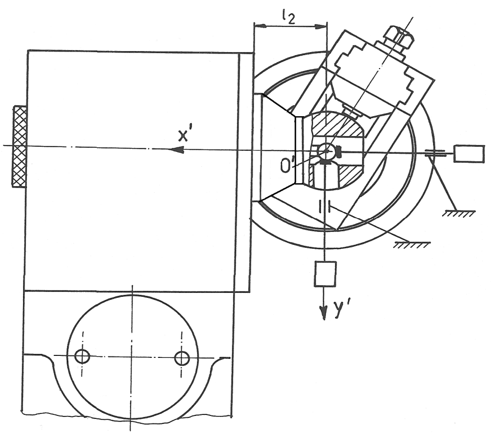

Fig. 11. Experimental equipment for measuring static rigidity of the carriage of engine lathe SNA 500.

Loading of MSA can be realized at a fixed axial position, l_1 (Fig. 10). Relative geometrical reference (RGR) is associated to the lathe's bed (Fig. 10).

A modified construction of stand in Fig. 10 for measuring the rigidity of the carriage of SNA 500 lathe is shown in Fig. 11. In this case, test bar is mounted on the cross slide of the lathe and dynamometric device is clamped on MSA.

3.2 Experimental data

Experimental conditions are as follows:

- Romanian engine lathe: SNA 500;
- TMS state: rest;

- Test bar in Fig. 9 is used in experimental stand with construction in Fig. 10 or Fig. 11;
- Relative physical reference: lathe’s bed;
- Relative geometrical reference: O’x’y’z’;
- Axial position: l1 = 65 mm, l2 = 65 mm;
- Static force: Fx, Fy, Fxy, Fxyz [daN];
- Deformation: X, Y, Z [µm].

Experimental data are presented in Tables 1, 2, 3 and 4.

Table 1

Fx and Fy loadings.

F_x [daN]	X [µm]		F_y [daN]	Y[µm]	
	incr.	**decr.**		**incr.**	**decr.**
0	0	0,65	0	0	0,9
50	7,30	7,65	50	7,7	8,1
100	14,60	15,75	100	15,2	16,4
150	20,90	22,05	150	21,7	22,9
200	27,45	27,80	200	28,4	28,9
250	32,00	33,10	250	33,2	34,4
300	38,25	39,00	300	39,7	40,5
350	42,50	43,10	350	44,1	44,6
400	44,50	44,50	400	46,1	46,1

Table 2

F_{xy} loading ($\varphi_y = 30^o$).

F_{xy} [daN]	X [µm]		Y[µm]	
	incr.	**decr.**	**incr.**	**decr.**
0	0	0,30	0	0,60
50	5,85	7,90	7,90	8,25
100	12,35	16,20	14,70	20,50
150	18,25	22,65	20,75	32,20
200	24,61	27,35	27,85	24,30
250	29,89	30,90	33,90	35,85
300	32,54	33,05	38,15	39,40
350	33,20	33,75	39,70	40,80
400	34,10	34,10	40,90	40,90

Table 3

F_{xyz} loading ($\varphi_y = 30^o$ and $\varphi_z = 75^o$).

F_{xyz} [daN]	X [µm]		Y[µm]		Z[µm]	
	incr.	**decr.**	**incr.**	**decr.**	**incr.**	**decr.**
0	0	0,30	0	0,55	0	0,9
50	5,75	6,10	6,70	7,05	1,5	1,8
100	10,75	14,85	12,45	17,35	2,9	4,2
150	15,20	19,35	17,65	22,45	4,2	5,3
200	20,30	23,40	23,45	27,25	5,4	6,4
250	24,80	26,15	28,80	30,40	6,8	7,2
300	27,90	28,70	32,30	33,30	7,5	7,8
350	28,95	29,85	33,60	34,50	7,9	8,0
400	29,90	29,90	34,70	34,70	8,1	8,1

Table 4

F_{xy} loading ($\varphi_y = 30^o$) of lathe carriage.

F_{xy} [daN]	X [µm]		Y[µm]	
	incr.	**decr.**	**incr.**	**decr.**
0	0	1,8	0	2,3
50	2,5	13,2	6,1	9,4
100	6,6	19,1	14,5	17,7
150	8,7	26,3	21,9	23,2
200	14,5	29,6	29,3	30,7
250	20,1	33,1	36,6	38,7
300	26,2	35,5	43,4	45,6
350	33,7	38,9	49,9	52,9
400	40,6	40,6	56,1	56,1

Using data in table 1, MSA rigidity can be computed in daN/mm as follows:

$$K_{xx} = \frac{F_x}{X} = \frac{400}{0,0445} = 8488 \tag{1}$$

$$K_{yy} = \frac{F_y}{Y} = \frac{400}{0,0461} = 8776 \tag{2}$$

Using data in table 2, MSA rigidity can be computed in daN/mm as follows:

$$K_{Px} = \frac{F_{xy}}{X} = \frac{400}{0,0341} = 11\,730 \tag{3}$$

$$K_{Py} = \frac{F_{xy}}{Y} = \frac{400}{0,0409} = 9779 \tag{4}$$

where P stands for the direction of planar force Fxy.

Using the data in table 3, MSA rigidity can be computed in daN/mm as follows:

$$K_{Sx} = \frac{F_{xyz}}{X} = \frac{400}{0,0299} = 13\,377 \tag{5}$$

$$K_{Sy} = \frac{F_{xyz}}{Y} = \frac{400}{0,0347} = 11\,527 \tag{6}$$

$$K_{Sz} = \frac{F_{xyz}}{Z} = \frac{400}{0,0081} = 49\,382 \tag{7}$$

where S stands for the direction of spatial force Fxyz.

Using the data in table 4, lathe's carriage rigidity can be computed in daN/mm as follows:

$$K_{Px} = \frac{F_{xy}}{X} = \frac{400}{0,0406} = 9852 \tag{8}$$

$$K_{Py} = \frac{F_{xy}}{Y} = \frac{400}{0,0561} = 7130 \tag{9}$$

where P stands for the direction of planar force Fxy.

4. CONCLUSION

Determination of static rigidity of lathes' MSA and carriage claims for a particular work environment, which refers to the structure of TMS, references, system's states, loadings and deformations.

This paper presents several schemes for measuring TMS loads and deformations, together with two constructions of an experimental stand that can be used for rigidity measurement of MSA and carriage of lathes. Several designs of the test bar that is used in experimental stand were also presented in the paper.

Proposed schemes and devised experimental stand may be used for measuring rigidity of other components of lathes, or of other types of TMS (with milling machines, grinding machines, etc.).

As shown by experimental data, the rigidity of lathe carriage is lower than the rigidity of MSA of lathe. This result is a direct consequence of the greater number of fixed and mobile joints that are used in the construction of carriage assembly as compared to MSA.

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Echipament şi metodologie pentru determinarea experimentală a rigidităţii statice a strungurilor normale

Rezumat: Deoarece precizia şi productivitatea prelucrării cu sisteme tehnologice de prelucrare (TMS) depind de rigiditatea sistemelor, este necesară determinarea precisă a rigidităţii TMS. Aceasta se poate realiza prin utilizarea unor echipamente care includ dornuri de control rigide, astfel încât să nu influenţeze precizia de măsurare. Dornurile de control pot fi utilizate pentru măsurarea rigidităţii oricărei maşini-unelte sau subansamblu al maşinii-unelte. Această lucrare prezintă echipamentul şi metodologia utilizate pentru determinarea experimentală a rigidităţii statice a unui strung normal. Experimentele au implicat aplicarea de forţe planare şi spaţiale şi măsurarea deformaţiilor corespondente ale subansamblurilor strungului. Rezultatele obţinute privind rigiditatea pot fi utilizate pentru stabilirea adecvanţei TMS pentru realizarea de prelucrări de anumite precizii impuse şi, respectiv, pentru estimarea influenţei deformaţiilor TMS asupra preciziei de fabricare a pieselor prelucrate prin aşchiere.

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