Improvement of the processes of forming tight shells of double curvature

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Abstract. The article analyzes the process of shaping double curvature shells made of aluminum sheet material used for covering the outer contour of an aircraft. The main rejection signs of casings made by the method of shaping by wrapping are considered. The main problems arising during the shaping of double-curvature shells by wrapping are presented, and the ways of their solution are considered and proposed.

1. Introduction

The modern development of air transport depends mainly on the creation of technology aimed at the development of methods, methods and means of obtaining shells of double curvature of complex spatial forms, the availability of production conditions and modern equipment with program control, the use of new materials from aluminum alloys, despite the great popularity composite materials on the same aluminum base. Most often, these are thermally or precipitation hardened aluminum alloys with a complex phase composition Al-Mg-Cu, including an aluminum-lithium alloy of the Al-Mg-Li system.

At the same time, the technological process is organized to achieve the goal: to improve the quality of the shells, by ensuring a more uniform distribution of the thickness of the workpiece after shaping by the wrap and to reduce the likelihood of its waviness and folds formation. The technological process (TP) is characterized by parameters that are divided into the following groups: material properties; friction conditions; dimensions of the sheet blank; heat treatment modes; tightening punch parameters; kinematic conditions of the shaping process by the skin. TP management is built on the basis of the analysis of the specified information, which is compared with the management objectives and a program is formed based on the results of the comparison.

However, first you need to carefully study the TP, realize the achievement of a certain goal, what exactly should result from the implementation of the TP, present each operation or action, the conditions for their implementation, and finally, describe in detail the sequence of actions. This sequence of actions leading to the achievement of a specific goal can be called a control algorithm. When compiling an algorithm, complex actions are broken down into simpler actions, up to elementary movements. Such
detailing allows the most complex action to be presented as a set of simpler actions, and the implementation of the simplest actions can be entrusted to program control, this will be a direct path to the automation of the technological process. In the general case, the technological route of wrapping is presented in the form of stages (figure 1):

Stage 1. The sheet blank is installed in the clamps of the press and fixed in them.
Stage 2. The sheet blank is pre-stretched in order to bring the material beyond the yield point.
Stage 3. The sheet blank is wrapped around the surface of the covering punch, forming the top of the double curvature shell. This is ensured by both the movement of the clamping devices and the lifting of the press table. In this case, the area of contact between the workpiece and the covering punch expands. This stage continues until the sheet blank comes into contact with the surface of the tightening punch [1].
Stage 4. The sheet blank is calibrated until it completely adheres to the surface of the covering punch by applying additional tensile deformations necessary to stabilize the geometric shape of the skin.

Figure 1. General case of the shaping process.

At the first stage, the aluminum sheet blank comes either in a «soft», pre-annealed state, or in a freshly hardened «viscous» state. Research by scientists from VIAM showed that some aluminum alloys after quenching for some time (up to several hours) have increased plastic properties, after which aging of the material occurs, as a result of which the plasticity decreases, but the strength properties increase [2]. This is the reason for the use of sheets in a freshly hardened state. For sheet blanks, the stage of rapid cooling is performed in water or 40% polyalkylene glycol solution [3].

During quenching, wavy warping occurs - the flat shape of the sheet blank deviates greatly. Therefore, it is very difficult to tuck it into the jaw of the press clamp. A clamping device [4] has been developed, which makes it possible to mechanize the laborious process of sheet threading without additional movements of the clamping devices and to reduce the time required for processing. The warping of the rest of the billet is eliminated at the second stage by straightening the sheet billet by stretching in the clamps of the stretching press. Shells of double curvature, complex in shape, are obtained by shaping by wrapping in several transitions. Each of the transitions of the skin, as a rule, includes all four stages.
Thus, before the first transition, the sheet blank is usually annealed or freshly hardened. Then, between the transitions, annealing is performed, and before the last one - quenching [5]. The accuracy of the tension calibration step depends both on the size of the leash and distortions of the shell contour during quenching, and on the elastic springback after shaping by the tightness, due to the difference in the stress-strain state of the material in different zones of the sheet blank. Therefore, the calibration operation does not always ensure the stability of the shape with deviations within the tolerances, and the details of the skin after calibration sometimes require manual finishing [6].

The main blanking and stamping equipment used for shaping are hydraulic shaping presses. Today, aircraft manufacturing enterprises have manual and programmed stretch presses. Here are the stretch presses installed and operating at JSC «Aviastar-SP». The equipment with manual control includes stretching and stretching presses RO-3M and RO-630-11. The equipment with programmed control (CNC) includes longitudinal stretching press FEL; transverse stretch stretch presses FEKD and FET.

The work [7] presents ideas on the modernization of domestic equipment for shaping with a close-fitting with manual control. To transfer it to the program control mode, programmable logic controllers (PLC) and personal computers (PC) are used. SMART 2 controllers were used as PLCs. To combine PLCs and PCs, a standard high-speed interface network PROFIBUS was used. An interface network based on high-speed buses makes it possible to integrate wrapping equipment, PLCs and computing facilities into a single system. The auto-control system is configured for a specific type of press and the wrapping process is performed by placing the corresponding control program in the PLC memory. The developed program control system allowed to achieve the level of automation comparable to the French presses of the ACB company.

At the same time, obtaining skin parts on presses with programmed control allows an unlimited number of times to reproduce a debugged control program for shaping by displacements, and invariant to a large proportion of disturbing factors. But in order to carry out shaping by wrapping on CNC presses, it is necessary to control all process parameters, practically excluding any chances, in conditions of instability of the properties of the initial sheet materials and the conditions of the deformation process of each individual sheet. In this regard, on the covering equipment, the control system also provides for manual control. However, when using the control system on existing strapping equipment, the following problems can hardly be solved:

- inhomogeneity of plastic deformations in the resulting shell, including thinning of the sheet blank, due to the complexity of the geometric shape, external friction forces and a great tendency to thinning of the aluminum alloy sheet;
- the unpredictability of the behavior of the sheet blank after preliminary heat treatment, carried out immediately before the shaping by the wrapping;
- the need to perform manual finishing in some places where the workpiece does not fit to the tightening punch.

In modern conditions, it is already unacceptable to use manual control of the shaping processes by wrapping and with manual finishing operations. This is due to the fact that high requirements are imposed on the aircraft skin in terms of the quality of the aerodynamic contour and in terms of strength and resource, which are difficult to ensure without solving the above problems.

2. Analysis of defects and the choice of ways to improve the shaping process with a wrap

For the wrap shaping process, the efficiency and feasibility of improvement can be assessed in the following ways:

- comparison of the costs for the quality of the cladding before improvement and after achieving the accuracy of the geometric shape of the surface of double-curvature shells (by comparing its waviness) [8];
• comparison of production costs before improvement and after.

The first assessment method affects the performance of the aircraft. The second method of estimation is determined by the production time with the minimization of the number of personnel involved in the production, as well as the cost of blanks and production costs. Both methods are united by the fact that they directly depend on the rejection signs that arise both after and during the shaping process. The main rejection signs arising in the process of shaping sheet blanks by covering are:

1. Folding. Corrugations. Waviness.

Folds are an irreparable sign of rejection. The appearance of folds is preceded by corrugations. Corrugations arise as a result of local loss of stability of the edge of the workpiece from compressive forces during bending along the tightening punch or during compression of the section of the workpiece located (in front of the gap) between adjacent press jaws. The main method for eliminating corrugations is additional stretching of the workpiece with simultaneous manual finishing with a rubber mallet. As a rule, the corrugations cannot be completely smoothed out, thereby leaving waviness in the skin. Waviness is a valid rejection characteristic within certain values. The limiting value of the relative height of waviness for the wing skins, empennage, engine nacelles, pylons and the front part of the aircraft fuselage was about 0.02 mm [9].

2. Breaks in the sheet blank. Localization of plastic deformation and uneven distribution of the thickness of the skin part.

The break of the workpiece is preceded by local thinning. Localization occurs as a result of excessive stretching of the workpiece material and high frictional forces. The reason for excessive stretching of the workpiece can be both the elimination of the corrugation that occurs accidentally, and an incorrectly selected kinematic mode of shaping. The influence of friction on the localization of the thinning of the workpiece during shaping by a tight-fitting is manifested in the slowing down of the plastic flow of the material of the workpiece, during its stretching, at the points of contact with the tightening punch when entering the section between its end face and the press clamps. As a result, the friction-free edge of the sheet blank undergoes excessive tensile deformations, leading to the localization of thinning and rupture of the blank. If there is no rupture, there is an uneven distribution of the thickness of the skin. This rejection feature is acceptable, but not required for modern aircraft.

The bypass-forming surfaces of the skins, associated with the spatial shape of the shells of double curvature and the parts of the aircraft frame in contact with them, have become more complicated, the requirements for their compatibility during assembly have increased due to the difference in thickness of the skin walls. It is required to minimize the thickness difference to the recommended limits, but this requires a new technology to increase the degree of deformation during stretching, which is achieved practically in one transition without localizing the thinning deformation and equalizing their values in different areas of the sheet blank.

3. Notches and scratches, as well as their filling.

This feature occurs as a result of friction of the aluminum sheet on the surface of the covering punch, especially if it is cast from secondary aluminum. It is successfully eliminated by using antifriction coatings and special technological lubricants [10]. If they appear after shaping, it must be eliminated by cleaning out the defective places, with further filling. The use of a putty for finishing defective areas is permissible only on the inside of the skins due to the high requirements for the outer contours of the aircraft. At the same time, there is a permissible proportion of filled defects from the total surface area of the skin, which is also set by the aircraft designers [9].

Therefore, when writing a technical task for the development in the field of shaping by wrapping skin parts, it is necessary to unequivocally know the limiting minimum of parameters that must be taken into account. Among these parameters, two groups can be distinguished:

1. Parameters affecting the performance of skin parts:
the amount of waviness of the skin, taken as a percentage, affecting the aerodynamic drag of the aircraft as a whole;
• the proportion of filled defects, which impairs the uniform strength of the skin parts. Therefore, companies operating an aircraft with filled defects need to periodically check and repair these elements. This defect is no longer acceptable for modern aircraft.

2. Parameters affecting the cost of aircraft production:
• uneven distribution of the thickness of the skin, which ultimately affects its cost. As a result, with its high value, the designer is forced to lay the increased thickness of the sheet blank;
• the proportion of notches and scratches from the total surface of the workpiece obtained after shaping. The more marks and scratches, the higher the labor intensity of their cleaning and filling, which increases the labor intensity of the plating production;
• the laboriousness of the shaping of the skins, depending on the duration of manufacture, the amount of highly paid manual labor for the manual removal of corrugations, as well as the number of personnel involved in the process.

Obviously, both groups of the above parameters are completely dependent on rejection signs. Therefore, the elimination of rejection signs is one of the main tasks of research and engineering work dedicated to improving the shaping process with a wrap. To eliminate the aforementioned rejection signs, various methods have been developed to intensify the shaping process with a wrap.

3. Intensification of the shaping process with a wrap
The intensification of sheet stamping processes is usually understood as a set of measures or actions that can improve the quality of a part, reduce the labor intensity of its manufacture, and reduce the number of equipment and tooling used [11].

Distinguish between direct and indirect intensification of the shaping processes by the covering. With direct intensification, the intensifying factor affecting the sheet blank is presented in an explicit form. It can be heating, additional force, high-speed, electromagnetic and other effects. Indirect methods of intensification are outwardly invisible, but they significantly change the traditional process of stretching and are usually associated with special preparation of the initial workpiece: optimization of its dimensions, a given distribution of mechanical properties, obtaining the desired anisotropy [12].

Changes to the die tooling are required. First of all, this concerns the tightening punch, the geometry of which must differ from the original design version, which is directly related to the theoretical contours of the aerodynamic contours of the aircraft units. The transition to a grid of curvatures of the surface of the covering punch gives great advantages in design automation and control of the processes of shaping by covering shells of any surface, as well as complex geometric shapes. It became possible to select on such a surface the position of the shaping contour of the tightening punch, which will be aligned with the longitudinal vertical plane of the press, including the surface pole and passing through the middle of the central jaw [13, 14]. However, this requires some external structural change of the tightening punch.

Based on the physical principle of action, we distinguish groups of intensification methods:
• changing the friction conditions on the contact surface of the workpiece and the covering punch;
• external design changes to the tightening punch;
• changing the kinematic scheme of loading sheet blanks;
• a change in the nature of anisotropy due to the presence of certain preferential crystallographic orientations in the sheet material;
• change in the kinematic scheme of loading sheet blanks.
By changing the friction conditions on the contact surface of the workpiece and the covering punch, it is meant a decrease in friction between the workpiece and the covering punch [15, 16], or by local increase in friction in the central part of the workpiece, practically blocking the movement of the metal in this zone under the action of a container with an elastic medium [17]. Reducing friction at the edges of the workpiece has a positive effect on the cladding, maintaining the locations of the greatest deformations in the central region of the sheet workpiece with a minimum probability of sheet breakage in one of its free areas between the edge of the punch and the press clamps and providing a more uniform distribution of the workpiece thickness.

Uniform distribution of thickness is ensured due to the zonal plastic flow of the metal during deformation. First, the central part of the blank is stretched, and then the outer parts. In this case, in order to avoid excessive deformation of the central part, it is possible to use a local increase in friction due to a profiled elastic medium having a high coefficient of friction with aluminum alloys. Also, this method, due to the profiled elastic medium, makes it possible to deform the concave parts of the skins having alternating curvature.

By changing the kinematic loading scheme, it is meant that additional forces are applied to the sheet blank, both in the longitudinal direction and in the transverse direction. Also, this group includes methods based on manipulating the angles of coverage of the workpiece of a tight-fitting punch, as in the case of a stepped covering [18] or, as in the case of covering over two tight-fitting punches [19]. In the transverse direction, forces are applied through the use of a clamp. As a rule, the clamp is resorted to in the case of the formation of the concave parts of the shells with alternating curvature. In the case of longitudinal-transverse tightening, there is a differentiated application of forces to the side edges of a wide workpiece by means of additional stretching devices. This makes it possible to smooth out the corrugations arising in the process of shaping the shell [20] or by sequential stretching of the shell, preliminary stretching of the flat billet to a full angle, unloading and unbending of the shell to a small angle of wrap, followed by repeated wrapping of the shell in the isometric state [21].

There are two main types of wrap angle manipulation:

- pre-bent at a small angle of coverage, the sheet blank is tightened along the tightening punch, stepwise, with a certain step, increasing the angle of coverage to the full value [18] and with longitudinal-transverse covering, stretching the central flat part of the workpiece when tightening trough-shaped parts [20];
- the sheet blank is preliminarily tightened along the tightening punch to the full angle of coverage, then unloaded and unbent to a small angle of wrap, followed by re-tightening along the second tightening punch [19] or with subsequent re-tightening of the shell in the isometric state to the full angle of coverage along the same tight punch [21].

Both types of manipulation of the wrap angles allow to obtain shells with a more uniform distribution of thickness, both in the longitudinal and in the transverse directions.

The plasticity of the material of the sheet blank can be increased by treating it with a pulsed electric current [22] or by heating during the forming process [23]. These heating methods make it possible to obtain titanium alloy shells with large wrap angles. This is achieved by further increasing the degree of ultimate deformation in one pass. By changing the resistance to deformation of individual sections of the workpiece is meant intensification by changing the values of the required forces, for the shaping of certain individual areas of the workpiece in the process of shaping by the wrap. In this case, workpieces of various widths, local heating, as well as linings made of various materials [13, 24] can be used, which increase the thickness of the workpiece in places where the tensile deformations are maximum.

The developments given in [21] apply the conditions of symmetrical tightening due to external structural changes of the tightening punch. They provide for the correspondence of the texture axes of symmetry of the properties of the sheet blank and the directions of the lines of curvatures of the shell of
double curvature intersecting at the geometric pole of the surface of the drawing punch, as well as the location of the vertical plane of symmetry of the drawing press. This plane will pass through the geometric pole of the surface of the covering punch and the middle of the central clamp of the sheet blank.

As a result, not only the mechanical and deformation properties of the sheet material are taken into account, but also their directionality. The directionality determines the magnitude and nature of the anisotropy of the properties of sheet metal, which will ensure stable control of the processes of shaping by wrapping shells of double curvature with a uniform change in thickness in different areas of the sheet blank without folds and ruptures. To do this, it is necessary to perform a geometric study of the covering punch in another operating system using metric transformations.

These methods make it possible to provide a more uniform distribution of the thickness of the workpiece by:

- an additional increase in the degree of local deformation, in the area where the workpiece had not been stretched before;
- reducing the degree of local deformation in the area where the workpiece is excessively stretched;
- the use of one or another kinematic scheme, which is accompanied by the oncoming movement of the boundaries of the deformation zone while maintaining the location of the greatest deformations in the central region of the sheet blank.

Obviously, most of the above methods for intensifying the skin are aimed at solving the problem of uneven distribution of skin thickness. As can be seen from the above, most of the methods solve the problem of uneven thickness distribution. At the same time, only one method aimed at eliminating corrugations with the help of additional stretching devices partially solves the problem of smoothing corrugations. However, as practice has shown, the shaping of a sheet blank under conditions of symmetric wrapping significantly reduces the likelihood of corrugations and folds [13, 14]. At the same time, additional stretching devices are designed for thin skin [20] and additional allowances for the width of the workpiece are required.

In our opinion, the main way to solve the above problems is to develop a system for adaptive control of the process of shaping sheet parts by wrapping. The adaptation consists in automatic real-time correction of the original control program, depending on the actual mechanical properties and the required deformations of the workpiece in the characteristic places of the skin, taking into account the geometric shape.

4. Adaptive wrap forming control

When creating conditions for symmetric wrapping due to external structural changes to the wrapping punch, great advantages can be obtained in design automation and control of the shaping processes of wrapping shells of any surface, as well as complex geometric shapes. Now it is possible to select on such a surface the position of the shaping contour of the tightening punch, which will be aligned with the longitudinal vertical plane of the press, including the surface pole and passing through the middle of the central jaw. For the contour of the central section of the surface, it is quite easy to establish the location of the axis of axial symmetry for a classical second-order surface contacting at a pole. Therefore, the properties of the local shape at the pole of the surface of the tight-fitting punch are easily determined, which greatly facilitates the analytical approach to modeling, which adequately reflects the real process of shaping by the tight-fitting.

However, the implementation of stable control of the shaping processes by wrapping shells, close in geometric shape of the shell, with a uniform change in thickness in different areas of the sheet blank without folds and rupture, is possible only on stretch presses with programmed control. In addition, it was provided for the correspondence of the texture axes of symmetry of the properties of the sheet blank
and the directions of the lines of curvatures of the shell of double curvature, intersecting at the pole of the surface of the covering punch.

Stable control of the shaping processes by the wrap is based on the initial position of the deformation zone in the central region of the sheet blank. The shaping of the sheet blank according to one or another kinematic loading scheme is accompanied by the counter movement of the boundaries of the deformation zone while maintaining the location of the greatest deformations in the central region of the sheet blank. This allows you to increase the degree of shaping, practically in one transition with a minimum probability of sheet breaking in one of its free sections between the edge of the punch and the press clamps.

At the same time, the use of computer and CNC facilities for the independent manufacture of a covering punch for the implementation of symmetric covering conditions in practice has increased the efficiency of using modern digital technologies. For this, it is required to develop a toolkit for converting the coordinates of the clamping elements into the parameters of the working bodies of the press and vice versa - the parameters into coordinates. It is necessary to have a kinematic model of the covering press, which will allow observing the position of the working bodies of the press in each frame of the control program. Now it is possible to perform the necessary adjustment of the parameters of the control program directly in the Unigraphics software environment based on the results of modeling a particular wrapping method using the PAM-Stamp or ANSYS/LS-DYNA software package. Therefore, the development of an automated system for the production of bypass-forming elements of aircraft became possible using modern simulation tools, calculating the tensile and thinning deformations of the sheet at individual characteristic points of the double curvature shell surface.

Accordingly, when designing a system for adaptive control of shaping by wrapping a sheet blank, it is necessary to determine the following:

- Rejection signs by which the control program will be optimized.
- A method for measuring the values of physical processes that affect the occurrence of rejection signs.
- Techniques for reducing and eliminating the likelihood of rejection signs.
- The method of constructing a mathematical model, on the basis of which the efforts and displacements of the working bodies of the covering equipment will be recalculated.

Ideally, the amount of waviness and uneven thickness distribution should be minimized, and wrinkling and tearing should be completely eliminated. In order to minimize these values, it is necessary to track the deformations of the workpiece using the digital image correlation (DIC) method, together with the movements and forces on the working bodies of the pressing equipment using sensors. In this case, the recorded deformations of the workpiece and the data from the sensors must be compared with the data available in the system software.

The model underlying the digital twin is calculated by the finite element method, and has the ability to almost instantly automatically update and correct in the case of not only deformation of the workpiece, but also displacements and efforts of the working bodies of the pressing equipment. When updating the finite element model on the digital twin, the control program is automatically recalculated, which is then transmitted to the sensors of the working bodies of the pressing equipment. Such a scheme of adaptive control of the shaping process by a wrap is shown in figure 2.
Figure 2. Ideal system of adaptive control of pressing equipment for shaping by wrapping double curvature skins.

Problems of the proposed system of adaptive control of wrapping equipment for shaping wrapping of double curvature shells:

1. FEM implies a long calculation time. In order to reduce the computation time, the digital twin will need to work on a supercomputer with a processor with 54,000 cores, each of which has a frequency of at least 3 Hz. The cost of such a supercomputer is tens of millions of rubles.

2. The speckle pattern applied with a water-based paint will need to be removed very carefully as it is applied to the outer surface of the skin overlooking the theoretical contour of the aircraft. The second disadvantage of the speckle pattern is the complexity of the application when covering with annealing between operations. The problem is that before annealing, it is necessary to remove the speckle pattern, which increases the duration of the plating manufacturing process by at least 20 minutes (it is necessary to wait until the wash swells the speckle pattern for further removal). After annealing, it is necessary to apply a speckle pattern and carry out a polymerization reaction using drying installations (for example, infrared lamps), which also adds 10 minutes to the labor intensity of the process. Plus, for the application of the speckle pattern, a special area must be allocated, equipped with exhaust ventilation and personnel qualified to carry out painting work. The cost of a Digital Image Correlation (DIC) system is significantly lower than that of a supercomputer and comparable to the cost of a stretch press equipment.

As a result of the above, one of the ways to solve the problem is a number of optimal pre-calculated finite element models, according to which the wrapping process is performed without preliminary and inter-transition heat treatment. Due to the lack of heat treatment, the parameters of the wrap forming process become more predictable. Thus, the measured sheet deformations using cameras in the digital image correlation (DIC) system will be within a certain range of scatter. Having a range of spread of sheet deformations during stretching at a certain stage of shaping, it will be possible to calculate a number of finite element models in advance within 1-2 days on a computer that is fairly average in terms of processor characteristics (for example, having 6 cores, 3 Hz each).

The process itself will look like this: the workpiece is inserted into the clamps of the press, stretched with clamps, and a tightening punch. In the process of deformation, the digital image correlation (DIC) system captures the process. The process itself is recorded by high-speed cameras, which is
automatically calculated in advance and compared with the available finite element models. Also, using feedback sensors from the working bodies of the pressing equipment, the data of forces and displacements are transmitted to a personal computer with finite element models and control programs. The closest finite element model to the measured deformations of the workpiece and displacements with the efforts of the working bodies of the press is selected as the main one and the related control program is activated.

It is believed that the use of the proposed scheme will allow:

- exclude or minimize manual labor on fine-tuning the shape of the workpiece;
- modernize the control system of the motion of the actuators (clamps, lifting table, portal) of existing tying presses;
- improve the quality of skins by ensuring a more uniform distribution of the thickness of the workpiece after deformation and reducing the value of its waviness;
- exclude breaks of workpieces.

Further research is aimed at developing finite element models of the wrapping processes, with a method for recalculating the simulation results into the control program of the pressing equipment.

5. Summary

The focus is already on the research carried out by the finite element method in modeling the processes of shaping a sheet blank by a tight-fitting punch placed on the table of a virtual stretch-drawing press. The use of computer and CNC facilities for the independent manufacture of a covering punch to implement the conditions of symmetric covering in practice will increase the efficiency of using modern digital technologies.

It is necessary to create a complex model and a computational algorithm by the processes of shaping by wrapping, accumulating many years of experience in operating domestic stretch presses, theoretical and experimental developments, patents that allow calculating the tensile and thinning deformations of the sheet at individual characteristic points of the double curvature shell surface.

However, the achievements of modern information technologies, raising the level of technologies based on the digital twin - the digital representation of the object, have led to the need to use the accumulated production and technological experience, the available developments in the field of storing and operating with information and applying in various fields. This made it possible to determine the main directions of improving the processes of shaping by wrapping shells of double curvature.

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