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Technological Quality Assurance of Assembling Machine Components Based on Modular Elements, Taking into Account the Contact Stiffness of the Joints

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***Abstract* — This paper presents the results of theoretical and experimental studies of the joint rigidity of the production equipment in relation to modular structures.**

***Keywords*— accuracy, unified modules, ball screw pair, linear guides, contact stiffness, macro deviations.**

I. INTRODUCTION

The most important trend in designing and manufacturing machine tools is the widespread use of modular solutions. In the construction solutions various unified nodes of different integration degrees are increasingly used.

In some cases, machine components can be supplied in the form of a full-fledged coordinate axis. But more often in the design they combine original parts of tables, consoles with unified modules: rail guides, carriages, bearing supports, ball screw gears (BSG), couplings, electric motors, etc.

There are recommendations [1, 2] for selecting standardized modules, components, parts, considering the accuracy requirements, carrying capacity in the technical literature, manufacturers' methodical recommendations. However, these techniques almost do not take into account contact stiffness.

Consider the example of a flat joint “base plate - rail-type rolling guide” some of the existing issues of the compliance evaluation.

II. THEORETICAL AND EXPERIMENTAL RESEARCH

Calculations and experiments were carried out in relation to a full-size model of the coordinate axis [3, 4]. The model (Figure 1) includes base plate 1 (steel 14G2), linear ball guides 2 of the model HGR30R. The table of design 6 is attached to carriage 3 through spacers 4. The movement of the feed is implemented by BSGs. The studies took into account the methods of processing the working surfaces of the plate, as well as the geometrical parameters (dimensions) of the joints. The theoretical analysis of the problem is based on the studies of the normal compliance of contact joints by K.V. Votinov, I.G. Goryachev, I.T. Gusev, N.B. Demkin, Yu.N. Drozdov, A.S. Ivanov, V.V. Izmailov, I.V. Kragelsky, Z.M. Levina, D.M. Reshetov, E.V. Ryzhov, A.P. Sokolovsky, A.G. Suslov, G.E. Chikhladze, V.V. Shelofast and others [5, 6].

The following empirical formula (1) is widely used to determine contact compliance:

$$\delta = C\sigma^{m} \quad (1)$$

where: σ is the average pressure at the junction, kg / cm^2;

C is the value of the coefficient taking into account the quality of processing: at a rough scraping the coefficient is 1.5; at an average scraping the coefficient is 0.8; at finishing planning the coefficient is 0,6; at finishing scraping and fine grinding the coefficient is 0,15-0,2; at regrinding the coefficient is 0.07 [5, 6].

The exponent m is 0.5 for steel, cast iron, bronze and it is 0.3 for non-metallic materials. This empirical dependence was derived for small contact areas and it does not take into account the waviness and macrogeometry of the parts.

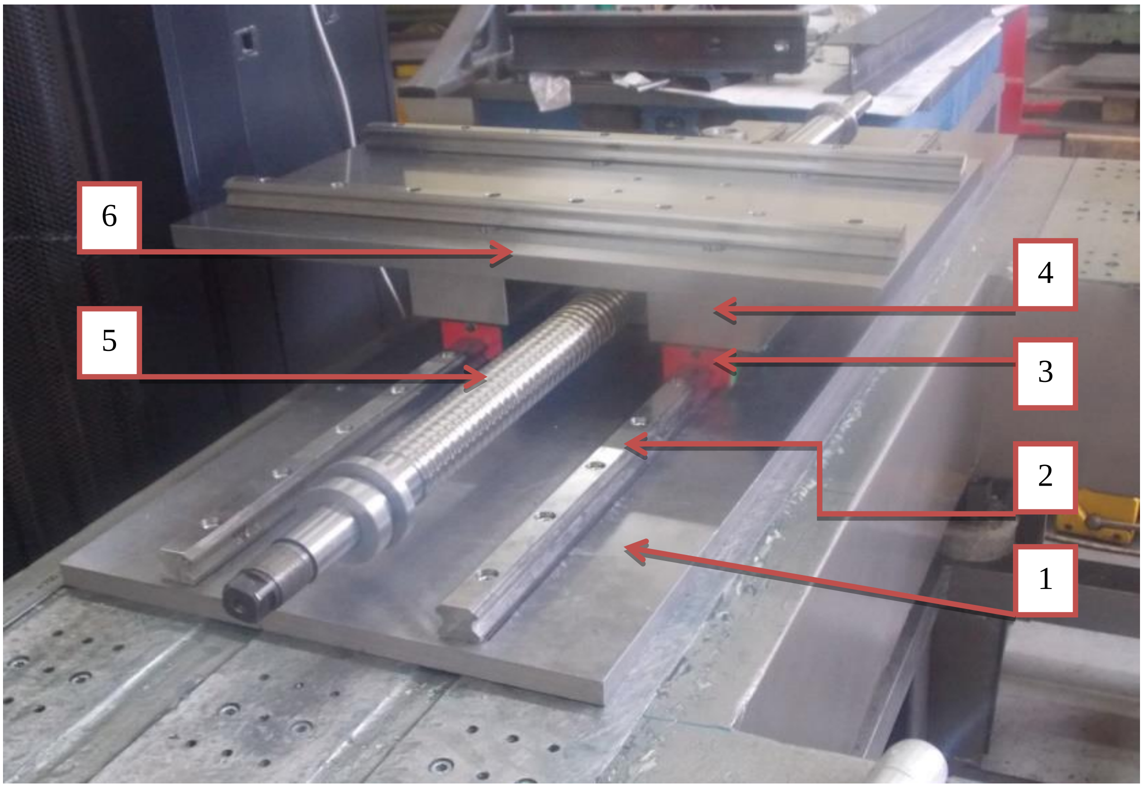


Fig. 1 Linear design solution

To determine the average pressure at the junction, we consider the scheme of fastening a linear guide to the base surface of the plate. The rail is fixed with screws M8 (Fig. 2). The joint loading scheme is shown in Figure 3.

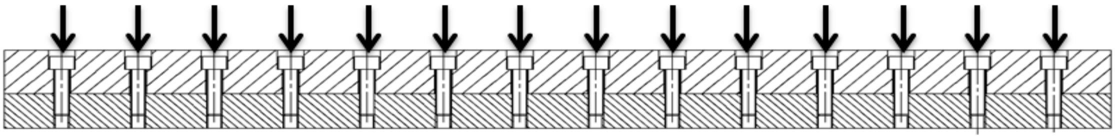


Fig. 2 Rail fastening scheme

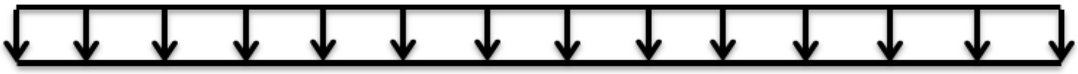


Fig. 3 Rail loading scheme

Determine the screw tightening parameters for this scheme. The tightening torque is related to the axial force by the dependence [7]:

$$M=0,15\cdot Q\cdot d \tag{2}$$

where: M is screw tightening torque; kg · cm; [3, 4].

According to the rail manufacturer's recommendations, the screws are tightened with a torque of M = 3041H · cm = 310 kg cm;

Q is tightening force, H respectively equals (3):

$$Q=M/0,15\cdot d \tag{3}$$

where: d is the outer diameter of the thread, cm;

Then we determine the rail pressure, exerting on the base plate of the guide by the formula(4):

$$\sigma = n\cdot Q/S,\ kg/cm^2 \tag{4}$$

where: S is the nominal area of the rail contact, n is the number of mounting screws.

In [8], A.S. Ivanova and V.V. Izmailov proposed a dependence between the contingence δ and pressure p in the contact layer, taking into account the parameters known to the designer at the project stage.

$$\frac{\delta}{Ra} = C_0 \cdot \varepsilon \cdot \sqrt{\frac{\sigma}{\mathrm{E}}} \tag{5}$$

From this formula (6), you can deduce compliance, then the formula will take the form:

$$\delta = Ra \cdot C_0 \cdot \varepsilon \cdot \sqrt{\frac{\sigma}{E}} \quad (6)$$

where: $Ra = (Ra_1 + Ra_2)/2$, Ra_1, Ra_2 are average arithmetic asperity heights of the contacting surfaces of parts.

The results of measuring the roughness of the contact surfaces are presented in the table.

TABLE I. SURFACE ROUGHNESS OF THE JOINT PARTS "BASE PLATE - RAIL»

Part name	Roughness in a different direction, micron					
	Longitudinal			*Cross*		
	R_a	R_z	R_{max}	R_a	R_z	R_{max}
Milled plate	0,4	2,0	2,5	0,40	2,0	3,2
Ground plate	0,063	0,4	0,5	0,32	2,0	2,5
Guide rail	0,2	1,6	2,0	0,32	2,5	3,2

E = 2E1E2 / (E1 + E2) is the reduced modulus of elasticity of the contacting surfaces of the parts,

C_0 is the coefficient taking into account the relative position of the asperities, which, as a result of research and testing, was established for the contacting surfaces obtained by face turning or planing in the case of parallel processing marks $C_0 = 160$; for contacting surfaces obtained by grinding or milling, regardless of the direction of machining marks and obtained by face turning or planning and in the case of non-parallel machining marks c0 = 500.

ε is the scale influence factor taking into account the effect of waviness and shape deviations ("scale factor").

ε = f (Δ - Wmax) is the scale influence factor depending on the flatness tolerance Δ, determined by the accuracy degree according to GOST (State Standard) 24643 - 81 and the largest size of the contact surface l, as well as the highest wave height W_{max}.

For a more accurate calculation, the plate waviness was measured in those areas where contact occurred. The measurements were carried out according to the scheme presented in figure 4.

A similar scheme is used for scraping. Plate 3 is mounted on testing plate 1, on two rollers 2. An indicator post with indicator 4 is mounted on plate 3. The plate is scraped on the contact side with the rollers, i.e. it has high flatness. The plate with the indicator is moved along the part along the coordinate grid. The magnitude of the waviness is estimated by the indicator deviation in the nodes of the adopted grid.

During the measurements, the waviness of the part was measured for different rail lengths. According to their results, the accuracy of the plate was established (10 - 11).

Figure 5 shows the results of measuring waviness for a rail with a guide length of 400 mm.

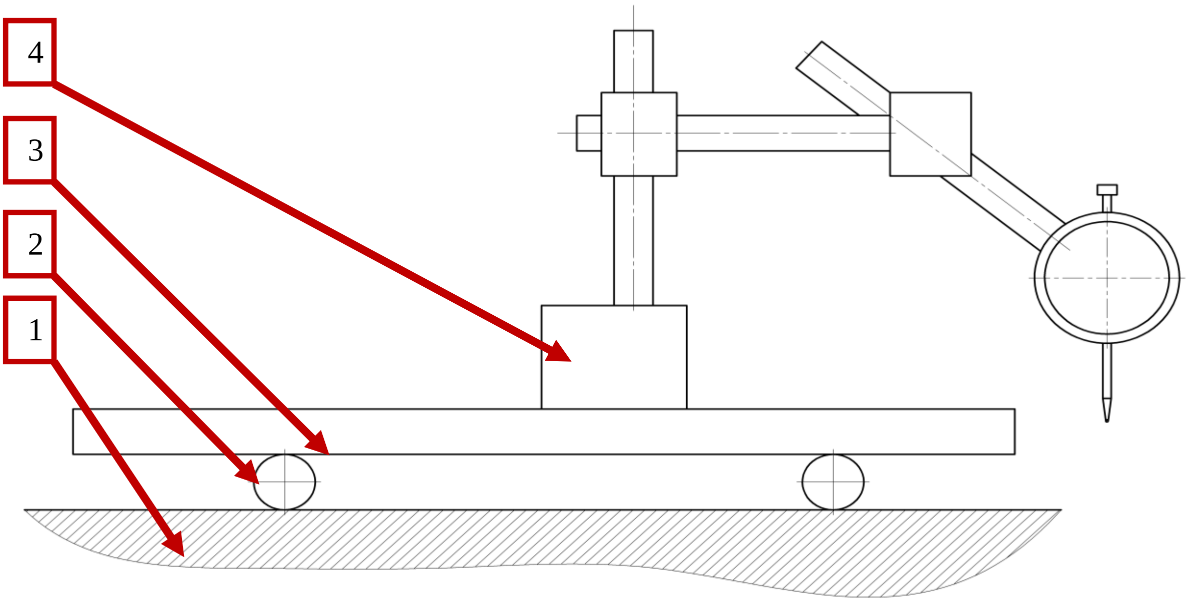
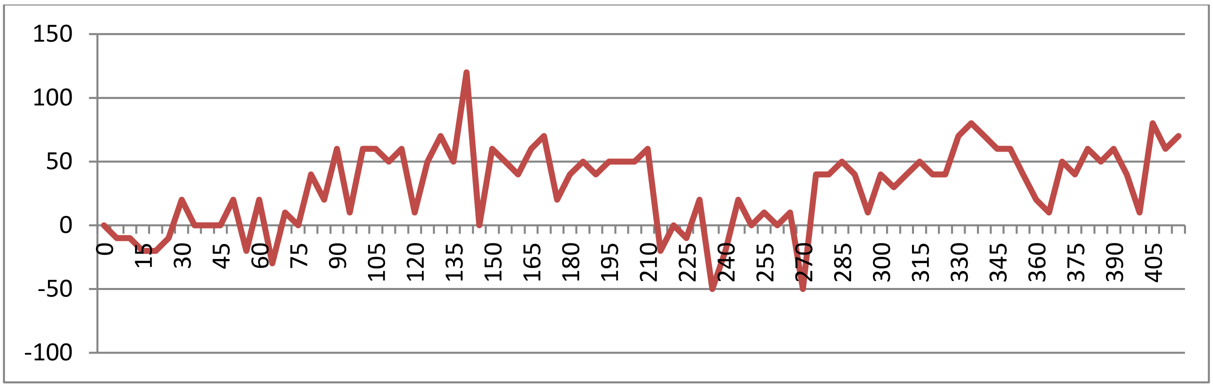
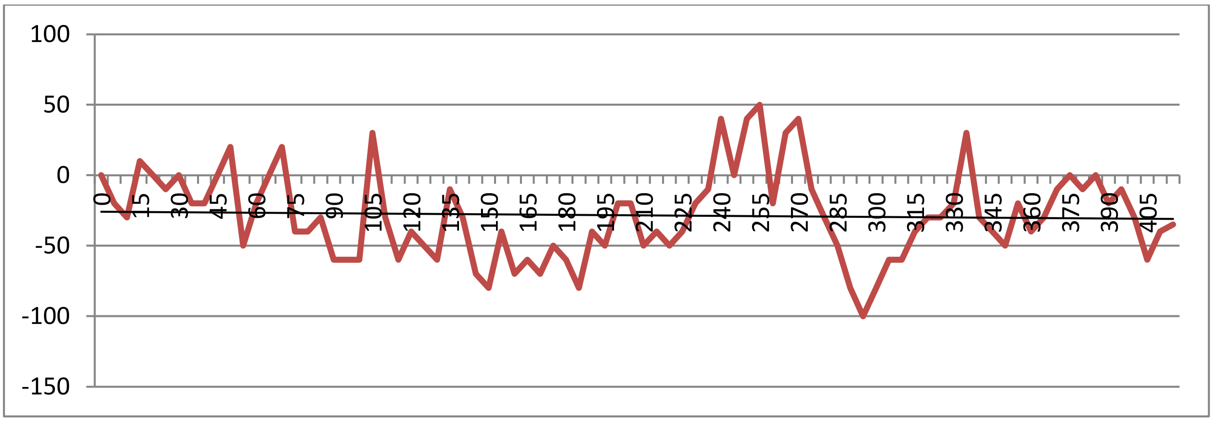


Fig. 4 Waviness measurement scheme



a)



b)

Fig. 5 Waviness measurement scheme:
a) plate waviness after milling; b) plate waviness after grinding

TABLE II. WAVINESS PARAMETERS OF THE JOINT PARTS "BASE PLATE - RAIL»

Plate processing	**Surface parameters**	**Rail length, mm**					
		125	***215***	***300***	***400***	***470***	***650***
Milling	W_{max}, micron	50	75	100	120	140	170
	Δ, micron 11th accuracy, State Standard 24643-81	100	120	160	160	200	250
Grinding	W_{max}, micron	50	60	70	140	120	160
	Δ, micron 10th- 11th accuracy, State Standard 24643-81	60	80	100	160	160	160

Table 2 shows the measured values of the maximum wave height and flatness tolerance according to GOST (State Standard) 24643 -81, for milled and ground plates.

The next stage of the research was experimental studies of the joints of prefabricated structures during the first and subsequent loads. Measurements were performed on models. Fragments of rails of various lengths were fixed on the base plate. The plate was made of steel 14G2, had a grid of holes for fastening rails. The plate was originally milled and then ground.

The measurements were carried out according to the scheme presented in Figure 7.

Fig. 7 Rail compliance measurement scheme

The rail on which the carriage with the indicator is mounted is attached to the base plate. The location of this rail is considered basic. It is fastened with M8 screws, with the recommended torque of 310 N cm [1, 2]. The screws are tightened one after the other according to the scheme recommended by the manufacturer [1, 2].

Measured rails are laid out with the same step in 7 parts. At these nodal points, compliance measurement was performed. The initially measured rail is fastened with minimal effort, till forming the surface contact. In this position, measurements are made on the grid points of the rail. Measurement results are accepted as reference positions of the rail and further evaluation of the joint compliance.

The next step is to measure the deformations of the loaded rail-plate interface. The loading is performed using a torque wrench. The magnitude of compliance is estimated by the deformations at the grid points relative to the initial position.

The next step is to measure the position of the control points of the rail after its release that is, after removing the joint load.

The measurement process is performed for repeated cycles “loading-unloading” twice more.

Figure 8a shows the graph obtained during the experiments for a 450 mm long rail on a milled plate, and figure 8b shows the graph obtained during the experiments on a ground plate. The average complience at the joints is presented in the table.

TABLE III. THE COMPLIENCE VALUE RELATING TO THE AREA DEPENDING ON PROCESSING

Milling		**Grinding**	
The rail length, mm	***Deformation value δ, micron***	***The rail length, мм***	***Deformation value δ, micron***
125	14,9	125	3,3
215	11,4	215	4,9
300	9,6	300	6,3
400	8,3	400	3,6
470	7,7	470	6,7
650	6,5	650	12,8

According to the measurement results, the maximum deformation value occurs at the first loading. The magnitude of the deformations is comparable with the tolerances on the rail size. Such deformations must be considered in the design practice.

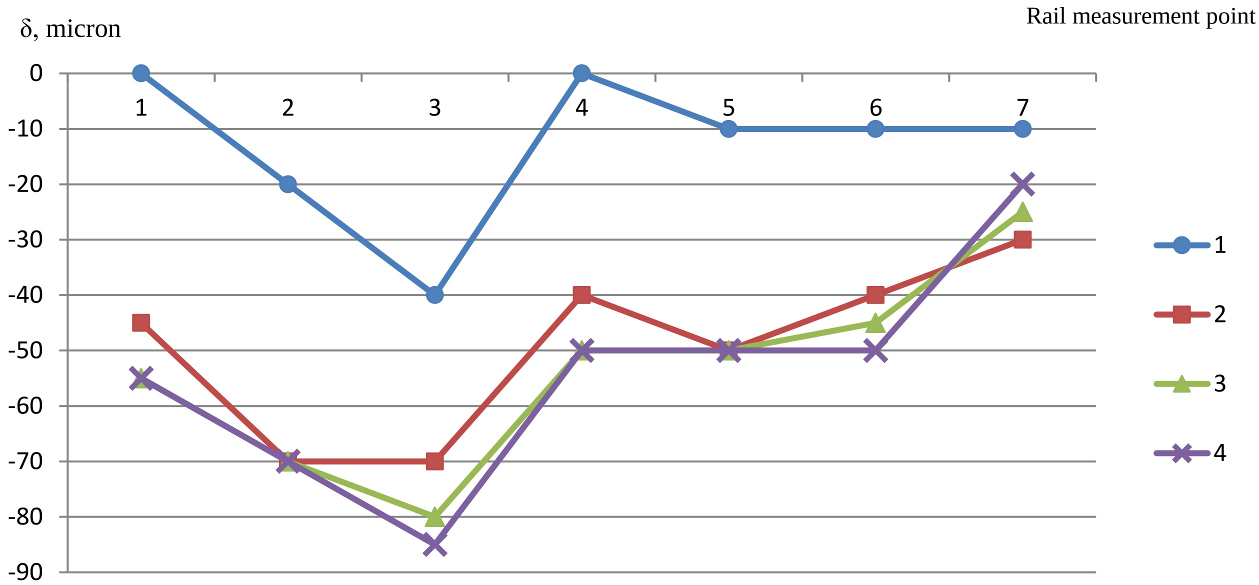
When unloading, the rail, due to elastic deformations, shifted towards the initial position, but the shift was by 15–20% less than that during the deformation under loading. Subsequent loading and unloading of the rail had very little effect on the position of the rail.

The joint compliance along the rail length is different. At some points, especially at the edges of the rail, this parameter differs from the average values. This can be explained by the shortcomings of the sequential scheme of tightening the screws.

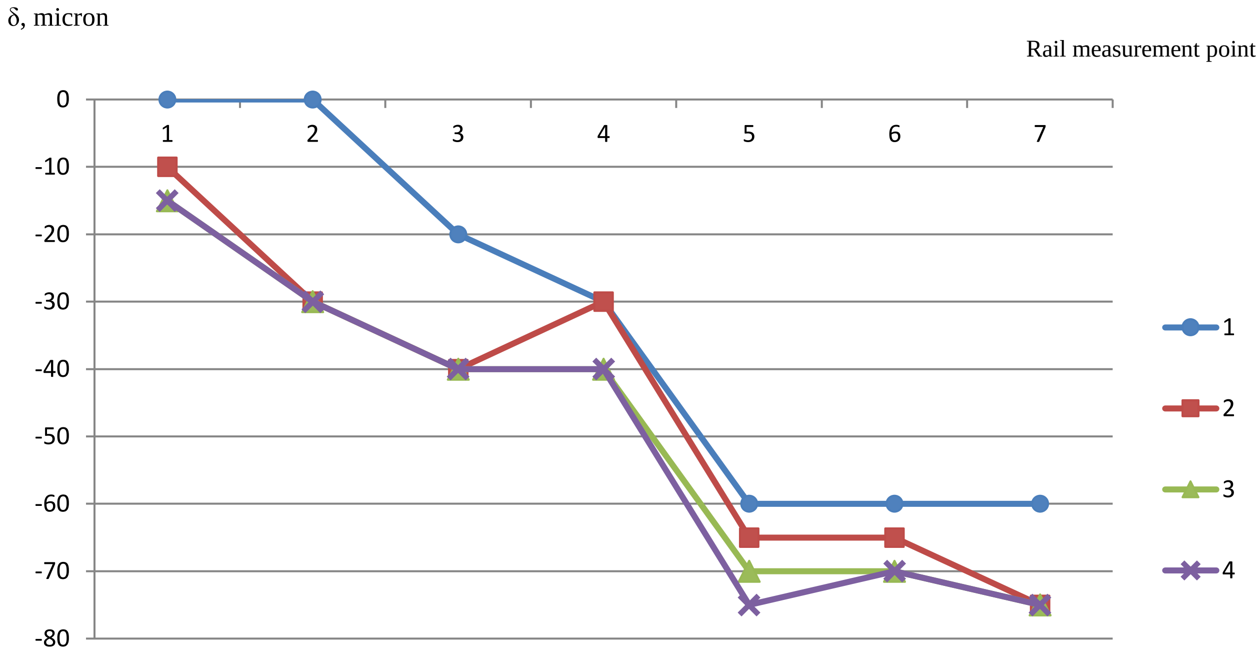
The results of experimental studies and their comparison with theoretical calculations are presented in Figure 9.

From the above graphs (Figure 9), it can be noted that the calculated data for the two formulae are similar, they do not have a large error, but the experimental data are quite different.

Table 4 shows the percentage deviation, where for the 100% result we take the experimental data (all calculations are made for the first loading).



a)



b)

Fig. 8 Deformation of the joint "rail (250 mm) - base plate" under the influence of the load:
a) milled plate; b) ground plate;
line 1 - the position of the rail in the measured sections without load; line 2 - deformations after the first loading of the rail; line 3 - deformations after the second loading of the rail; line 4 - deformations after the third loading of the rail.

TABLE IV. PERCENTAGE DEVIATION OF EFFECTIVE COMPLIANCE FROM EXPERIMENTALLY OBTAINED

Calculation formula	**Type of processing**	**Percentage deviations of calculated compliance from experimentally obtained values for different rail lengths, %**					
		125	***215***	***315***	***400***	***450***	***650***
1	Rough scraping	45	68	12	7,5	12	67
	Grinding	90	88	74,4	61	64	66
2	Milling	40	69	14	19	48	43
	Grinding	84	62	26	26	135	9

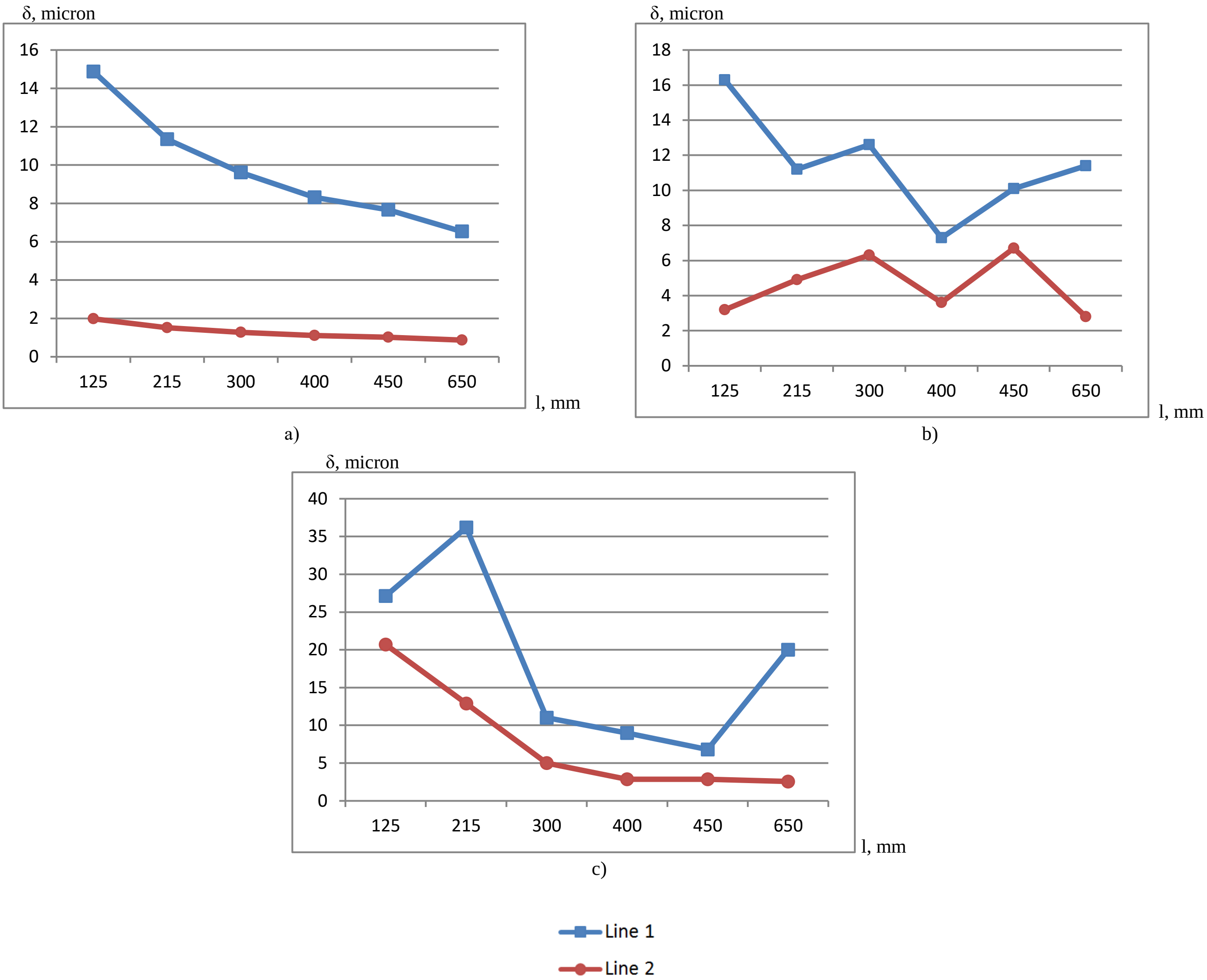


Fig. 9 Graphs of compliance values along the rail length:
a) according to empirical formula 1; line 1 - for rough scraping, line 2 - for fine grinding;
b) according to formula 6; line 1 - for milling, line 2 - for fine grinding;
c) experimental dependencies, line 1 - for milling, line 2 - for fine grinding

III. CONCLUSION

Experimental studies have shown that the error of the theoretical estimate of the joint stiffness for rough processing can reach 70%, and for ground surfaces it can reach 88-90%. This is due to the fact that formulae (1 and 2) were derived for small nominal contact areas. They do not take into account waviness and macrogeometry, which have a great influence on the joint stiffness of real parts. Therefore, for methods suitable for practical activities, it is necessary to make changes to them, for example, in the form of correction factors.

A characteristic feature is that for large parts the nominal contact [9] area has a significant effect on the magnitude of deformations, which should also be taken into account in the calculations.

Existing macrodeviations and waviness are inherited during assembly. At the same time, the nature of the surface that existed before the first loading is preserved.

Studies have shown that for basic parts made from rolled products (plates, strips), significant deformations are possible due to redistributing internal residual stresses. After a single double-sided milling of plate blanks, the maximum deviation from flatness reaches 0.3 mm, after a single grinding the maximum deviation from flatness reaches up to 0.15 mm. It is impossible to compensate for such errors during assembly. The stabilizing heat treatment reduces these errors by more than an order of magnitude.

For precise assemblies, situations are possible when joint deformations will be equal to the tolerances for important mounting dimensions. In particular, this is observed for the dimensions of locating the axis of BSG relative to the surfaces of the carriages. In this case, there is a bias screw relative to the nut, rigidly attached to the table. With such an imbalance, the load on the feed drive increases dramatically, which degrades its power characteristics, and the drive accuracy and smoothness are reduced.

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