Features of making non-rigid parts from titanium and aluminium alloys

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Abstract. The work is devoted to the question of machining non-rigid parts. The results of studies on the efficiency of making non-rigid parts from titanium and aluminium alloys by reducing the cost of technological preparation of production and use of energy of low-power modulated ultrasonic field are presented

1. Introduction

A feature of modern small-scale and single-unit production is the ever-increasing production volumes of complex and non-rigid, thin-walled parts, which are widely used in various machines and mechanisms, and especially in aircraft. The latter is explained, on the one hand, by an increase in the speeds of their executive movements (and, consequently, by the desire to reduce inertial loads), and on the other hand, by the removal of almost complete previous restrictions on designers in creating complex parts due to the existing new technological capabilities of 3–5 axis machines and CNC machining centers. The main part of such parts is made of titanium and aluminum alloys.

Considering the increasing use of high-performance metal-cutting equipment (machining centers) and modern tools (ultra-finely dispersed hard alloys, cermets, combined with increased rigidity of technological equipment), situations arise more often when the processing of a workpiece is shorter than the process of its technological preparation. Thus, the key to reducing the cost of engineering products is to reduce engineering costs by using computer-aided design of management programs (including intelligent) and automating a number of processes that require repeated repetition.

2. Description of theoretical research

One of these processes is the appointment of a processing mode for each planned transition, in which the process engineer must choose a rational combination of cutting mode elements, which allows to ensure the quality parameters specified by the drawing, starting with the tolerance of the processed element and surface roughness and ending with the state of the surface layer (SL).

The complexity of this process lies in the almost complete absence of recommendations for the manufacture of non-rigid parts from difficult to process (titanium, heat-resistant, etc.) and, characterized by a lower melting temperature and significantly lower strength in combination with good machinability, aluminum alloys. The manufacture of non-rigid parts from such materials is fraught with the danger of technological residual stresses (TRS) occurring in the surface layer, the magnitude of which is usually sufficient for volumetric warping and spatial change in the relative position of the treated surfaces during their temporary relaxation. In the first case, this is explained by...
low thermal conductivity (4–5 times lower in titanium alloys than in steels), in the second, by the proximity of contact temperatures in the cutting zone to the melting temperature of aluminum alloys.

The problem of ensuring the specified operational properties in the manufacture of non-rigid parts from difficult-to-process materials, in which residual stresses of any sign arising due to heat-stress and structural-phase transformations can cause significant changes in shape and spatial orientation, is much more acute than for other structural materials. This is also due to the fact that all the heat arising in the cutting zone is localized in the surface layer of the workpiece. In addition, the volume of thin-walled non-rigid parts in which the generated heat is distributed is significantly less than that of massive parts. In practice, this translates into the need to reduce the elements of the regime, and in some cases even the need to experimentally select the production sequence for each individual design of non-rigid parts. The machining of workpieces of parts with complex spatial shapes is most often carried out at modern machining centers for which such productivity losses are unacceptable.

In addition to non-rigid parts, which are deformed after manufacture to such an extent that in a free state they go beyond the tolerances of dimensions and (or) shape and arrangement, there are also rigid parts that do not fall within the definition of GOST 30987-2003, because they do not change their shape after processing, but consist of a large number of difficult to combine non-rigid elements, the processing of which separately causes certain difficulties, and in combination with elements similar in stiffness, make the processing of such parts in accordance with the requirements of the drawing very time-consuming.

Further intensification of the processes of processing blanks by cutting can be carried out by external energy influences on objects of contact interaction to facilitate the process of forming new surfaces.

Of the large number of types, forms and patterns of energy effects on the cutting process [1], the most simple and economical is the use of ultrasonic field energy. Earlier, after numerous studies carried out in various countries, the possibility of implementing dimensional machining with ultrasonic testing was limited by the need to create special devices, installations for applying the energy of the ultrasonic field to the workpiece (tool, coolant, machine parts and technological equipment, etc.) [2-4]. Currently, DMG MORI has developed and mass-produced a line of 18 models of machines of the ULTRASONIC series, in which a device for applying ultrasonic testing to a cutting tool is integrated in the spindle assembly [5]. AXILE Machining machines are similar in design. At the same time, ultrasonic mandrels (Altrasonic, CRENO Industry, Pulchertool) are commercially available, the use of which is permissible on machined centers.

A promising direction in solving a set of issues to ensure the accuracy of milling processing of non-rigid parts blanks is to improve the models for calculating the cutting force components and build on their basis clearly structured algorithms for calculating the deflection of non-rigid parts during their manufacturing. The development of adequate mathematical models and the automated calculation of the elements of the milling mode, taking into account the introduction of ultrasonic fields into the energy processing zone, will make it possible to use to the maximum extent the potential opportunities to increase the productivity of modern multi-purpose machining centers in the manufacture of non-rigid parts.

The algorithm for automated assignment of the milling mode developed in the course of research allowed to solve the problem of searching for rational elements of the cutting mode both using the experience of user groups (employees of the workshop / enterprise / industry) and by calculating based on the technical requirements specified by the drawing. At the same time, it was proposed to determine the identification of the type of the processed element both during the design process of its processing and during the collection and accumulation of the experience of user groups using an algorithm that allows the formation of a database (DB) consisting of a set of input (geometric parameters of the processed element used cutting tool (CT), material of the workpiece) and output (cutting mode, cutting method, quality parameters of the processed surface) parameters allows you to use the experience to create new manufacturing technologies of machine parts, significantly reducing the time required for the CCI as well as the risk of errors associated with the human factor was carried
out on newly developed technique. To implement the automation algorithm, it was determined whether the workpiece belongs to rigid or has significant flexibility, which is an obstacle to its mechanical processing, a free-standing vertical wall was represented as a rectangular plate with a length $W_l$, thickness $S$ and height $l$ (see Fig. 1). During machining, the point of application of the force $P_y$ moves along a line perpendicular to the axis of the tool, which is explained by the geometry of the CT, namely the spiral-shaped cutting edge. The point moves along the line in the range from 0 to $T$ (milling depth), where 0 corresponds to the upper point of contact of the tool with the workpiece, and $T$ to the lower point. In the calculations, the upper point of the application of force is considered, the farthest from the base of the wall, the magnitude of the possible elastic deforming of which is the largest. The calculation of the deform was performed according to the formula obtained analytically:

$$ w(x,y) = \frac{2P_y}{Dwl} \sum_{n=0}^{\infty} \left[ \sinh \left( \frac{m}{wl} x \right) \cdot \cosh \left( \frac{m}{wl} x \right) + \frac{(1+\mu)\sinh \left( \frac{m}{wl} l \right) + (1-\mu)\frac{m}{wl} l \cos \left( \frac{m}{wl} l \right)}{2\cosh \left( \frac{m}{wl} l \right) + (1-\mu)\frac{m}{wl} l \sinh \left( \frac{m}{wl} l \right)} \cdot x \sinh \left( \frac{m}{wl} x \right) \right] \times \cos \left( \frac{m}{wl} (y-y_0) \right) + \left( \frac{m}{wl} \right)^3 \times $$

$$ \times \left( -2 \cosh \left( \frac{m}{wl} x_0 \right) - \frac{m}{wl} x_0 \sinh \left( \frac{m}{wl} x_0 \right) + \frac{(1+\mu)\sinh \left( \frac{m}{wl} l \right) + (1-\mu)\frac{m}{wl} l \cos \left( \frac{m}{wl} l \right)}{2\cosh \left( \frac{m}{wl} l \right) + (1-\mu)\frac{m}{wl} l \sinh \left( \frac{m}{wl} l \right)} \right) $$

where: $P_y$ is the radial component of the cutting force, N; $l$ - wall height, mm; $w_l$ - wall length, mm; $D$ is the cylindrical wall stiffness N * mm; $n$ is the number of grid steps.

Figure 1. Representation of a wall of a plate pinched at the base
As mentioned above, there are also details in which non-rigid walls are adjacent to other structural elements (Fig. 2). In this case, the wall can be represented as a plate fixed from three sides. The calculation of the maximum elastic wall deform in the presented case was carried out according to the following dependence:

$$w = k_w \frac{P_y \times l^2}{\pi D}$$  \hspace{1cm} (2)

where: $k_w$ is the coefficient for the middle of the wall equal to 0.527; $P_y$ is the radial component of the cutting force, N; $l$ - wall height, mm; $D$ – cylindrical wall stiffness, kg * cm.

![Figure 2. A part consisting of a series of adjacent non-rigid elements](image)

To verify the efficiency of the above methods, the corresponding calculations were made. Using the $P_y$ value obtained as a result of calculation according to known dependences or as a result of measurement using the UDM-100 universal dynamometer, we calculated the maximum elastic deform for the wall, which is presented as a beam in the NX CAE engineering analysis package and by the analytical method.

Comparison of the results of the first and second calculation methods, namely the CAE calculation and analytical calculation of a rectangular beam, showed that they are interchangeable. Moreover, the difference in the calculations does not exceed 7%. However, due to the fact that CAE calculation is more time-consuming, an analytical calculation of the wall deviation in the form of a rectangular beam is adopted as the main method. At the same time, CAE calculation is applicable for checking the results of analytical calculations.

To check the results of calculating the maximum elastic deform of the wall, presented in the form of a plate, a wall model was created with structural elements adjacent to it from three sides. After the calculation, Siemens NX CAE obtained the scattering field of the calculation results (see Fig. 3). The difference between the analytical and CAE calculations was 4%. Further, the analytical method of calculations was adopted as the main one. CAE analysis is used for verification calculations.

![Figure 3. Representation of a wall in the form of a plate fixed on three sides](image)
To determine the rational cutting mode, it is necessary to determine a number of restrictions: the maximum spindle speed, the maximum allowable elastic deform of the workpiece, maximum productivity.

The maximum spindle speed limits the permissible cutting speed. The values proposed by existing standards (mainly for billets made of aluminum alloys) are often unattainable due to the technical capabilities of the main part of the equipment used in the production and small tool diameters used to form the transition radii.

A limiting condition is the maximum allowable elastic deform of the wall:

\[ w_{\text{max}} = 0.8 \frac{d_{\text{op}}}{2} \quad (3) \]

where: \( d_{\text{op}} \) - the maximum allowable deviation of the linear size of the processed element, mm; \( 0.8 \) - coefficient providing a margin (20%).

The main factor determining the application of one or another set of cutting mode elements is productivity (the amount of material removal per minute):

\[ Q = \frac{T \times B \times S_z \times n \times N_z}{1000} \quad (4) \]

where: \( N_z \) - number of teeth of the cutter; \( T \) - milling depth, mm; \( B \) - milling width, mm; \( S_z \) - feed per tooth, mm / tooth; \( n \) - frequency of mill rotation, rpm;

Automation of the search for rational cutting conditions is carried out in several stages. At the first stage, a source data table is formed, including the technological parameters of the tool recommended by the manufacturer, geometric characteristics and material of the processed element. At the second stage, possible combinations of cutting elements are calculated, and an output data table is formed. At the third stage, they search for a rational cutting mode, depending on the set of limiting conditions.

The search for a rational cutting mode was carried out by brute force. At the same time, the elastic deform values were calculated (any quality parameter can be set as the limiting one) and the material removal rate per minute.

Variable parameters: milling width \( B \), milling depth \( T \), tooth feed \( S_z \). The range of variation is determined by the catalogs of the manufacturers of radiation sources, in which the maximum and minimum values of the variable parameters are presented. The variation step for each parameter remains unchanged: for the milling width \( B \)- 0.05 mm, for the milling depth \( T \)- 0.1 mm, for the tooth feed \( S_z \)- 0.002 mm / tooth. The step size is determined empirically.

The number of sets of cutting mode parameters was determined as follows:

\[ N_H = \frac{B_{\text{max}} - B_{\text{min}}}{0.05} \times \frac{T_{\text{max}} - T_{\text{min}}}{0.1} \times \frac{S_{z_{\text{max}}} - S_{z_{\text{min}}}}{0.002} \quad (5) \]

The algorithm for enumerating the parameters of the cutting mode is shown in Fig. 4.

Among the remaining sets of cutting mode parameters, a search was made for the most productive one, the value of \( Q \) of which is maximum. The resulting set was transferred to the CAM system.

A promising solution to the problems of reducing the heat-stress intensity of the processing process, on which the \( Py \) value depends and which has the greatest influence on the elastic deform of the processed element, is the use of combined technologies implemented by controlled additional action on the tool and / or preparation of concentrated flows additional energy, including mechanical vibrations of the ultrasonic frequency.

The efficiency of introducing the energy of the ultrasonic field into the forming zone of non-rigid thin-walled billets for cutting forces and phase transformations, which are the main cause of the process residual stresses, was verified when milling model billets from titanium and aluminum alloys.
For experimental studies evaluating the effect of ultrasonic vibrations on the quality parameters of the treated surfaces, the setup shown in Fig. 5. When processing varied the depth of milling, feed to the tooth, cutting speed.

![Figure 4. Brute force scheme](image)

![Figure 5. The scheme of ultrasonic installation: 1-reflector; 4- ultrasonic - emitter; 6 screws; 5 - racket](image)

After processing blanks (50x30x5 (2.5)) from D16T aluminum alloy with removal of a two-sided allowance of 2 (1) mm, the following were evaluated: the TRS level in the SL - with the Siton-ARM measuring complex; the phase composition of the surface layer - X-ray using the device "RICOR-7". The solid carbide monolithic mill for working with non-ferrous alloys Haltec MA2NNN 100 072 000 with a diameter of 10 mm was selected as experimental mill. The range of variation of each parameter was determined: milling depth 0.1 <T <15 mm, milling width 0.05 <B <5 mm, feed per tooth 0.01 <Sz<0.12 mm / tooth. The cutting speed was taken constant based on the capabilities of the equipment used (processing center DMU 50 ecoline) V = 630 m / min. In the process of research, we determined the parameters that are input for use in the developed program: wall height l, cylindrical wall stiffness D, spindle speed n. The treatment was carried out with a 10% aqueous semi-synthetic Cimstar 620
coolant being irrigated. After processing the thin-walled workpiece, the position of the treated surface was measured using a contact sensor Renishaw OMP40.

3. Results
During the experiments, we determined the range of ratios of thickness to the height of the walls, in which the proposed method for calculating the value of elastic deform is efficient. Milled walls of various thicknesses with the same cutting conditions. After processing, the real position of the treated surface relative to the predicted one was determined (see table). Analyzing the data obtained, we can conclude that the developed mathematical model works correctly in the range of ratios of wall thickness and height from 1: 3.3 to 1:30. The actual deviation of the position of the treated surface falls within the limits calculated using the proposed dependence.

| Thickness to Height Ratio | 1:3,3 | 1:4.3 | 1:5 | 1:6 | 1:7,5 | 1:10 | 1:15 | 1:30 |
|---------------------------|-------|-------|-----|-----|-------|------|------|------|
| Elastic deform, mm        | 0,003 | 0,005 | 0,008 | 0,010 | 0,018 | 0,026 | 0,047 | 0,151 |
| Estimated deform, mm      | 0,003 | 0,005 | 0,008 | 0,010 | 0,018 | 0,027 | 0,049 | 0,154 |

The experimentally determined position of the treated surface diverges from that predicted by 8.6% downwards, ensuring that it falls into the tolerance field.

The presence in the cutting zone of the energy of the ultrasonic field during the processing of titanium alloys leads to an increase in the level of TRS and provides a decrease in the scattering field of the considered parameter, which makes it possible to predict this quality parameter at the stage of the CCI. When processing aluminum alloys, the introduction of ultrasonic vibrations into the milling zone reduces the magnitude of tensile TRS by (30-35) %. In both cases, there is a decrease in cutting forces by 1.4-1.5 times compared to machining without ultrasonic.

Thus, the studies performed allow us to draw the following conclusions:

1. An algorithm has been developed for the automated search for rational elements of the cutting mode by calculation and method of adapting the experience of user groups.
2. The presented mathematical model for calculating the elastic deform of the workpiece under the action of a cutting force, either separately standing or connected to other structural elements, made it possible to determine the probability of the dimensions of manufactured non-rigid parts exceeding the tolerance field.
3. The proposed technique for the automatic assignment of elements of the cutting mode made it possible to choose a rational mode for milling walls with a ratio of thickness to height from 1: 3.3 to 1:30 during the CCI based on the conditions of their rigidity, minimizing the downtime of metal-cutting equipment during adjustment of control programs after pretreatment.
4. The performed studies of the effectiveness of the use of ultrasonic vibrations in the manufacture of non-rigid parts made it possible to identify the possibility of reducing the cutting forces and intensify the milling process, as well as assess the possibility of predicting the quality parameters of the surface layer at the stage of the CCI.
5. Theoretical and experimental studies of the process of formation of TRS and the phase composition of SL of billets from aluminum and titanium alloys made it possible to obtain regression dependences of the calculation of technological residual stresses, which predict the state of the surface layer at the CCI stage. The maximum achieved decrease in the level of TRS in the SL of the treated sample is 26%.

References
[1] Kumabe D. Vibrating cutting/translation from yap. S.L. Maslennikova/ Under Ed. And, I, Portnova and V.V. Belov. M. Mechanical Engineering, 1985.- 424 p.(1985)
[2] MarkovA.I. Ultrasonic processing of materials. Mechanical engineering,p. 94-101 (1980)
[3] Kiselev E.S. *Machining of workpieces under critical heat and mass transfer/* E.S. Kiselev, V.N. Kovalnogov, Selected Works of the Russian School on Science and Technology, p. 63-81 (2008)

[4] Kiselev E.S. *Management of the formation of residual stresses in the manufacture of critical parts/* E.S. Kiselev, O.V. Blagovskyi – Lanbook, 140p/ (2020)

[5] ULTRASONIC 20 linear. Flexible integration technologies in DMG machines MORI. ULTRASONIC mobile BLOCK.ULTRASONIC2-thgeneration/ www.dmgmori.com