Effects of spring action of a non-rigid body stamped from 30KhGSA steel sheet on the accuracy of machining

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The high mechanical properties of 30KhGSA steel create a spring action effect when a non-rigid box-shaped body is fixed in a machine fixture. Comparisons are made between the results of mathematical simulation of elastic deformations of the base wall of a non-rigid box-shaped body when fixed in a fixture for machining and statistical processing of the results of an experimental study of changes in the dimensions obtained during machining, specified from the base wall of the body, under comparable conditions. The mathematical simulation of elastic deformations of the base wall of a non-rigid box-shaped hull under given conditions and assumptions showed that the displacement curve of the base wall of the body with a concave bottom at a measurement height of more than 50 % of the body height implies displacements approximately two times greater than for the displacement curve of the base wall of the body with a convex bottom. To assess the accuracy of fulfilling the dimensions specified from the base wall of the body, two test batches of non-rigid box-shaped housings were made in an amount of 10 pieces. Bodies with non-flatness of the base surface in the form of concavities were selected in the first batch, in the form of convexities in the second batch. Dimensional measurements were made at a height of 75 % from the bottom of the box body, as the closest to the maximum height values in the mathematical experiment. Statistically significant coefficients are found in the equations of regression of the errors in the dimensions x, y, z from the concavity of the base surface EFK of the bottom of a non-rigid box-shaped body. Regression coefficients for given sizes are ambiguous for bodies with a concave and convex bottom. Such a difference in the experiment can be explained by the presence of local shape errors on some workpieces.
For one size there is a tenfold ratio of coefficients; at the same time, for another size in the equations, this ratio is close to unity. Such a difference in the experiment can be explained by the presence of local shape errors on some workpieces.
Key words: 30KhGSA steel sheet, non-rigid box-shaped body, elastic displacements of the base wall, non-flatness of the base surface, concavity, convexity, mathematical simulation, regression equations, spring action, dimensional errors.
DOI: 10.17580/cisisr.2022.02.14

Introduction

In mechanical engineering, body thin-walled parts of the Box type are widely used [1]. These parts are obtained by stamping [2, 3, 4], which makes it possible to obtain extended solid thin-walled parts with high mechanical characteristics. Designs for determining allowances at intermediate machining operations are considered. In other words, the known methods of shaping box-shaped profiles [1-5] do not allow them to be obtained without distortion.

With additional deformation of thin-walled profiles, a significant deformation of the cross section occurs [6]. The study of deformations of box complexes with the graph theory showed satisfactory agreement between the experimental results and numerical calculations for the values of the horizontal and vertical deflection of the wall, as well as for the experimental, calculated and numerical characteristics of the bending moment, and not only for closed but also unclosed box profiles [7]. Local defects additionally increase the sensitivity of profiles of a rectangular hollow section to the creation of a shape error [8].

When bending workpieces from a steel sheet with a high tensile strength and elasticity, a spring action effect can be recorded when the bending angle is greater than the stamping angle [4]. When choosing pressure treatment modes, great focus is put on the mechanical properties of sheet materials, which significantly depend on the accepted heat treatment modes [9].

The specified errors in the shape of the workpieces on a certain scale are transferred to the manufactured parts and to the objects assembled from them [10, 11]. In [11], the effects of technological heredity on the accuracy of obtaining dimensions during machining of machine parts were considered. Schemes for determining allowances for intermediate machining operations are considered. However, in the case considered in [12], no allowance for machining of the outer surfaces is provided. To improve the accuracy, it is necessary to take into account elastic displacements during machining of workpieces of reduced rigidity. The paper [12] presents the methodology and results of mathematical simulation of elastic displacements of the walls of a non-rigid body made of sheet 1.5 (GOST 19904-90) of steel 30KhGSA when fixed in a fixture for machining.

The analyzed elastic displacements of the walls are due to the elastic deformation of the convex or concave bottom of the box when it is brought to close contact with the base surface of the fixture by applying clamping forces through the upper open shelves of the body and an additional prismatic liner. It has been established that the type of deviation from the flatness of the bottom of the workpiece affects the amount of springing action of the body walls, namely The convex bottom of the workpiece has less effect on the movement of the side walls (0.01-0.07 mm) than the concave one (up to 0.01-0.086 mm).

Purpose of research

The paper is aimed at comparing the calculated values of the elastic deformation of the basing wall of the body obtained in [12] using computer simulation by the finite element method, with the results of experimental research carried out on full-scale samples in a production environment on special devices.

Theory

According to the well-known method [12], we calculated the elastic displacements of the base wall of a non-rigid box-shaped body C at various heights *h* (from 3 to 38 mm) from the bottom of the body (**Fig. 1**) with the same application of force.

Fig. 2 shows a diagram of the application of fixing forces to a non-rigid box-shaped body in a device in which the workpiece was sent to a fixed mounting base and with the adjustable bracket *5* and screw *6*, and fixed without the use of clamping forces. With this method of basing for the workpiece walls, elastic deformation restrictions are created to the outside.

In the calculation, the non-flatness of the bottom of the body was taken equal to the tolerance, $TFK = 0.3$ mm. The results of calculations are shown for the case when the bottom of the body is concave curve *1* and convex curve *2* (**Fig. 3**). As can be seen from Fig. 2, the liner 3 for a box body with a concave bottom should have a height less than the liner *3* for a box body with a convex bottom by the amount of the actual non-flatness of the bottom of the *EFK* body bottom, which potentially increases the deflection of the base wall *X*.

Comparison of curves *1* and *2* shows that under the given conditions and assumptions made, curve 1 of displacements of the base wall of the body with a concave bottom at a measurement height of more than 23 mm assumes displacements about two times greater than curve *2* for the displacements of the base wall of the body with a convex bottom.

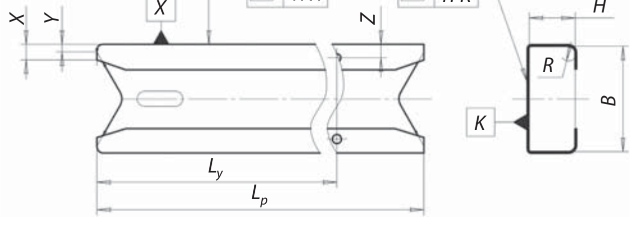

Fig. 1. Control sketch of a non-rigid box hull: checked dimensions: *x*, *y*, *z*, other dimensions are presented for reference

Research study. Experimental techniques

To assess the accuracy of the dimensions *x*, *y*, *z* specified within the limits respectively 15h13(-0.27), 7h14(-0.36), 15±0.1, two test batches of non-rigid box-shaped cases were made in the amount of 50 pieces. The impossibility of attracting more buildings for research is associated with the continuity of the process, which does not provide for a large number of buildings in the backlog. Bodies with a concave base surface were selected for the first batch (Nos. 1÷25), and convex surfaces for the second one (Nos. 26÷50).

In the control programme of the CNC milling machining centre, the nominal values of the coordinates were set to the middle of the tolerance fields of *x*, *y*, *z* dimensions, equal to 14.865, respectively; 6.82; 15 mm. Therefore, most of the values of *x*, *y*, *z* dimensions on the test batch of workpieces are within their tolerance fields.

For measurements, an Axiom too CNC coordinate measuring machine and a dial indicator (GOST 577-68) with a division value of 0.01 mm were used. Dimensions were measured at the height $h = 35$ mm from the bottom of the box-shaped body, as the closest to the limit values of the height in the mathematical experiment (see **Fig. 3**). The experiment results are summarised in **Table 1**.

A batch of workpieces for the experiment was adjusted and selected according to the established requirements. For example, some dimensions for parts No. 9, 11 fall outside the tolerance limits. It can be assumed that local shape errors were on these workpieces. In the table, for clarity, the maximum values of bottom non-flatness are highlighted in bold, and the minimum ones, as well as the corresponding values of variable sizes *x*, *y*, *z*, are in italics.

For a concave body bottom, the regression equations obtained by the least squares method are as follows

$$x = 14.904 - 0.4584EFK; \quad (1)$$

$$y = 6.8506 - 0.4656EFK; \quad (2)$$

$$z = 15.028 - 0.4598EFK; \quad (3)$$

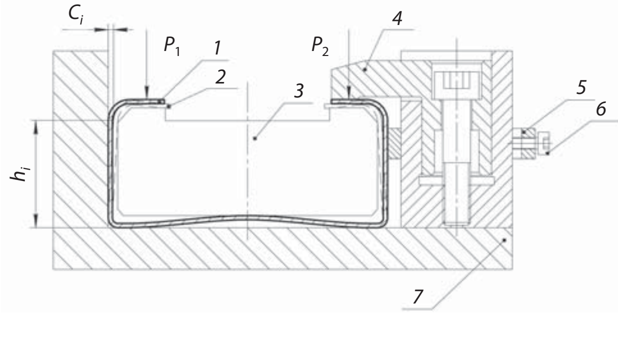

Fig. 2. Application of forces to fix a non-rigid box-shaped body in the fixture:
1 – body before clamping; *2* – body after clamping; *3* – liner; *4* – clamp; *5* – bracket; *6* – screw; *7* – fixture body

for the convex body bottom

$x = 14.886 - 0.2917EFK;$ (4)

$y = 6.806 - 0.1049EFK;$ (5)

$z = 15.01 - 0.2399EFK.$ (6)

Comparison of the regression dependences of the dimensions of the part as a function of bottom non-flatness (*EFX*) and the results of simulation of the displacements of the side walls of a non-rigid box-shaped body confirms that the concavity of the bottom has a stronger effect on the dimensions than the convexity.

As an example of visual representation of regression equations in **Fig. 4** is a graph of equation (2) of the change in size y from the concavity of the base surface of the *EFK* body. On the graph, in addition to the points corresponding to the parameters of the empirical values of the y and *EFK* variables, there is a (solid) line of linear regression (2) and two (dashed) lines of 95 % confidence intervals for the regression dependence.

If we take the maximum allowable value $EFK = TFK = 0.3$ mm, then, according to equations (1-6), then the maximum influence will be on the dimension y for the concave bottom of the body (2): $Ey = 0.3 \times 0.4656 = 0.13968 \approx 0.14$ mm, which is 38.9% of the tolerance Ty=0.36 mm.

Some dimensions, for example, for parts No. 9, 11 fall out of tolerance. It can be assumed that local shape errors were on those workpieces; therefore, it is necessary to take into account possible displacements of the side walls of a non-rigid box-shaped body with a non-flatness of its bottom and, if necessary, introduce additional adjustment of that surface.

Comparison and discussion of theoretical and experimental results

Simulation shows that under given conditions and accepted assumptions, the movement of a workpiece wall with a concave bottom at a measurement height of more than 23 mm implies displacements approximately two times greater than for the workpiece wall with a convex bottom (**Table 2**).

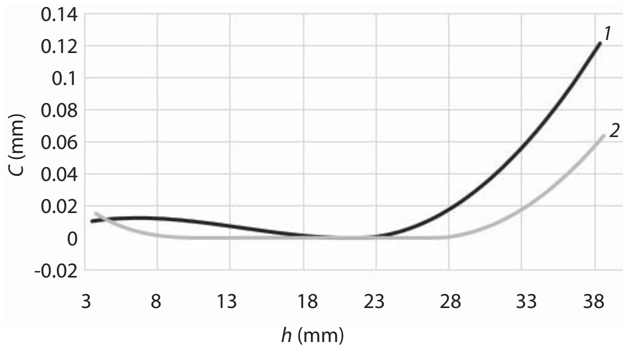

Fig. 3. The results of simulation of the displacement of the base wall of a non-rigid box-shaped body *X* when clamped with a liner: *1* — displacement curve of the base wall of the body with a concave bottom *K*; *2* — displacement curve of the base wall of the body with a convex bottom; *C* — wall deviation; *h* — wall height

Table 1. **Measured dimensions *x, y, z* depending on the flatness of the bottom of the non-rigid box body *EFK***

Number of body *n*	Concave bottom				Number of body *n*	Convex bottom			
	EFK, mm	*x*, mm	*y*, mm	*z*, mm		*EFK*, mm	*x*, mm	*y*, mm	*z*, mm
1	0.16	14.83	6.78	14.95	26	0.1	14.86	6.8	14.98
2	0.12	14.85	6.79	14.97	27	0.26	14.8	6.78	14.95
3	0.21	14.81	6.76	14.93	28	0.15	14.85	6.79	14.97
4	0.20	14.82	6.77	14.94	29	0.12	14.85	6.8	14.99
5	0.15	14.83	6.78	14.96	30	0.15	14.83	6.78	14.98
6	0.2	14.8	6.75	14.94	31	0.18	14.84	6.79	14.96
7	0.1	14.84	6.78	14.97	32	0.23	14.82	6.78	14.95
8	0.16	14.83	6.77	14.96	33	0.21	14.83	6.78	14.95
9	**0.3**	**14.76**	**6.7**	**14.89**	34	0.2	14.83	6.79	14.96
10	0.15	14.85	6.8	14.97	35	0.2	14.84	6.78	14.97
11	0.29	14.77	6.71	14.87	36	0.11	14.85	6.8	14.98
12	0.11	14.87	6.81	14.98	37	0.18	14.83	6.79	14.97
13	0.12	14.85	6.79	14.97	**38**	**0.28**	**14.81**	**6.78**	**14.95**
14	0.12	14.86	6.81	14.98	39	0.12	14.86	6.79	14.98
15	0.28	14.79	6.73	14.91	40	0.24	14.81	6.78	14.95
16	0.15	14.82	6.77	14.95	41	0.11	14.85	6.79	14.98
17	0.23	14.79	6.74	14.92	42	0.14	14.84	6.79	14.97
18	0.19	14.81	6.75	14.94	43	0.26	14.81	6.78	14.94
19	0.26	14.78	6.72	14.91	44	0.25	14.81	6.78	14.95
20	0.27	14.77	6.71	14.9	45	0.14	14.85	6.79	14.98
21	0.21	14.8	6.75	14.93	46	0.12	14.85	6.8	14.98
22	0.26	14.79	6.74	14.91	47	0.23	14.82	6.78	14.96
23	0.25	14.8	6.75	14.92	48	0.24	14.81	6.78	14.95
24	0.23	14.81	6.75	14.94	49	0.1	14.85	6.79	14.99
25	0.21	14.81	6.76	14.93	50	0.15	14.84	6.79	14.98

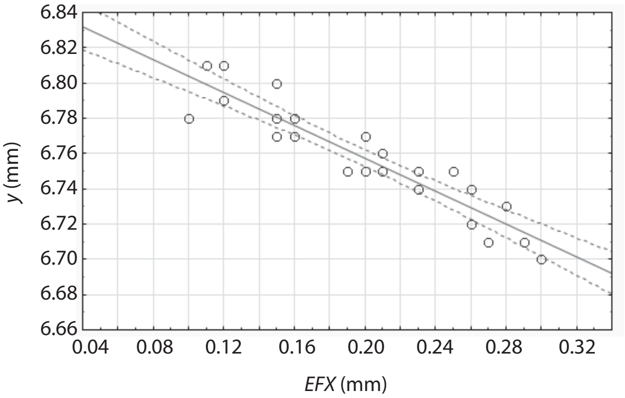

Fig. 4. Graph of regressional dependence (2) of dimension y versus the concavity of the base surface *EFK* of the bottom of a non-rigid box body

Comparison of the maximum values of the actual errors of the part in size y and the displacements of the side walls of the non-rigid box-shaped body, obtained by simulation, shows their close coincidence. Moreover, experimental data confirm the mathematical simulation conclusions that the concavity of the bottom has a stronger effect on the dimensions than the convexity.

When the bottom of the non-rigid box-shaped body is concave, then the side walls are bent inward, onto a liner made across the width with a guaranteed clearance relative to the overall dimension *B* of the non-rigid box-shaped body 1 (see Fig. 1). The more the liner *2* corresponds to the overall dimension *B* of the non-rigid box-shaped body 1, the less possible movement of the side walls will be with the concave bottom of the non-rigid box-shaped body (see Fig. 2). A decrease in the height of the liner ***3*** for a box-shaped body with a concave bottom has a similar effect on the actual non-flatness of the bottom of the *EFK* body.

When the bottom of a non-rigid box-shaped body is convex, the side walls are bent outward, onto a fixed base and onto a fixed bracket, which limits the allowable movements. In this case, liner *3* (see Fig. 2) can have a maximum height, which reduces possible deflections of the base wall *X*.

Conclusion

High mechanical properties of steel 30KhGSA (tensile strength and elastic limit), in combination with a given direction of sheet rolling and billet bending, create a spring action effect when a non-rigid box-shaped body is fixed in a machine tool. Spring action occurs at the time of forced alignment of the body bottom, which has shape errors in the form of deviation from flatness, by clamping forces.

The convex bottom of a non-rigid box body has less effects on the movement of the side walls than the concave one, due to the fact that when the bottom is convex, the side walls are bent outward, onto a fixed base and onto a fixed bracket.

In the case when the bottom of the non-rigid box-shaped body is concave, the side walls are bent inwards onto the liner, which is made to fit with a guaranteed clearance relative to the nominal size of the internal cavity of the non-rigid box-shaped body with a clearance from the nominal size of the non-rigid box-shaped body.

Table 2. **Comparison of the maximum values of the actual errors of the part in terms of size *y* and the displacements of the side walls of a non-rigid box-shaped body, obtained by simulation**

Shape error type	*EFK*, mm	*y*, mm	Actual error (from Table 1)	Estimated error (from Fig. 2)
Concave bottom	0.3	6.7	0.12	0.08
Convex bottom	0.28	6.78	0.04	0.04

Based on the results of the work done, it was proposed to introduce an additional locksmith operation for straightening the bottom of a box-shaped workpiece, with the prevention of concavities. The time for this operation was 0.083 n/h. Due to the introduction of this operation, the defect in the manufacture of the ‘Box’ part decreased from 25 % to 14 %. Even after the introduction of adjustments, defects can be explained by the stochastic properties of the metal, and the spread of the parameters of the initial geometry of a workpiece.

The labour intensity of manufacturing this part, without additional locksmith operations, is 1.467 n/h. The labour intensity of manufacturing the ‘Box’ part with the adjustment operation is 1.55 n/h. The economic effect for the enterprise, with a reference annual batch of 10,000 pieces, amounted to 374,375 roubles.

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