Increasing the accuracy of processing thin-walled box-shaped parts

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Abstract. The paper describes the development of a procedure for increasing the accuracy of processing thin-walled parts. The paper proposes a new method for fixing and processing thin-walled box-shaped parts, during which the coordinate of the workpiece base side position is measured using an RMP40 sensor before and after the application of clamping forces, followed by compensation for processing on a CNC milling machine. A special control program that takes into account elastic deformations has been developed. A comparative analysis of dimensions performance showed that the accuracy of coordinate dimensions performance taking into account the compensation of elastic deformations is higher than without compensation.

1. Introduction
Thin-walled box-shaped parts are widely used in the development of sporting and hunting weapons [1]. These parts are made using stamping and bending [2, 3], which makes it possible to obtain extended one-piece thin-walled parts with high mechanical performance. However, the small ratio of the wall thickness to the length of these thin-walled parts, which are characterized by low rigidity in the transverse direction [1], leads to the shape errors, when they are fixed in fixtures during cutting, which is associated with manifestations of technological heredity [4-7].

The scientists experience is summarized in the standard [8], which formalizes the concept of "non-rigid part": "A part that is deformed to such an extent that, in the free state, it goes beyond the dimensional and/or geometrical tolerances and location related to the part in a fixed state". In connection with the specified properties of parts, manufacturing errors appear, and as a result, production defects [8].

2. Statement of the problem
Improving the accuracy and quality of products, especially non-rigid box-shaped parts, at machine-building enterprises where the thin-walled parts are manufactured is an urgent scientific task, the solution of which is almost impossible without the use of modern equipment.

The purpose of the study is to develop a method for compensating of errors in fixing thin-walled box-shaped parts when machining on CNC milling machines.

3. Theory
When fixing thin-walled box-shaped workpieces in special devices for processing holes, elastic deformations can be most noticeable [9, 10]. Clamping forces can distort the hole coordinates. After releasing the box-shaped workpiece from the clamping forces of the fixture, its outer surface takes on its original shape due to the elastic forces, and the coordinates of the hole are distorted ‘figure 1’.
Therefore, when fixing thin-walled box-shaped workpieces in special fixtures of the machine, it is necessary to take into account possible distortions of their shape and size during processing. In the practice of engineering technology, the following methods of placing workpieces on machine tools are known:
- placement of the workpiece with the alignment of its position relative to the working elements of the machine,
- placement of the workpiece without aligning its position relative to the working elements of the machine.

When placing the workpiece with alignment, it is placed directly on the machine table or in a general purpose machine tool, which does not provide high accuracy of its position on the machine without aligning the workpiece. When the workpiece is placed without alignment, it is placed in a special machine tool, which ensures the accuracy of its position on the machine without aligning the workpiece [11, 12]. The disadvantages of these methods is the long duration of alignment, since it is necessary to control the position of the workpiece processed surfaces using planimeters, rulers, level gauges, indicator devices and other measuring instruments, and the position of the workpiece being aligned is controlled by using shims, set screws, wedges and other means. When applied to non-rigid prismatic workpieces, the above alignment does not take into account the elastic deformation of thin-walled parts. Since thin-walled workpieces are distorted during clamping, then alignment and subsequent processing occurs, and after release from the clamping forces, the part returns to its original position.

To obtain the required accuracy of the relative position of the surfaces of the processed non-rigid prismatic part, it is necessary to check the correct position of the workpiece. For this purpose, an option for aligning a thin-walled box-shaped workpiece to size, fixed in a machine vice, is being considered. To configure, it is necessary to perform the following steps [13]:
1. Set and slightly clamp the workpiece in a vise.
2. Set the workpiece down with slight blows of a hammer with a soft striker made of non-ferrous metal until it fits snugly against the vise guides or shims. If the workpiece bends in a vice, it is necessary to use inserts or wedges.
3. Finally secure the workpiece.
4. Using the indicator fixed on the mandrel inserted into the spindle, bring it to the base surface and load the indicator by a certain value (for example, 1 mm) and reset it to zero.
5. Move the machine table to the required size.
6. Process the workpiece.
7. Unclamp the vice, remove the part.  

The previously proposed multiple purpose methods for fixing thin-walled box-shaped workpieces do not ensure the fulfillment of the specified requirements of the drawing or led to an increase in the cost of a special device by making a large number of inserts with an internal size of 60 ± 0.2. Therefore, at present, appropriate methods are being developed for installing blanks on CNC machines [14-20].
To find out the possibility of using devices aligned for the size, calculation of the dimensional chain is performed when installing the workpiece in the accompanying device, and then the set in the machine tool using the maximum-minimum method.

![Figure 2. Dimensional chain 1: workpiece complete with accompanying device.](image)

**Figure 2.** Dimensional chain 1: workpiece complete with accompanying device.

Links of the dimensional chain 1 ‘figure 2’: \(A_1 = 25 \pm 0.2\) (mm); \(A_2 = 40 \pm 0.1\) (mm); where \(A_1\) – decreasing link, \(A_2\) – increasing link, \(A_\Delta\) - closing link.

![Figure 3. Dimensional chain 2: workpiece set - accompanying device in the machine tool.](image)

**Figure 3.** Dimensional chain 2: workpiece set - accompanying device in the machine tool.

Links of the dimensional chain 2 ‘figure 3’:

\(B_1 = 120H7 \pm 0.04\) (mm);

\(B_2 = 120f7 \pm 0.036 \pm 0.071\) (mm);

where \(B_1\) – decreasing link, \(B_2\) – increasing link, \(B_\Delta\) - closing link.

The largest size of the \(i\)-th link is determined by the formula:

\[
A_{i\text{max}} = A_i + E_i (A_i).
\]  

(1)

where \(A_i\) – rated value of the \(i\)-th link.

The smallest size of the \(i\)-th link is determined by the formula:

\[
A_{i\text{min}} = A_i + E_i (A_i).
\]  

(2)

Limit dimensions of the dimensional chains links: \(A_{1\text{max}} = 25 + 0 = 25\) (mm); \(A_{2\text{max}} = 40 + 0.1 = 40.1\) (mm); \(B_{1\text{max}} = 120 + 0.04 = 120.04\) (mm); \(B_{2\text{max}} = 120-0.036 = 119.964\) (mm); \(A_{1\text{min}} = 25-0.2 = 24.8\) (mm); \(A_{2\text{min}} = 40-0.1 = 39.9\) (mm); \(B_{1\text{min}} = 120-0 = 120\) (mm); \(B_{2\text{min}} = 120-0.071 = 119.929\) (mm).

The tolerance of the \(i\)-th link of the dimensional chain is determined by the formula:

\[
T(A_i) = A_i (E_i - E_i).
\]  

(3)
Calculation of the tolerances of the dimensional chains links: $T(A_1) = 0 - (-0) = 0.2$ (mm); $T(A_2) = 0.1 - (-0.1) = 0.2$ (mm); $T(B_1) = 0.04 - 0.04 = 0.04$ (mm); $T(V_2) = -0.036 - (-0.071) = 0.035$ (mm).

The coordinate of the middle of the tolerance field of the component link is determined by the formula:

$$C(A_i) = 0.5A_i(E_{s_i} + E_{i}) \quad (4)$$

Calculation of the coordinates of the middle of the tolerance fields of the dimensional chains links:

$$C(A_1) = 0.2; \quad C(A_2) = 0; \quad C(B_1) = 0.2; \quad C(B_2) = -0.0535.$$  

The rated value of the closing link $A_\Delta$ is determined by the formula:

$$A_\Delta = \sum_{j=1}^{n} \Delta_j - \sum_{q=1}^{m} \Delta_q \quad (5)$$

Where $A_j$ – rated size of any increasing link; $A_q$ – rated size of any decreasing link; $j$ – index of the increasing link; $q$ – index of the decreasing link; $n$ – number of increasing links; $m$ – number of decreasing links.

Then for the dimensional chain 1, formula (5) takes the form:

$$A_\Delta = A_2 - A_1,$$

whence $A_\Delta = 40 - 25 = 15$ (mm).

For dimensional chain 2: $B_\Delta = B_2 - B_1$, whence $B_\Delta = 120 - 120 = 0$ (mm).

The tolerance of the closing link $A_\Delta$ is determined by the formula:

$$T(A_\Delta) = \sum_{i=1}^{k} T(A_i) \quad (6)$$

where $T(A_i)$ – tolerance of any component link; $i$ – link index; $k$– number of links in the dimensional chain.

Then, for a dimensional chain 1, formula (6) takes the form: $T(A_\Delta) = T(A_1) + T(A_2)$, whence

$$T(A_\Delta) = 0.2 + 0.2 = 0.4$$ (mm). For the dimensional chain 2: $T(B_\Delta) = T(B_1) + T(B_2); T(B_\Delta) = 0.04 + 0.035 = 0.075$ (mm).

The coordinate of the middle of the closing link tolerance field is determined by the formula:

$$C(A_\Delta) = \sum_{j=1}^{n} C(A_j) - \sum_{q=1}^{m} C(A_q) \quad (7)$$

where $C(A_j)$ – coordinate of the middle of the tolerance field of any increasing link; $C(A_q)$ – coordinate of the middle of the tolerance field of any decreasing link: $C(A_\Delta) = C(A_\Delta) - C(A_1); C(A_\Delta) = 0 - (-0.2) = 0.2$ (mm); $C(B_\Delta) = C(B_\Delta) - C(B_1); C(B_\Delta) = -0.0535 - (-0.02) = -0.0335$ (mm).

The upper deviation of the closing link $E_{s_i}(A_\Delta)$ is determined by the formula:

$$E_{s_i}(A_\Delta) = C(A_\Delta) + 0.5T(A_\Delta) \quad (8)$$

Then: $E_{s_1}(A_\Delta) = 0.2 + 0.5 \times 0.4 = 0.4$ mm; $E_{s_2}(A_\Delta) = -0.0335 + 0.5 \times 0.075 = 0.004$ (mm).

The lower deviation of the closing link $E_{i}(A_\Delta)$ is determined by the formula:

$$E_{i}(A_\Delta) = C(A_\Delta) - 0.5T(A_\Delta) \quad (9)$$

Then: $E_{i_1}(A_\Delta) = 0.2 - 0.5 \times 0.4 = 0$ ; $E_{i_2}(A_\Delta) = -0.0335 - 0.5 \times 0.075 = -0.071$ (mm).

The maximum gap is determined by the formula:

$$S_{\text{max}} = \sum_{i=1}^{n} \Delta_{\text{max},i} - \sum_{n+1}^{m-1} \Delta_{\text{min},i} \quad (10)$$

For the dimensional chain 1, formula (10) takes the form: $S_{\text{max}} = A_{\text{max}} - A_{\text{min}} = 40.1 - 24.8 = 15.3$ (mm).

For the dimensional chain 2: $S_{\text{max}} = B_{2\text{max}} - B_{1\text{min}} = 119.964 - 120 = -0.036$ mm.

The minimum gap is determined by the formula:
\[ S_{\text{min}} = \sum_{i=1}^{n} A_{\text{min},i} - \sum_{n+1}^{m} A_{\text{max},i} \quad (11) \]

For the dimensional chain 1, formula (11) takes the form: \( S_{\text{min}} = A_{2 \text{ min}} - A_{1 \text{ max}} = 39.9 - 25 = 14.9 \) (mm).

For the dimensional chain 2: \( S_{\text{min}} = B_{2 \text{ min}} - B_{1 \text{ max}} = 119.929 - 120.04 = -0.111 \) mm.

For the assembly dimensional chain 1: gaps are formed in the master link: \( S_{\text{max}} = 15.3 \) and \( S_{\text{min}} = 14.9 \) (mm).

For the assembly dimensional chain 2: gaps are formed in the master link: \( S_{\text{max}} = -0.036 \) and \( S_{\text{min}} = -0.111 \).

Closing links in the considered dimensional chains: \( A_\Delta = 14.9 +15.3 \) (mm) and \( B_\Delta = -0.111 -0.036 \) (mm).

Thus, it was found that in the sum of the closing links, a gap can be formed that exceeds the tolerance for the size to be performed 15 ± 0.1. Therefore, it is necessary to develop a method for increasing the accuracy of the size being performed.

4. Experimental results

It has been experimentally established that when the workpiece is clamped in an accompanying device, elastic deformation of the workpiece occurs due to the non-flatness of the upper bent elements within the established tolerances. After removing the clamping forces from the workpiece, it returns to its original shape. Therefore, it was proposed to measure the position of the base for size \( A_1 \) of the workpiece (see ‘figure 2’) before clamping and after on a CNC machine using RMP40 sensors manufactured by RENISHAW. These values were taken into account in the control program and displacements of the tool movement were made when processing a thin-walled workpiece.

Installation of thin-walled box-shaped workpieces during processing on a vertical CNC milling machine is as follows ‘figure 4’.

![Figure 4](image)

**Figure 4.** Device diagram: 1 – plate; 2, 3 – bracket; 4 - support; 5 – bracket; 6 – insert; 7 – clamp; 8 – plate; 9 – bolt; 10 – screw; 11 – pin.

The workpiece is connected to the base 6 using feet 7 without the use of clamping forces. Then the workpiece, fastened to the base 6, is installed on the support 4 and the brackets 2, 3 installed on the plate 1, and sent to the plate 8, fixed on the bracket 2 with the help of the screw 10 and the pin 11. Next, the base side of the thin-walled workpiece is measured using the RMP40 sensor in automatic mode. This coordinate along the Y axis is recorded in the machine cell.
Then the workpiece is fixed to the base 6 with the help of the presser feet 7, and then the connected structure is pulled to the support 4 and the brackets 2, 3 using the bolt 9 and the bracket 5, thereby deforming the workpiece. After that, another measurement of the base side of the workpiece is made. This value is compared with the previous one, and compensation is made for the amount of elastic deformation $\Delta$ to zero of the machine ‘figure 5’.

![Figure 5. Scheme for measuring the base side of the workpiece using the RMP40 sensor.](image)

Then the workpiece is machined. A special control program was developed for automatic alignment of the workpiece along the surface to be processed and for compensating elastic deformation, a fragment of which is presented in Table 1.

| Command | Action |
|---------|--------|
| T119M6 (ZAMER KOORDINATI Y DETAL NE ZAGATA) | Tool change (comment) |
| G0G90G40G53X0Y0 | Security string |
| G0G17G54.1P43 | Set coordinate system 43 zero |
| M26 | Swivel axis release |
| B0 | B-axis table rotation |
| M41 | Enabling RENISHAW |
| M19 | Spindle orientation |
| G1X30.Y10.F3000 | Tool exit in X and Y coordinates |
| G43H119Z100. | Enabling tool length compensation |
| Z6.F1000 | Tool exit in Z coordinate |
| G65P9013Y0.S1 | Measuring cycle in Y coordinate |
| M42 | Disabling RENISHAW |
| G0G90Z300. | Tool exit in Z coordinate |
| G49G53X0Y0Z0 | Zeroing of the machine in coordinates X, Y, Z |
| #7842=#5222( P43=G54 Y ) | Recording the measured Y coordinate in the 43rd cell of the machine |
| T119M6 (ZAMER KOORDINATI Y DETAL ZAGATA) | Tool change (comment) |
| G0G90G40G53X0Y0 | Security string |
| G0G17G54.1P44 | Set coordinate system 44 zero |
| M26 | Swivel axis release |
| B0 | B-axis table rotation |
| M41 | Enabling RENISHAW |
| M19 | Spindle orientation |
The table below shows the 4H9 hole size values in the Y coordinate of a CNC milling machine, measured with the RMP40 sensor in two different methods.

| No. | Rated coordinate value | The actual value of the coordinate using the RMP40 sensor, without compensation | The actual value of the coordinate with the use of the RMP40 sensor and with compensation |
|-----|------------------------|---------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| 1   | 15±0.1                 | 15.12                                                                            | 15.02                                                                            |
| 2   | 15±0.1                 | 15.2                                                                             | 15.02                                                                            |
| 3   | 15±0.1                 | 14.95                                                                            | 14.97                                                                            |
| 4   | 15±0.1                 | 14.86                                                                            | 15                                                                                |
| 5   | 15±0.1                 | 15.05                                                                            | 15.02                                                                            |
| 6   | 15±0.1                 | 14.79                                                                            | 15.01                                                                            |
| 7   | 15±0.1                 | 15.23                                                                            | 14.98                                                                            |
| 8   | 15±0.1                 | 15.1                                                                             | 14.99                                                                            |
| 9   | 15±0.1                 | 15.03                                                                            | 14.99                                                                            |
| 10  | 15±0.1                 | 15.26                                                                            | 14.98                                                                            |
| 11  | 15±0.1                 | 14.95                                                                            | 15.01                                                                            |
| 12  | 15±0.1                 | 14.89                                                                            | 15.03                                                                            |
| 13  | 15±0.1                 | 15.13                                                                            | 15.02                                                                            |
| 14  | 15±0.1                 | 15.3                                                                             | 15                                                                                |
| 15  | 15±0.1                 | 14.86                                                                            | 14.99                                                                            |

5. Results and discussion
The result of the study is increasing the accuracy and reducing the labor intensity of the alignment of non-rigid prismatic workpieces when they are fixed in fixtures and further processing. It has been experimentally established that the alignment duration by the proposed method is approximately 3 times less compared to the alignment carried out by multiple purpose methods: using a thickness gauge from the plane of the table, using an indicator, using an indicator fixed on a mandrel inserted into the spindle. The thing that is especially critical in terms of duration difference is the competence of the worker who carries out the alignment using multiple purpose methods. When aligning using the method presented by the authors, the competence level of the worker is not taken into account, since the alignment is carried out according to the developed control program. When aligning using multiple purpose methods, the elastic deformation of the workpiece is not taken into account, which in turn
affects the accuracy of manufacturing the part. The proposed method takes into account elastic deformation, thereby increasing the accuracy of manufacturing parts.

6. Conclusions
1. When processing thin-walled box-shaped parts, it is necessary to take into account the elastic deformation of the metal and make appropriate adjustments during processing.
2. The proposed method for aligning non-rigid prismatic (box-shaped) workpieces when placing for machining on numerically controlled machines makes it possible to compensate the resulting elastic deformations.
3. The developed control program makes it possible to take into account the elastic deformation of thin-walled box-shaped parts and make compensation according to the coordinates of the machine.

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