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STUDY OF INCREMENTAL DEEP-DRAWING OF BIMETALLIC SHEETS

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Abstract: *The usage, as blanks, of bimetallic sheets it's justified because of the addition of the advantages offered by both materials of which it is composed and to a reduction of the disadvantages presented by each material if taken separately. There are cases in which certain properties are needed on the part's outer side, while on the part's inner side there are needed very different properties. The theoretical researches have targeted the development of models that would allow the analysis through numerical simulation of the behaviour of this type of blanks. Another research direction referred to the manner of generating the shape of parts obtained through the incremental forming process. For the experimental researches there were employed complex trajectories for generating the part's shape. The researches unfolded in this direction targeted a better understanding of the influence of the punch's movement trajectory on the formability degree of bimetallic sheets, as well as on the quality of the realised parts, on the shape errors and on the dimensional precision.*

Key words: *incremental deep-drawing, bimetallic sheets, numerical simulation, trajectories, spiral.*

1. INTRODUCTION

Currently, the processes for the deep drawing of materials are well represented at industrial level, especially in the domain of manufacturing car components. There can be noticed, however, a certain discrepancy between the current endowment of the industrial companies from Romania with equipments for the "classical" deep drawing process and the modern trends concerning the shape of car parts and concerning the usage of materials with superior characteristics, respectively. On the other hand, the competition from the automotive industry requires an advanced flexibilisation of the technological processes and implicitly of the employed equipments.

In this regard, the deep drawing with single block, stiff punch, which realise the shape of parts does not allow a quick changing of the shape, thus emerging a need for the material's forming with unit tools of relatively small sizes or with segmented tools.

The incremental deep drawing of metal sheets allows the realising, through metal forming, of cavities of various shapes and sizes in metal sheet parts, for a small batch production or for unique parts production, starting from the movement, on certain trajectories, of a punch with simple geometry. Thus, without using dies or punches with a high complexity, depending on the movements required for the active elements and using the same type of technological equipment, relatively widespread nowadays (usually a machine-tool with at least three numerical controlled axes), there can be obtained a wide variety of hollow shapes.

The idea of incremental forming of sheet-type blanks using a tool with singular contact was patented by Leszak [8] long before it was even feasible from a technical point of view [7].

In the case of the incremental forming of metal sheets, the forming is done by a punch 1, having at the top a radius *r*, in rotation motion around its axis with the angular speed ω, which comes into contact with the surface of the blank 2, Fig. 1. The blank, having the initial thickness g_i, is fastened to the die 4 with the help of a blankholder ring 3. In order to achieve the final shape of the part 5, with a thickness g_f and a sloping angle ϕ, between the punch and the blank there needs to exist a relative motion composed of a continuous or incremental axial feed displacement on vertical direction by the punch and a displacement in the horizontal plane by the blank.

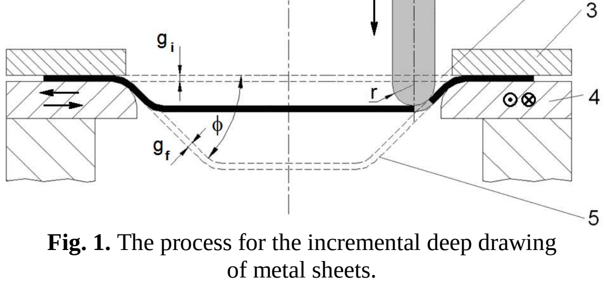

Fig. 1. The process for the incremental deep drawing of metal sheets.

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The forming begins in the area where the punch penetrates. The punch follows a plane circular trajectory and after its completion, descends for the next step and continues the forming. The punch's trajectory and the vertical pitch depend on the final shape of the part.

The incremental deep drawing process, having been developed only relatively recently, is not yet well represented in the speciality literature, especially with regard to the forming conditions for certain categories of materials, despite the numerous advantages it presents and the potential industrial applications.

Moreover, even though the published researches are relevant, often the obtained results are limited or contradictory [4], which makes it necessary to continue the researches in this domain.

The studies regarding this process have so far focused on three main directions: measuring the strains and displacements produced in the sheets, assessing the strains with the help of the finite element method and measuring the forming forces [4].

The numerical simulations carried out by various researchers have shown that in the case of realising, by incremental deep drawing, of a cone frustum with circular or elliptical base [3 and 2] or of a pyramid frustum [9, 1, and 7], the material does not present a significant displacement on the direction parallel to the plane of the undeformed sheet, but is moving especially perpendicularly to this plane.

2. MULTILAYER METALLIC MATERIALS USED FOR INCREMENTAL DEEP-DRAWING

Although this represents a relatively recent development in the industry, the composite multilayer sheets are currently encountered in almost all industrial domains, due to the density, mechanical strength and energy absorbtion properties that are higher than those of the blanks realised from a single material. These materials are useful especially in domains such a the automotive industry, where the vehicles must fulfil simultaneously conditions of increased passenger safety, increased comfort, increase of the loading capacity in conditions of a reduced energy.

Basically, the multilayer sheets, Fig. 2, consist of two or more layers of different materials and different thicknesses (usually two outer layers s_1 and s_2 and an inner layer s_i also called core), organised so that they combine the best properties of the components and leading in the end to properties that are better than those of the base materials. The outer layers s_1 and s_2 have generally reduced thicknesses but an increased density, a good mechanical strength and stiffness, while the core has a larger thickness and a low density.

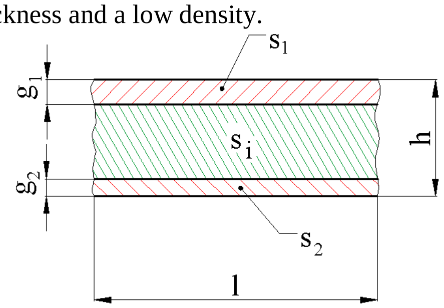

Fig. 2. Principle sketch of the multilayer sheets.

In Fig. 2 g_1, g_2 – thickness of the outer layers, s_1, s_2 – outer layers, s_i – inner layer, h – total thickness, l – sheet length.

These layers are bonded mechanically or using adhesives, so that they behave as a single component. Usually, in the case of multilayer structures, the outer layers withstand the bending stresses, while the inner layer (the core) withstands the shearing stresses.

Currently, multilayer materials are used for a wide range of applications, due to the high strength-weight and stiffness-weight efficiency. Numerous applications can be encountered in the fuselage and wings of airplanes, in spaceships, cars and race ships, in buildings and sports equipments:

- in the furniture used in the aeronautics and aerospace industry;
- in airfreight containers;
- in cars, for the chassis and for energy absorption, for directing the air, for heat insulation, reflecting surfaces for the headlights [5 and 6];
- heat shields and vibration-dampening shields [5];
- soundproof bodies for the automotive industry [10];
- in medical domain, for cranial plates or dental applications [10 and 7].

3. THEORETICAL STUDY OF THE INCREMENTAL DEEP DRAWING PROCESS FOR BIMETALLIC SHEETS

The researches have frequently used information on the material characteristics and on the forming behaviour of bimetallic sheets. These data were determined experimentally using specific processes.

In order to determine the behaviour of the employed materials, there have been unfolded tests for determining the intrinsic characteristics (tensile tests) and for drawing the forming limit curves (Nakajima test).

During the theoretical and experimental researches, there have been used two types of materials, DC04 steel and AA6016 aluminium. The experimental layout used for the tensile testing included the tensile testing machine Instron 5587 and the optical strain measurement system – Aramis.

Based on the experimentally determined results, it was possible to know exactly the mechanical characteristics and the intrinsic parameters of both materials, as well as the model of the materials elasto-plastic behaviour, needed for the numerical simulation through the finite element method.

The model of the system for manufacturing through incremental deep drawing is presented in Fig. 3.

The manufacturing system consists of a square-shaped blank made of two metal sheets (a sheet made of DC04 steel with a thickness of 0.6 mm, marked in Fig. 3 with 4, an AA6016 aluminium sheet with a thickness of 0.8 mm marked with 3), pressed by a spherical punch 1.

The bimetallic sheet is fastened between the blank holder plate 2 and the die plate 5 by means of a blank holding force.

The die plate was realised in round-shaped die plate, both having a fillet radius of 6 mm.

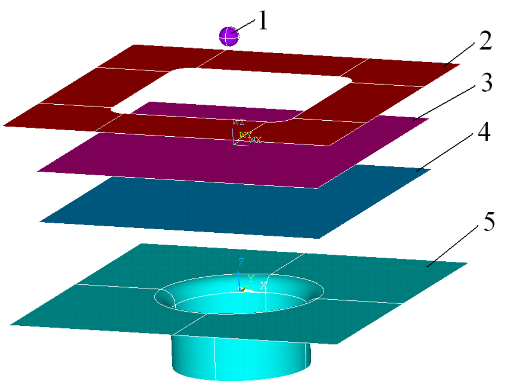

Fig. 3. Model of the system for manufacturing through incremental deep drawing.

Table 1

The main geometrical data characteristic for the process

Blank dimensions	$L \times l$	[mm]	120×120
Initial thickness of the DC04 steel sheet	g_{DC04}	[mm]	0.6
Initial thickness of the AA6016 aluminium sheet	g_{AA6016}	[mm]	0.8
Radius of the die plate	R_{pl}	[mm]	6
Punch diameter	D_p	[mm]	6.10

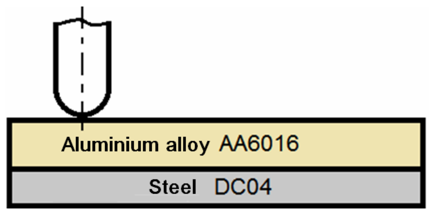

Fig. 4. Orientation of the bimetallic layer with regard to the punch.

The blank made of the two typodimensions of materials is placed on the die plate and is fastened with the blankholder ring by means of a blankholding force, evenly applied on its surface.

Thus it is ensured that it is impossible for the blank to slide through the gap between the ring and the die plate, the analysed process being one during which a certain deepening of the part can be obtained through the material's thinning.

The main geometrical data characteristic for the process are presented in Table 1.

The contact between punch and blank is done at the aluminium layer level of the bimetallic sheet Fig. 4.

The analysis by numerical simulation intended to determine the strains in the blank. The blank model used in the simulation has taken into account its bimetallic nature, but the results have to be analysed individually for each of the two layers.

The results of the analysis by numerical simulation describe the behaviour of the aluminium layer of the bimetallic blank, while the results describing the behaviour of the steel layer being presented in the paragraph dedicated to the experimental researches.

There were realised simulations through the finite element method for parts whose shape was generated by moving the punch along various trajectories.

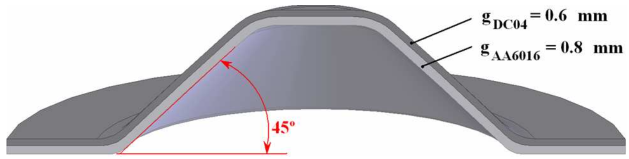

Fig. 5. The models of the cone frustum type parts with 45° cone angle.

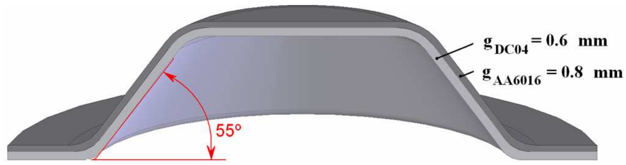

Fig. 6. The models of the cone frustum type parts with 55° cone angle.

The behaviour of the bimetallic sheet with this composition has not been treated in the speciality literature and therefore it was necessary to realise a detailed study for determining the behaviour during forming in conditions of respecting the surface's quality characteristics and of assuring the shape precision of the finished part. In order to determine the forming behaviour of the bimetallic sheet, there were analysed several representative parameters from the incremental deep drawing process.

The model for the part obtained through incremental deep drawing is presented in Fig. 5.

In order to obtain this kind of parts, a sloping angle of the cone frustum of 45° Fig. 5 and 55° Fig. 6 were used. From the figures the two layers of the sheet may be observed.

The incremental deep drawing process was realized using a punch with a radius of 6 mm.

For generating the trajectories of the punch, two kind of movements of the punch, simple and complex trajectories were created.

First of all, for the cone frustum, the simple trajectory consisted of six circles, in *XOY* plane, spaced on the *Z* axis by 2 mm.

In Fig. 7 the trajectories for movement of the punch used to generate the cone frustum shape of the part are presented. For generating the shape a number of steps were necessary which are described below.

The steps for generate cone frustum the shapes were:

- rapid feed (represented by dotted line) above the starting point;
- technological feed on *OZ* axis at $Z_1 = -2$ mm (represented by solid line);
- describing the circular path with technological feed at diameter $D_1 = 36$ mm;
- rapid retraction of the punch to safety position;
- positioning of the punch at circle with D_2 diameter;
- technological feed in depth at $Z_2 = -4$ mm;
- repeating steps 1–6 for diameters $D_3 - D_7$ for processing depths of $Z_3 - Z_7$.

Feed was set at a $v_{av} = 240$ mm / min.

Another approach was to use complex trajectories. The complex trajectories were represented in a first phase by a combination of archimedean spiral and circle.

Fig. 7 presents this trajectory type for a certain dimension on *Z*.

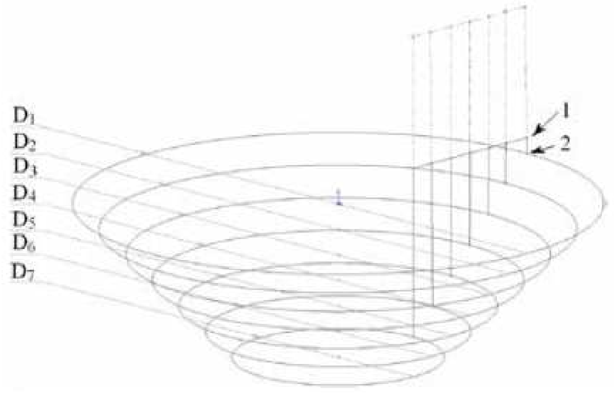

Fig. 7. The movement of the punch in simple trajectories.

All cone frustum type parts were obtained using complex trajectories consisting of level curves made of an archimedean spiral completed by a circle, incrementally displaced on the Z axis (ΔZ = 2 mm).

Fig. 8 presents all trajectories required for generating a part, but for a better understanding of the picture here was presented only a single plane, which must be repeated to obtain the final part.

The trajectories of the cone frustum type parts with 55° cone angle are presented in Fig. 9 and for the cone frustum type parts with 45° cone angle in Fig.10.

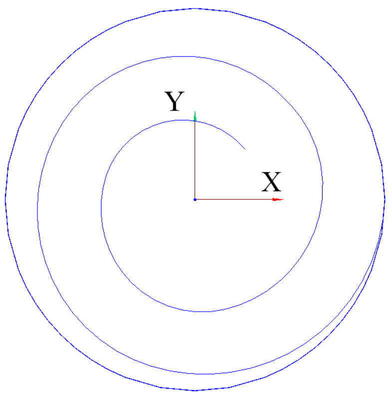

Fig. 8. Complex trajectories consisting of an archimedean spiral completed with a circle.

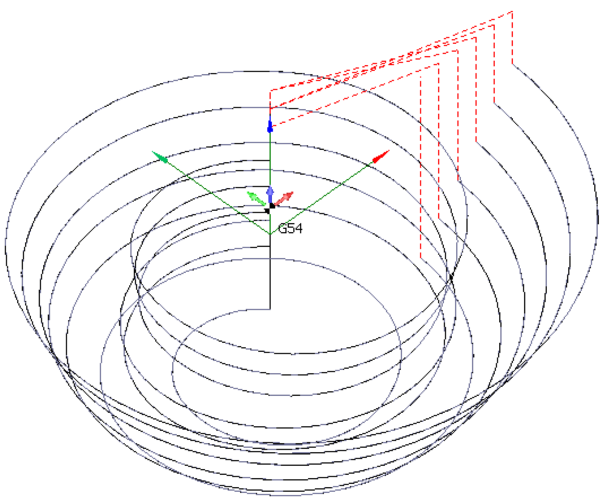

Fig. 9. The trajectories of the cone frustum type parts with 55° cone angle.

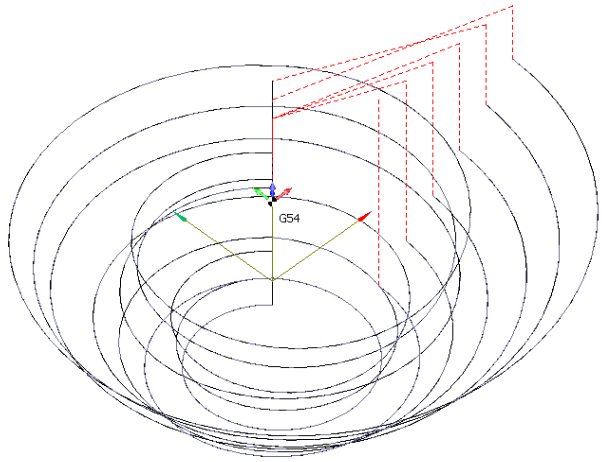

Fig. 10. The trajectories of the cone with 45° cone angle.

The characteristic parameters obtained through the numerical simulation are as follows: maximal thickness reduction $S_{\max}$%, maximal major strain ε_1%, maximal minor strain: ε_2 %, maximal effective Von Mises strain ε_{VM} %.

It can be noticed that the location of the major strains (Fig. 11) of maximal values is along the archimedean spiral on which the punch is moving. The maximal value occurs in the initial point of the archimedean spiral, corresponding to the area of the punch's penetration into the material. Subsequently, these values decrease slightly, afterwards remaining constant on the final part of the trajectory. The parameters' evolution is relatively similar in the case of the minor strains (Fig. 12), thickness reduction (Fig. 13) and effective von Mises strains (Fig. 14). In the case of minor strains, the maximal value is located more precisely in the area of the punch's penetration into the material. As indicated above, this paragraph presents the results obtained through numerical simulation regarding the behaviour of the aluminium layer of the bimetallic blank.

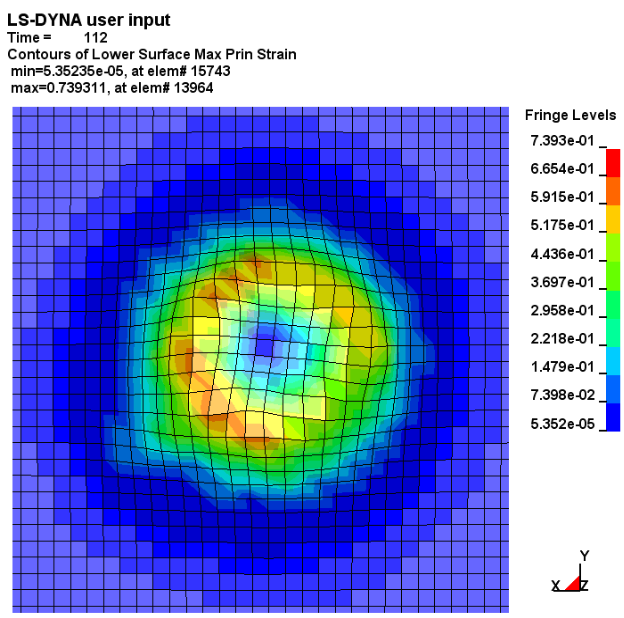

Fig. 11. Major strain for aluminium (simulated).

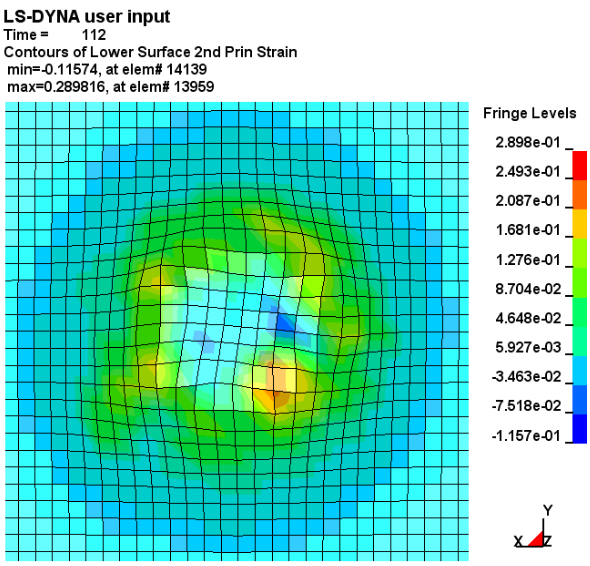

Fig. 12. Minor strain for aluminium (simulated).

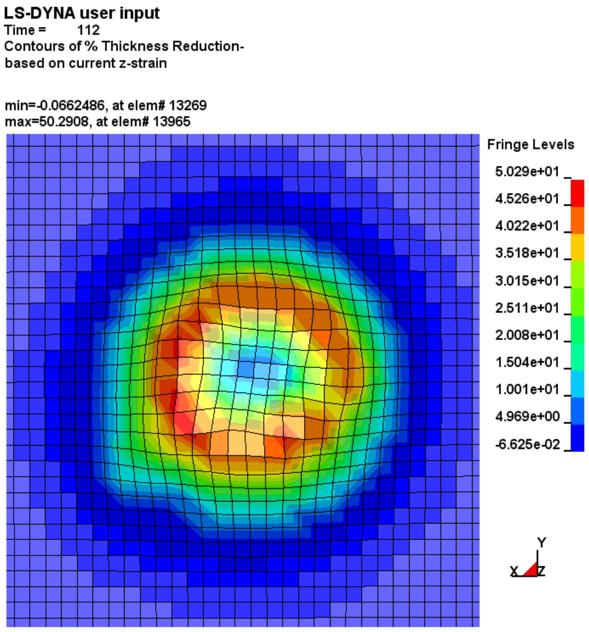

Fig. 13. Thickness reduction for aluminium (simulated).

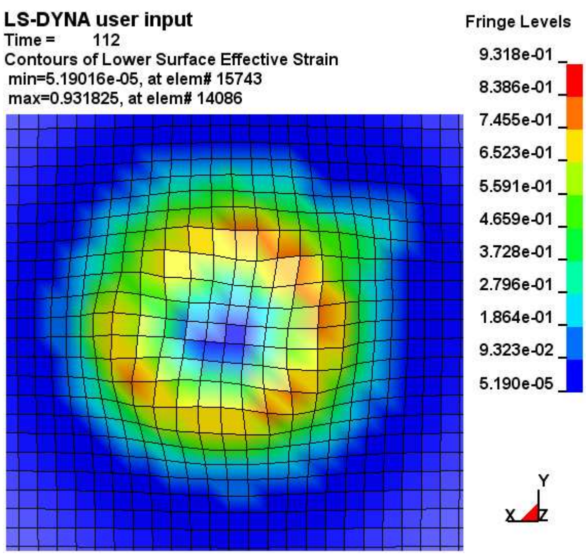

Fig. 14. Effective Mises strain for aluminium.

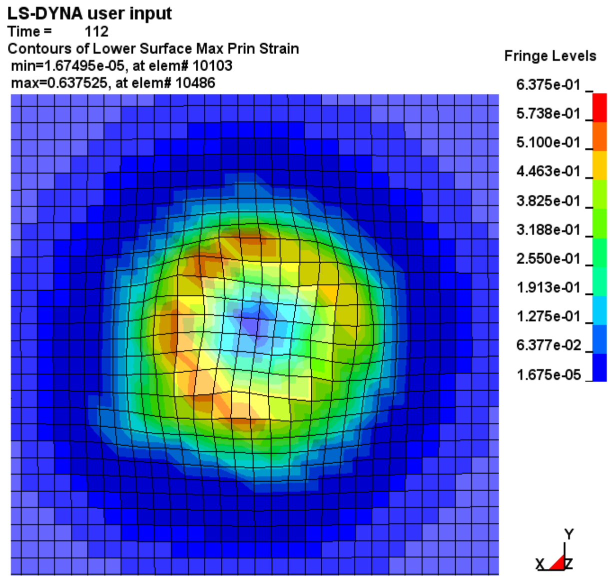

Fig. 15. Maximal major strains for steel (simulated).

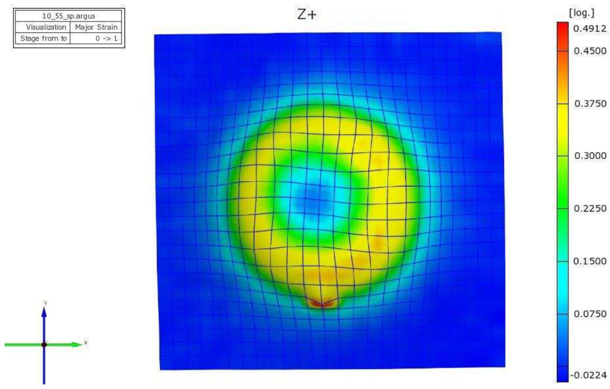

Fig. 16. Maximal major strains for steel (measured).

From the analysis of Fig. 13, it can be noticed that the thickness reductions have an even distribution on the surface of the blank subjected to forming.

The strains with maximal values are located on the cone frustum's side walls, corresponding to the punch's trajectory along the archimedean spiral. The minimal thinning occurs at the base of the cone frustum.

The variation of the effective Mises strains is presented in Fig. 14, while their distribution corresponds to the behaviour described for the thickness reductions.

4. COMPARATIVE ANALYSIS OF THE THEORETICAL AND EXPERIMENTAL RESULTS

Within this paragraph, there were comparatively analysed the experimental results with those obtained by means of the numerical simulation of the incremental deep drawing of the bimetallic sheet.

Determination of deformation of the parts was done in order to assess the experimental plastic deformation behaviour of the bimetallic material.

Furthermore, the real strains, experimentally determined, were compared with the real strains resulted from the numerical simulation.

In Figs. 15 and 17 the results for numerical simulation are presented, while in Figs. 16 and 18 the results obtained

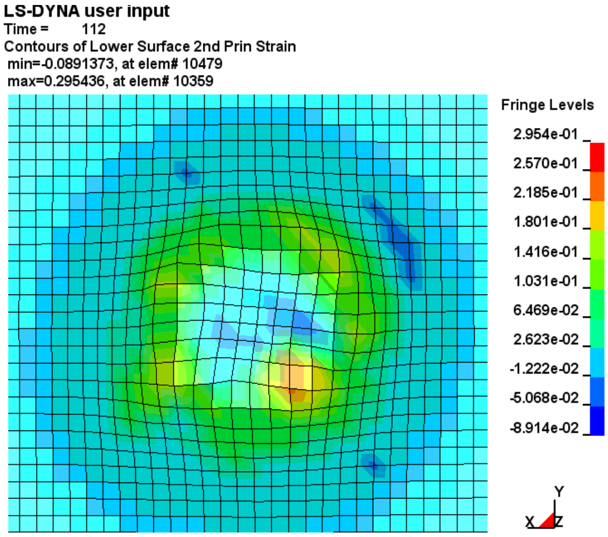

Fig. 17. Maximal minor strains for steel (simulated).

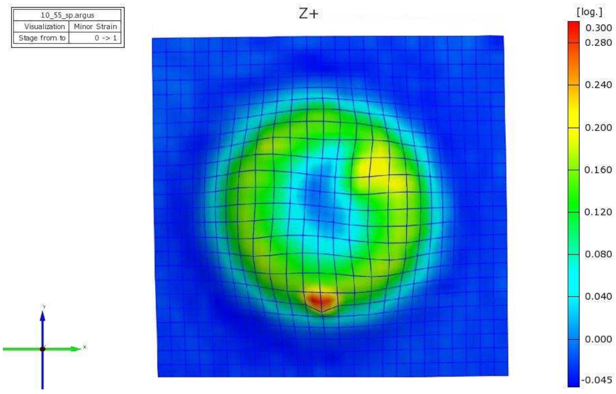

Fig. 18. Maximal minor strains for steel (measured).

through measuring the deformations of the parts are presented. Deformation measurement was performed using the optical ARGUS measurement system.

Due to the orientation of the bimetallic blank during the manufacturing process the comparison was made only for the steel layer.

Following the comparison of experimental results with those obtained by numerical simulation, we see that the differences between values in the two situations are relatively low.

Also the distribution of the characteristic parameters obtained by numerical simulation is similar to experimental results.

5. CONCLUSIONS

The behaviour of the bimetallic sheet with this composition has not been treated in the speciality literature and therefore it was necessary to realise a detailed study for determining the behaviour during forming in conditions of respecting the surface's quality characteristics and of assuring the shape accuracy of the finished part.

In order to determine the forming behaviour of the bimetallic sheet, there were analysed several representative parameters from the incremental deep drawing process.

The paper presents the evolution of characteristic parameters for the bimetallic sheet. These results obtained by means of numerical simulation regarding the behaviour of the aluminium layer of the bimetallic blank. The steel layer behaviour is analysed also experimentally and through numerical simulation.

There was realised a comparative analysis of the theoretical results obtained by means of numerical simulation and of the experimental results. As a result the proposed theoretical models were validated.

There certainly exist further possibilities for developing the researches such as: a study of the influence of using various manufacturing strategies and trajectories upon the mechanical properties of the processed parts and realising high complexity parts, through incremental deep drawing.

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