Development of digital manufacturing technologies for frame and casing parts

A E Pashkov¹, A Yu Malashchenko¹, A A Pashkov¹, K V Bogdanov², A V Kryuchkin²

¹Irkutsk National Research Technical University, 83, Lermontov St., Irkutsk, 664074, Russia
²Irkutsk Aviation Plant (IAP), an affiliate of Irkut Corporation

E-mail: pashkov@istu.edu; mlk17@mail.ru; pashk0ff@mail.ru; bogdanov_kv@irkut.ru; kryuchkin_av@irkut.ru

Abstract. The purpose of the study is to develop basic approaches to digital models of cross-cutting production of frame and casing parts in order to forecast stress-strain behavior and change of a part form at all production stages. The proposed method covers stage-by-stage modeling of part production including machining, shaping (levelling) and face hardening using mechanical characteristics of a material, technological residual stress and initial shape. This approach in combination with equipment under control will allow optimizing machining conditions and achieving the required accuracy of parts and maximum capacity without pilot-scale works. The use of developed technique will make it possible to increase the production efficiency of parts due to time minimization of finishing operations and cost reduction for preproduction for the launch of new products.

1. Introduction

Large-size low-rigid frame and casing parts from high-strength aluminum alloys are widely used in aircraft industry, rocket production, shipbuilding and other industries. These parts are the most complex, critical and expensive in the design of manufactured products. The specified technical characteristics of products substantially depend on the quality of their production.

In most cases frame and casing parts include such structural elements as blade and reinforcement ribs, which usually have small thickness (1.5 … 5 mm) to reduce weight. Sheets or plates received by rolling as well as pressed profiles and pressworks from high-strength heat hardenable aluminum alloys are used as workpieces.

The main type of machining in the production of considered parts is milling. At present, high-performance processing centers and software ensuring automation of part-program creation on the basis of CAD models are developed to implement this process. The known issue in the production of low-rigid parts is their deformation (distortion) after machining caused by formation and redistribution of residual stress being the consequence of thermal treatment and machining of a workpiece.

The required form of parts is achieved through forming and levelling. The problems of these operations are connected with design features of parts – big overall dimensions, existence of reinforcement ribs, as well as small values of received (eliminated) curvature, which requires general deformation comparable to elastic component. In this regard the production of considered parts utilizes different methods of local deformation: advancing bending, shot peening as well as rolling, charging.
and distribution. The advantage of press methods is their universality. Today the country offers its own domestic equipment ensuring advancing bending in programmable mode [1]. Technological capabilities of this equipment are limited to sheet parts such as casing with linear surface form. Press bending of reinforced high-strength low-plastic alloys increase the probability of rejection due to crack formation. The main advantages of peen forming are the distributed nature of loading and total absence of springing effect. Effective technological method includes the combination of peen forming with press bending or bending-rolling of sheet casing in longitudinal direction thus obtaining various surfaces of single, double and fluctuating double curvature. For ribbed panel the single-axle bending before peen forming is created by rib rolling with a special roller machine. To implement this technology Irkutsk National Research Technical University (INRTU) together with PJSC Irkut Corporation and National Institute of Aviation Technologies developed and tested the complex of automated equipment [2, 3]. The production of ribbed panels may include forming and local deformation of ribs with a blade via charging and distribution [4]. There is also the method of levelling of reinforced parts by rolling where the two-axis bending of parts is achieved by serial processing of ribs and blades [5].

To ensure the set performance characteristics the critical parts are exposed to strengthening treatment through surface plastic deformation (SPD) using shock methods, such as peen forming and shock-vibrating machining. It is known that these types of processing, causing deformation and lengthening of surface layers, lead to distortion. The size of distortion of reinforced parts depends on their design features. For example, if uniform bilateral peen forming of sheet parts almost does not influence the form, then the same processing for reinforced parts disturbs the balance of internal forces and leads to bending due to lengthening of ribs. Another reason causing distortion of reinforced parts is technological heredity. If surface layers already have residual stress caused by previous operations, then the uniform processing of equally rigid part will result in inequality of deformations of surface layers and distortion. To ensure the guaranteed resource of a part there is a need to keep residual stress of reinforced parts in assembled units. Therefore, after hardening it is unacceptable to apply levelling by elasto-plastic deformation and elastic assembly as operations influencing the residual stress obtained at strengthening treatment [6]. It is obvious that to solve the problem of minimization of distortion of parts strengthened by surface plastic deformation there is a need to set the processing modes depending on design features and residual stress-strain behavior (SSB) of processed parts [7, 8].

Thus, the quality of large-size low-rigid parts of a frame and casing in the course of their production depends on a variety of mutually influencing factors defining SSB and form of parts. Complex accounting of these factors is only possible on the basis of digital modeling of all technological operations and availability of operated equipment.

Today the development of computer technologies made it possible to substantially increase the adequacy of physical models of products and processes of their production. Such models, which closely resemble real objects, are called digital twins, the adequacy of which is ensured by data on manufacturing technologies of modelled products. According to [9], the main components of digital twins are geometrical (CAD) and computing finite-element (CAE) full-scale models of objects and physico-mechanical processes; full data on materials and their behavior at different types of loading; data on production technologies, including accounting of preliminary stress-strain behavior, distortion of parts after technological processes, etc.

The paper considers the main approaches to the creation of digital manufacturing technologies of high-precision low-rigid parts of a frame and/or casing. The term “digital technology” is understood as a complex of interconnected digital models of a primary part and the technological sequence of operations of its processing in various combinations. This technology is ensured through the complex of computer controlled equipment. The purpose of modeling is to define SSB of a part in any times of its processing and a set of process parameters ensuring controlled change of SSB and form of a part taking into account opportunities of applied equipment.

2. Definition of digital model parameters of a workpiece
To describe the digital model parameters of a workpiece there is a need to tackle some uncertainty
caused by previous metallurgical operations, which control within machine-building enterprise is impossible. These include the mechanical properties of a material specific to each workpiece, deviation of sizes and spatial form of workpieces from nominal values and their residual stress.

Mechanical properties for the model of anisotropic elasto-plastic material are defined as follows. According to GOST 1497-84 tension tests of flat samples from the material of a part with thickness of 3.0...4.0 mm and an initial reference length $l_0 = 5.65 \sqrt{F_0}$ are performed, where $F_0$ – sample cross-sectional area. Thus the following is defined:

1) Elastic modulus – by graphical method according to initial section of tensile diagram written with electrical weighing devices and a strainmeter according to formula (1)

$$E = \Delta P \cdot l_0 / \Delta l \cdot F_0$$

where $\Delta l$ – mean increment value of sample lengthening corresponding to block step $\Delta P$. It is also possible to define the elastic modulus by studying hardness of a material via indentation methods according to GOST P 8.748-2011 and subsequent analysis of a diagram “loading-residual deformation at introduction”. The inclination of this diagram when unloading is defined by elastic modulus of a material;

2) Offset yield strength $\sigma_\text{_offset}$ with allowance for plastic deformation when subjected to loadings (or with another fixed allowance) and tensile ultimate strength limit $\sigma_\text{u}$ – according to diagram received on a tester or by special devices;

3) Coefficients of normal anisotropy $R$ reflecting change of metal properties in various directions – according to tension tests [10], as a relation of logarithmic deformations by width $b$ and sample thickness $t$, according to formula (2):

$$R = \frac{e_0}{e_i} = \frac{\lg h_0 / b_i}{\lg h_i / b_0}$$

where $h_0$, $t_0$, $b_i$, $t_i$ – initial and final values of width and thickness of flat samples respectively. These coefficients are defined depending on cutting direction: along rolling $R_\perp$, in perpendicular direction $R_\|$, and at an angle of 45° $R_{45}$.

As it is noted in some sources [11-13], workpieces of reinforced high-strength thermally strengthened aluminum alloys in the condition of supply have volume residual stress caused by previous operations. Since the residual stress caused by previous metallurgical operations is fully removed at thermal treatment, the initial tension of a workpiece before machining may be called thermal. This tension is mainly caused by two factors: structural and phase transformations and uneven temperature deformations due to thermal treatment. Due to different speed of cooling of external and internal layers there is a non-uniform change of specific volume caused by supersaturation of $\alpha$-solid aluminum solution by alloying elements and formation of precipitate particles, which density in surface layers will be higher than in middle layers. This leads to residual stress – stretching on the surface and squeezing in the center. At the same time when the workpiece is cooled while quenching the external layers receive initial plastic tensile deformation as they cannot accept sizes corresponding to their temperature. As a result, the tension stress is formed in the center, which is counterbalanced by compressive stress in external layers.

Thermal residual stress depends on alloy properties, cooling conditions while quenching, configuration and size of a workpiece. To ensure approximation of epures of thermal residual stress some researchers of this problem apply parabolic distribution

$$\sigma' = \sigma'_0 \left( \frac{6}{H^2} z^2 - \frac{6}{H} z + 1 \right)$$

where $\sigma'_0$ – residual stress on the surface of a workpiece; $H$ – thickness of a workpiece.

On the basis of distribution (3) and the strip method developed by I.A. Birger [14] the work [15] proposes the express method to define quenching residual stress in plates. As an assumption the condition, according to which residual stress in the plane of a plate is similar in all directions, is accepted.
The summary of the method is as follows. Narrow strip is cut from a quenched plate for its tension after cutting to be single-axis. Then the strip is cut into two parts parallel to the middle plane of a plate and measured on received plates of bending deflection \( f_1 \) and \( f_2 \). The residual stress is defined on a plate surfaces by the following expression

\[
\sigma'_r = \frac{-2EH(f_1 + f_2)}{[3l^2(1-\mu)(H+b)]},
\]

where \( E \) – elastic modulus; \( l \) – spacing of bending deflection; \( \mu \) – Poisson’s ratio; \( b \) – cutting width.

Work [16] describes the techniques to define volume distributions of thermal residual stress in workpieces of prismatic, P-shaped and E-shaped form based on removal of metal layers from samples and measurement of resulting deformations.

There are some studies of finite-element modeling of thermal treatment of workpieces from aluminum alloys. Work [17] shows the results of modeling a pilot study of quenching residual stress in workpieces from aluminum alloy 2024 (D16 analog). It is shown that in prismatic samples after quenching the compressive stress is formed on a surface and tension stress in the middle. Numerical values of this tension are coherent with experimental data given in work [16].

Thus, to define the distribution of thermal residual stress in such workpieces as plates it is sufficient to define surface residual stress. Thus, it was suggested to use the methods of nondestructive testing of residual stress, one of which is resistive electrical contact technique based on relations between electrical and mechanical properties of metal conductors and their skin-effect phenomenon [18]. Instrumentware and software for this method is developed by ITMO University (Figure 1). The equipment is calibrated by mechanical or x-ray residual stress measurement.

**Figure 1. Measurement of stress by resistive electrical contact technique via SITON-TEST 8.1**

Deviations of sizes and spatial form of workpieces from nominal values can have significant effect on the results of machining. To study this influence, we carried out the analysis of deviations of a plate form from V95pch2 alloy with the size of 3500x1600x35 mm [19]. After removing a 4 mm allowance from this plate, the plate was separated from a vacuum table caused by the cumulative influence of tension from fixing and imbalance of thermal residual stress diagram. According to preliminary measurements of deviations from flatness the plate conformed to technical requirements of GOST 17232-79 – deviations on a 1000 mm base did not exceed 3 mm at admissible 5 mm. However, the measurements of deviations from surface flatness of a plate on a 200 mm base showed that they have complex fluctuating nature (Figure 2).
Thus, to increase the adequacy of forecasting of deformation during machining it is advisable to introduce additional control operation into the technological process ensuring the definition of real spatial form of initial workpiece.

3. Main approaches to modelling of technological operations

A. Machining

The major factors defining SSB during machining include the bending moment caused by imbalance of thermal residual stress diagram when the allowance is removed and surface loading caused by cutting action. The difference of these factors is as follows. In the first case internal forces are counterbalanced to external ones and are unambiguously defined by balance equations, while the deformation is uniform and collateral by section. In the second case the appearance of internal forces is connected with plastic deformation of a surface layer influenced by a tool when processing a workpiece. These forces cannot be reflected by balance equations, and deformation is non-uniform and does not coincide by section.

The measurement methods allowing defining the deformation of a part by calculating the internal forces and moments resulting from imbalance of thermal residual stress and initial tension diagrams caused by cutting are known from 1970s of the last century [12, 13]. In this case the residual stress can be found by experimental, generally mechanical methods, based on removal of layers from technological samples and measurement of resulting deformations. Practical application of these techniques to define SSB of real large-size products represents a problem due to low accuracy of calculations caused by some simplifications and assumptions.

Finite-element modeling gives more adequate solutions to forecast forming of thin-walled parts during mechanical treatment. This method is being actively developed abroad [20-22]. Today there are also some domestic studies published on this matter [23, 24].

The results of finite-element modeling of forming of a part such as a frame of a plane lamp in the course of machining as a result of redistribution of residual stress formed at previous fabrication stages are given in work [20]. The distribution of residual stress in a workpiece is defined by flat methods on technological samples. The received residual stress is attached to corresponding final elements of a model by means of a special program. Modeling of processing consisted in consecutive removal of metal layers.

Work [21] describes an approach to define distortions of a form of low-rigid parts of aviation equipment connected with residual stress being the consequence of cutting and previous production operations. To solve this, the study uses AdvantEdgeTM and Production Module software by Third Wave Systems, Inc. (USA) specializing in machining modeling. The finite-element model of a part is created on the basis of geometry of initial workpiece using Boolean subtraction tool taking into account its trajectory. The model considers strain hardening, thermal influence and cutting speed. The residual stress diagrams caused by cutting are defined by finite-element modeling for various modes and
conditions of processing with thermomechanical relaxation of a workpiece material and are kept in the corresponding database. When modeling the process of forming there is a need to calculate forces caused by cutting and imbalance of the initial residual stress diagram. These forces are applied to grid point of final elements of a model surface. The technique to define these forces is not given in work. The authors [21] suggest to define the initial residual stress of a workpiece based on literature sources or using the results of thermal treatment modeling and to keep the obtained data in a special database. The standard residual stress diagram defined at finite-element modeling of cutting [21] is shown in Figure 3a.

The study showed that the definition of internal force leading to deformation of a part by the integration of diagrams similar to the ones shown in Figure 3a does not give the required calculation accuracy (disagreement with experimental results by more than 20%). The diagram in Figure 3a shows two main sides – plastically deformed surface layer and the underlying layer where reactive tension stresses were formed. It is obvious that such diagram is not counterbalanced by section, which is typical for processing of parts with big thickness.

The forces used at forming modeling under the influence of tension caused by cutting can be performed on the basis of the developed technique to define internal force factors of processes of surface treatment [25]. Internal force factors here are understood as the distributed force arising due to plastic deformation of a surface layer and the coordinate of its point of application (distance from the surface) based on the approach of “initial tension” proposed by Ovseenko A.N. [26]. The term “deformation source” is used in foreign literature [27]. The proposed technique includes the definition of initial tension on the basis of residual stress diagram determined by modeling of surface treatment of a massive body. Figure 3b shows the scheme of initial tension formation demonstrating that in order to find epure 1 of

![Figure 3. Standard residual stress diagram defined during machining modeling [21] (a); scheme of residual stress formation: 1 – initial tension; 2 – reactive tension; 3 – residual stress – sum epures 1 and 2 (b) [25]](image)
initial tension it is necessary to subtract epure 2 from resulting epure 3 defined by modeling, which can be found using known coordinates of points $A \ (z = h_{pl}, \ \sigma = \sigma')$ and $B \ (z = h_{el}, \ \sigma = 0)$ lying on straight line $BC$.

Let us define the internal force factors typical for the majority of surface treatment processes on the basis of known parameters of initial tension diagram (Figure 3b)

\[ P = -\frac{(\sigma_{in}^{n} h_{in} + \sigma_{in}^{m} h_{pl})}{2}; \]
\[ z_{c} = \frac{\sigma_{in}^{n} h_{in}^{2} + \sigma_{in}^{m} (3h_{in}^{2} - 2h_{in} h_{pl} + h_{pl}^{2})}{3(\sigma_{in}^{n} h_{in} + \sigma_{in}^{m} h_{pl})} \]

(5)

where $P$ – internal distributed force representing the area of initial tension diagram; $z_{c}$ – point coordinate of application of force $P$ (distance from the surface).

Experimental verification of the adequacy of this technique showed the disagreement with experimental results by less than 10%.

On the basis of obtained values of internal force factors it is possible to find surface distributed $P_s$ force equivalent to $P$ force according to created bending moment

\[ P_s = P(z_0 - z_{c})/z_{0} \]

(6)

where $z_{0}$ – coordinate of a neutral layer.

Thus, the results of machining modeling include components $\kappa_j$, $j = x, y$ of residual surface curvature, $\kappa = 1/R$ where $R$ – curvature radius, as well as residual stress diagrams in control points of a part in set directions.

**B. Forming and levelling**

The results of machining modeling serve the basic data to define process parameters of process of forming (levelling) of parts. The achieved components of curvature $\kappa_j$ of a part were defined as follows

\[ \kappa_j' = \kappa_j - \kappa_j^m, \]

(7)

where $\kappa_j$ – required curvature of a part; $\kappa_j^m$ – residual curvature of a workpiece after machining; $j = x, y$.

Today the market offers some universal and specialized software products ensuring modeling of metal treatment under pressure. There is sufficient number of works devoted to modeling of forming and levelling of parts via press bending [28], peen forming [29], rolling [30], charging and interconnection [31]. These works describe the modelling of separate technological processes without considering technological heredity of parts.

The current study showed that all technological operations changing SSB of a workpiece shall be taken into account to ensure the accuracy of forms of high-precision low-rigid parts. Today some studies are devoted to technological sequences of production of frame and casing parts, including elasto-plastic bending, rolling, peen forming, flap wheel cleaning and surface strain hardening. The main approaches to the study of production of parts like large-size casings are given in [32]. Active development of engineering analysis allowed expanding the opportunities and increasing the adequacy of modeling.

Regarding perspective combined forming technology of large-size p parts such as double curvature casings, including elasto-plastic deformation and peen forming, the modeling of the technological sequence of operations “elasto-plastic bending – fixing – peen forming” were carried out. The modeling was performed using nonlinear finite-element analysis LSTC LS-Dyna Version R10 with the generation of models in MATLAB.

For deformable workpiece we used the model of anisotropic elasto-plastic material where the elastic tension and deformations are set according to linear Hooke’s law, and the dependence of tension on deformation in plastic area – on the basis of a piecewise linear curve of loading built by approximated results of tension tests according to GOST 1497-84. The Mises/Hill criterion was used as criterion of plasticity. The explicit method was used to solve dynamic equations not connected with the solution of differential equations, but using recurrence relations, which express movements, speeds and
accelerations on a given step through their values at previous steps.

The modeling of elasto-plastic bending for the required radius of residual curvature of sheet workpiece (Figure 4) was carried out by technique given in [33]. The model of plate rolls was made in the form of cylindrical sectors, on the basis of which a grid from hexahedral envelope four-nodal finite elements was constructed. In the central part of a sample we created a grid of finite elements with condensation to increase the adequacy of further modeling of the process of introduction of balls. The grid size in the given field 1 made 0.08×0.08×mZ mm, where 0.01<mZ<0.08. Using the received model we calculated elasto-plastic bending before obtaining the radius of residual curvature Rr = -5 m. The negative value of the curvature radius was accepted due to imitation of conditions for fluctuating double curvature, where cross curvature was considered positive.

![Finite-element model of bending-rolling](image)

Figure 4. Finite-element model of bending-rolling

Fixing with elastic deformation of samples was modelled by absolutely rigid spherical supports located on both sides on a longitudinal axis of sample symmetry via restraints of three forward axes (Figure 5).

Elastic deformation of a workpiece was carried out by unbending to a flat condition, as well as by obtaining curvature radiiuses of -10; 10; 5 m. After modeling of bending and fixing the deformed grid was imported to a new calculation sheet where it was fixed on all sides except the processed surface to exclude movement of a part at the introduction of balls.

![Modeling of fixing of samples with elastic deformation in longitudinal direction](image)

Figure 5. Modeling of fixing of samples with elastic deformation in longitudinal direction

Modeling of multiple introduction of balls in a sample was performed taking into account the real structure of a processing zone by a shotblaster, the study of which covered sample plates of 4×110×110 mm from V95pcht2 alloy. The samples were processed with balls from ShH-15 steel with a diameter of 3.5 mm, then they were measured by a 3D-optical Bruker Contour GT-K1 profilometer to define parameters of a microrelief with the area size of 20×20 mm. As a result of measurements we received the distribution of diameters and depths of prints in a processing zone. To define the incidence angles of balls we used volume surface models received through scanning (Figure 6). A ball trajectory tilt angle in relation to the processed surface was defined according to formula (8)

\[
\alpha = \arctg\left(\frac{0.5d - d'}{h}\right) \tag{8}
\]
Figure 6. Profile of microroughness of a processed sample (a) and a scheme to define the incidence angles of a ball (b), print profile (c)

The dependence of the indentation diameter on a ball speed was received via modeling of a single shock introduction of a ball with a diameter used when processing in a parallelepiped with the side of 10 mm from the studied material. The received diagram of dependence of a print diameter on a ball speed was approximated by polynomial dependence used to set the speed of balls in a processing zone of a shotblaster. The models of randomly distributed 325 balls with received speeds and tilt angles were automatically generated in MATLAB. After the introduction into a sample deformed through bending fixing by the first set of balls (Figure 7) the grid of finite elements was imported to a new calculation model thus maintaining the values of tension and deformation, and then modelled the introduction of a new set of grains with randomly generated coordinates, etc.

Figure 7. Model of multiple introduction of balls in a deformed sample

Figure 8 shows initial tension diagrams in a surface layer after rebound of balls, which are defined in a fixed sample. The internal force factors Ppf and zc created by this tension were calculated by expressions (5).

Figure 8. Epures of normal initial tensions in a surface layer of samples V95pcht2 (4 mm thick) subjected to bending with Rr = -5 m, elastic bending and processing by balls (D = 3.5 mm; N = 800 min.-1, t = 4 s): 1 – bending; 2 – elastic bending up to R = 10 m; 3 – unbending to a flat state; 4 – elastic bending up to R = 10 m; 5 – elastic bending up to R = 5 m; 6 – unstrained sample

Modeling of forming of parts through shot peening was carried out by applying the relative stretching force Ppf to model knots located at calculated distance zc from the surface of a workpiece (Figure 9).
Experimental verification of modeling was performed on 4×230×1400 mm samples made by milling from sheet V95pcht2. The samples were subjected to bending-rolling on I2222BM bending machine, then the plates were cut from their central part with the sizes of 4×230×250 and processed by balls with a diameter of 3.5 mm on UDF-4 sandblasting machine with preliminary elastic deformation in a special device. Internal force factors and forming of samples were defined by the above technique, then compared to experimental data (Figure 10).

The received results allowed concluding the following. In comparison with processing in a free state of a sample with initial longitudinal curvature with the radius \( R_r = 5 \) m the elastic control of a form when getting cross curvature with the radius \( R_x = 8 \) m allows increasing processing efficiency by \( 5\%-23\% \) at elastic deformation up to curvature radiiuses from -10 to 5 m respectively. The results of calculation and experiment data have the relative deviations not exceeding 11\%, which confirms sufficient adequacy of the developed technique.

C. Face hardening

Today there are many works by both foreign [34-37] and domestic authors [38-39] devoted to the study of surface strain hardening. Some works give the results of finite-element modeling of peen forming of low-rigid sheet parts such as plane casing to define their forming. Most of them note that direct modeling of the process representing numerous shocks of grains on a surface of a large-size detail is not possible. In this regard to forecast the forming of parts through shot peening the indirect methods applying equivalent loadings to surface layers of a part are generally used. Thus, when modeling shot peening of a low-rigid sheet part the work [35] uses loading by specific bending moment determined by the integration of residual stress diagram under a single print with subsequent multiplication by the quantity of prints placed on a line parallel to movement trajectory of a bead-blasting nozzle. As it was noted above, such approach decreases the adequacy of modeling. The work [40] gives the results of modeling of consecutive peen forming and grinding. It is obvious that the residual stress diagram created through shot peening almost does not change after grinding. Unfortunately, we could not find works devoted to the study of the influence of previous operations on a form of reinforced parts.

The study aimed to develop recommendations on ensuring the accuracy of a form of frame part at
peen forming are being carried out by IRTU for the benefit of PJSC Irkut Corporation.

The problem of preserving the form at peen forming of reinforced parts with unilateral longitudinally cross fins represents a sufficient difficulty. Bilateral peen forming of such parts inevitably leads to distortion of a part contour as the deviation from flatness. The problem of minimization of such deviations is solved by preventive forming in opposite direction [41]. The size of this forming is calculated by finite-element modeling [42]. Preparation of the calculation model includes simplification of a part design by averaging the thickness of a cloth and eliminating radial transitions, fillets, facets and other elements preventing breaking a part down into a grid consisting from hexahedral elements. Loading of a part when modeling is carried out by stretching forces applied to grid knots. These forces can be defined by calculation on the basis of experimental data in the form of deformation of processed samples, as well as by peen forming modeling using technique described in work [25]. The modes of preventive deformation can be defined by rolling on the basis of empirical data in the form of dependence of the bending moment on the force of indentation of rollers into the processed surface. The bending moment required for levelling is defined by calculations considering deviations received by modeling (Figure 11) and rigidity of calculated sections.

![Figure 11. Modeling in the form of distribution of movements after peen forming of a part “Frame Rim” in relation to axes: a – OZ; b – OY [42](a)](image1)

![Figure 11. Modeling in the form of distribution of movements after peen forming of a part “Frame Rim” in relation to axes: a – OZ; b – OY [42](b)](image2)

Production approbation of the developed technique on structurally similar samples showed encouraging results. For example, for the piece shown in Figure 12, the deviations were reduced from 6.8 to 1.8 mm in the plane of a cloth and from 0.5 to 0.1 mm on a theoretical contour.

4. Main approaches to digital models of cross-cutting technological processes

At present, there are all necessary conditions to implement the joint project of INRTU and Irkut Corporation on the creation of digital models of cross-cutting technological processes of production of frame and casing parts from thermally reinforced workpieces, including machining, forming (levelling) and face hardening using measurements of mechanical characteristics of material, technological residual stresses and forms of workpieces.

The project requires a software complex for modeling of workpieces and technological operations of their processing; procedures of converting and data transmission between software environments being part of a complex.

The preparation of digital models of workpieces causes the need to develop a technique for parametrical finite-element models of standard workpieces used to make parts with such variable
parameters as mechanical properties of materials, thermal residual stresses, standard deviations of a workpiece form. There is also a need to develop recommendations on modification of existing techniques to test the samples in production to obtain relevant information necessary for subsequent modeling; to create the database of mechanical properties of workpieces from different suppliers; to review and analyze express methods to define mechanical properties of workpieces via devices based on indenting (static and shock); to define technological capabilities of chosen express methods; to develop a technique for thermal residual stress diagrams on the basis of known surface tension values for various types of workpieces; to define the nature of distributions of thermal residual stress in different workpieces there is a need to model their thermal treatment and thus define the influence of modes and conditions of this process on the distribution of residual stress and on the ratio of surface tension with parameters of epures; to study the application of resistive electrical contact technique in order to measure surface tension of workpieces in comparison with other known methods (x-ray, mechanical stripping, etc.); to develop a technique of return design of real workpieces to create their 3D models; to address the issue of applying robotic complexes for automatic implementation of express methods of defining mechanical properties of workpieces, surface residual stress and return design.

The solution of task related to the creation of a model of machining requires taking into account the specifics of chosen software products to develop a technique of finite-element modeling of milling of parts with volume thermal residual stress and deviations of a form: to create the database of internal force factors of milling depending on modes and conditions of processing of parts; to carry out pilot works to confirm the adequacy of modeling.

Besides, there is a need to perform the following: to study various technological combinations of forming and levelling of low-rigid parts; to develop a technique of finite-element modeling of combinations of elasto-plastic bending, peen forming, cleaning and local plastic deformation by rolling, charging and distributing on the basis of models received as a result of milling modeling; to test the results of modeling in production; to develop and introduce controlled equipment for forming and levelling of parts by rolling, charging and distributing.

There is a need to perform works to increase the adequacy of finite-element modeling of face hardening by shock methods taking into account the influence of technological heredity of a part and such features of this process as particle-size distribution a working environment (friction or balls), probabilistic nature of structure formation of a processing zone, need to achieve the required coating on remote sides of parts. It is necessary to continue the study on modeling of technological combinations “preventive deformation – face hardening” with further recommendations concerning the above operations.

5. Conclusion

At present, some technical guidelines require that technological processes of production of frame and casing parts after machining include levelling to eliminate deviations of a form. Due to unpredictability of deviations these operations differ by complexity and labor input. Levelling of parts subjected to face hardening is inadmissible. In case of creation of digital models of cross-cutting technological processes there will be an opportunity to predict forming of parts at all stages of processing. It will provide for levelling at the preproduction phase to produce frame parts. In case of production of casing parts, the results of milling modeling in the form of deviations will be used to set the modes of forming. It will make it possible to completely refuse from levelling operations. The problem of excepting distortions of a form of reinforced parts will be solved due to controlled preventive change of a part form at forming and levelling stages.

The suggested approach in combination with the developed controlled equipment will allow optimizing modes of processing and achieving the required accuracy of parts and maximum capacity without pilot works. The use of developed technique will make it possible to increase the production efficiency of parts due to time minimization of finishing operations and cost reduction for preproduction for the launch of new products.
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