Research on the influence of deformable sheet aluminum alloy rheological behavior on stretch forming process limits

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Abstract. Our research was aimed at modeling a symmetrical wrapping and stable control of the processes of shaping by wrapping a sheet blank along a wrapping punch having a double curvature surface and placed on the table of a virtual stretch-tightening press. The main task of modeling was to determine the deformed state with a uniform change in thickness in different regions of the sheet blank without folds and breaks, but without the influence of the rheological behavior of the deformable aluminum alloy. Here, the LS-DYNA software package is used with the use of an explicit or implicit solver for nonlinear problems of solid mechanics, characteristic of nonequilibrium transitions of the initial dissipative phase due to viscosity and heat transfer. Now it is possible to predict defect formation from a practical point of view, using the forming limit diagram (FLD), which makes it possible with sufficient accuracy to determine the degree of deformation of a given sheet material, at which any defects do not occur. The presented results of the study revealed the features of the influence of the rheological behavior of a wrought sheet aluminum alloy on the limits of the shaping process by a wrap.

1. Introduction
The development of new processes of shaping by a double-curvature shell is to a certain extent restrained by the poor knowledge of the rheology of the behavior of sheet aluminum alloy in the annealed, especially in the freshly hardened state. In addition, there is no information about the influence of a particular rheological state of the material on the stress-strain state in these processes, which determine the nature of the flow of a deformable sheet blank and the formation of the quality of the finished product. The rheological behavior of deformable materials is quite fully characterized by flow curves: \( \sigma - \varepsilon \), which reflect the interaction of strain hardening processes and dynamic softening processes [1]. Any deformable material can be represented as a set of elementary models: elasticity, viscosity and plasticity [2]. In our opinion, the behavior of a deformable body in all its diversity is most accurately reflected by a medium where a «spring» describing strain hardening is included in series with a viscous element that simulates diffusion-relaxation processes.

It is known that heat treatment of deformable aluminum semi-finished products, in particular sheet, has a significant effect on their structure and properties. A wide variety of structures that can be obtained in aluminum alloys D16 and 1163 after different heat treatment is the result of different degrees of deviation of alloys from the thermodynamic equilibrium state at room temperature [3]. The equilibrium (annealed) state of thermally hardened aluminum alloys is a solid solution with a low content of alloying
elements (tenths of a percent). With this phase composition, the alloy has low strength and very high ductility.

The most unstable structure at room temperature in thermally hardened aluminum alloys is a supersaturated solid solution of alloying elements in aluminum, the concentration of which can exceed the equilibrium state by tens of times. With this structure, the aluminum alloy is also very ductile, but stronger than in the equilibrium state. The instability of the freshly quenched state of the alloy at room temperature and the tendency at the initial stage to premature decomposition of the supersaturated solid solution technologically limits the possibilities of shaping the sheet material by the skin. However, this intermediate structure, which corresponds to the initial stages of the decomposition of a supersaturated solid solution, attracts attention. There are results of stabilization of the freshly hardened state of an aluminum alloy under regulated heating for hardening and holding the freshly hardened sheet blank in the cold before the forming operation [4].

If the deformation of the sheet blank during shaping occurs under such conditions when the diffusion-relaxation processes are inhibited, then the work of the viscous element can be neglected and a model of an elastoplastic body with strain hardening can be considered. Strain hardening is accompanied by an increase in the nonequilibrium of the system, i.e. a forced process that occurs due to external forces. In turn, the spontaneous diffusion-relaxation process is inverse, removing the strain hardening.

The main goal of modeling the process of shaping by wrapping shells of double curvature is to select the technological mode of sheet shaping with minimization of rejection and maximization of the degree of shaping at an acceptable level of thinning of the sheet blank. Simulation of the process by the finite element method is carried out on a covering punch, with a surface oriented relative to the curvature lines and placed on the table of a virtual stretching press, which leads to symmetry during shaping by a covering [5]. In LS-DYNA, the modeling of sheet material in the process of shaping with a wrap has become reliable after the introduction of a number of algorithms. These include:

- adaptive rebuilding of the mesh of the workpiece finite elements; generation of a specialized mesh for contact sheet forming;
- models of material behavior for sheet forming, taking into account the anisotropy of the sheet, such as Barlat (MAT_036) and Hill (MAT_037);
- advanced post-processing for sheet forming processes, including building FLD.

Now it is possible to perform the necessary adjustment of the parameters of the control program based on the results of modeling a particular wrapping method using the ANSYS/LS-DYNA software package, using a number of pre-calculated finite element models for controlling the shaping of the wrapping on a stretching press. The development of an automated system for the production of bypass-forming elements of aircraft has become possible with the use of modern simulation tools. The operator of the software complex selects a model of material behavior, enters into the computational model the geometry of the tightening punch and the dimensions of the sheet blank, constants from the material database, selects the characteristics of friction. Next, the solver calculates stresses, strains and displacements based on the input data on materials, geometry, dimensions, boundary conditions. At the same time, the system predicts the moment of destruction or formation of folds of sheet material. Therefore, when designing an optimal shaping scheme with a wrap, it is necessary to have specific information on the current state of the sheet material, using the FLD diagrams of the limiting shaping of the sheet material during modeling.

At this stage of modeling the shaping process by the wrapping, we used the toolkit of the graphical user interface (Create and control RO-630) of the computer application of the kinematics control system of the virtual stretch-tightening RO-630-11. In practice, we have just started machine learning of the control system. In the course of the preparation, more than three dozen numerical calculations were carried out, as a result of which a stable kinematic model of the shaping process by a wrap was developed, which significantly reduces the degree of uneven deformation of the sheet blank.
A decrease in the thickness difference of the double curvature shell formed by the covering was carried out in the modeling process by manually adjusting the values of the controlled coordinates on the graphical control interface of the virtual model of the RO-630-11 stretch-tightening press based on the results of the analysis of the thickness values at the points indicated by us on the surface of the sheet blank. Two innovative wrap shaping methods have been proposed, each with a control parameter matrix. The preparation of geometric models of elements for calculation in the LS-DYNA processor was carried out in the LS-PREPOST program.

It was necessary to go through a cycle of machine learning of the control system using the graphical user interface toolkit (Create and control RO-630) to control the kinematic movements performed by the working bodies of the press. Using the example of a simple user, the control system allows you to accurately simulate the real kinematics of the RO-630-11 stretch-tightening press, using grounded kinematic methods of forming the cover. Matrices of press control parameters were generated in the form of animation for both methods. At the stage of calculations, the calculation results were sequentially checked and possible adjustments that had to be made to the animation in question were evaluated in order to send a new animation into the calculation, comparing the current results.

This took a lot of time from us and so far we decided to carry out mathematical modeling of one of the method options taking into account the influence of the rheological behavior of the wrought aluminum alloy under various annealing modes, hardening conditions and friction conditions of the sheet on the surface of the tightening punch. The main object for the analysis and optimization of the method is the graphs of deformation and thickness changes at characteristic or selected points on the surface of the sheet blank. To visualize the size and shape of the deformation zone in a particular method of wrapping, we used the data of the simulation results, drawn up in the form of graphs, histograms of thickness changes. Analysis of the histograms allows you to make a conclusion about the state of the process. By the simplicity of its construction, the histogram gives useful information about the spread of indicators (shell thickness), average values, accuracy and stability of technological processes, and the accuracy of the kinematics of technological equipment.

2. Application of FLD curves for sheet forming simulation

An important step in the production of aircraft skin sheet components is the development of forming limit diagrams (FLD), which are composed of forming limit curves (FLC). First introduced by Keeler [6] and Goodwin [7], FLC is an empirical relationship between critical (or limiting) strains in a plane that describe the deformability limits of a sheet material. FLCs distinguish combinations of major and minor deformations that are «safe», that is, for which a given combination of deformations in the FLD is not expected to fail. Major deformation occurs vertically (y-axis) and minor deformation occurs horizontally (x-axis) FLD [8]. Localized necking is usually of interest to the fracture mechanism itself, since the necking regions are potential sites for fracture (note that the key differences between «diffuse» and «localized» necking are detailed in Hosford and Cadell [9].

Efforts are currently under way to develop stress-based FLD. The stress-based approach has some advantages over the widespread strain-based approach, which may well lead to its becoming the preferred method in the future. Because experiments can be costly and time consuming, some effort has been made to predict strain-based FLD using various theoretical methodologies. The theoretical prediction of FLD for sheet materials relevant to the transport industry was based on one of three existing theories.

The first one belongs to Hill, and it is assumed that a band or neck of localized deformation is formed along the direction of zero tension, and there is an angle between the normal direction of the neck in the plane of the sheet and the direction of the main deformation: this is the so-called «hypothesis of zero elongation». However, Hill's zero elongation hypothesis is only applicable to the left side (LHS) FLD, since there is no direction of zero elongation in a positive slight strain stretched sheet, and of course, predicting localized necking is not possible.

The second theory is based on the hypothesis of the groove (or inhomogeneity of the initial thickness) by Marcinyak and Kuchinsky [10], also known as the «MK theory». It postulates that a localized neck
arises from a geometric discontinuity or groove in the initial thickness of the sheet from which the localized neck develops. The obvious physical significance of the MK theory and its simple mathematical form have contributed to its widespread application for more than four decades. Unfortunately, MK models are overly sensitive to the assumed initial thickness inhomogeneity. In addition, several studies have been published that question the extent to which the underlying geometric discontinuity is a direct cause of local necking. For example, Zhang and Wang [11] showed that localized geometric softening at a certain strain state is in fact the cause of localized necking in 2036-T4 aluminum, rather than the initial geometric inhomogeneity.

The third theory is Storen and Rice’s vertex theory [12], also known as the «STO theory». Here, it is assumed that the localized necking corresponds to the angle or vertex that develops on the yield surface at the loading point.

Theoretical prediction of the FLD of sheet alloys requires a yield criterion and a hardening model. Various non-quadratic tests developed recently are good candidates. F. Barlat [13] proposed high-order yield criteria known as Yld89, Yld91, Yld94, Yld97, Yld2000 and Yld2004, respectively. Hill’s fluidity criterion, known as Hill’s criterion since the 1950s, is still used today because it has a relatively simple mathematical form. Most theoretical methods based on the high-order yield anisotropy criterion do not account for in-plane anisotropy due to mathematical complexity. Predicting defect formation from a practical point of view makes it possible with sufficient accuracy to determine the degree of deformation of a given sheet material, at which no defects arise. In production, this possibility is extremely important, especially when shaping the skin parts of the aircraft. One way to determine the allowable deformation for sheet materials is to use a forming limit diagram (FLD).

Forming limit diagrams are constructed experimentally for each grade of sheet material based on test results under various stress states. The plane strain limit corresponds to the point where the FLC intersects the major strain axis. The data required to create the FLD is produced in a series of additional experiments on special equipment. The field on the surface of deformed samples is measured either with etched grids consisting of an array of circular elements or with digital image correlation, using an optical method of displaying the whole field.

The ordinate of the diagram shows the largest principal deformations, and the abscissa shows the smallest principal deformations. The resulting curve is called the ultimate shape change curve. The region of positive values of deformations $\delta_2$ corresponds to biaxial tension, at $\delta_2 = 0$, a plane deformed state is observed, in the region of negative values of $\delta_2$, uniaxial tension. The shape and location of the ultimate strain curve is unique for each material (figure 1).

![Diagram of ultimate deformations](image)

**Figure 1.** Diagram of ultimate deformations.

The forming limit diagram is valid in cases where the ratio of the main plastic strains is constant throughout the entire deformation process, that is, the deformation is monotonic. The diagram is divided into zones, the combination of the main deformations in which predicts a particular defect.
3. Different rheology behavior of aluminum sheet material

To compare the various rheologies of the behavior of aluminum sheet material, we use the results of modeling in the ANSYS/LS-DYNA software package of the process of forming a wrapped anisotropic sheet blank, primarily in the state of an elastoplastic body under strain hardening. As a rheological model of the material for the billet, the 3-Parameter Barlat Model was used - a model used to simulate aluminum sheet material under conditions of a plane stress state. For this material rheology, it was necessary to first create a local coordinate system taking into account the rolling direction of the sheet blank. The properties of the material of the workpiece according to the 3-parameter Barlat model are summarized in table 1.

However, when analyzing the simulation results, some inconsistencies with the cases observed in practice appeared, the breaks of the sheet blank in the process of its shaping. In the modeling, the results of which are given in [14-15], attention was paid, first of all, to the symmetric covering due to the external symmetry of the shaping punch relative to the main planes and directions in the «pole» of the double curvature shell. At the same time, the alignment of the directions of the lines of the main curvatures in the «pole» of the shell surface with the directions of anisotropy of the orthotropic sheet blank (directions along the RD (rolling direction) and across the TD (transverse direction) of the rolling direction of the sheet) was also ensured.

An EVP-model (Elastic Viscoplastic Thermal Model) is used as a rheological model of the material for the workpiece, which makes it possible to take into account internal friction with an irreversible transition of elastic energy into thermal energy. This is a complex rheological model of an elastic-viscoplastic medium. Low stresses during pressure treatment, high plasticity and formability easily explain the ability of the alloy under the considered rheological state to viscous flow. The EVP model of the medium can describe the rheology of the sheet material during shaping over a wide range of strain rates.

The irreversible transition of elastic energy to heat is a relaxation process that restores the disturbed equilibrium during deformation of the workpiece by activating diffusion. In annealed alloys in an equilibrium stable state, the mobility of atoms is uniquely determined by the energy of the interatomic bond, i.e. the energy of the ground state, where the diffusion activation energy is equal to a constant fraction of the binding energy. In a nonequilibrium unstable state, as a result of distortion of the crystal lattice, temporary energy barriers are created for atoms of different heights. The mobility of atoms and the activation energy in such a state depends on the values of these barriers, which are determined by structural features, i.e. depends on the energy of the transition state and is not directly related to the energy of the ground state.

As a result, the external force field from the working bodies of the press, spreading over the sheet material, can be scattered. When deformed, the material begins to absorb mechanical energy to one degree or another. The accepted model can describe the rheology of the elastic-viscoplastic flow of the material, which exhibits the effects of quasi-plastic deformation. They can be associated with the
activation of diffusion along the boundaries or near the grain boundaries. From the rheological point of view, the elastic-viscoplastic flow of the material can be attributed to the quasi-liquid phase of the deformable material. The properties of the material of the elastic-viscoplastic behavior of the workpiece material are summarized in tables 2, 3, 4, 5 and 6.

Table 2. Properties of the workpiece material according to the EVP model of the elastic-viscoplastic behavior of the workpiece material.

| Parameter                  | Designation | Dimension | Parameter value |
|----------------------------|-------------|-----------|-----------------|
| Density                    | DENS        | kg/m³     | 2700            |
| Coefficient of thermal expansion | ALPX | m/m-C | 2.1E-005    |
| Elastic modulus            | EX          | Pa        | 7.2E+010        |
| Initial yield stress       | In Yld Sts  | Pa        | 1.12E+008       |
| Load curve ID              |             |           |                 |
| LCID1                      |             |           | 1               |
| LCID2                      |             |           | 2               |
| LCID3                      |             |           | 3               |
| LCID7                      |             |           | 7               |

The loading curve is a functional dependence of the parameters and is set by the ratio of tables with data on the values of these parameters. For a given material, four load curves are set:

- LCID1 - function of effective stress on effective plastic deformation.
- LCID2 - a function of the dependence of the elastic modulus on temperature.
- LCID3 - Poisson's ratio function on temperature.
- LCID7 - function of the dependence of the coefficient of thermal expansion on temperature.

Table 3. Load curve parameter values 1 (LCID1).

| Parameter          | Designation | Dimension | Value number |
|--------------------|-------------|-----------|--------------|
| Effective stress   | STRESS      | MPa       | 0 340 375 405 423 438 |
| Effective plastic strain | STRAIN | –         | 0 0.05 0.1 0.15 0.2 0.3 |

Table 4. Load curve parameter values 2 (LCID2).

| Parameter          | Designation | Dimension | Value number |
|--------------------|-------------|-----------|--------------|
| Elastic modulus    | EX          | MPa       | 67000 66000 65000 52500 |
| Temperature        | TEMP_EX     | °C        | 100 125 150 175 |

Table 5. Load curve parameter values 3 (LCID3)

| Parameter          | Designation | Dimension | Value number |
|--------------------|-------------|-----------|--------------|
| Poisson's ratio    | NUXY        | –         | 0.3137 0.3195 0.3252 0.3478 |
| Temperature        | TEMP_NUXY   | °C        | 100 170 240 310 |

Table 6. Load curve parameter values 4 (LCID7)

| Parameter          | Designation | Dimension | Value number |
|--------------------|-------------|-----------|--------------|
| Coefficient of thermal expansion | ALPHA | m/m-C | 2.1E-005 2.94E-005 4.85E-005 11.7E-005 |
| Temperature        | TEMP_ALPHA  | °C        | 100 200 300 390 |

Aluminum alloys that undergo phase transformations during deformation can show, under certain conditions, elastic-viscoplastic behavior, independent of the deformation rate. However, it is impossible
to establish how the rheological state of the material changes in the process of phase transformation, accompanied by a strong change in the structure upon deformation. In [16], it was concluded that islands of the «quasi-liquid» phase can appear for a short time in the process of phase transformation at the grain boundaries of the heterogeneous system. The existence of islands of the «quasi-liquid» phase at grain boundaries is substantiated from a thermodynamic point of view. The material may not deform as a viscoplastic medium, and then, for example, in the middle of the phase transformation, it may show a linear-viscous state and then will not return to its original state. This behavior of materials deformed during phase transformation was recorded during polymorphic transformation of pure iron [17].

4. Methodology, hardware and software
When investigating the influence of the rheological behavior of a deformable sheet aluminum alloy on the limits of the shaping process of a double curvature shell, it is necessary to have specific information on the deformed state of the sheet material using FLD diagrams of the limiting shaping of the sheet material during simulation. The construction of the ultimate strain curve is based on the ISO 12004-2 standard. FLD construction is carried out by two main methods: the Nakazima method and the Marchignac method. To accurately determine the FLD points, friction between the punch and the workpiece must be almost completely eliminated. The Nakazima method is based on the use of a hemispherical punch to deform the workpiece and on the use of a multi-layer lubricant between the punch and the workpiece. One FLD uses one specific multi-layer grease. One of the following blanks is used: a round blank with a parallel fillet in the center; round blank with round cutouts along the edges (applied to biaxial tension). Examples of workpieces are shown in figure 2. By changing the fillet width, cut radius or workpiece width, various deformed states are obtained. Different strain states give different points on the ultimate strain curve. The samples were tested on a Zwick Roell BUP200 universal testing machine. Forming limit diagrams were constructed experimentally for a certain brand of sheet material based on the results of tests under conditions of various stress states (variability is achieved through the manufacture of blanks with different sizes of the bridge).

![Figure 2](image_url)

**Figure 2.** Deformed states depending on the width of the fillet of the workpiece.

Varying the width of the fillets and the radii of the cutouts in the samples is required to construct the FLD by points, which allows you to obtain various stress-strain state in the workpiece during deformation. The sample without side cutouts produces a point on the FLD curve that corresponds to bilateral tension \( \delta_1 = \delta_2 \); a sample with maximum notches allows obtaining a point that approximately corresponds to uniaxial tension \( \delta_1 = -2\delta_2 \). When testing blanks by the Nakazima method, the results were obtained for plotting the curve of the limiting shape change in the uniaxial tension zone, the value of \( \delta_1 \), at plane deformation and in the biaxial tension zone for the original sheet material of aluminum alloys 1163RDMV, 1.5 mm thickness. Four samples were taken for one point. Figure 3 shows the curves of the limiting deformation of each specimen and shows the average values in the zones of uniaxial and biaxial tension. The original sheet billet made of aluminum alloy 1163RDMV, 1.5 mm thickness and
dimensions in terms of 1880x10500 mm x mm. Sheathing (B) sheet of grade 1163 alloy with regulated hard plating (HP), in annealed condition (M).

Figure 3. Experimentally obtained FLD diagram for sheet material 1163RDMV, 1.5 mm thickness.

For the main shaping operation, we give preference to the weakened state. According to the VIAM instruction No.904-67, in addition to the initial state, we will subject this alloy to five different anneals and one quenching:

- Full annealing: 380 ... 420°C., exposure for 30 minutes, cooling with an oven, then in air. Options: 1a - temp. 360°C., 1b - 400°C, 1c - 420°C.
- Reduced annealing: 360°C, holding for 30 minutes and cooling: 2a - air, 2b - water.
- Hardening: 500 ... 505°C., Holding for 30 minutes and cooling in water at room temperature.

The range of values of the coefficient of friction is quite wide, which is associated with the study of various rubbing pairs. The following values of the coefficient of friction were determined:

- 0.08 - fluoroplastic and lubrication with machine oil; rubber grade 7338 with grease lubrication; film B-118 and grease lubrication. In addition, later studies of rubbing pairs, which include a cast metal punching punch made of secondary aluminum, showed that an oxide film with fluorinated graphite and a plasma layer of aluminum bronze BrA10, even with dry friction, provides a friction coefficient of 0.04.
- 0.1 - this value is found in several rubbing pairs that are typical for production.
- 0.2 - this value most often refers to the friction of an aluminum sheet and a covering punch from a sand-glue mass.

The mechanical properties of sheets of alloy 1163RDMV after each annealing were obtained in the course of testing four samples and statistical processing of the results. The results of mechanical properties after testing and processing are summarized in table 7.

The preparation of geometric models of elements for calculation in the LS-DYNA processor was carried out in the LS-PREPOST program. All geometry is exported for further processing, which is presented in the form of creating a mesh, specifying the main parameters, generating an output calculation file, and so on. The necessary formatting for the installation and preparation of the initial data for the calculation is carried out in the graphical user interface (Create and control RO-630) of the computer application of the developed control system, which is used to perform actions.
Table 7. Mechanical characteristics of samples in the initial, freshly hardened state and various annealing.

| Mode | $\sigma_n$ [MPa] | $\sigma_{0.2}$ [MPa] | $\delta_{n}$ | $\mu_{21}$ (0) | $\mu_{12}$ (90) | $\mu_{1}$ (45) |
|------|------------------|----------------------|-------------|----------------|----------------|----------------|
| 420  | 173              | 56                   | 0.164       | 0.404          | 0.426          | 0.468          |
| 400  | 157              | 41                   | 0.142       | 0.308          | 0.311          | 0.342          |
| 380  | 154              | 44                   | 0.1846      | 0.325          | 0.280          | 0.308          |
| 360 2a| 159             | 47                   | 0.149       | 0.366          | 0.383          | 0.421          |
| 360 2b| 155             | 40                   | 0.0669      | 0.293          | 0.328          | 0.360          |
| ishod| 158              | 69                   | 0.113       | 0.4             | 0.428          | 0.4708         |
| sveshezak | 357        | 189                  | 0.199       | 0.258          | 0.364          | 0.383          |

The computer application of the control system consists of a simplified three-dimensional virtual model of the RO-630-11 stretch-tightening press and a graphical user interface designed to control the kinematic movements performed by the working bodies of the press, which makes it possible to accurately simulate its real kinematics using grounded kinematic shaping schemes. In addition to this, the interface includes control and positioning of each working body of the virtual press. As a result, it will be possible to customize the animation of the movements of the working bodies of the press for a specific shaping process. In figure 4, the virtual model of the RO-630-11 stretch-tightening press contains 10 controlled coordinates: LB1, LB2, LB3, LB4, STO1, STO4, PB1, PB2, PB3, PB4 (main and auxiliary hydraulic cylinders of the press).

![Figure 4. Three-dimensional virtual model of the stretching and drawing press RO-630-11.](image)

To simulate the process using the computer application of the kinematics control system of the RO-630-11 virtual stretch-tightening press, a diagram of the step movements of the main and auxiliary working cylinders of the press was previously obtained using kinematic techniques in the presence of two effects. This made it possible to minimize the thickness difference of the simulated shell to the recommended limits. To create the conditions for symmetric wrapping, it is necessary to import the skinning punch surface (the model of the skinning punch in IGES format) into a curved coordinate system, to a double curvature surface attached to the grid of the main curvature lines with a pole point.
as the origin. As a result, we have left one version of the kinematic methods of shaping by the tight-fitting. So far, we decided to simulate one option, taking into account the influence of the rheological behavior of the wrought aluminum alloy. The features of the properties of sheet material under various modes of annealing, quenching and conditions of friction of the sheet on the surface of the tightening punch are given above.

The considered variant of the shaping method by the wrap provides a uniform change in thickness in different areas of the sheet blank without folds and breaks. It includes an innovative element at the outset where the slab was forced flat with rectilinear discrete clamping devices. This provides a plastic configuration of the middle part of the sheet blank without localizing the thinning deformation and sheet breakage in one of its free sections between the edge of the punch and the press clamps. The second innovative element is associated with the formation of the second curvature of the shell surface due to the position of discrete clamping devices along the contour after the plastic configuration of its middle part and unloading, providing, upon subsequent stretching of the shell, deformation of only the corner parts of the sheet blank.

5. Results of the influence of the rheological behavior of a wrought aluminum alloy on the limits of the shaping process

In figure 5, the results of calculations in the LS-DYNA processor of the values of the main deformations $\delta_1$ and $\delta_2$ are collected in separate files for their placement on FLD forming limit diagram of the sheet material of one of the annealing options. The minimum difference in thickness refers to the case when a sample of sheet material made of alloy 1163 passed the reduced annealing $360^\circ$C at a soak time of 30 minutes and was cooled in water. All samples were cut in the direction of sheet rolling. The mechanical characteristics of the samples for this case were: ultimate strength - 155 MPa; yield point - 40 MPa; uniform elongation - 6.69%; hardening index $n = 0.386$, tangential modulus - 440.2 MPa and anisotropy coefficients $\mu_{11} = 0.293$, $\mu_{12} = 0.328$ and $\mu_1 = 0.361$.

![Deformed state (equivalent deformations) of the shell under study](image)

**Figure 5.** Deformed state (equivalent deformations) of the shell under study (calculation option - annealing at 360°C, holding for 30 minutes, air cooling and friction coefficient of 0.20). Calculations are performed in the LS-DYNA processor (finite element mesh is off).

The limiting deformation of the shaping process by the wrap was evaluated in the LS-DYNA postprocessor. The dialog for working with the diagram of ultimate deformations is called after clicking on the characteristic icon. Figure 6 shows the FLD post-processing for annealing at 360°C, holding for 30 minutes, cooling in air and with a friction coefficient of 0.20.
Figure 6. Post-processing FLD. The data source is taken from a separate file associated with the deformed state of the shell under study in figure 6.

The string fields «t =» and «n =» on the FLD diagram are responsible for the appearance of theoretical curves, one of which is displayed in the diagram by default in red and is responsible for fracture deformations, and the other is yellow, and shows the boundary of the theoretical safe deformation zone. The radio buttons «t_n» and «File» select the theoretical curve or the real one taken from the file. Figure 7 shows the result of processing the deformed state of the shell under study in the LS-DYNA postprocessor.

Figure 7. Result of processing the deformed state of the shell in the LS-DYNA postprocessor using FLD data (calculation option - annealing at 360°C, holding for 30 minutes, air cooling and a friction coefficient of 0.20). Compare with the colored area in the ultimate strain diagram (figure 1).

In figure 8, the results of calculations in the LS-DYNA processor of the values of the main deformations δ1 and δ2 are collected in separate files for their placement on forming limit diagram FLD of a material in a freshly hardened state.
Figure 8. Deformed state (equivalent deformations) of the investigated shell MAT_sveshezak_VISCOPLASTIC_ftr0.20 (calculation option - hardening: 500 ... 505°C, holding for 30 minutes, cooling in water at room temperature and friction coefficient 0.20). Calculations are performed in the LS-DYNA processor (finite element mesh is off).

The limiting deformation of the shaping process by the wrap was evaluated in the LS-DYNA postprocessor. The dialog for working with the diagram of ultimate deformations is called after clicking on the characteristic icon. Figure 8 shows post-processing FLD for hardening mode 500...505°C, holding for 30 minutes and cooling in water at room temperature and with a friction coefficient of 0.20.

Figure 9. Post-processing FLD. The data source is taken from a separate file associated with the deformed state of the shell under study in figure 8.

Figure 9 shows the result of processing the deformed state of the shell under study in the LS-DYNA postprocessor.
Figure 10. The result of processing the deformed state of the shell in the LS-DYNA postprocessor (calculation option - quenching: 500...505°C, holding for 30 minutes and cooling in water at room temperature, quenching at 505°C and friction coefficient 0.20). Compare with the colored area in the forming limit diagram (figure 1).

6. Summary
The main goal of modeling the wrapping process is to apply the graphical user interface toolkit (Create and control RO-630) of the computer application of the kinematics control system of the RO-630-11 virtual stretch-tightening press. A decrease in the thickness difference of the part formed by the stretch during the modeling process was carried out by manually adjusting the values of the controlled coordinates on the graphical control interface of the virtual model of the RO-630-11 stretch-tightening press based on the results of the analysis of the thickness values at the points designated by us on the surface of the sheet blank. The preparation of geometric models of elements for calculation in the LS-DYNA processor was carried out in the LS-PREPOST program.

At the computation stage, the calculation results were carefully checked and possible adjustments that had to be made to the animation in question were evaluated in order to send a new animation into the calculation, comparing the current results. Our research was aimed at creating conditions for symmetric wrapping and the implementation of stable control of the shaping processes of wrapping shells, close in geometric shape to the skin, with a uniform change in thickness in different areas of the sheet blank without folds and ruptures. Verification of material behavior models can be carried out on the basis of LS-DYNA. The only thing that remains to be introduced into the model is the criterion of destruction.

In production, the FLD chart can be used as this criterion, where the limit levels of deformation are indicated. In modeling, the main deformations in the model of the molded part are compared with the FLD: if the found deformations fall into the safe zone, then in production, the wrapping of the real metal will be successful. The result of processing the deformed state of the shell in annealed form in the LS-DYNA postprocessor using the FLD postprocessing data in our case indicates the absence of defects on the shell (the FLD zone is green). But in the case of processing the deformed state of the shell in a freshly hardened form, it indicates the danger of folds (FLD zone in blue).

We believe that the prediction of defect formation from a practical point of view makes it possible to determine with sufficient accuracy the degree of deformation of a given sheet material, at which no defects arise. In production, this possibility is extremely important, especially when shaping the skin parts of the aircraft from new sheet materials. The most unstable structure at room temperature in thermally hardened aluminum alloys is a supersaturated solid solution of alloying elements in aluminum, the concentration of which can exceed the equilibrium state by tens of times. In this state, the aluminum sheet is also very ductile, more precisely, very viscous, therefore, not resistant to shaping than in the equilibrium state.
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