RIGA TECHNICAL UNIVERSITY

Irina Belyaeva

COMBINED DEFORMING OF SHEET MATERIALS WITH THE USE OF THE PULSED MAGNETIC FIELD

Summary of Doctoral Thesis

Branch: Machine Science
Subbranch: Mechanical Engineering

Riga-2015

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Faculty of Mechanical Engineering, Transport and Aeronautics
Institute of Mechanical Engineering

Irina BELYAEVA

Doctorant of study Programme „Engineering Technology, Mechanics and Mechanical Engineering”

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THE PROMOTION WORK IS PRESENTED AT RIGA TECHNICAL UNIVERSITY FOR A DEGREE OF DOCTOR OF TECHNICAL SCIENCES

The promotion work for obtaining a degree of Doctor of Engineering Sciences is submitted for public defence on the ....2015 at Riga Technical University, Faculty of Mechanical Engineering, Transport and Aeronautics, 6k Ezermalas street, room 405.

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CONFIRMATION

Hereby I confirm that I have developed the presented dissertation which has been submitted for reviewing to Riga Technical University for a degree a Doctor of Engineering Sciences. This work was not submitted to any other university for a scientific degree.

Belyaeva I...(Signature)

Date:................................

The promotion work is written in Russian and comprises an introduction, six chapters, key conclusions and results of the work, references and two appendices. The work is set out on 162 pages of typewritten text, contains 122 figures and bibliography.

CONTENT OF WORK

1. USED TERMS

- *Folding* – technological process in mechanical engineering, in which take place deformation of materials in necessary direction.
- *Hybrid technology* in folding – folding process, envolving several deformation factors.
- *Combined folding* - folding process in which the workpiece simultaneously or sequentially is exposed to several sources of loading.
- *Bort of machine part* – side surface of machine part.
- *Pulsed magnetic field processing* – mode of metal plastical deformation in which process is going by the help of pulsed magnetic field.

2. ACTUALITY OF THE DISSERTATION

Combined technologies are of especially great interest to the automobile industry, first of all, to the operation of folding sheet metal. It is necessary to conduct exhaustive research of static-dynamic processes to ensure upgrading of quality of assemblies.

In this connection development of new combined technologies of folding is an urgent problem. The proposed technology of folding combines static and dynamic loadings. In this case a pulsed magnetic field is used as a source of dynamic loading. Pulse-magnetic loading has such advantages as contactless micro- or millisecond action. This makes it possible to perform the operation of folding in a single stroke of the press (without stopping it). Moreover, it is possible to simplify considerably the stamping tooling, to raise productivity and quality of finished products.

3. THE AIM AND TASKS OF THE WORK

The goal of the work: Upgrading of quality of assembly joints from a sheet metal with the help of the combined technology of folding which combines static and dynamic loadings.
To achieve this goal the following tasks have been solved:

- the technological scheme of the combined operation “folding” has been developed;
- the procedure of computer simulation of the static-dynamic process of deforming has been developed;
- influence of the form and intensity of load, geometrical sizes of a blank and tooling, their mutual arrangement on quality of assemble joints has been investigated;
- experimental studies of the fast-flowing stage of the folding process have been performed;
- the mechanism of deforming has been revealed and the scientifically-substantiated recommendations on control over the folding process have been developed;
- practical recommendations on the use of combined folding for production of automotive components have been developed;
- factors of economic efficiency of the new technical decision have been evaluated.

4. RESEARCH METHODS

To solve the set tasks, the following methods were used:

- Mathematic simulation of the process of combined stamping with application of numerical integration of systems of differential equations with the use of the computational medium MSC.NASTRAN/MARC;

- For modeling process determination it was used system CATIA.

- Experimental methods of determining the energy, force and deformation parameters for combined folding with the use of the pulse-magnetic technology and high-speed recording equipment.

5. SCIENTIFIC NOVELTY

1. Based on theoretical and experimental studies, it has been established that kinematics of the sheet metal edge being folded is determined in large measure by intensity and the form of the dynamic load.
2. While combined folding, on the stressed-deformed state of the material of the edge at the static stage is superimposed on the stressed-deformed state of the material at the dynamic stage. It was found the occurrence of tensile stresses along the edge being deformed as well as collision of the edge with the inner panel, leading to the additional plastic flow of metal through the thickness of the blank. This reduces the effect of rebound of the edge from the inner panel and eliminates the formation of air pockets.
3. Procedure of computer simulation of static-dynamic processes has been created with the help of which it was determined that the level of critical compressive stresses, leading to formation of corrugations, is achieved much later compared to static loading.
4. The results of computer simulation of the folding operation made it possible to assess influence of constructive-technological factors – geometrical sizes of blanks, the mutual arrangement of the blank and inductor, the loading modes – on the quality of the obtained joint.
5. On the basis of computer simulation and experimental studies the mechanism of the second stage of the folding process was revealed which allowed scientifically grounded control over the deforming process.

6. PRACTICAL APLICATION

- The device for combined assembling of sheet parts has been developed;
- The procedure of calculation of the process of combined folding on the basis of the finite-element method with regard to static and dynamic types of loading without stopping the process has been created;
- The recommendations on practical implementation of the proposed technology have been formulated. The combined process of folding: the special tooling has been designed and manufactured assembling of outer and inner panels has been performed for a door of a car ВАЗ 1118 “Калина”, city of Togliatti, Russia. Appropriate procedures and instructions have been developed.

7. THESES TO BE DEFENDED BY THE AUTHOR

- Method and device for implementing of combined folding combining static and dynamic (pulse-magnetic) loadings;
- The procedure of calculation of the combined technology on the basis of the finite-element method taking into account static and dynamic types of loading without stopping the process;
- Results of computer simulation of the folding process taking account of properties of the material and its interaction with the tool and allowing to determine completely the sizes and stressed-deformed state of the blank material at any time of deforming;
- Mechanism of deformation depending on the form and intensity of load, geometrical sizes, properties of the material of the blanks being processed;

8. APPROBATION OF THE DISSERTATION

1) Main points and materials of the work were reported and discussed on scientific-technical conferences, seminars, forums (including international):

1. International youth scientific conference "Tupolev readings", 2009, Kazan. Belyaeva I.A., Khardin M.V. "Technology of the folding operation by pulse-magnetic method".
2. International youth scientific-practical conference "Man and the cosmos", 2010, Dnepropetrovsk. Belyaeva I.A., Khardin M.V. "Combined technologies of sheet stamping by the pulse-magnetic method".
3. All-Russian scientific-practical conference "Actual problems of aviation and cosmonautics", 2010, Krasnoyarsk. Belyaeva I.A., Khardin M.V. "Application of pulse-magnetic loading in combined technologies of sheet stamping".
4. XIII Russian conference of users of MSC software systems, 2010, Moscow. Belyaeva I.A., Khardin M.V. "A possibility of combining static and dynamic loading".
5. Conference of young scientists and specialists "Future of mechanical engineering of Russia", 2010, Moscow. Belyaeva I.A., Khardin M.V. "Development of a combined technology on the example of the operation of folding".
6. International conference XXXVII "Gagarin readings-2011", 2011, Moscow. Belyaeva I.A., Khardin M.V. Moscow. "Simulation of combined technologies with help of the software complex MSC. NASTRAN/ MSC.MARC".
7. Regional scientific-practical conference dedicated to 50th anniversary of the first manned flight into space, 2011, Samara. Belyaeva I.A. "Development of a combined technology of flanging with use of static and dynamic loading".
8. JOM-17. International Conference of Joining Materials.-Helsingor, Denmark, 5-8 may 2013. V.A.Glushchenkov, Osama Al-Erhayem, M.V. Khardin, L.A. Belyaeva "Assembly of parts by flanging method combining static and dynamic loading".
9. Proceedings of the XVII International Forum on problems of science, technology and education, M.: Academy of Sciences about earth, 2013, Moscow. Belyaeva I.A.,

Glushchenkov V.A. “Combined technologies of folding in automotive industry”. Winners of the award “Golden Diploma-2013” Nomination “Mechanical Engineering”: Belyaeva I.A., Glushchenkov V.A.

10. The 3d scientific seminar, 12-14 May, 2014: НИЯУ МИФИ. 2014, Moscow. Belyaeva I.A. “Combining of static and dynamic (pulse-magnetic) loadings in development of mechanical engineering technologies”.
11. XII Conference “JUNIOR EUROMAT 2014” 20 -26 July, 2014. Lausanne, Switzerland. Belyaeva I.A. «Hybrid and combined technologies using static and dynamic loads».
12. IX International scientific-technical conference “Present-day methods and technologies of creation and processing of materials”, 17-19 September, Minsk, Belyaeva I.A., Glushchenkov V.A. “Combining of static and dynamic loads in technologies of mechanical engineering”.
13. Belyaeva I.A., Mironov V.A. НИЯУ МИФИ, 16-21February, 2015. Moscow. “Schemes of hybrid and combined technologies of pressing of powders”.
14. Belyaeva I.A., Jusupov R.Ju., Glushchenkov V.A. IY International scientific-technical conference «Physics of metals. Mechanics of materials and deforming processes (“MetalDeform-2015”). 14-17 September, 2015, Samara. “Problems of implantation of static-dynamic processes and way of their solving”. (Accepted for publication).

2) were presented at International exhibitions:

1. The 62d World Salon of Innovations, scientific research and new technologies “Brussels-Innova/Eureka 2013”, Belgium, November 14-16, 2013. Glushchenkov V.A., Chernikov D.G.,Belyaeva I.A., Hardin M.V., “The combined technology “folding” combined static and dynamic loadings and the device for its implementing”. The exhibit was awarded a Diploma and golden medal.
2. The 42d International Exhibition of inventions “Inventions Geneva”, April 02-06, 2014, Geneva (Switzerland). Glushchenkov V.A., Chernikov D.G., Lazareva A.A., Belayeva I.A., Voronin S.S. “Composite material “metal-nonmetal” and method for production of it”. The exhibit was awarded the Diploma and the Gold medal of the exhibition “SALON INTERNATIONAL DES INVENTIONS GENEVA”.
3. The 43-d International Exhibition of inventions “Inventions Geneva”, April 15-19, 2015, Geneva (Switzerland). Glushchenkov V.A., Jusupov R.Ju., Belayeva I.A., Chernikov D.G. “Pulse-magnetic installation for production of parts from aluminum and magnesium alloys”. The exhibit is awarded the Gold medal and the special prize.

3) The main content of the dissertation is reflected in publications:

1. Beļajeva I.A., Hardin M.V. Detaļu salikšanas kombinētās tehnoloģijas izstrāde. Кузнечно-штамповочное производство, 2012, №3.17-19.lpp. (krievu val.)
2. Beļajeva I.A. Atloka stabilitātes analīze pie impulsu magnētiskās noslodzes. IX zinātniski-tehniskās konferences raksti “Молодежь в науке”, 2010, Maskava, 38 -42.lpp. (krievu val.)
3. Beļajeva I.A. Kombinēto tehnoloģiju matemātiskā modelēšana. Вестник СГАИИ. 2011, №6, 53-59.lpp. (krievu val.)
4. Beļajeva I.A., Hardins M.V., Gluščenkovs V.A. Detaļu salikšanas kombinētās tehnoloģijas praktiskā realizācija. Вестник СГАИ, 2011, №6, 67-72.pp.(krievu val.)

5. Beļajeva I.A., Hardins M.V. Kombinētās tehnoloģijas izstrāde, piemērojot valcēšanas operācijas. Konferences raksti „Будущее машиностроение Росси”, 2010, Maskava, lpp.44-45. (krievu val.)
6. Beļajeva I.A. u.c. Lokšņu materiālu savienošanas iekārta ar atloku. Patents № 111468. - 2011 (Krievija).
7. Beļajeva I.A., Hardins M.V., Gluščenkovs V.A. Detaļu salikšana ar valcēšanas metodi, ietverot statisko un dinamisko noslodzi. Starptautiskās konferences raksti. JOM 17 – 2013.Helsingor, Dānija, 1-7.lpp.
8. Beļajeva I.A., Gluščenkovs V.A. Valcēšanas kombinētās tehnoloģijas autorūpniecībā. XVII starptautiskās konferences raksti. “Форум по проблемам науки, техники и образования”. 98-99.lpp. Maskava, 2013. “Zelta diploms-2013”(krievu val.)
9. Gluščenkovs V.A., Beļajeva I.A. Valcēšanas kombinētas operācijas īpatnības. Известия Самарского научного центра РАН. Samāra, 2014, Nr.4, 146-153.lpp. (krievu val.).
10. Beļajeva I.A., Gluščenkovs V.A. Kombinētās valcēšanas rezultātā salikto detaļu kvalitāte. Известия Самарского науного центра РАН. Samāra, 2014, Nr.6, 312-315.lpp. (krievu val.).
11. Beļajeva I.A., Gluščenkovs V.A. Cilindrisku sagatavju saspiešanas modelēšana ar impulsu-magnētisko lauku. Известия Самарского научного центра РАН, Samāra, 2015, Nr.2, 113-118.lpp. (krievu val.).

3) The main content of the dissertation is reflected in publications:

1. Belyaeva I.A., Hardin M.V. Development of a combined technology of parts assembling // Forging and Stamping Production. Plastic metal working, 2012.-№3, p.17-19 (in Russian);

2. Belyaeva I.A. Analysis of buckling of the flange when pulse-magnetic loading // IX scientific-technical conference “Youth in science”, 2010.- p.38-42 (in Russian);

3. Belyaeva I.A. Mathematic simulation of combined technologies // Bulletin of SSAU, 2011.-№6.-p.53-59 (in Russian);

4. Belyaeva I.A., Khardin M.V., Glushchenkov V.A. Practical implementation of the combined technology of parts assembling // Bulletin of SSAU, №6, 2011.-p.67-72 (in Russian);

5. Belyaeva I.A., Khardin M.V. Development of a combined technology on the example of the operation of folding //Conference of young scientists and specialists “Future of mechanical engineering of Russia, 2010.-p.44-45 (in Russian);

6. Belyaeva I.A. Device for fold joining of sheet workpieces // Belyaeva I.A., Khardin M.V., Glushchenkov V.A., Chernikov D.G. //Patent №111468.-2011 (Russia);

7. Belyaeva I.A., Glushchenkov V.A., Khardin M.V. Assembly of parts by the “folding” method combining static and dynamic loading // Osama Al-Erhayem, The International conference on joining of materials JOM-17, 2013.-p.1-7 (in Russian);

8. Belyaeva I.A., Glushchenkov V.A. Combined technologies of folding in automotive industry”// Proceedings of the XVII International Forum on problems of science, technology

and education, M.: Academy of Sciences about earth, Moscow. 2013. –p.98-99. Winners of the award "Golden Diploma-2013", Nomination "Mechanical Engineering": Belyaeva I.A., Glushchenkov V.A. (in Russian);

9. Glushchenkov V.A., Belyaeva I.A. Features of the combined operation of folding. Results of computer simulation // News of the Samara scientific centre of the RAN, Samara, 2014, № 4.-p.146-153(in Russian);

10. Belyaeva I.A., Glushchenkov V.A. Quality of panel joints obtained by combined flanging // News of the Samara scientific centre of the RAN, Samara, 2014, № 6.- p.312-315 (in Russian);

11. Belyaeva I.A., Glushchenkov V.A. Simulation of the process of pulse-magnetic reducing of cylindrical workpieces // News of the Samara scientific centre of the RAN, Samara, 2015, № 2.- p.113-118(in Russian).

9. STRUCTURE OF THE DISSERTATION

In the introduction the actuality of the theme of the dissertation work is substantiated and its goal is formulated.

In the first chapter analysis is performed of literary sources devoted to questions of assembling of facing parts of cars.

In this chapter are considered the existing schemes of deforming and technical decisions which allow performing the operation of folding. At the present time this problem is solved by domestic and foreign researchers.

In Russia the study of high-speed flanging and bending of thin-walled sheet parts with the use of the pulsed magnetic field were taken up by Isarovich G.E., Lebedev G.M., Judaev V.B., Kurlaev N.

Vlasov A.V., Golovashchenko S.F., Koptelov A.A. and Ilinich A.M. considered bending on a small radius.

Abroad these questions were studied by Baartman R., Guohua Zhang, Xin Wu, Guohua Zhang, Livatyali H., Muderrisoglu A. and others.

Analysis of domestic and foreign literary sources revealed the lack of a method of assembling that would fully satisfy main requirements of the automotive industry (high quality of the face surface of a part, possibility of obtaining small radii of bending; tool life sufficient for industrial application; a possibility to use the standard equipment). Implementation in industry of most of methods requires developing the specialized equipment or entire production lines.

The second chapter presents the developed schemes of implementation of combined folding which combine static and dynamic loads without stopping or interrupting the process.

In the first proposed scheme the initial pass is the operation of drawing the outer panel with the placement of the inner part, the second pass performs bending- under the edge at an angle of 135˚in an instrumental stamp with the subsequent pulse-magnetic action – bending at an angle of 1800. Such approach makes it possible to achieve the higher quality radius of bending of the product being manufactured. Implementation of this proposal supposes the use of an instrumental stamp with the inductor built in the die and connected with the PMI.

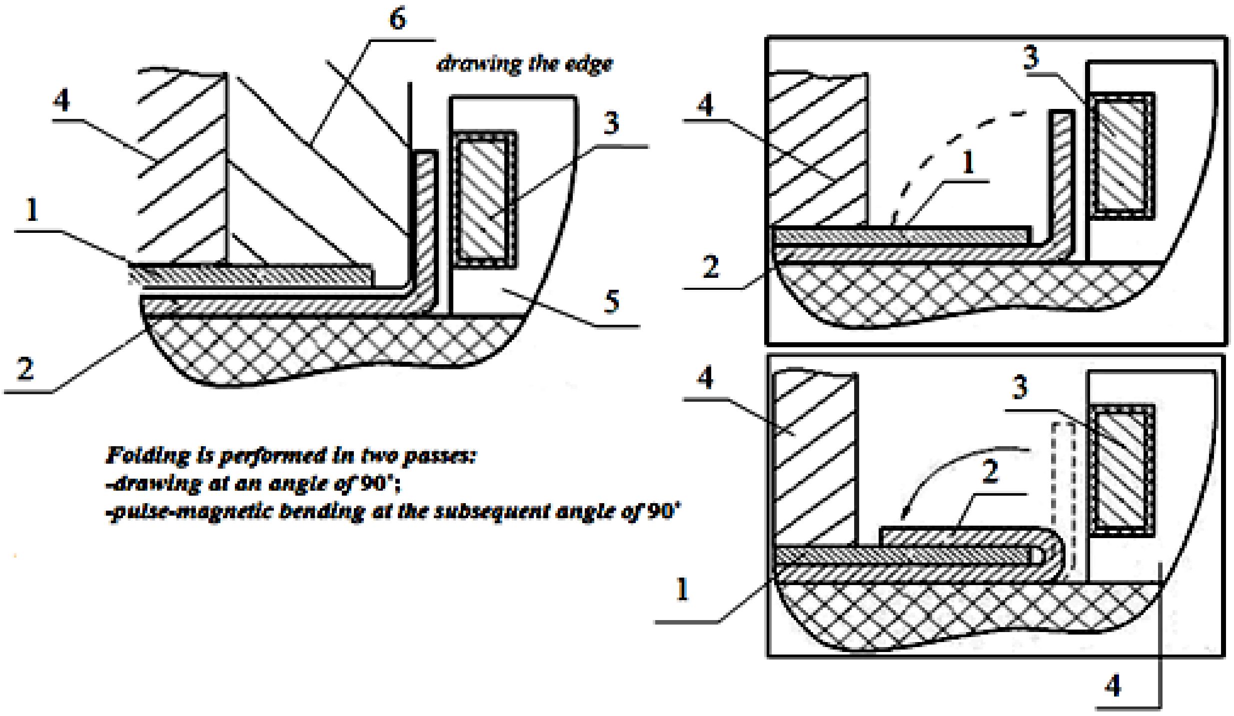


Fig.1. Technological scheme of combined folding
1 – inner panel, 2- outer panel , 3 – inductor, 4 – clamp, 5 – die, 6 – punch

The second scheme (combined folding) is also performed in two passes (Fig.1). After drawing, the punch stops or returns to its original position and both panels with the clump continue to move. When the drawn edge (α = 90°) achieves the location of the inductor, the capacitor bank discharges. The edge is folded at an angle of 180° under the action of the pulse-magnetic field. A peculiarity of the proposed technology is a possibility of sequential coincidence of two types of loading without stopping the process as a whole.

The patent № 111468 of 20.12.2011”Device for fold joining of sheet blanks” was issued for this device.

The third chapter presents the mathematical model of combined folding. Numerical methods of calculation were used for mathematic simulation of dynamic processes.

In simulation of the process of combined folding the following assumptions were accepted:

1. Pressure of the magnetic field applied to the edge being folded is considered independent of the motion of the edge.

$$P(H) = \int_0^\infty \sigma B dz = \frac{\mu_o H_m^2}{2} e^{-2\sigma t} \sin^2 wt;$$

$$P(\varphi) = \frac{\mu_o H_m^2}{4} e^{-2\sigma\Delta} (1 - \cos 2\varphi),$$

where Δ - depth of magnetic field penetration in material.

2. Thermal effects, arising while dynamic deforming the edge, are not considered.

3. From a mechanical point of view the process of interaction of a force pulse and the construction was considered as the process of elastic collision of two bodies.

4. In the calculation of pressure of the pulsed magnetic field the edge effects were not taken into account.

The procedure of computer simulation of the process of combined folding has been proposed and implemented. It based on the following equations:

$$\frac{\partial \sigma_{ij}}{\partial x_i} + pf_i = \rho \ddot{x}_i \text{ - equation of motion;}$$

$$\dot{x}_i(X_0, 0) = V_i(X_0) \text{ - initial conditions;}$$

$$\sigma_{ij} n_{ij} = p_i(t) \text{ - boundary conditions,}$$

where σ_{ij} - tensor of Koshi densities;

f_i - vector of strength density;

ρ - density of material.

Using principle of displacement equation of motion we can write in following way:

$$\int_V (\rho \ddot{x}_i - \frac{\partial \sigma_{ij}}{\partial x_i} - \rho f_i) \delta x_i dV + \int_{\partial h_i} (\sigma_{ij} n_j - p_i) \delta x_i dS + \int_{\partial b_3} (\sigma_{ij}^{+} - \sigma_{ij}^{-}) n_{ij} \delta x_i dS = 0,$$

where δx_i - displacements according boundary conditions.

Obtained equation formulates value of work. The changes of work according to the displacements can be assumed equal zero:

$$\delta\pi = \int_v \rho \ddot{x}_i \delta x_i \, dV + \int_v \sigma_{ij} \frac{\partial \delta x_i}{\partial x_j} dV - \int_v \rho f_i \, \delta x_i dV - \int_{\partial 1} \rho_i \delta x_i \, dS = 0.$$

Dividing the region of changes in n elements and after summing by the help of the method of finite elements we can get:

$$\delta_{ij} = \sum_{m=1}^{n} \delta\pi_m = 0.$$

The result allows assume the mathematical model of dynamic deformation as elastic-plastic deformation model. The scheme of static-dynamic stages of calculations is shown in Fig.2.

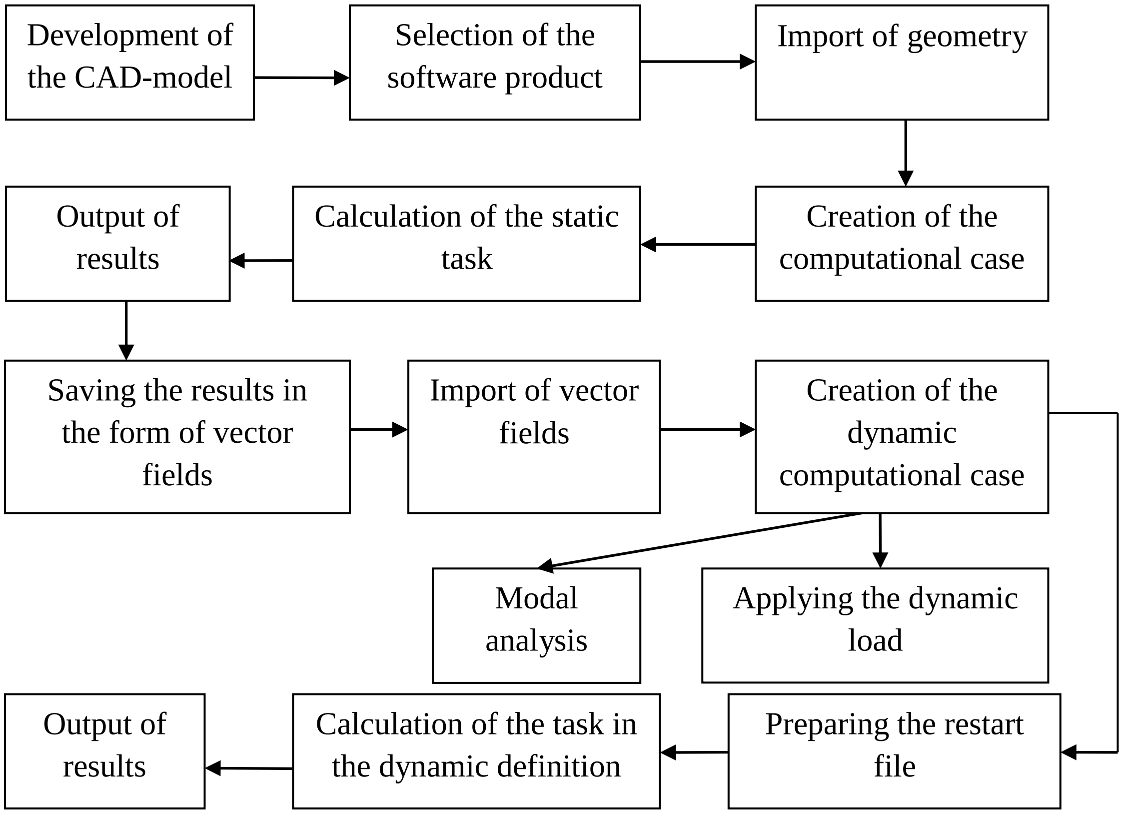


Fig.2. Scheme of creation of the combined computational case

To simulate the process of combined folding, a part was chosen which is rather simple on the one hand and on the other hand its obtaining reflects real production processes. In the shape, the part is close to a hatch of the filling neck of the fuel tank, in which the inner panel is joined with the outer one through the operation of folding. Roundings of different radii (R=10, 20, 30, 40 mm) are made along its perimeter (Fig.3).

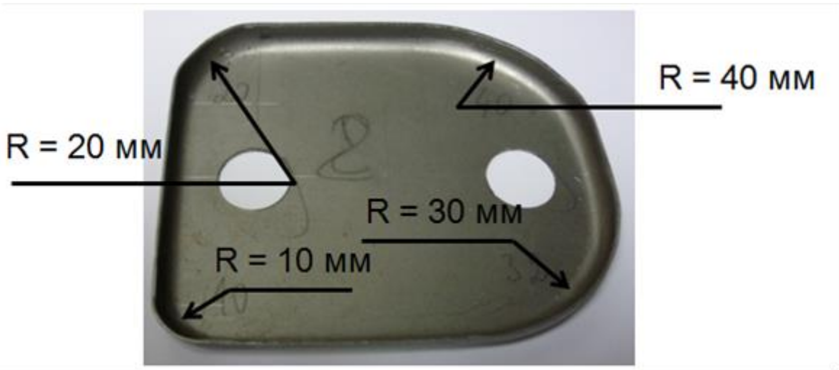


Fig.3. Model of the blank

The computer model of the instrument in the simplified form corresponds to the proposed tooling for experimental study. The software product MSC.NASTRAN/ MSC.MARC was used for static and dynamic calculations. The basis for the computational model is the finite-element method using equations of motion, Maxwell equations and appropriate boundary conditions.

In the process of simulation the modal analysis was performed. Some results of the modal analysis are shown in Fig.4.

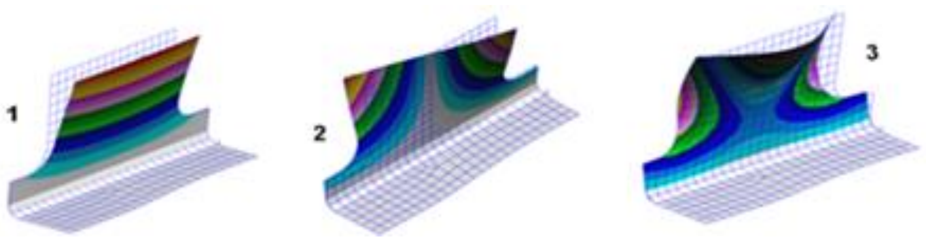


Fig.4. Results of the modal analysis for the three first lowest natural frequencies and their forms of oscillations

The value of the force acting on the edge should be less than the critical force at which the formation of corrugations begins. Excess of the force can lead to an uncontrolled process of deforming and to unstable solution.

In the procedure of computer simulation, import of vector fields is used to transfer the static result in the dynamic solution (Fig.5).

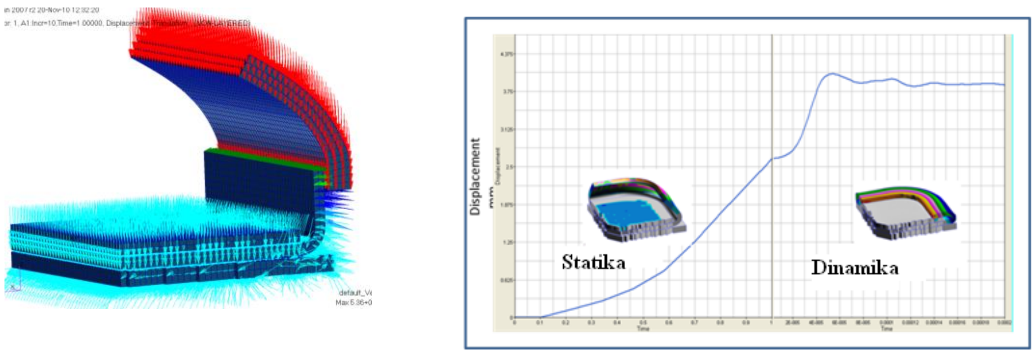


Fig.5. Combining of static and dynamic solutions

For realization of the combined mathematic calculation, was developed and implemented the procedure of performing of virtual tests 34110.37.101.0004-2011on the order and building of the computational model in combined calculations.

The forth chapter presents main results of computer simulation of the process of combined folding. There are developed 6 questions.

1) Change of stressed state of the edge material while dynamic folding:

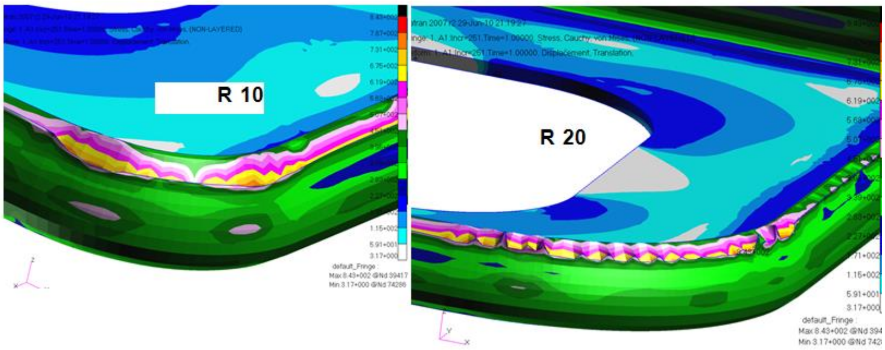


Fig.6. Stressed-deformed state of the material of the edge of the flange on the radius section (R10, R20)

The obtained patterns of stressed state of the material on the radius sections of the edge being folded make it possible to evaluate the critical values of stresses in dynamic loading which lead to the formation of corrugations.

2) *Influence of intensity (value) of dynamic load on the nature of the deformed state of the edge while folding;*

Fig.7 shows fragments of the deformed state of the blank material after applying a dynamic pulse under an angle of 45° (a) and when the pulse is located horizontally (b).

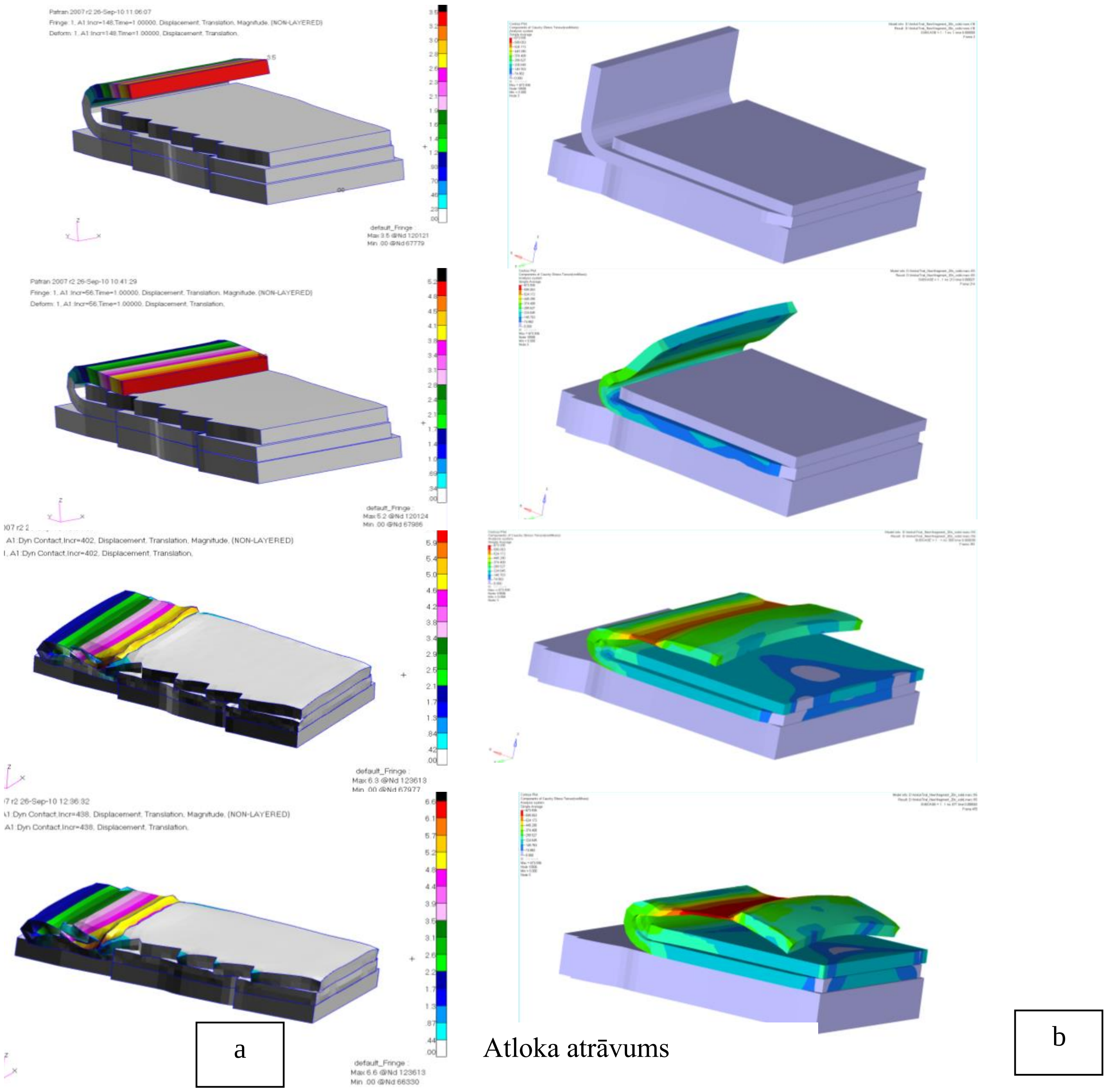


Fig.7. Kinematics of the process of combined folding at various direction of the pulse

On the presented figures one can observe development of deformations in the processes of bending and collision of the edge with the inner panel (Fig.7). When energy is in excess one can observe the processes of flowing the edge, distortion of the inner panel or even breakout of the edge. The performed simulation made it possible to find the optimal value of load (6 - 8 kJ).

3) *Influence of the pulse shape on kinematics of the edge being folded (Fig.8)*

The mutual arrangement of the inductor and the edge being folded provides a possibility to change a form of the applied pulse. The performed computer simulation allowed studying kinematics (movement) of the edge: advancing, along the radius or lagging movement of the edge.

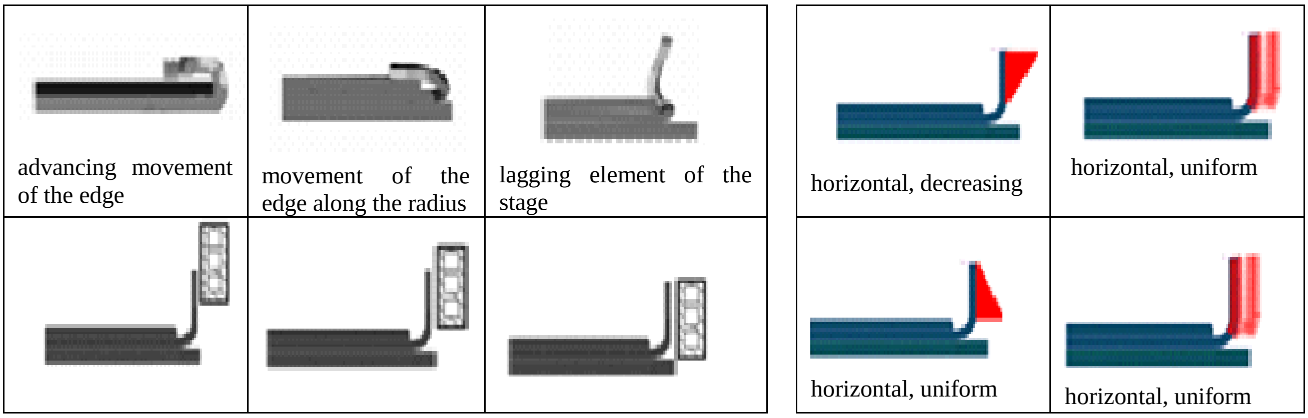


Fig.8. Influence of the pulse shape and placement of the inductor on kinematics of the edge

The nature of movement of the edge determines the stressed-deformed state of the blank material while folding.

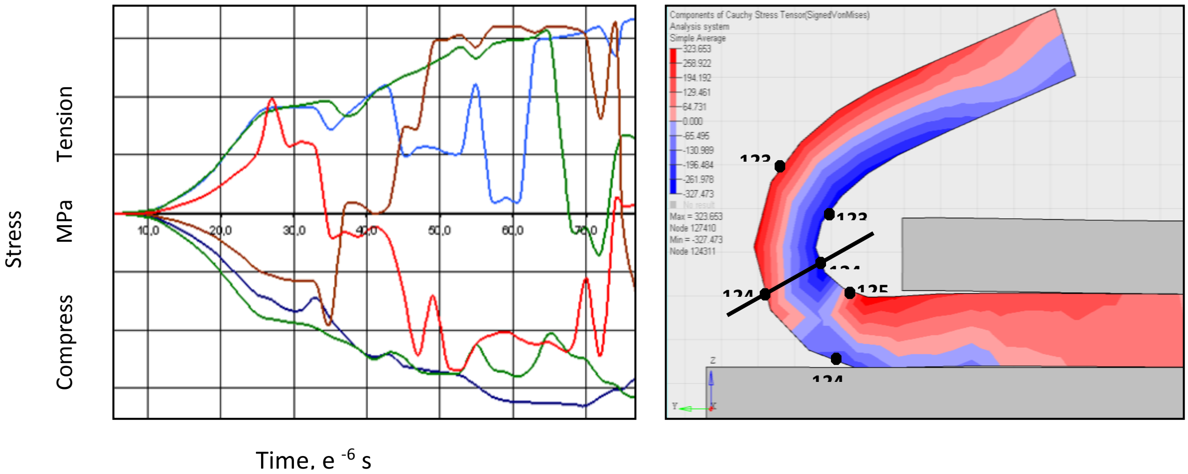


Fig.9. Deformed state of the flange

As it is seen from Fig.9, when folding the edge, the prevailing tensile stresses act in the deformation zone.

4) *Influence of geometrical sizes of the blank on the limit parameters of the process under the condition of providing the given quality of assembling;*

Computer simulation of processes of folding with various heights of the edge h = 3, 5, 7 mm and with the radius of rounding R= 10,20,30,40 mm allowed determining rational values of height “h” and of the minimum radius R (h_{min} = 5 mm и R_{min} =10 mm). Moreover, the minimum radius of bending was determined r_{min} = 1.3t instead of 1.5t while static folding.

Additionally, there were provided surface roughness measurements of samples. It was find out that surface roughness 3D parameters Sa=5,81 µm, St=50,8 µm allow to get necessary quality of assembly process.

5) *Analysis of the interrelation of movements, stresses and deformations for characteristic points of the edge while dynamic folding;*

Computer simulation makes it possible to consider the stressed-deformed state of the edge material in conjunction with movement, deformation, stress. The interrelation of these characteristics is seen from Fig. 10 and 11.

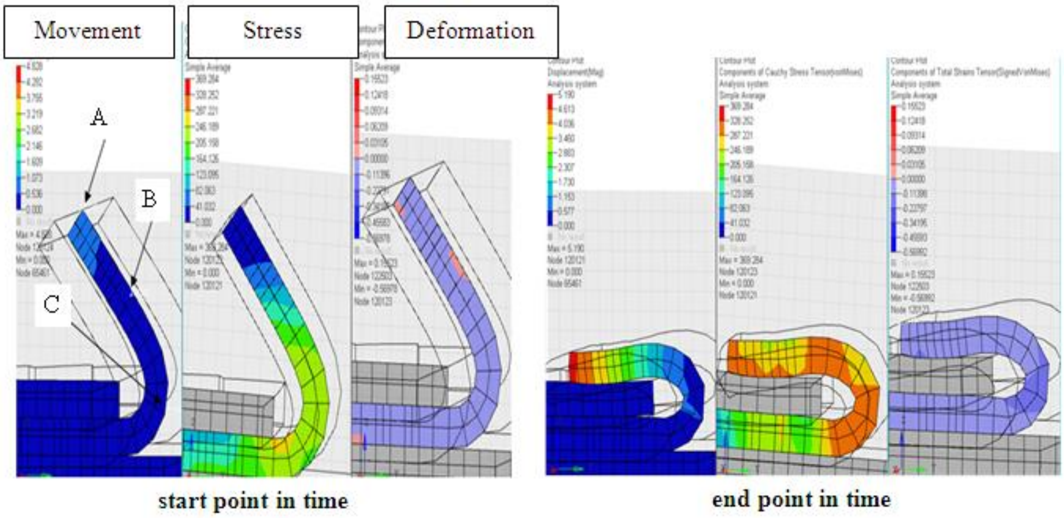


Fig.10. Pattern of changes of values of parameters at three points A, B, C

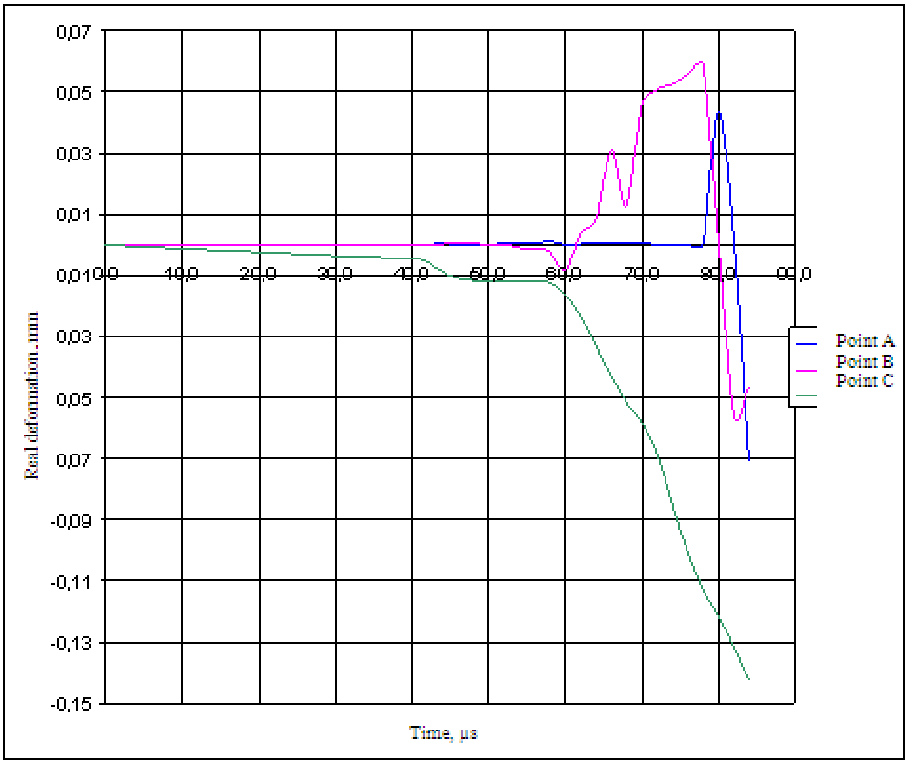


Fig.11. True deformation in relation to time

6) Assessment of quality of the joints obtained through folding.

Under production conditions rigidity and strength of joints are checked in the finished state for torsion, bending, fracture.

Computer simulation allows determining of quality of fit of the folded edge of the outer panel to the inner panel by the value of contact stresses.

For example, with height of the edge being folded h=5 mm at energies of W=2; 6.7; 12.3 kJ the contact stresses achieve values of 50-70; 356-387; more than 600 MPa, relatively.

Comparison of the results of production tests of assemblies and contact stresses gave a possibility to define $\sigma_{cont.}$, at which the required quality of joints is provided.

Analysis of the folding process, performed **in the fourth chapter**, made it possible to describe the mechanism (peculiarities) of folding.

- A complex pattern of kinematics of the edge being folded was established which depends on the load form: lagging of the edge, lapping the edge, uniform deforming along the radius, the occurrence of a plastic hinge, the deforming of the assembled product.
- While dynamic folding, the additional tensile stresses arise at any form and intensity of load. These additional tensile stresses change the pattern of the stressed state, for example, along the bending radius ‘r”, bringing it closer to the processes of bending with tension or even to stretching the outer edge over the inner panel.
- At the final stage of folding, collision of the edge with the inner panel occurs. This is particularly typical for the extreme points. As computer simulation showed, the collision can lead to plastic deforming of the metal through thickness (flowing of the metal) eliminating the rebound effects.
- It was established that there is a possibility of tight fit of the outer panel edge to the inner panel (with respect to the end face) without formation of inner “pockets”. The cause of tight fit is the action of load in the direction of the end face of the inner panel. This pressure prevents movement of the edge being folded in the direction of the “pocket” when lapping the edge, for the most part.
- Having regard to the formation of corrugations along the radius R, the limiting values of radius Rmin and height of the edge being folded “h” were determined. As it was established, the level of critical compressive stresses, leading to formation of corrugations, is achieved much later in comparison with static loading. This extends the limiting capabilities of the folding process. Moreover, during collision (excess of kinetic energy) the corrugations were partially straightened.
- Mechanical properties of metal play a positive role in dynamic folding. Increase in plasticity during dynamic deforming gives a possibility to obtain the minimum radius of bending Rmin = 1.3t while static folding.

The fifth chapter contains description of the procedure and results of experimental studies of the process of combined folding, correlation of them with the results of computer simulation.

Kinematics of the edge in folding was investigated at the second stage (dynamics) of the process. When studying the kinematic parameters, by-the-frame photographic recording was used with the help of the digital high-speed camera “Cordin-505”. Therewith the parameters of the discharging circuit (current, magnetic field intensity) were recorded. Simultaneously, geometrical sizes of the obtained assembly were measured. Fig. 12 shows a plot of change in velocity of deforming for the chosen point on the radius section of the edge being folded.

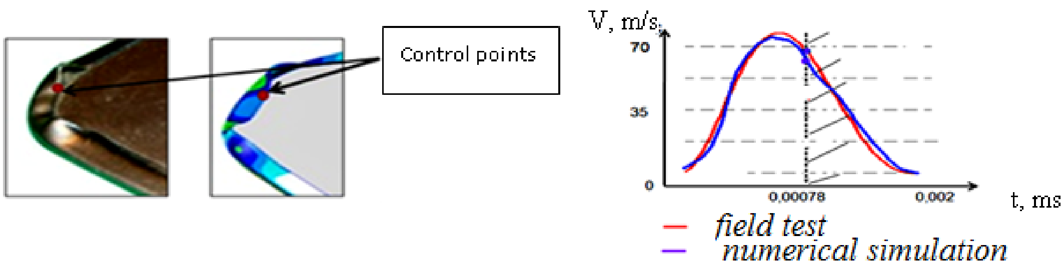


Fig.12. Exterior view of the joint obtained through folding
(Experiment and digital simulation)

As a result of comparison of field and virtual tests one can observe 5 – 8% convergence of the results.

Good qualitative convergence is observed concerning geometry of the outer panel obtained in simulation and in the experiment (Fig.13).

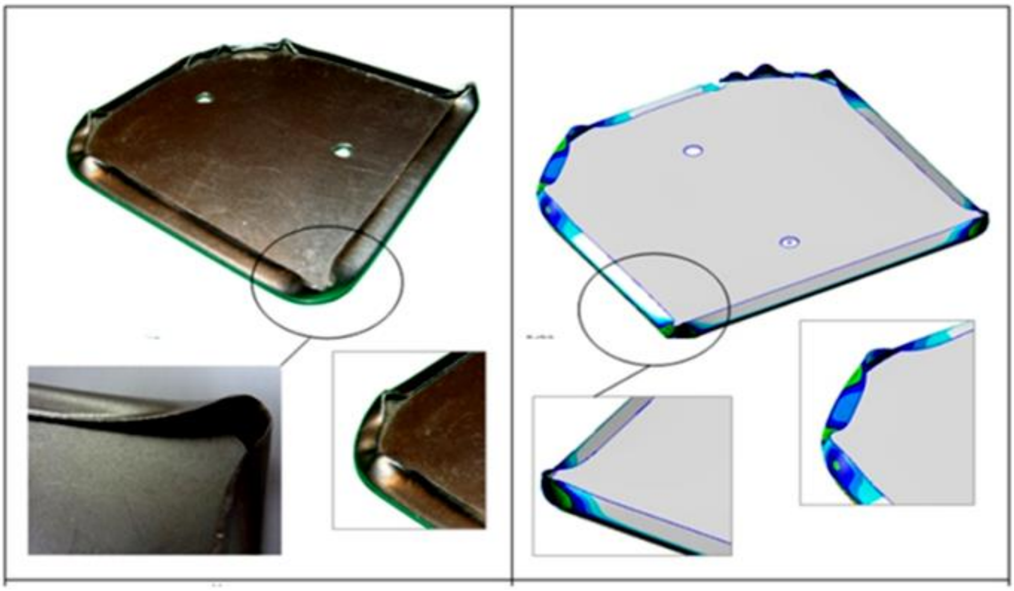


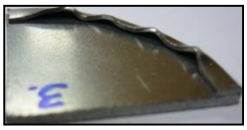
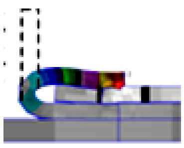
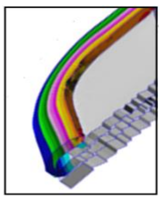
Fig.13. Comparison of field and numerical tests at control points

In comparison of the results of simulation and the experiment when determining the height of corrugations from the radius of curvature in plan, high convergence was observed (Table 1).

The presented data serve as a basis to make assertion about adequacy of the created mathematical model.

Table 1

Comparison of experimental and computer simulation data

Corrugation height, mm		Minimum radius of bending, mm		Minimum radius of rounding in plane, mm	
Calculated	*Experiment*	*Calculated*	*Experiment*	*Calculated*	*Experiment*
0,15-0,30	0,20-0,40	1,20-1,35	1,20-1,30	10	10
					

The sixth chapter presents recommendations on practical implementation of the developed technology and modification of the constructive elements of joints being obtained through folding.

1. The program for computer calculation of parameters of combined folding has been proposed; the procedure of practical use has been given. The developed procedure has been introduced at JSC “AVTOVAZ” (И.34/10/37 101 004-2011, the act of introduction 34110-77/154) and sampled in manufacturing a model of a back door of the car “Kalina” (Fig. 14).

2. 

Fig.14. Back door of a car of series 2118 which was obtained with the proposed technology

3. Calculation of the inductor in interrelation to the parameters of the installation and blank is given. This calculation was verified when designing the experimental technological tooling.

4. Based on the results of simulation and experiments, the recommendations have been formulated on main geometrical sizes of the edge being folded (R, r, h) on condition that high quality of products is obtained.

10. MAIN RESULTS AND CONCLUSIONS

1. The technology for assembling of body parts by plastic deforming, combining static and dynamic loadings without stopping the main process, and the device for implementation of this process have been developed (patent № 111468, « Device for fold joining of sheet blanks »).
2. The procedure of computer simulation of combined folding has been developed which makes it possible to calculate geometrical and force parameters when assembling the complex-shaped parts.
3. The use of numerical methods allowed to reveal the nature of the change of the stressed-deformed state of the blank material during the entire time of deformation and to take into account the change of intensity of pressure both with time and space.
4. The mechanism of the process of combined folding has been studied that allowed taking into account the influence of geometrical and force factors for the control over the process of assembling the parts.
5. Due to combination of static and dynamic loads, productivity and quality of finished products increase, production of parts is cheapened (simplification of design and reducing the number of stamps).
6. On the basis of generalization of the results of numerical simulation and experimental studies, the following recommendation have been developed on practical implementation of combined folding: for designers – recommendations on choice of optimal values of the edge height, radii of bending and rounding; for technologists – recommendations on choice of the optimal form and intensity of load, on designing the stamps with built-in inductors.