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DOCTORAL THESIS

Contribuții la optimizarea unor caracteristici constructive ale pieselor realizate prin deformare plastică la rece

Contributions to the optimization of design features of the products made by cold plastic deformation

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Content

Foreword

Research and development of the parts feasibility estimation and solution of problems regarding the optimization of the flanged parts obtained by cold plastic deformation, belonging the automotive industry, using numerical simulation, represent the motivation and the direction of the doctoral studies.

The doctoral program consisted in preparation, presentation and defense of scientific reports, thoroughgoing the study, analyzing the problems related to the development of mathematical models of reproduction of studied phenomena, respectively, feasibility of the parts, thickening or thinning of the parts during and at the end of the cold plastic deformation processes. Also, the doctoral program consisted in the elaboration and publication of the scientific papers, as well as the elaboration of this doctoral thesis concerning the optimization of the constructive characteristics of the cold plastic deformation parts.

In order to achieve these results, I received guidance and support from both the PhD supervisor and the professors from evaluation commissions for doctoral exams and reports.

I am deeply grateful to Emeritus Prof. Florian DRĂGĂNESCU, Ph.D., for his scientific guidance and coordination of the entire doctorate program, for his confidence, support and total availability during this period.

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Constantin Drăghici

Introduction

The research and development activity of this doctoral study, is an integral part of the author's scientific concerns in the field of cold plastic deformation. This thesis, presents the results of the study, regarding the flange forming of the convex and concave exterior outline edges of the complex parts with visual impact from the automotive industry.

* * *

The current state of research - development in relation to the PhD thesis, analyzes in three chapters, the researches regarding the flange forming of the exterior outline edges of the metal parts made by cold plastic deformation and researches concerning the numerical simulation and statistical modeling of the flange forming process characteristics.

Based on data and conclusions drawn from the current state of the art, the main directions and the main objective of the research - development activity of the doctoral studies are: the research of the thickening and thinning characteristics of the flanged outer edges of the metal sheet parts using Finite Element Simulation and statistical modeling

A methodology was developed in order to estimate the feasibility of the parts with the flanged outer edges after a convex and concave curvilinear contour. Also, a methodology for adapting the Response Surface Method has been developed to obtain estimation models for the flanged outer edge characteristics. Following the application of the developed methodologies, functional relations were obtained in order to optimize the geometrical characteristics of the flanged outer edge of the parts. With the help of the relationships for the estimation of the feasibility of the parts with flanged outer edge after a convex and concave curvilinear contour and a certain imposed restriction, the optimum values recommended for the different considered cases of work were determined.

The last part of the PhD Thesis presents the main contributions to the optimization of some constructive characteristics of the parts made by cold plastic deformation, the scientific and practical importance of the PhD Thesis, as well as the perspectives related to the research - development activity for the optimization of some constructive characteristics of the parts made by cold plastic deformation using numerical simulation.

Part I. The actual state of the art research regarding the flanged parts processing from sheet metal

Chapter 1. Researches regarding the flange forming of the parts made from sheet metal by cold plastic deformation

1.1. Shapes, design features and feasibility of these parts

1.1.1. Parts with simple and complex shapes

The flange forming process is a widespread operation applied to a wide variety of parts with simple or complex shapes belonging to cars or other products (bodywork, parts of aircraft, etc.). These parts can be divided into three major groups according to their functional role, namely:

- structural parts;
- parts with visual impact on customers (appearance parts);
- parts with appearance and strength functional roles.

1.1.2. The shrink and stretch flange forming necessity process

The flange forming process of the parts consists in forming a side wall at the edges of outer contours of the parts in order to:

- increasing the stiffness;
- creation of support areas;
- creations of welding assembly areas;
- providing sealing areas.

This side wall can be obtained, by case, in one or more flange forming operations with dies mounted on presses.

1.1.3. Feasibility of the shrink and stretch flange forming parts

Feasibility evaluation of the stretch and shrink flange forming parts is made with the help of flange ratio, respectively, with fillet radii of the side wall [R01, C02, S03].

If the value of the flange ratio is greater than a recommended limit value indicated in literature, then it can be said that the parts are feasible.

Another method to evaluate feasibility of the flanged parts is presented by Ivana Suchy [I02]. Starting from the fact that these types of forming processes are always accompanied by shrink stresses in the case of parts with exterior concave contours and, respectively, to tensile stretch in the case of parts with exterior convex contours. Thus, knowing the value of the deformation, in %, which occurs during the flange forming process, the shape of the blank can be determined.

1.1.4. Defects of the flanged parts

The defects which appear in the flanged formed parts are generated by the stress state that occurs during the deformation of the blank, namely:

- in the case of shrink forming process of the parts (parts with convex contour), when circumferential compressive stresses occur they produce the wrinkles in the flange and, respectively, an increase of its thickness to the flange end;

- in the case of stretch forming process of the parts (parts with concave contour), when circumferential tensile stresses occur they produce the thinning in the flange;

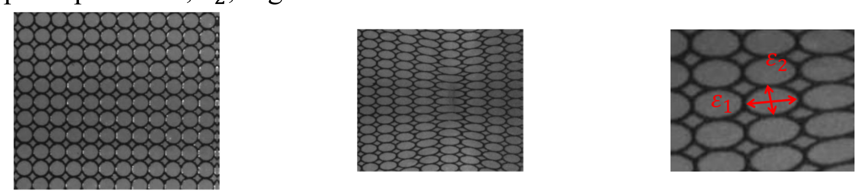
Frequently, both types of flange forming can be encountered on the same piece, or sometimes, flange forming after a concave-convex concave contour.

1.2. Experimental methods for establishing the mechanical characteristics of the material and Forming Limit Curve (FLC (CLF)

1.2.1. General concepts regarding the graphical evaluation of the feasibility of the numerical simulation of parts

The graphical evaluation of the formability of the parts, namely of the potential defects that can occur during the numerical simulation, is performed using the Forming Limit Curve (CLF). The principle of this assessment is based on the fact that the state of each point on the surface of a piece can be described by two parameters:

- major principle strain, ε_1, Fig. 1.1;
- minor principle strain, ε_2, Fig. 1.1.



a) b)

Fig. 1.1. Determination of major and minor principal strains values

Drawing the Curve Limit Curve Graph, Fig. 1.2, [S01], is carried out following the experimental tests of tensile stress, plane stress, bi-axial stretching and equidistant axial stretching, Fig.1.3, assuming a linear relation between the major principle strain ε_1 and the minor principle strain ε_2, according to rel. (1.1) [A05], Fig. 1.3.

$$\varepsilon_1 = const * \varepsilon_2 \quad (1.1)$$

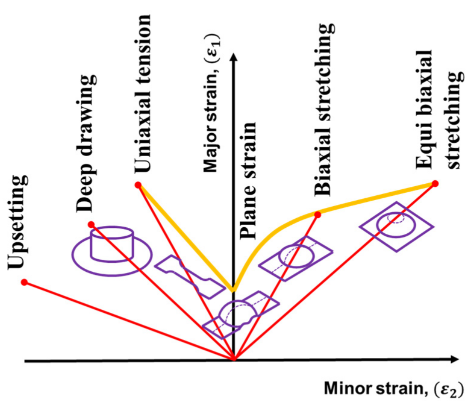


Fig. 1.2. Forming Limit Curve graph, (FLC)

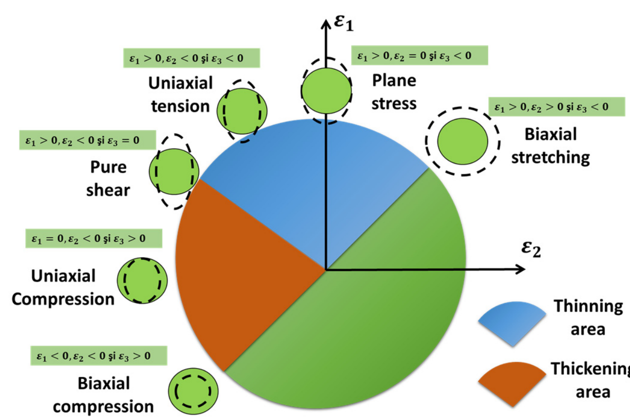


Fig. 1.3. Characteristic areas of the deformation state

1.2.2. Experimental tests used to determine the Forming Limit Curve

Researches for analyzing and determining the mechanical properties of materials, or criteria and experimental models describing the behavior of these materials under the action of complex stress states that occurring during cold plastic deformation processes are a continuing concern for many researchers. Among the experimental tests used both in industry and research to determine the Limit Forming Curve, are:

- Nakazima Test
- Hydraulic Bulge Test
- Tensile Test

1.3. Technological processes for processing the flanged parts

The most common flange forming processes used in the automotive industry are those made by regular hard tooling or rubber forming.
In Fig. 1.4 schematically is presents the most commonly flange forming process where the direction of movement of the flange steel is parallel to the working direction of the press in the case of performing this processing from the bottom to top or from the top to bottom. There are also special situations where the direction of movement of the flange steel is not parallel to the working direction of the press. In these situations, cams are used, which transforms the vertical movement taken from the press slide into movements in directions with certain angles to the working direction of the press.

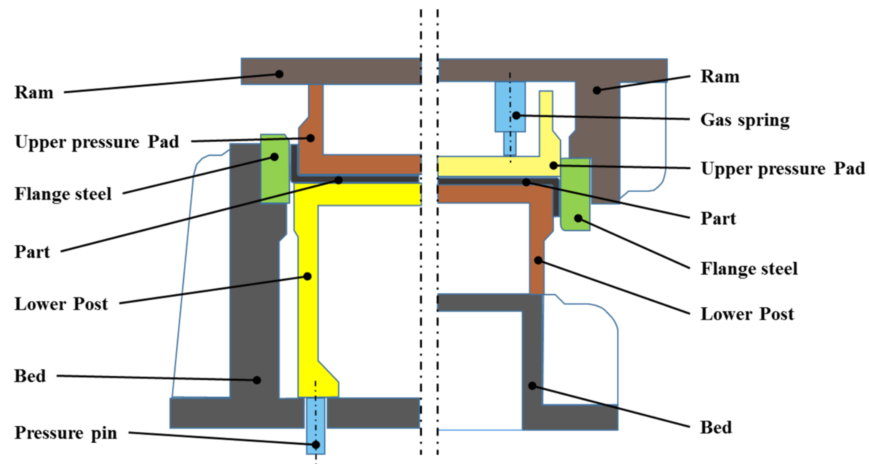


Fig. 1.4. Schematic representation of flange forming process

Chapter 2. Researches regarding numerical simulation and statistic modeling of the characteristics of the shrink and stretch flange forming process

2.1. Numerical simulation of the shrink and stretch flange forming process

2.1.1. Numerical simulation of cold plastic deformation processes. Definition, purpose and advantages compared to experimental research

Cold plastic deformation processes are frequently used in the automotive industry, but also in other fields such as, the aircraft industry, electrical machinery and equipment, fine mechanical, light industry etc.

Because of this, numerical modeling and simulation has appeared and developed.

These programs are based on practical experience, industrial knowledge and expertise in sheet metal forming. They can model and simulate almost all technical requirements that may occur during cold plastic deformation processes, with a very high accuracy results.

The main problems analyzed and solved by numerical simulation of cold plastic deformation processes are:

- ***validation of using*** in cold plastic deformation processes of new High Strength Steels (HSS) [S02, S08];

- ***feasibility and formability analysis of stamping process of the parts with complex shapes*** [P05, J01, V01];
- ***determination the values of the blank holder forces or restraining force of the draw-bead by numerical simulation,*** which preventing appearance of wrinkles during the deformation processes [P04, S10];
- ***highlighting and preventing the various defects that may occur during the deformation process*** [M03];
- ***determining the optimal shape of the blanks (minimum dimensions)*** [A04, J02];
- ***prediction of cracks appearance during the cold plastic deformation process*** [V03, T01, R02];
- ***complex stress state analysis: uniaxial tension, plane strain or biaxially stretching (expansion)*** [S07, S09];
- ***determining the springback that occurs in the parts, both global and locally in certain areas of interest***;
- ***improving and validating the concept of design;***
- ***designing the transition areas between the final piece and the blank,*** areas necessary for carrying out the cold plastic deformation processes.

Based on all the above, it is noted that the use of numerical simulation has become an integral part of the design and planning of cold plastic deformation processes. This tool offers a number of advantages compared to experimental research such as:

- allows identification of areas on the surface of the parts that will cause problems in obtaining them during the deformation process;
- allows to determine the degree of deformation of the material for parts with complex shapes from the beginning of the stage of the technological process, which was impossible to estimate until the appearance of the numerical simulation;
- allows the optimization of the geometrical characteristics of the surfaces that define the shape of the parts or blanks;
- allows verification of the technical solutions adopted to avoid obtaining nonconforming parts;
- allows to determine the minimum number of operations needed to obtain the parts;
- reduce design costs;
- validation of using in cold plastic deformation processes of a new materials type, cheaper than those commonly used, or with smaller thicknesses;
- allows the determination of the working conditions necessary to obtain the lowest cost parts;
- allows to determine the minimum dimensions of the blanks.

2.1.2. The role of numerical simulation in the manufacturing process

Numerical simulation is present throughout the conception of the manufacturing process of a product, the results of the numerical simulation representing the input data for the realization of the future dies with which the future product will be made.

Immediately after completing the design phase of a new product, the numerical simulation is used to verify the feasibility of both the shape of the product and the proposed manufacturing process for obtaining it. In most cases, for products with complex forms, the first verification of the feasibility of the product is to identify critical areas subjected to excessive stretching or compression stresses, i.e. areas that are susceptible to excessive thinning, respectively, cracks or splits of the material on the surface of the part, and/or areas susceptible to wrinkles or to the increased thickness of the material over a required maximum limit.

2.1.3. Types of defects predicted and studied with numerical simulation

During cold plastic deformation processes, due to the continuous change in the stress state acting on the parts, various defects appears. Defects can be transient or remnant, but all negatively affect the quality of the part. Depending on the functional role of the part, these defects can be accepted or not.

- Among the most common defects are:
- Cracks or tears of the parts - appear in the stretched areas;
- Wrinkles - appear under the blank holder element or on the surfaces of the part in the areas subjected to compression stress states;
- Concave areas (Oreilles de Mickey), appear in the areas insufficiently stressed at stretching tensions and, consequently, the material has not yet exceeded the flow limit, σ_c;

2.1.4. Statistical modelling of the process characteristics using the Response Surface Methodology

The statistical programming of the experiments, respectively the analysis of the influence of the process parameters on the result or the final results is done using the Response Surface Method. This method is used in their works by [D01, D02, D03, D05, D06, V05, S06], to determine the influences of process parameters on surface roughness at face milling of an aluminum-silicon alloy [D01], statistic modeling of maximum force and medium force's coefficient in punching [D02] or statistical modelling of the spring back behavior for bending of V-Shaped PARTS from common sheet metal [D06]. The use of this method allows a ranking of the influence of the considered factors and the emphasis of the existing interactions between the independent variables.

2.2. Modelling the characteristics of shrink and stretch flange forming processes with data obtained from finite element simulation

2.2.1. Mathematical modeling using the response surface method

Experimental research of a process is to emphasize the most significant parameters that can influence the considered process, $x_1, x_2, \dots, x_i$, and establishing the links between them and their answers, $y, y_2, \dots, y_n$, Fig. 2.1.

The Response Surface Method considers the connection between the parameters of a process, $(x_1, x_2, \dots, x_i)$, and their effects on the phenomenon studied as surfaces in the three-dimensional space of the variables, called response surfaces. this assumes that for each value of the considered parameters, a value for the dependent function will be determined, which will be on the response surface, Fig. 2.2, [D04, S04].

Fig. 2.1. Experimental research of a process

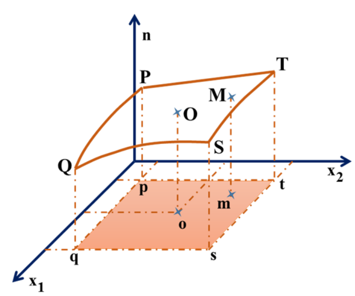


Fig. 2.2. The response surface of a studied process

The problems which appears to the determination of a regression function, are the following:

a) statistical programming of the experiments;
b) establishing the type of the function (the model);

c) calculation of regression coefficients;
d) regression analysis;
e) determination of statistical errors and confidence intervals for the dependent variable.

Chapter 3. Conclusions referring to the actual state of the art on the achievement of shrink and stretch flange forming parts made by metal sheet

From the analysis of the current stat of the art stage of the research - development regarding the obtaining of the flange formed parts from steel sheet by cold plastic deformation, important conclusions are drawn as follows.

- The use of numerical simulation has become an integral part of the design and planning of cold plastic deformation processes;
- The use of this tool from the beginning of design stage allows identification of the areas that will cause problems in obtaining them during deformation;
- Numerical simulation is used to check the technical solutions adopted to minimize the probability to obtaining defective parts;
- Numerical simulation is used to optimize the geometric characteristics of the surfaces that define the shape of the parts;
- The numerical simulation is used to optimize the geometric characteristics of the surfaces of the active elements of the dies;
- Numerical simulation is used to determine the minimum number of operations needed to obtain the parts;
- Numerical simulation is used for validation of a new types of materials for cold plastic deformation processes;
- The paperwork's that have been the subject of documentary research treats extensively the feasibility evaluation of the sheet metal parts with the help of numerical simulation, being an important support for the research made within the doctoral activity.
- Therefore, it can be said that over 90% of all cold plastic deformation processes in the automotive industry are validated based on the results obtained by numerical simulation, a method used by all automotive manufacturers.

Part II.
Contributions referring to the actual state of the art on the flange forming of exterior outline edges of the part made by cold plastic deformation

Chapter 4. Directions, main objective and research - development methodology on optimizing the constructive characteristics of the flange forming parts

4.1. Research - development directions

Based on the analysis of the current state of the art research, the following research -development directions are considered to be relevant regarding the flange forming of the convex or concave exterior outline edges of the metal parts by cold plastic deformation:

- metallic flange formed parts have a wide use today, especially in the construction of car bodies;
- the flanged edges of these parts are used as surfaces for assembling, for stiffening or for supporting or sealing surfaces;
- depending on the visual impact of the parts, these can be divided in visual impact parts and structural parts. The parts of the first category have more severe execution requirements;
- a numerical simulation will be used to analyze the influence of the constructive characteristics of these parts on the feasibility using a program that allows them to be modeled for optimization;
- numerical simulations will be performed using a statistical planning of simulation;
- the response surface methodology will be used to obtain the models of the studied characteristics;
- the obtained models will be statistic analyzed;
- the response surfaces of the modeled characteristics will be represented graphically in 3D;
- the influences of the considered parameters will be studied and conclusions will be made concerning to the optimization of the flange forming process;

4.2. The main objective of the research - development activity

Based on data and conclusions drawn from the present state of the art on, as well as the research - development directions regarding the flange forming of the of the convex and concave exterior outline edges of the metal parts made by cold plastic deformation, it is assume as the main objective of the research-development activity within the doctoral thesis: **numerical simulation research and statistical modeling of the characteristics of the exterior outline flanged edges of the metal parts, manufactured by cold plastic deformation.**

4.3. Research - development methodology

The following methodology is proposed for achieving the main research - development objective:

4.3.1. Numerical simulation of the shrink and stretch flange forming parts made by cold plastic deformation

a. Establishing the simulation program and its structure;
b. Designing the simulation program;
c. Establish the initial data needed for simulation;
d. Entering the data into your computer;
e. Running the simulation program;
f. Extracting the simulation results.

4.3.2. Statistical modelling of the simulation results

a. Establishing the structure and complexity of the models;
b. Estimation of model coefficients;
c. Statistical analyses of the obtained models:
   - checking the significance of model coefficients;
   - Determination of confidence intervals of 95% for model coefficients and predicted models responses.
d. Simplification of models by retaining only terms with highly significant coefficients.

4.3.3. Graphic representation of the obtained models and analysis of the influence of the parameters on the flange forming characteristics

a. 3D and 2D graphic representation of the obtained models;
b. Analysis of the influence of the parameters on the flange forming process characteristics of the convex or concave exterior outline edges;
c. Optimizing the thickening and thinning of the flanged edges taking into account certain imposed restrictions
d. Conclusions.

Chapter 5. Researches on shrink and stretch flange forming process using numerical simulation

5.1. Defining the constructive characteristics

In the case of complex parts with convex or concave exterior outline edges, the literature does not provide sufficient information regarding the feasibility of these parts. All important automotive manufacturers are based on their own experience of producing similar parts and to copy values of the geometric constructive characteristics from parts that were previously manufactured.

It can be considered that the feasibility of the parts with convex or concave exterior outline edges is influenced by the following constructive characteristics of the part (Fig. 5.1, a, b c and d):

r_{so} - fillet radius in horizontal plane, mm, Fig. 5.1 (c);
r_{sv} - left hand fillet radius in vertical plane, mm, Fig. 5.1 (b) (section C-C);
r_{mv} - medium fillet radius in vertical plane, mm, Fig. 5.1 (a) (section A-A);
r_{dv} - right hand fillet radius in vertical plane, mm, Fig. 5.1 (d) (section B-B);
$\propto_{ro}^{\circ}$ - connection angle between the lateral side walls, degree, Fig. 5.1 (c);
$\propto_{m}^{\circ}$ - medium bend angle between the side wall of the part and normal to the surface of the part, degree, Fig. 5.1 (a);
$\propto_{s}^{\circ}$ - bend angle between the left-hand side wall of the part and normal to the surface of the part, degree, Fig. 5.1 (b);
$\propto_{d}^{\circ}$ - bend angle between the right-hand side wall of the part and normal to the surface of the part, degree, Fig. 5.1 (d);
l_s - length of the left hand flanged wall, mm, Fig. 5.1 (b);
l_m - length of the medium flanged wall, mm, Fig. 5.1 (a);
l_d - length of the right hand flanged wall, mm, Fig. 5.1 (a);
g - thickness of the blank, mm, Fig. 5.1 (b).

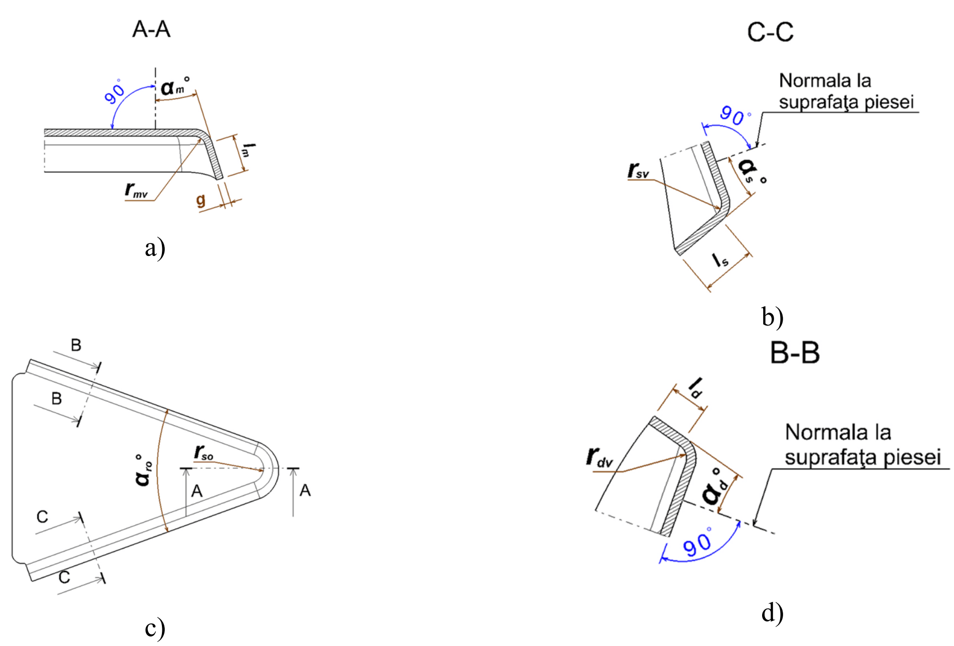


Fig. 5.1. Geometrical parameters of forming flange process

All these constructive characteristics mentioned above influence the feasibility of the parts with convex or concave exterior outline edges.

5.2. The flanging process technology used

The numerical simulation provides the possibility of assessing the feasibility and correct values of the constructive characteristics of the parts, by analyzing the increase of the thickness of the part in the areas subjected to compressive stresses, or by analyzing the decrease of the thickness of the part in the zones subjected to tensile stresses.

5.3. Flange forming process parameters studied

To establish the parameters of the flanging process of the parts with convex or concave exterior outline edges it is assumed that the feasibility of the deformation process is influenced by all the geometrical constructive characteristics of the part.

Because the number of parameters of the flange forming process to be studied is very high, which implies a large number of simulations, and taking into account that in reality some of the parameters previously defined do not have imposed values or may have the same values, were considered the following simplifying assumptions in order to reduce the number of these parameters.

Conclusively, of the 11 initial geometric parameters considered to influence the flange forming processes of the parts with convex or concave exterior contours, the following six parameters will be used:

r_{so} - fillet radius in horizontal plane, mm;
r_v - fillet radius in vertical plane, mm;
$\propto_{ro}^{\circ}$ - angle between the lateral side walls, degree;
$\propto_{s}^{\circ}$ - bend angle between the left-hand side wall of the part and normal to the surface of the part, degree;
$\propto_{d}^{\circ}$ - bend angle between the right-hand side wall of the part and normal to the surface of the part, degree;
l - wide of the flanged wall, mm.

5.3.1. The range of geometric parameters

The limits of the variation intervals of the geometric parameters considered for the flanged parts after a convex or concave exterior outline edges, were chosen on the basis of the observations, the working cases and the experience gained in the design of the car parts at the RENAULT TECHNOLOGY ROUMANIE headquarters.

5.3.2. Variation levels of the geometrical parameters

In order to determine the polynomial statistical model used, an interactive second order polynomial model was used and five levels of variation of the independent variables were considered.

5.4. Establishing the type of simulation program, designing it and determining the number of simulations required for statistical modeling

Starting from the recommendations from the published literature, based on the experience gained in the research of cold plastic deformation processes, a composite factorial program with central orthogonal points was chosen for concept of simulation programs for the flanged parts after a convex or concave exterior outline edges [D03].
Thus, for a number of six geometric parameters (independent variables), the composite factorial program with orthogonal central points will contain a number of 100 experimental simulations, including 64 points, 12 axial points and 24 central points.

5.5. The software used for numerical simulation of the flange forming process

The simulation software used to study the process of the sheet metal parts with the flanged outer edges after a convex and concave curvilinear contour is called Auto Form, a software used by many of the major automotive companies such as Renault, Audi, BMW, Chrysler, Fiat, Ford, GAZ Group, General Motors, Honda, Volkswagen, Volvo etc.

For running the process simulations of the parts with flanged outer edges after a convex and concave curvilinear contour, the following steps were taken:

1. Importing the geometric model and the curve that defines the shape and dimensions of the blank;
2. Establishing the type of press;
3. Establishing the operation sequence;
4. Defining objective surfaces to generate active elements;
5. Defining the dimensional characteristics of the flange steel;
6. Defining the blank characteristics: dimensions, material type, its thickness;
7. Defining the working characteristics of the press: the restraining force, value of the stroke, the position of the active elements etc.;
8. Analysis and evaluation of the obtained results;

5.6. Initial data required for numerical simulation

5.6.1. Concept of numerical geometric model

The numerical geometric model, Fig. 5.2 and 5.3, is the virtual representation of the physical part that is intended to be obtained.

Fig. 5.2. Representation of the numerical geometric model and the blank used for parts with convex contour

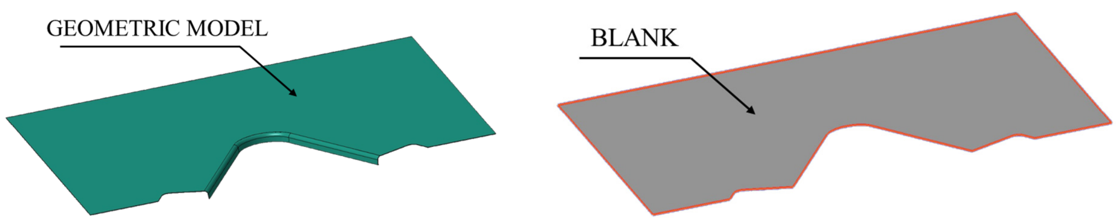
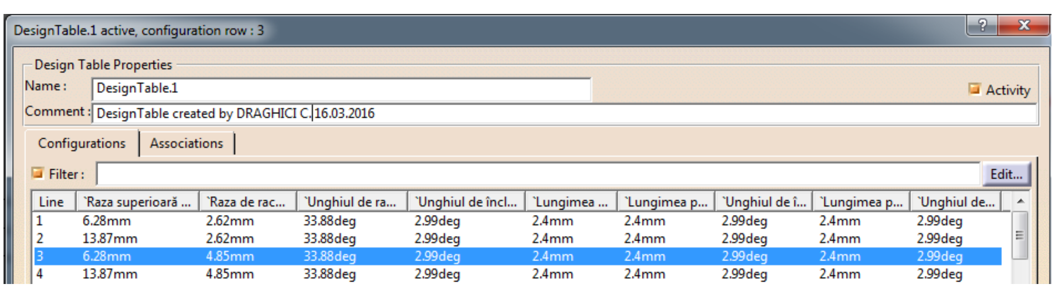


Fig. 5.3. Representation of the numerical geometric model and the blank

used for parts with concave contour

For a quick change of the size and shape of the part and the blank, an interface was made with the CATIA software, Fig. 5.4, which links the parameters of the geometric model with a table, of Excel type, Fig. 5.5, which contains the values of the geometric parameters considered, ordered according to the structure of the program of experimental simulations adopted.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1	6.28mm	2.62mm	33.88deg	2.99deg	2.4mm	2.4mm	2.99deg	2.4mm	2.99deg
2	13.87mm	2.62mm	33.88deg	2.99deg	2.4mm	2.4mm	2.99deg	2.4mm	2.99deg
3	6.28mm	4.85mm	33.88deg	2.99deg	2.4mm	2.4mm	2.99deg	2.4mm	2.99deg
4	13.87mm	4.85mm	33.88deg	2.99deg	2.4mm	2.4mm	2.99deg	2.4mm	2.99deg

Fig. 5.4. Table of geometrical parameters

	A	B	C	D	E	F	G	H	I	J	K
1	Nr. Crt.	`The fillet radius in horizontal plane` (mm)	`The fillet radius in vertical plane` (mm)	`The connection angle in the horizontal plane between the side walls` (deg)	`The bend angle between the right-hand side wall of the part and normal to the surface of the part` (deg)	`The length of the right hand flanged wall` (mm)	`The medium bend angle between the side wall of the part and normal to the surface of the part` (deg)	`The length of the medium flanged wall` (mm)	`The bend angle between the left-hand side wall of the part and normal to the surface of the part` (deg)	`The length of the left hand flanged wall` (mm)	`Thickness of the blank` (mm)
2	1	6.28	2.62	33.88	2.99	2.40	2.99	2.40	2.99	2.40	0.65
3	2	13.87	2.62	33.88	2.99	2.40	2.99	2.40	2.99	2.40	0.65
4	3	6.28	4.85	33.88	2.99	2.40	2.99	2.40	2.99	2.40	0.65

Fig. 5.5. Geometrical parameters of CAD model

5.6.2. Concept of numerical model

The numerical models were created by importing surfaces of numerical geometric models into the simulation software for each simulation.

Numerical models, Fig. 5.6 and 5.7 consist in three rigid elements, namely, punch, die, blank holder and one deformable element, the blank.

The kinematic of the flanging process corresponds to the processing on a simple effect press and is shown in Fig. 5.8.

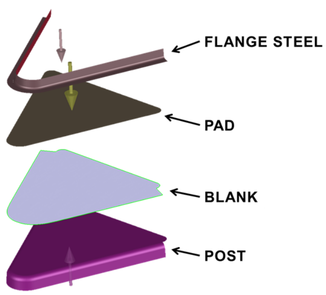


Fig. 5.6. Numerical model for parts with convex outer contour

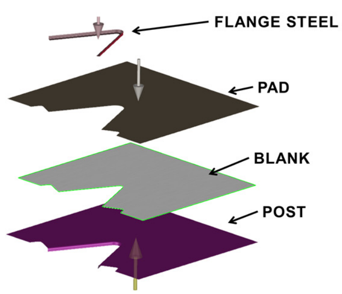


Fig. 5.7. Numerical model for parts with concave outer contour

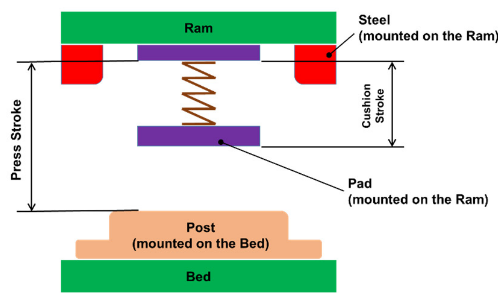


Fig. 5.8. Tool kinematic

5.6.3. Working conditions considered

Simulations were carried out under the following working conditions:

- imported digitized surface corresponds to the inner surface of the piece;
- material thickness g = 0,65 mm;
- radius of flange steel, r_{rp} = 2 mm;
- the flange steel must exceed by at least 5 mm the flange radius;
- type of material used is DC04;
- the value of friction's coefficient between flange steel, pad, post and blank is 0,16;
- the press stroke is 700 mm, speed 233,33 mm/s, cycle time is 6 sec. resulting 10 stroke/minute;
- the cushion stroke is 450 mm;
- deviation from the contour of the final part does not exceed 0.15 mm;
- the value of the retention force developed by the blank holder plate is, 100 kN;

5.6.4. Determination of measured responses

To determine the process characteristics (dependent variables) to be studied and which are influenced during the flange forming process by the geometric characteristics considered, has been take into account the possible defects that may occur during the processing.

It was considered that the dependent variables that will be studied for the flange forming process analysis are the maximum allowable thinning, the maximum allowable thickening and respectively, the variation of the thickness of the side walls.

5.7. Numerical simulation of the flange forming process for each points of the simulation programs

5.7.1. Qualitative evaluation of the state stress using the Forming Limit Diagram

The analysis of the deformability of the parts is done using the Forming Limit Diagram, generated by the simulation software at the end of each simulation, Fig. 5.9. To do this, a color code is used that has the following significances[D05]:

- **grey area -** is the area where deformations in the material are very small and are not permanent
- **green area -** it is the area where the stresses state of the material was changed and its values do not exceed the acceptable limits
- **blue area -** is the area where the material is subjected to a uniaxial compression state
- **purple area -** is the area where the material is subjected to a strong biaxial compression stress state
- **brown area -** is the area were the material is subjected to a bi-axial tensile state and its thickness decrease by more than 10%, in which case the obtained piece is considered to be unfeasible
- **red area -** is the area where the stress state exceeds the acceptable values, cracks appear on the surface of the piece, this being considered to be a non-compliant product.

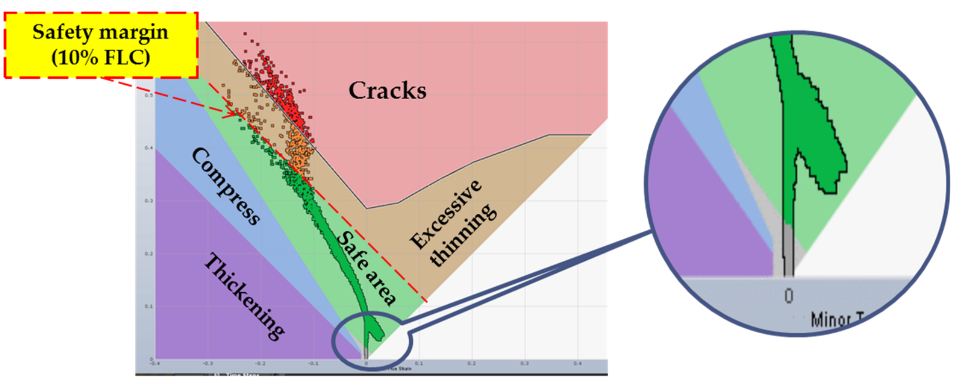


Fig. 5.9. Feasibility analysis of parts with Forming Limit Diagram

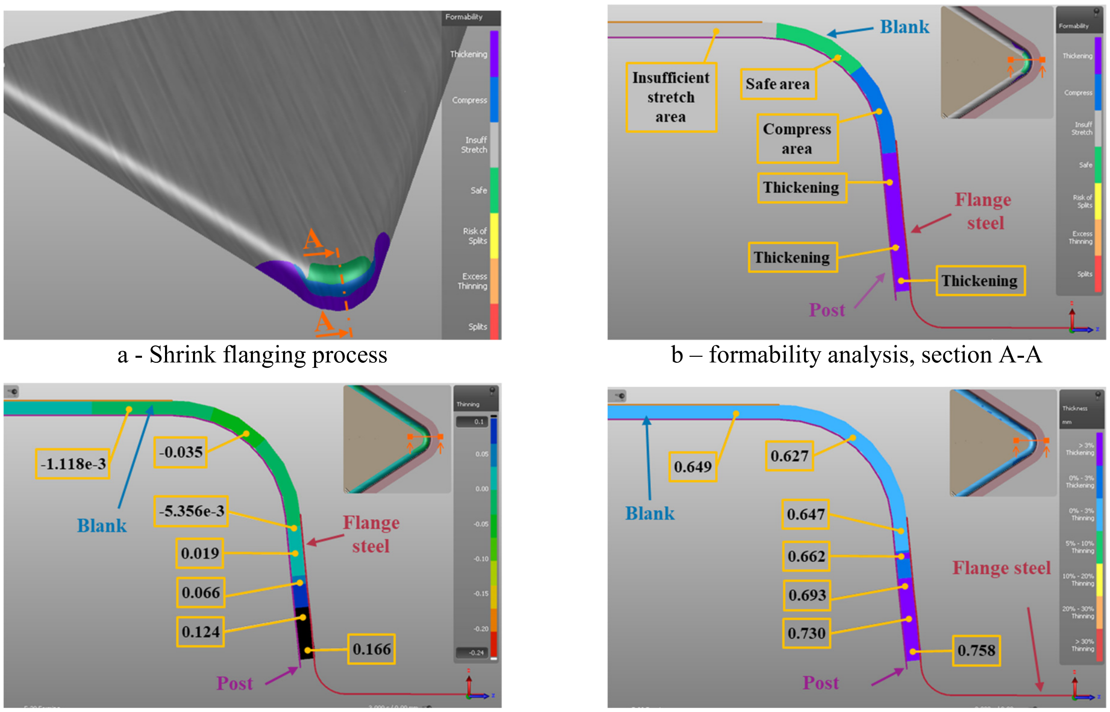
5.7.2. Qualitative graphical evaluation of flange ratio

In order to determine and interpret the stress state of the material of the flanged forming parts with convex or concave contours, a total of 200 simulations was run. This study provides a first qualitative graphical assessment of the formability of the blank.

5.7.3. Quantitative evaluation of thickness and thinning of the blank during the shrink and stretch flange forming process

For the quantitative determination of the compressive and stretch stress influences on the final part and the forming process, were analyzed for the parts subjected to the flange forming process, Fig. 5.10, variation in material thinning, variation in the thickness of the side-walls and the flange ratio, between the top dead center (TDC) and bottom dead center (BDC) of the press.

Based on the analysis of the shrink flanging process, Fig. 5.10, respectively, stretch flanging process, from the analysis of the 200 simulations performed, it was possible to acquire the necessary information about the essential process characteristics.



a - Shrink flanging process

b – formability analysis, section A-A

c - thickness distribution $\hat{I}_g$ [%], section A-A

d - thickness distribution g_r [mm], section A-A

Fig. 5.10. Quantitative analysis of compressive and stretch stress influences in the side-wall area: BDC

5.8. Conclusions regarding numerical simulation of shrink and stretch flange forming process

Based on the data obtained from the analysis of numerical simulation of the flange forming processes, in the case of parts with convex contours, the following observations were made:

- a decreasing of thickness of the part, S_g, in the area of the flange radius, thinning produced due to the friction forces between the steel flange and the blank, with values between 1.6% - 7.4% from the nominal thickness of the piece and, respectively,
- an increasing of thickness at the end of the flange due to the excess of material, with values between 2.9% (exp. nr. 5) - 23.6% (exp. nr. 76) from the nominal thickness of the part;

In the case of parts with concave contours, the following observations were made:

- a decreasing of thickness of the part, S_g, at the end of the flange due to the circumferential stretching stresses with values between 9.5% (exp. nr. 4) - 31.1% (exp. nr. 35) from the nominal thickness of the piece and, respectively,
- the compressive stresses in the flange wall are non-existent.

Tacking in account the admissible values of the parameters analyzed, 24% of the nominal thickness of the part for the maximum acceptable thinning and, 1% of the nominal thickness of the part for the maximum acceptable thickening, it can be concluded that:

- the influence of the thinning produced in the shrink flanged parts is negligible, of 7.4% of the nominal thickness of the part, the minimum thickness value of the part reaching 0.602 mm value compared with the significant thickening of 23.6% of the nominal thickness of the part, the maximum thickness value reaching 0.803 mm;
- the influence of the thinning produced in the stretch flanged parts has an appreciable value, the minimum thickness of the piece reaching 0.448 mm which means a potential high risk of cracking or split;
- there are no compressive stresses in the flange, and in according to that, the influence of thickening on the formability of the piece can be neglected.

Chapter 6. Researches regarding the shrink and stretch flange forming process using statistical modelling

6.1. Establishing the shape and complexity of the models

In the study of cold plastic deformation processes, the link between the parameters and the characteristics of the process is expressed through polynomial relations. In this case, the experimental program was carried out taking into account 6 parameters, namely:

- r_{so} - fillet radius in horizontal plane, mm;
- r_v - fillet radius in vertical plane, mm;
- $\propto_{ro}^{\circ}$ - angle in horizontal plane between the side walls, degree;
- $\propto_{s}^{\circ}$ - bend angle between the left hand side wall of the part and normal to the surface of the part, degree;
- $\propto_{s}^{\circ}$ - bend angle between the right hand side wall of the part and normal to the surface of the part, degree;
- l - wide of the flanged wall, mm.

Due to the wide range of variations of the considered parameters, it is considered appropriate to use mathematical models of order 2 with interactions with 48 coefficients.

6.2. Estimation of model coefficients

Determining of the coefficients by the smallest square method involves the solving of the system of normal equations corresponding to the proposed models. Using the matrix forms of the systems with normal equations corresponding to the form of the mathematical models considered, the coefficients of the models with natural variables were determined. In the case of parts with concave contour, they are presented in Table 6.1.

Table 6.1

Coefficients of the model with natural variables

b_0	=	0.28129377	b_{66}	=	0.004627554	b_{36}	=	0.000405759	b_{146}	=	0.000271915
b_1	=	-0.019794384	b_{12}	=	0.001653903	b_{45}	=	-0.000534868	b_{156}	=	0.000164534
b_2	=	-0.032505167	b_{13}	=	0.000409064	b_{46}	=	-0.006887872	b_{234}	=	-7.48E-05
b_3	=	-0.0088978	b_{14}	=	-0.00104063	b_{56}	=	-0.006630418	b_{235}	=	-5.66E-05
b_4	=	0.005359221	b_{15}	=	9.61E-05	b_{123}	=	-5.34E-05	b_{236}	=	-5.98E-05
b_5	=	0.000283628	b_{16}	=	-0.003674727	b_{124}	=	0.000115531	b_{245}	=	5.88E-05
b_6	=	0.048026495	b_{23}	=	0.001531539	b_{125}	=	-3.48E-05	b_{246}	=	-2.95E-05
b_{11}	=	0.000468213	b_{24}	=	0.00186304	b_{126}	=	0.000184949	b_{256}	=	0.000785894
b_{22}	=	-0.002412187	b_{25}	=	-0.000792806	b_{134}	=	-7.98E-06	b_{345}	=	-3.65E-05
b_{33}	=	-8.07E-06	b_{26}	=	0.000787298	b_{135}	=	-1.48E-05	b_{346}	=	1.35E-05
b_{44}	=	-0.000276335	b_{34}	=	0.000543806	b_{136}	=	-1.36E-05	b_{356}	=	-2.65E-05
b_{55}	=	-5.63E-05	b_{35}	=	0.000681121	b_{145}	=	5.57E-05	b_{456}	=	0.000257912

6.3. Statistical analyzing of obtained models

6.3.1. Checking the adequacy of the obtained models

In order to verify the adequacy of the mathematical models determined, the following statistical parameters were calculated, Tables 6.2 and 6.3:

Table 6.2

Checking model's adequacy for shrink flanged parts

Dispersion	Value
$SP_{rz} = \sum_{i=1}^{n} (y_u - \tilde{y}_u)^2$	0.006823
$f_{rz} = n - m - 1$	52
$PM_{rz} = SP_{rz}/n - m - 1 = s_{rz}^2$	0.000131217
$SP_{er} = (Y_0 - \tilde{Y}_0)^T \cdot (Y_0 - \tilde{Y})$	0.002760958
$f_{er} = n_0 - 1$	23
$PM_{er} = SP_{er}/f_{er} = s_{er}^2$	0.000120042
$SP_{in} = SP_{rz} - SP_{er}$	0.004062373
$f_{in} = f_{rz} - f_{er} = n - m - n_0$	29
$PM_{in} = SP_{in}/f_{in}$	0.000140082
$F_{ci} = PM_{in}/PM_{er}$	1.166943436
$F_{T(f_{in};\, f_{er};\, 95\%)}$	1.976923077

Table 6.3

Checking model's adequacy for stretch flanged parts

Dispersion	Value
$SP_{rz} = \sum_{i=1}^{n} (y_u - \tilde{y}_u)^2$	0.0061426
$f_{rz} = n - m - 1$	52
$PM_{rz} = SP_{rz}/n - m - 1 = s_{rz}^2$	0.000131217
$SP_{er} = (Y_0 - \tilde{Y}_0)^T \cdot (Y_0 - \tilde{Y})$	0.000118128
$f_{er} = n_0 - 1$	23
$PM_{er} = SP_{er}/f_{er} = s_{er}^2$	0.000077650
$SP_{in} = SP_{rz} - SP_{er}$	0.004356715
$f_{in} = f_{rz} - f_{er} = n - m - n_0$	29
$PM_{in} = SP_{in}/f_{in}$	0.000150232
$F_{ci} = PM_{in}/PM_{er}$	1.934717991
$F_{T(f_{in};\, f_{er};\, 95\%)}$	1.976923077

The adequacy of models is given by the ratio representing the value of a Fischer statistical distribution. This is compared to the known critical value of the one corresponding to the number of degrees of freedom, f_{in}, f_{er} and to the 95% probability.

Conclusively, it can be observed that the proposed models are adequate and can correctly reproduce the relationship between the considered parameters and the considered answers.

6.3.2. Checking the coefficients' significance

In order to check the significance of the coefficients of the determined models, these being adequate, for each coefficient is calculated the value of the ratioF_{cs_i}, where the mean square of the coefficients PM_{b_i}, is calculated for each coefficient. For adequate models, the tested coefficient is significant and should be retained if [D04]:

$$F_{cs} > F_T\ (1;\ f_{rz};\ 95\%) = 4.023 \tag{6.1}$$

Analyzing of the obtained data, it can be observed that all the coefficients of the determined models are strongly significant, conclusion reflected on the basis of the high values of the Fcs ratio.

6.3.3. Determination of confidence intervals of 95% for model coefficients and predicted models responses

The confidence intervals characterize the precision of the responses predicted by the determined model based on the dispersion of measured response errors. These are calculated with rel. (6.2) [D04]:

$$V(\tilde{y}) = x^T \cdot (X^T X)^{-1} \cdot x \cdot s_{rz}^2 \tag{6.2}$$

were:
- $V(\tilde{y})$ is the dispersion of predicted responses by the model;
- s_{rz}^2 is the mean squared of the residuals PM_{rz}, the mean square of the experimental error PM_{er}, as determined model is adequate or inadequate;
- X is the matrix of the natural values of the process variables;
- x is the vector of the model terms;
- x^T is transposed to the vector of the model terms.

It is noted that most of the measured responses have values inside of the 95% confidence intervals of the predicted responses, and the erosions of predicted responses measured are quite small, most of them having values below 10% in the case of the shrink flanged parts, Fig. 6.1 and less than 3% in the case of the stretch flanged parts, Fig. 6.2.

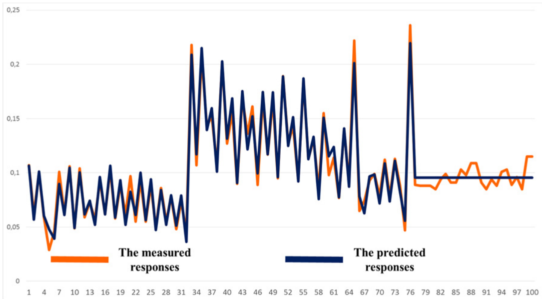


Fig. 6.1. Predicted errors by the determined model in the case of the shrink flanged parts

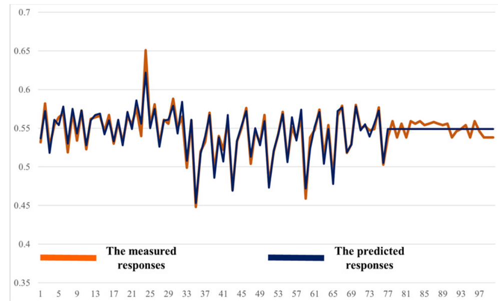


Fig. 6.2. Predicted errors by the determined model in the case of the stretch flanged parts

***Chapter* 7. Investigation regarding the influence of parameters of the convex or concave exterior outline edges on the flange forming process characteristics**

7.1. 2D and 3D graphic representation of characteristics' models of the flange forming process

This chapter presents the theoretical contributions of the author, synthetically disseminated within [D07].

Since all the coefficients of the determined models have a very strong influence on the predicted characteristics, the determined forms of the models for the process responses studied are of the second order with all the interactions considered, given by rel. (7.1) and (7.2):

$$
\begin{aligned}
y = {} & 0.28129377 - 0.019794384 r_{so} - 0.032505167 r_v - 0.0088978 \propto_{ro} + 0.005359221 \propto_s + 0.000283628 \propto_d \\
& + 0.0480264951 l + 0.000468213 r_{so}^2 - 0.002412187 r_v^2 + -8.07e^{-6} \propto_{ro}^2 + -0.000276335 \propto_s^2 \\
& - 5.63e^{-5} \propto_d^2 + 0.004627554 l^2 + 0.001653903 r_{so} r_v + 0.000409064 r_{so} \propto_{ro} \\
& - 0.00104063 r_{so} \propto_s + 9.61e^{-5} r_{so} \propto_d - 0.003674727 r_{so} l + 0.001531539 r_v \propto_{ro} \\
& + 0.00186304 r_v \propto_s - 0.000792806 r_v \propto_d + 0.000787298 r_v l + 0.000543806 \propto_{ro} \propto_s \\
& + 0.000681121 \propto_{ro} \propto_d + 0.000405759 \propto_{ro} l - 0.000534868 \propto_s \propto_d - 0.006887872 \propto_s l \\
& - 0.006630418 \propto_d l - 5.34e^{-5} r_{so} r_v \propto_{ro} + 0.000115531 r_{so} r_v \propto_s - 3.48e^{-5} r_{so} r_v \propto_d \\
& + 0.000184949 r_{so} r_v l - 7.98e^{-6} r_{so} \propto_{ro} \propto_s - 1.48e^{-5} r_{so} \propto_{ro} \propto_d - 1.36e^{-5} \propto_{ro} l \\
& + 5.57e^{-5} r_{so} \propto_s \propto_d + 0.000271915 r_{so} \propto_s l + 0.000164534 r_{so} \propto_d l - 7.48e^{-5} r_v \propto_{ro} \propto_s \\
& - 5.66e^{-5} r_v \propto_{ro} \propto_d - 5.98e^{-5} r_v \propto_{ro} l + 5.88e^{-5} r_v \propto_s \propto_d - 2.95e^{-5} r_v \propto_s l \\
& + 0.000785894 r_v \propto_d l - 3.65e^{-5} \propto_{ro} \propto_s \propto_d + 1.35e^{-5} \propto_{ro} \propto_s l - 2.65e^{-5} \propto_{ro} \propto_d l \\
& + 0.000257912 \propto_s \propto_d l
\end{aligned}
\tag{7.1}
$$

$$
\begin{aligned}
y = {} & 0.300984411 + 0.016606830\, r_{so} + 0.039160636\, r_v + 0.000584447 \propto_{ro} + 0.002735605 \propto_s \\
& - 0.027617219 \propto_d - 0.033452961\, l - 0.000255803\, r_{so}^2 - 0.000194866\, r_v^2 \\
& + 0.000000956 \propto_{ro}^2 + 0.000067308 \propto_s^2 - 0.000072692 \propto_d^2 - 0.001286434\, l^2 \\
& - 0.000677554\, r_{so} r_v - 0.000020013\, r_{so} \propto_{ro} - 0.000147606\, r_{so} \propto_s - 0.000323460\, r_{so} \propto_d \\
& + 0.001763188\, r_{so} l - 0.000628189\, r_v \propto_{ro} + 0.002677515\, r_v \propto_s + 0.001881626\, r_v \propto_d \\
& - 0.010794844\, r_v l + 0.000264110 \propto_{ro} \propto_s - 0.000241390 \propto_{ro} \propto_d + 0.000420432 \propto_{ro} l \\
& + 0.003331836 \propto_s \propto_d - 0.007584001 \propto_s l + 0.012452777 \propto_d l + 0.000015337\, r_{so} r_v \propto_{ro} \\
& - 0.000086640\, r_{so} r_v \propto_s + 0.000113009\, r_{so} r_v \propto_d + 0.000068180\, r_{so} r_v l \\
& - 0.000009374\, r_{so} \propto_{ro} \propto_s + 0.000011473\, r_{so} \propto_{ro} \propto_d - 0.000014182 \propto_{ro} l \\
& + 0.000019588\, r_{so} \propto_s \propto_d + 0.000170178\, r_{so} \propto_s l - 0.000223359\, r_{so} \propto_d l \\
& - 0.000010494\, r_v \propto_{ro} \propto_s + 0.000036203\, r_v \propto_{ro} \propto_d + 0.000029439\, r_v \propto_{ro} l \\
& - 0.000697832\, r_v \propto_s \propto_d + 0.000678055\, r_v \propto_s l - 0.000744531\, r_v \propto_d l \\
& - 0.000012823 \propto_{ro} \propto_s \propto_d + 0.000018271 \propto_{ro} \propto_s l - 0.000030617 \propto_{ro} \propto_d l \\
& - 0.000124443 \propto_s \propto_d l
\end{aligned}
\tag{7.2}
$$

From the studying of the regression equation determined to estimate the thickening characteristics of the flanged outer edges of the parts $\hat{I}_g$, the following considerations can be made:

- once with increasing value of the width of the of the flanged side wall l, Fig. 7.1, the value of the thickening of the material $\hat{I}_g$ is increased also, phenomena explained by the intensify of the excess material that has to be deformed and redistributed;
- the same phenomenon of increase of the thickness of the flanged side wall is also manifested once to the decrease of the bend angles between the left and right hand side wall of the part and normal to the surface of the part, $\propto_s^{\circ}$ and $\propto_d^{\circ}$, but to a smaller extent, Fig. 7.2 and 7.3;
- variation of the fillet radius in vertical plane r_v, Fig. 7.4, influence in a negative sense the value of thickening produced once with the increase in its value;
- it has also been found that, with increasing the values of the fillet radius in the horizontal plane r_{so}, Fig. 7.5, respectively, of the connection angle between the lateral side walls $\propto_{ro}^{\circ}$, Fig. 7.6, the value of the thickening of the material $\hat{I}_g$ decreases, phenomenon explained by the fact that in these situations, the volume of material that needs to be deformed and redistributed decreases.

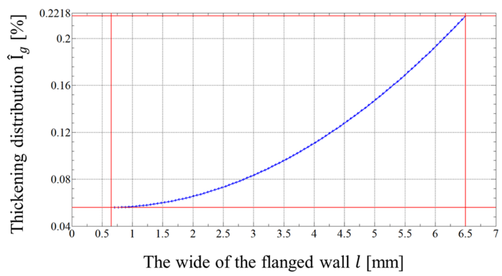


Fig. 7.1. Thickening distribution $\hat{I}_g$ [%] as function of the wide of the flanged wall values l [mm]

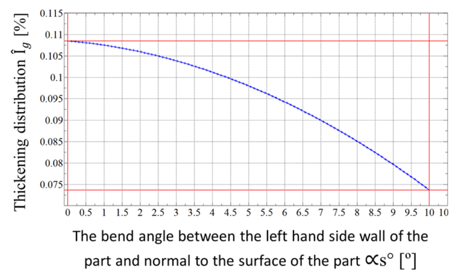


Fig. 7.2. Thickening distribution $\hat{I}_g$ [%] as function of the bend angle between the left hand side wall of the part and normal to the surface of the part values $\propto_s^{\circ}$ [º]

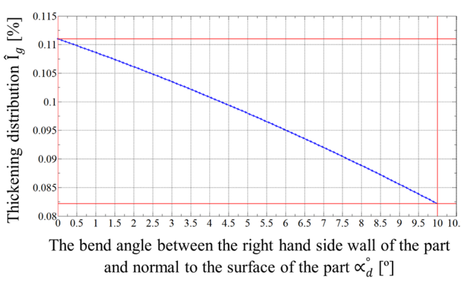


Fig. 7.3. Thickening distribution $\hat{I}_g$ [%] as function of the bend angle between the right hand side wall of the part and normal to the surface of the part values $\propto_d^{\circ}$ [º]

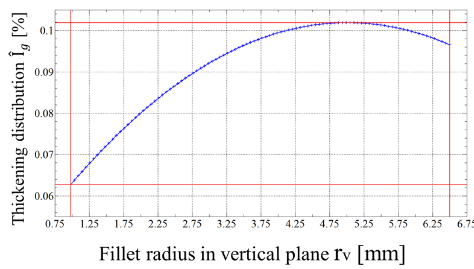


Fig. 7.4. Thickening distribution $\hat{I}_g$ [%] as function of the fillet radius in vertical plane values r_v [mm]

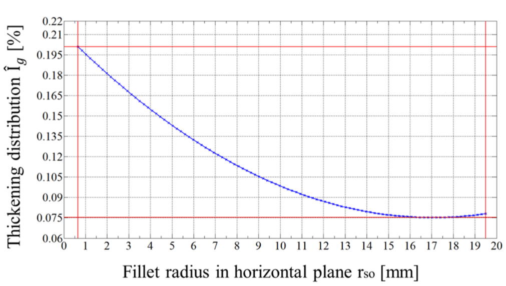


Fig. 7.5. Thickening distribution $\hat{I}_g$ [%] as function of the fillet radius in horizontal plane values r_{so} [mm]

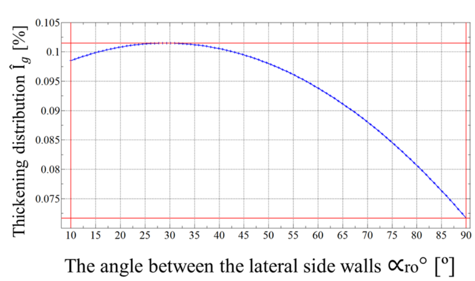


Fig. 7.6. Thickening distribution $\hat{I}_g$ [%] as function of the angle between the lateral side walls values $\propto_{ro}^{\circ}$ [º]

From the examination of 3D graphs shown in Fig. 7.7. - 7.11, we can observe the shape of the response surfaces corresponding to the process characteristics studied using the determined model, by which the dependencies and the influences between the parameters considered and the dependent variable analyzed are very well approximated.
The following were found:

- by increasing the value of the connection radius in horizontal plane between the side walls r_{so}, Fig. 7.7, the value of the thickening $Î_g$ decreases;
- the wide of the flanged wall *l*, Fig. 7.11, has a great influence on the thickening occurring in the flanged side wall, in that it is the main geometric parameter that directly influences the contribution of the volume of material which must be deformed and redistributed;
- regarding to parameter, the fillet radius in vertical plane r_v, din Fig. 7.7 and 7.8, once with the increase of its value, it is noted that its influence on the thickening is disadvantageous;
- regarding to parameter, the connection angle between the side walls $\propto_{ro}^{\circ}$, from the analysis of Fig. 7.8 and 7.10, it has been observed that its influence is favorable to reduction of the thickening when it takes values from the upper limit of the studied variation range, respectively, 90°;
- the both bend angles between the left and right hand side wall of the part and normal to the surface of the part $\propto_s^{\circ}$ and $\propto_d^{\circ}$, Fig. 7.9 - 7.11, have a similar influence, respectively, a decrease in produced thickening if their values tend to the upper limit of the studied ranges;

In the case of the stretch flange parts, from the study of the 2D and 3D graphs, the following conclusions were made:

- by increasing the value of the connection radius in horizontal plane between the side walls r_{so}, the slope of the variation curve of the thickness of the flanged edges of the part increases, Fig. 7.7,
- the influence of the connection angle in the horizontal plane between the side walls of the part, $\propto_{ro}^{\circ}$, Fig. 7.8, on value of the thickness of the flanged side walls, is reduced when the value of the parameter tends to the upper limit of the studied range,
- fillet radius in vertical plane r_v, Fig. 7.8, has a positive influence on the thickness of the flanged side walls of the parts with the increase of its value,
- from the examination of 3D graphs shown in Fig. 7.9. - 7.12, we can observe that the both bend angles between the left and right hand side wall of the part and normal to the surface of the part $\propto_s^{\circ}$ and $\propto_d^{\circ}$, have similar influence, respectively, achieving a high value of thickness in the flanged side walls of the part, if their values tend to the upper limit of the studied ranges,
- a higher value of the parameter, the wide of the flanged wall *l*, means a large amount of material to be redistributed, and thus, a high probability of appearance of an excessive thickening of the flanged walls, Fig. 7.11 and 7.12.

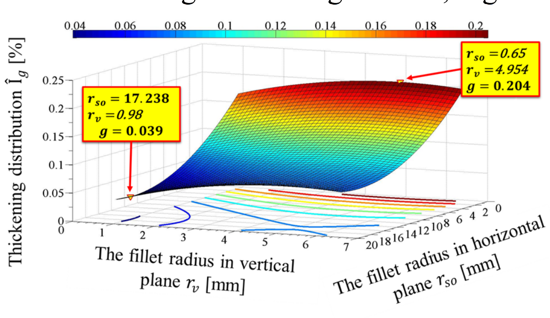


Fig. 7.7. Thickening distribution $Î_g$ [%] as function of the fillet radius in horizontal plane values r_{so} [mm] and the fillet radius in vertical plane values r_v [mm]

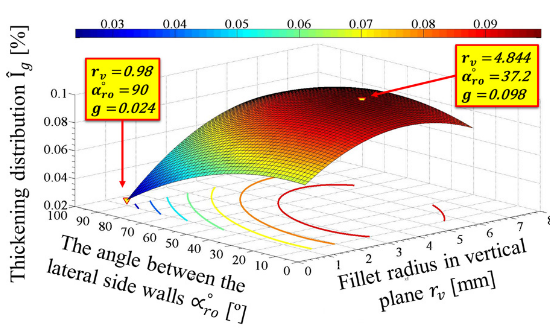


Fig. 7.8. Thickening distribution $Î_g$ [%] as function of the fillet radius in vertical plane values r_v [mm] and the angle between the lateral side walls values $\propto_{ro}^{\circ}$ [°]

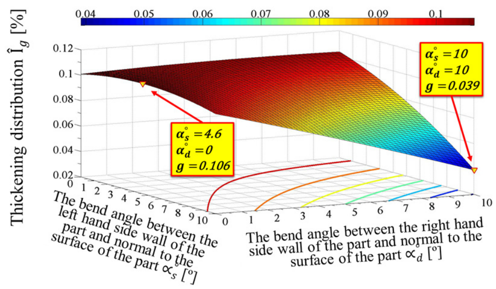


Fig. 7.9. Thickening distribution $\hat{I}_g$ [%] as function of the bend angle between the left hand side wall of the part and normal to the surface of the part values $\propto_s^\circ$ [º] and the bend angle between the right hand side wall of the part and normal to the surface of the part values $\propto_d^\circ$ [º]

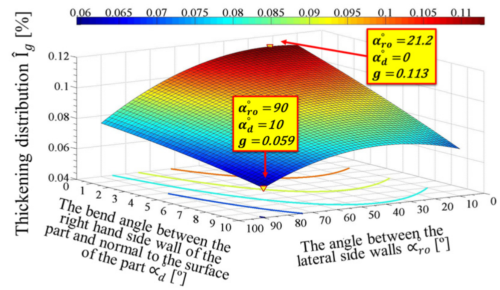


Fig. 7.10. Thickening distribution $\hat{I}_g$ [%] as function of the angle between the lateral side walls values $\propto_{ro}^\circ$ [º] and the bend angle between the right hand side wall of the part and normal to the surface of the part values $\propto_d^\circ$ [º]

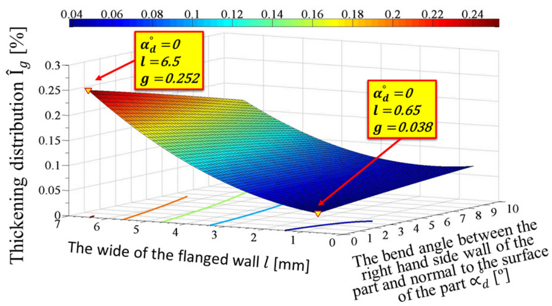


Fig. 7.11. Thickening distribution $\hat{I}_g$ [%] as function of the bend angle between the right hand side wall of the part and normal to the surface of the part values $\propto_d^\circ$ [º] and the wide of the flanged wall values l [mm]

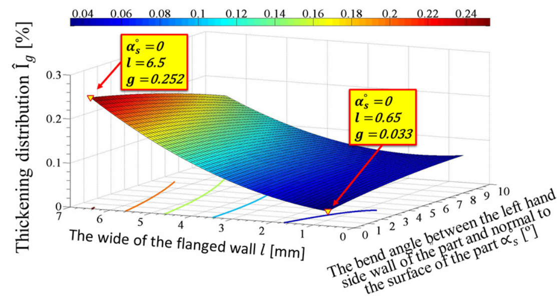


Fig. 7.12. Thickening distribution $\hat{I}_g$ [%] as function of the bend angle between the left hand side wall of the part and normal to the surface of the part values $\propto_s^\circ$ [º] and the wide of the flanged wall values l [mm]

In the case of the shrink flange parts, from the study of the 2D and 3D graphs, the following conclusions were made:

- by increasing the value of the connection radius in horizontal plane between the side walls r_{so}, the slope of the variation curve of the thickness of the edges of the piece increases, Fig. 7.13,
- the influence of the connection angle in the horizontal plane between the side walls of the part, $\propto_{ro}^\circ$, Fig. 7.13, on value of the thickness of the flanged side walls, is reduced when the value of the parameter tends to the upper limit of the studied range
- fillet radius in vertical plane r_v, Fig. 7.14, has a positive influence on the thickness of the flanged side walls of the parts with the increase of its value,
- from the examination of 3D graphs shown in Fig. 7.14. - 7.16, we can observe that the both bend angles between the left and right hand side wall of the part and normal to the surface of the part $\propto_s^\circ$ and $\propto_d^\circ$, have similar influence, respectively, achieving a high value of thickness in the flanged side walls of the part, if their values tend to the upper limit of the studied ranges,
- a higher value of the parameter, the wide of the flanged wall l, means a large amount of material to be redistributed, and thus, a high probability of appearance of an excessive thinning in the connection area between the edges of the part, Fig. 7.16.

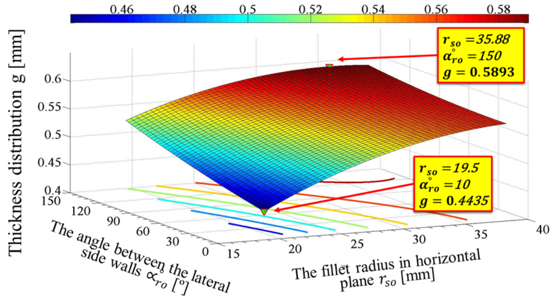


Fig. 7.13. Thickness distribution g [mm] as function of the fillet radius in horizontal plane values r_{so} [mm] and the angle between the lateral side walls values $\propto^{\circ}_{ro}$ [º]

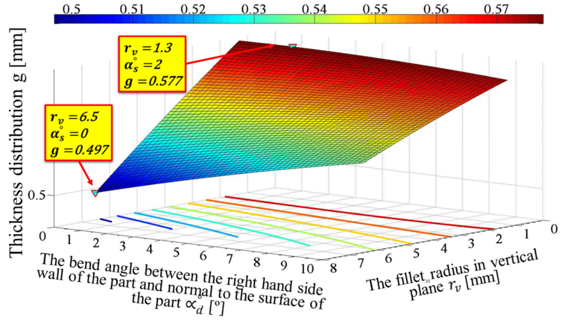


Fig. 7.14. Thickness distribution g [mm] as function of the fillet radius in vertical plane values r_v [mm] the bend angle between the right hand side wall of the part and normal to the surface of the part values $\propto^{\circ}_{d}$ [º]

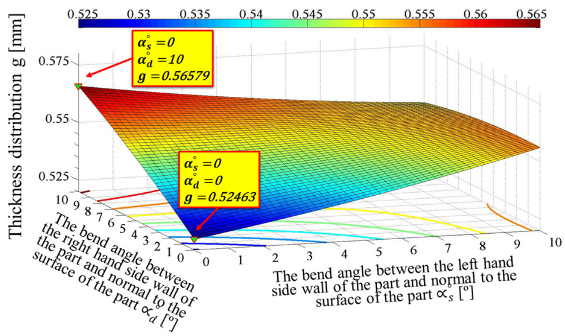


Fig. 7.15. Thickness distribution g [mm] as function of the bend angle between the left hand side wall of the part and normal to the surface of the part values $\propto^{\circ}_{s}$ [º] the bend angle between the right hand side wall of the part and normal to the surface of the part values $\propto^{\circ}_{d}$ [º]

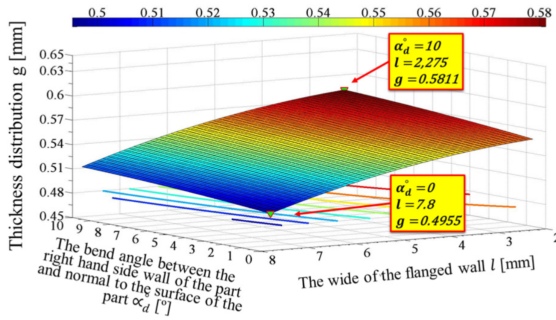


Fig. 7.16. Thickness distribution g [mm] as function of the bend angle between the right hand side wall of the part and normal to the surface of the part values $\propto^{\circ}_{d}$ [º] and the wide of the flanged wall values l [mm]

7.2. Optimal values of form flanging process parameters

With the data acquired using the determined mathematical models and the observations made after the analysis of the 2D and 3D representations of these models, the optimal values of the geometrical characteristics studied for various work cases were determined, Tables 7.1 and 7.2.

Table 7.1

Geometrical characteristics of shrink flanged parts with thickness of 0.65 mm and maximum acceptable thickening of 1%

Geometrical characteristic						Side-wall thickening estimation, $\hat{I}_g$ [%]	Thickness of the side-wall, g [mm]	Geometrical characteristic						Side-wall thickening estimation, $\hat{I}_g$ [%]	Thickness of the side-wall, g [mm]
r_{so} [mm]	r_v [mm]	$\propto^{\circ}_{ro}$ [º]	$\propto^{\circ}_{s}$ [º]	$\propto^{\circ}_{d}$ [º]	l [mm]			r_{so} [mm]	r_v [mm]	$\propto^{\circ}_{ro}$ [º]	$\propto^{\circ}_{s}$ [º]	$\propto^{\circ}_{d}$ [º]	l [mm]		
8	2	60	8	8	5	0,093	0,590	11,8	2	60	8	8	5	0,070	0,604
8,2	2	60	8	8	5	0,091	0,591	12	2	60	8	8	5	0,069	0,605
8,4	2	60	8	8	5	0,090	0,592	12,2	2	60	8	8	5	0,069	0,605
8,6	2	60	8	8	5	0,088	0,593	12,4	2	60	8	8	5	0,068	0,606
8,8	2	60	8	8	5	0,087	0,594	12,6	2	60	8	8	5	0,067	0,606
9	2	60	8	8	5	0,085	0,594	12,8	2	60	8	8	5	0,067	0,607
9,2	2	60	8	8	5	0,084	0,595	13	2	60	8	8	5	0,066	0,607

Table 7.1(continuation)

Geometrical characteristics of the shrink flanged parts with thickness of 0.65 mm and maximum acceptable thickening of 1%

Geometrical characteristic						Side-wall thickening estimation, $\hat{I}_g$ [%]	Thickness of the side-wall, g [mm]	Geometrical characteristic						Side-wall thickening estimation, $\hat{I}_g$ [%]	Thickness of the side-wall, g [mm]
r_{so} [mm]	r_v [mm]	$\propto^{\circ}_{ro}$ [°]	$\propto^{\circ}_{s}$ [°]	$\propto^{\circ}_{d}$ [°]	l [mm]			r_{so} [mm]	r_v [mm]	$\propto^{\circ}_{ro}$ [°]	$\propto^{\circ}_{s}$ [°]	$\propto^{\circ}_{d}$ [°]	l [mm]		
9,4	2	60	8	8	5	0,083	0,596	13,2	2	60	8	8	5	0,065	0,607
9,6	2	60	8	8	5	0,082	0,597	13,4	2	60	8	8	5	0,065	0,608
9,8	2	60	8	8	5	0,080	0,598	13,6	2	60	8	8	5	0,064	0,608
10	2	60	8	8	5	0,079	0,599	13,8	2	60	8	8	5	0,064	0,608
10,2	2	60	8	8	5	0,078	0,599	14	2	60	8	8	5	0,064	0,609
10,4	2	60	8	8	5	0,077	0,600	14,2	2	60	8	8	5	0,063	0,609
10,6	2	60	8	8	5	0,076	0,601	14,4	2	60	8	8	5	0,063	0,609
10,8	2	60	8	8	5	0,075	0,601	14,6	2	60	8	8	5	0,062	0,609
11	2	60	8	8	5	0,074	0,602	14,8	2	60	8	8	5	0,062	0,610
11,2	2	60	8	8	5	0,073	0,603	15	2	60	8	8	5	0,062	0,610
11,4	2	60	8	8	5	0,072	0,603	15,2	2	60	8	8	5	0,062	0,610
11,6	2	60	8	8	5	0,071	0,604	**15,4**	2	60	8	8	5	0,062	0,610

Table 7.2

Geometrical characteristics of the stretch flanged parts with thickness of 0.65 mm and admissible thinning of 24%

Geometrical characteristic						Side-wall thinning estimation, $\hat{I}_g$ [%]	Admissible thinning [%]	Thickness of the side-wall, g [mm]
r_{so} [mm]	r_v [mm]	$\propto^{\circ}_{ro}$ [°]	$\propto^{\circ}_{s}$ [°]	$\propto^{\circ}_{d}$ [°]	l [mm]			
19.5	2	10	8	8	7	22.9	24	0.501
19.5	2	20	8	8	7	22.3	24	0.505
19.5	2	30	8	8	7	21.6	24	0.509
19.5	2	40	8	8	7	21.0	24	0.513
19.5	2	50	8	8	7	20.3	24	0.518
19.5	2	60	8	8	7	19.6	24	0.522
19.5	2	70	8	8	7	18.8	24	0.527
19.5	2	80	8	8	7	18.0	24	0.532
19.5	2	90	8	8	7	17.2	24	0.538
19.5	2	100	8	8	7	16.4	24	0.543
19.5	2	110	8	8	7	15.5	24	0.549
19.5	2	120	8	8	7	14.6	24	0.555
19.5	2	130	8	8	7	13.7	24	0.561
19.5	2	140	8	8	7	12.7	24	0.567
19.5	2	150	8	8	7	11.7	24	0.5737

7.3. Conclusions regarding the influence of the shrink and stretch flange forming parameters on the process characteristics

In conclusion, according to the data synthesized in Table 7.3 and 7.4, it has been found that in order to obtain an acceptable value of the thickening or thickness of the flanged walls, it is necessary that the parameters:

- fillet radius in horizontal plane r_{so},
- connection angle between the lateral side walls $\propto^{\circ}_{ro}$,
- bend angle between the left hand side wall of the part and normal to the surface of the part $\propto^{\circ}_{s}$,
- bend angle between the right hand side wall of the part and normal to the surface of the part $\propto^{\circ}_{d}$

must have values as high as possible.

Also, it is necessary that the parameters:

- fillet radius in vertical plane r_v,
- wide of the flanged wall l

must have values as lower as possible.

The remarks are presented synthetically in Tables 7.3 and 7.4.

Table 7.3

Influence of the shrink flange forming parameters on thickening

Geometrical characteristic	Variation mode of the parameter	Thickening distribution $Î_g$, [%]
Fillet radius in horizontal plane r_{so}, [mm]	↗	↘
Fillet radius in vertical plane r_v, [mm]	↗	↗
Connection angle between the side walls $\propto^{\circ}_{ro}$, [grade]	↗	↘
Bend angle between the left hand side wall of the part and normal to the surface of the part $\propto^{\circ}_{s}$, [grade]	↗	↘
Bend angle between the right hand side wall of the part and normal to the surface of the part $\propto^{\circ}_{d}$, [grade]	↗	↘
Wide of the flanged wall l, [mm]	↗	↗

Table 7.4

Influence of the stretch flange forming parameters on thickness

Geometrical characteristic	Variation mode of the parameter	Thickness distribution g, [mm]
Fillet radius in horizontal plane r_{so}, [mm]	↗	↗
Fillet radius in vertical plane r_v, [mm]	↗	↘
Connection angle between the side walls $\propto^{\circ}_{ro}$, [grade]	↗	↗
Bend angle between the left hand side wall of the part and normal to the surface of the part $\propto^{\circ}_{s}$, [grade]	↗	↗
Bend angle between the right hand side wall of the part and normal to the surface of the part $\propto^{\circ}_{d}$, [grade]	↗	↗
Wide of the flanged wall l, [mm]	↗	↘

Chapter 8. Final conclusions and main contributions on the optimizing of cold plastic deformation processes with numerical simulation

(1) From the analysis of the current state of the art research regarding the flange forming process of the parts made from metal sheets, important conclusions have been made, which are presented in Chapter 3.

(2) Taking into consideration the data and the conclusions of the analysis of the current state of the art research regarding the processing of the flanged parts from metal sheets, the following research and development directions were considered: the theoretical - experimental deepening of the design and processing of the areas with the flanged edges, inclusive in the construction of car bodies; wide-scale application of numerical simulation and statistical modeling, by case studies, to determine the influence of material and geometry characteristics of the flanged parts from metal sheets on their feasibility; to create of product/ part databases, which contain flanged areas to be used in the designing and manufacturing processes of the products; the development of modular equipment for processing of the flanged walls in cold plastic deformation technological systems.

(3) in line with the present stage of the art and the research - development directions regarding the optimization of some constructive characteristics of the parts made by cold plastic deformation, it was assumed the main objective of the research - development activity within the doctorate activity: (see § 4.2): numerical simulation and statistical modeling research of

the characteristics of the flanging of the parts made from sheet metal processed by cold plastic deformation.

(4) To the realization of the general objective of main objective of the doctoral research - development activity, this doctoral thesis brings a number of contributions, of which the most important are as follows.

- Evaluation of the stage of the research on the performances achieved in the design and processing of flanged parts made by cold plastic deformation.
- Establish the main objective and the methodological stages of research - development regarding the optimization of the constructive and technological characteristics of flanged parts made by cold plastic deformation.
- Applying numerical simulation with Finite Element Method (FEM) and Forming Limit Curves (FLD), respectively, the Auto Form software used by research institutes and major car manufacturing companies to investigate the cold plastic deformation process of metal sheets, which made it possible to carry out in economic conditions to the extensive research presented in the PhD thesis.
- Highlighting the random character of the characteristic values of the flanged walls in defining the central points of the simulation program, thus being possible to determine the simulation error and, accordingly, the statistical analysis of the results.
- Determination of the second-order polynomial mathematical models with interactions of the thickening of the flanged walls in case of the shrink forming process and, the thinning of the flanged walls in the case of the stretch flanging process, according to the six parameters based on the data obtained by numerical simulation and their statistical analysis with the support of the surfaces response method.
- Determination of the optimal values of the thickening and thinning characteristics for different considered cases of work, based on the mathematical models obtained.
- Establishing an appropriate method for optimization of research by applying the numerical simulation with MEF, of the forming limit curves and of the statistical modeling in the field of cold plastic deformation production process.

* * *

The scientific importance of this PhD thesis is proved by contributions to the development of models for the optimization of the constructive characteristics of the flanged parts.

The practical importance of this PhD thesis consists in the fact that the models and case studies constitutes a system - support useful for specialists in the field of cold plastic deformation.

The issue of products that include complex functional areas requires a continuous research - development constructive activity in relation to product development and industrial production conditions.

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