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Viorel Paunoiu, Virgil Teodor, Nicusor Baroiu, Georgiana-Alexandra Morosanu, Alexandru Epureanu, et al.. Contribution to the formability improvement in sheet metal stamping by a novel technique to control press kinetics. *Mechanics & Industry*, 2024, 25, pp.19. 10.1051/meca/2024015 . hal-04615036

HAL Id: hal-04615036

<https://hal.science/hal-04615036v1>

Submitted on 17 Jun 2024

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Contribution to the formability improvement in sheet metal stamping by a novel technique to control press kinetics

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Received: 8 December 2023 / Accepted: 21 May 2024

Abstract. The thickness variation during sheet deep drawing process has an impact on the quality of the final product and can lead to local material fractures. To minimize this phenomenon caused by varying degrees of stretching in different areas of the sheet, various methods can be employed. This research paper introduces a novel technique for metal sheet deep drawing, specifically designed for parts with complex geometric shapes that exhibit significant variations in deformation levels across different areas. The objective of this method is to enhance the quality of the deep drawing process by reducing thickness variations in the final part. In this proposed approach, the vertical movement of the punch is accomplished through two vertical rotational movements. This increases the flexibility of the deformation process, ensuring that the active tools elements occupy the most advantageous positions determined by the material flow in the die. As a result, the material's deformability is improved, allowing for a higher degree of deformation. Additionally, this new method offers a relatively simple design and kinematics solutions for the press and eliminates the need for lengthy assembly-disassembly times.

Keywords: Sheet deep drawing / deformability / hydraulic presses / kinetic control

1 Introduction

Various techniques have been developed to reduce plastic deformation variations across different areas of a drawing part by controlling restraint loads. These loads are applied using specific blank holders, defined to be monobloc, segmented or elastic. For complex shape parts, a model utilizing a monobloc blank holder with draw beads perpendicular to the deformation direction is presented in [1]. This model represents the draw bead as a two-dimensional flat band within the use of a conventional stamping die. By calculating the forces acting on the sheet metal at each state, a series of iterative steps accurately describe the metal's sheet transformation from initial to final shape. The accuracy of estimating the applied restraint force is improved by considering the length and position of the flat strip. In [2] a method and equipment for stamping with a restraint plate and segmented draw beads along the part's contour are proposed. This approach

allows for different depths of draw bead penetration along the boundaries contour, resulting in varying restraint forces on different portions of the blank. Segmented plates are employed to distribute restraining forces based on the complexity of the part's geometry. Pneumatic or hydraulic cylinders, closely correlated with the punch movement, drive these plates, controlled by Programmable Logic Controllers (PLC). They enable a pressure adjustment to achieve uniform deformation along the blank's contour, as described in [3–8]. Elastic blank holder plates feature an elastic honeycomb structure with individually controlled pins that transmit pressure. This design allows for adaptive control of the flow characteristics of the material in the mold. A closed-loop control system, involving servo-valves, ensures proportional control of each pin, enabling individual force adaptation throughout the working stroke [9–12]. This system effectively addresses disturbances in the deformation process caused by friction force variation, material heterogeneity, sheet thickness variations, mold element centering issues, mold wear, blank positioning, and elastic deformation of the press. In another kind, a scientific paper [4] presents a solution to control the pressure applied

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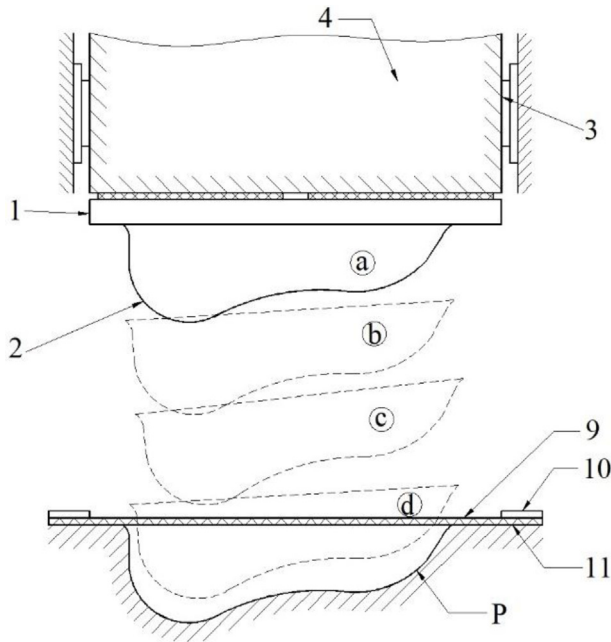


Fig. 1. Conventional sheet deep drawing and corresponding stages [13].

to the blank holder using a 3D servo-press. This press incorporates additional degrees of freedom in the slide, enabling adaptable pressure application through controlled tilting, thus influencing the blank deformation process. However, these restraint systems have several disadvantages: use of non-interchangeable blank holders across different dies or products, use of complex and expensive construction of elastic plate dies, lengthy assembly times for the blank holder, oversized blank products, additional actuators requiring extensive design efforts. It can be adding the need for extensive experimental or numerical tests when employing hydraulic deep drawing with control of both holding force and fluid pressure.

Along this paper the authors proposes a novel concept for press construction, where a special die is mounted on the slide to facilitate a combination of vertical displacement and punch rotation during all the deformation process, accommodating a various shapes of the product's geometry [13].

2 New press concept and working principle

During a conventional metal sheet deep drawing, as depicted in Figure 1, the punch (2) moves vertically towards the blank (9) through the press slide (4) and the die (11) until the blank becomes into contact with the die plate profile, P. Throughout the deformation process, the punch maintain a fixed position relative to the blank. The movement stages of the punch for material deformation are illustrated in Figures 1a and 1d. By use of this simple press's kinematics can result large variations in wall thickness, generally depending on the clearance between the punch and the die plate. The proposed new deep

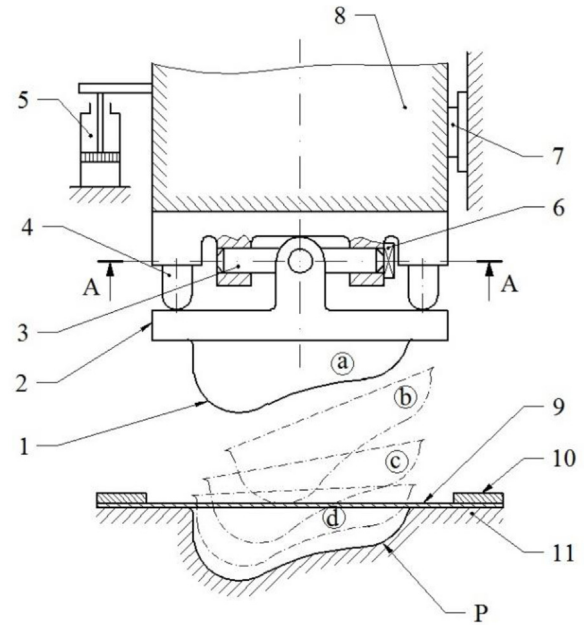


Fig. 2. Scheme of the new design die for sheet deep drawing [8,13].

drawing die design, shown in Figure 2, introduces a novel feature: the ability to combine vertical movement of the punch with its rotation. This enables accommodation of the varying degrees of deformation generated by the shape of the workpiece.

Figure 2 presents the new die with kinetostatic deformation control. It consists of a punch (1) attached to the mobile punch port subassembly (2). The subassembly includes the cardan cross (3), regularized the weak rotation point concerning the punch stretching finding automatically a stable dynamic equilibrium, rotary transducers (6) for each axis and pairs of plungers (4) driven by the hydraulic cylinder (5) through three specific distributors (Ds, Dx, and Dy). The press slide (8) is equipped with a translation transducer (7) to control its movement. The blank holder (10) within the die plate (11) deforms the blank (9) until it makes contact with the die plate profile P.

The patented kinetostatic deformation control die operates from specific data generated by dedicated software that establishes a connection between the slide's position and its rotation, as depicted in Figure 3. The rotational movement is controlled when the deformation value at a point on the blank exceeds the permissible value according to the Drawing Limit Flow (FLD) curve [14] and deep drawing Ericksen formability ratio [15]. The drawing limit curve and Ericksen formability ration can be obtained from specific experimental tests and easier through use of process numerical simulations. It determines the moment when rotation is necessary using limit deformation values, providing important information about the displacement size and the rotation angle. In the proposed solution, the drawing limit curve serves as the driving factor for die operation (Fig. 3). Rotation is facilitated by the cardan cross (3) (see Fig. 2), acted upon by four independent

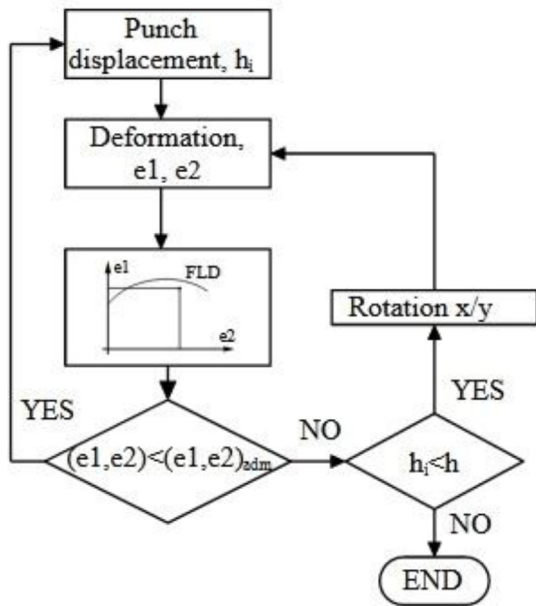
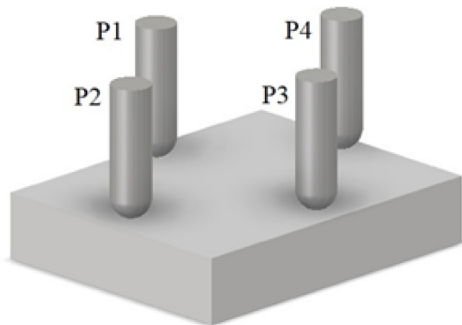


Fig. 3. Scheme of new die kinematics control [13].



Plunger 1	Plunger 2	Plunger 3	Plunger 4
+	0	-	0
-	0	+	0
0	+	0	-
0	-	0	+
+	+	-	-
-	-	+	+
-	+	+	-
+	-	-	+

(+) down ; (-) withdrawal
(0) maintaining contact

Fig. 4. Plunge work diagrams [13].

hydraulic plungers (P1-P4). Figure 4 illustrates the eight positions that the plungers, and consequently the mobile punch port subassembly (2), can assume, depending on the controlled rotation.

The rotation control is transmitted to the plungers (4) from Figure 2. The movement of the stamping die's punch (1), which is captured by the mobile subassembly punch (2) comprising the cardan cross (3) and pairs of plungers (4), is controlled by the transmitted pressure from the cylinder (5). This movement is monitored by the rotary transducers (6) and the translation transducer (7). The mobile punch

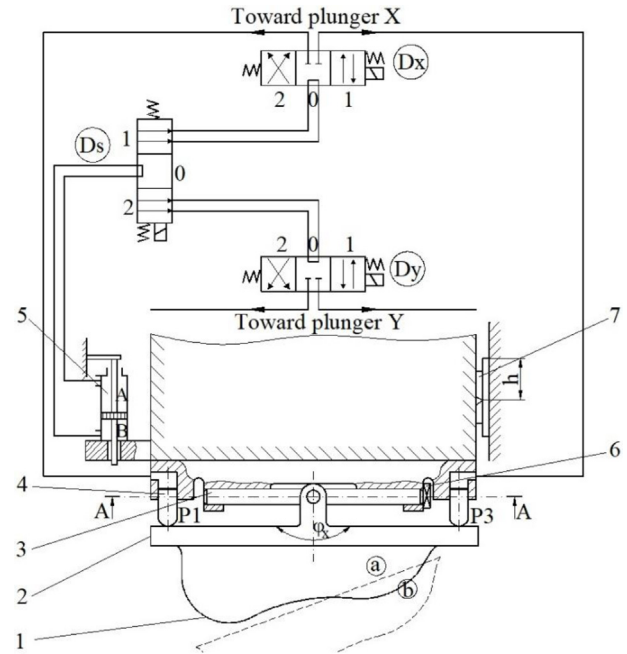


Fig. 5. Hydraulic scheme of the new die [13].

holder subassembly (2), attached to the press slide (8), moves vertically. Upon initial contact with the blank (9) in position a, the punch (1) assumes the most favorable position for material deformation due to the two rotational movements. The restraining force applied to the blank's flange also influences the magnitude of both the translation and rotation movements. Subsequently, by combining the two punch movements, the blank (9) held by the blank holder (10) is deformed within the die plate (11), successively occupying positions b, c, and so on, until it contacts the plate profile, P.

3 Hydraulic operations of the new system

The hydraulic system depicted in Figure 5 use a hydraulic cylinder (5) which works as a pump. This double-rod cylinder is secured to the press slide with one rod attached to a plate. The cylinder consists of two chambers: A and B. As the slide descends, the oil in chamber A of the cylinder is compressed and directed to the distributor Ds, which serves to select the rotation axis.

The distributor Ds has three positions:

- position 0 allows the oil from chamber A to flow through Ds and return to chamber B,
- position (1) of the distributor Ds where the oil from both chambers A and B of the cylinder (5) is directed to the distributor Dx while the y-axis remains inactive
- position (2) where the oil from chambers A and B of the cylinder (5) is directed to the distributor Dy while the x-axis remains inactive. In position (0) of the distributor Dx, the oil returns to the distributor Ds.

It is important to focus solely on the movement controlled by the distributor Dx, noting that the discussion for distributor Dy follows the same principles. When Dx is

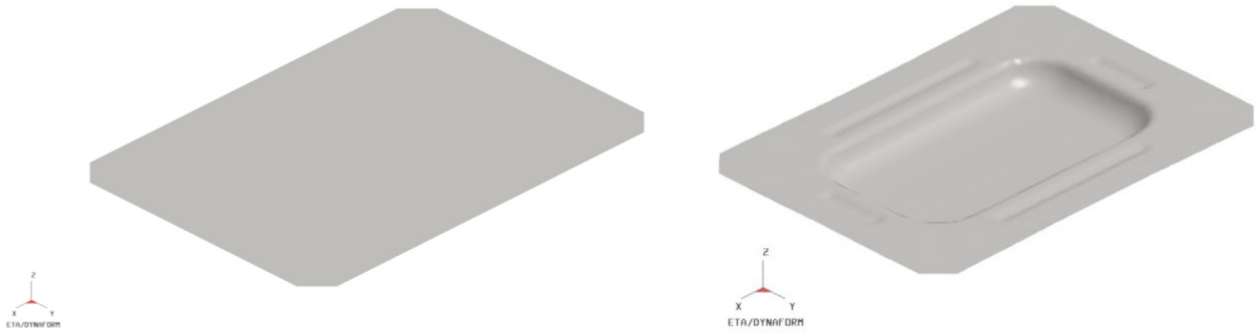


Fig. 6. Blank and part obtained by deep drawing with draw beads.

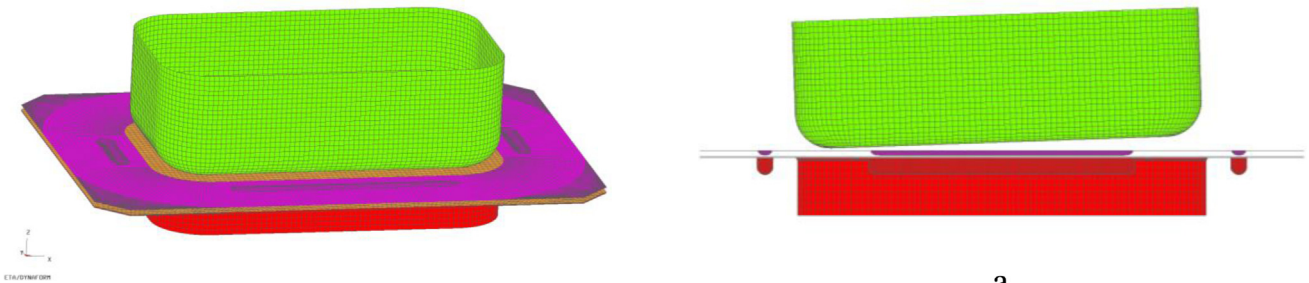


Fig. 7. Numerical design of deep drawing process with blank holder and draw beads.

in position (1), the left plunger P1 is pressurized and moves down ward, while the right plunger P3 is pushed upward, resulting in a rotation with an angle ϕ . Conversely, when Dx is in position (2), the right plunger P3 is pressurized and moves downward, while the left plunger P1 is pushed upward, resulting in a rotation with an angle ϕ in the opposite direction. The control of the distributors Ds, Dx, and Dy is established through a specific software using a CNC system following the principles described above. The translation transducer (7) continuously measures the vertical displacement (h), while the transducers (6), one for each axis, provide information about the rotation angle. The hydraulic system allows for make operation of only one axis at a time.

4 Numerical simulations

Dynaform software of Ls-Dyna package family was used to perform finite element numerical simulations. The analysis starts by considering a rectangular part obtained by deep drawing with draw beads (Fig. 6), having a depth of 16 mm. The blank has the dimensions 520×370 mm.

Design and mesh of the tools and workpiece is pictured in Figure 7 together with the general model undergoing deformation with a blank holder and using draw beads.

Figure 8 illustrated the three steps of the kinematic tools during elastic-plastic deformation according to the numerical simulation proposed for the new deep drawing process taken in consideration a flat blank holder respective using blank holder with draw beads.

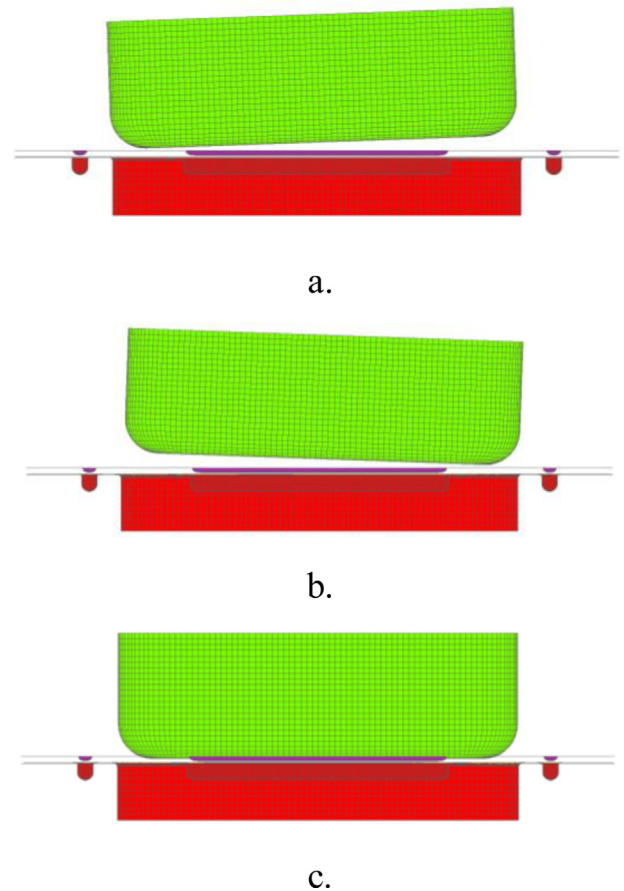


Fig. 8. The numerical steps a), b), c) concerning new deep drawing forming kinematics with blank holder and draw beads.

The deformation take place for both cases in three steps: firstly, an inclination of the punch in the left direction with an angle of 2° (a), followed by an inclination of the punch in the right direction with an angle of 2° (b) and finally a step where the punch is moving vertically to be aligned with the die (c). The simulation uses 4-node Belytschko-Tsay shell elements with five integration points through the thickness of the sheet metal. The One Way Surface to Surface Contact Forming was employed applied a constant force of 20 KN along the binder. The material considered in this numerical study is the mild sheet steel

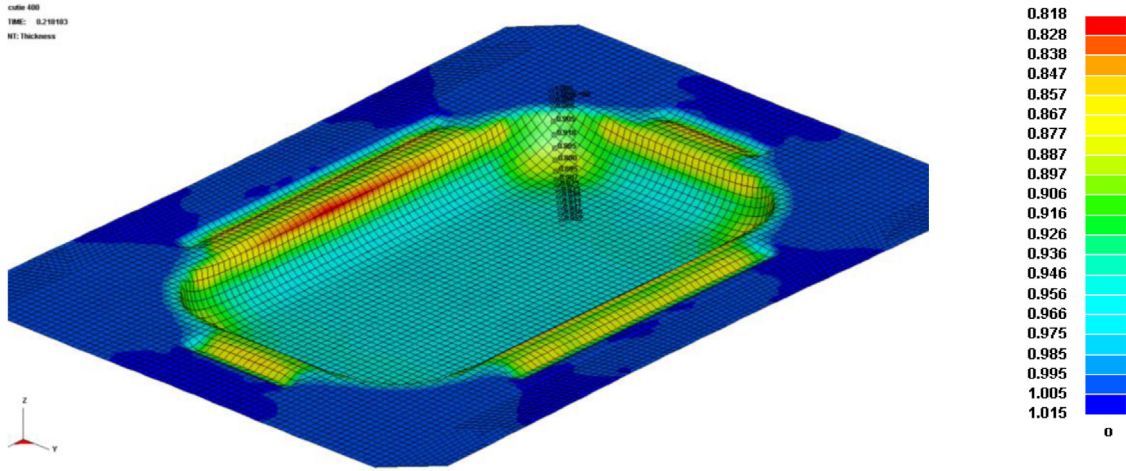


Fig. 9. Chart of thickness iso-values along whole sheet corresponding to the conventional drawing and selected computed points on the edge of the part.

DC05 with a blank thickness of 1.0 mm. The elastoplastic constitutive model considers anisotropic plastic behavior defined by a hardening power law and using an anisotropic yield criterion, considered acceptable to accomplish accurate results in a first realistic study.

The power hardening Hollomon law has the following classical expression:

$$\sigma_Y = K\varepsilon^n \quad (1)$$

where: σ_Y is the equivalent stress, K is the consistency coefficient ($K = 565.30$ MPa) and n is hardening exponent ($n = 0.237$). According to the anisotropic yield function, the R -values have been set to $R_{00} = 1.85$, $R_{45} = 1.78$ and $R_{90} = 2.45$ according to the values presented in the material database of the Dynaform program corresponding to the DC05 sheet steel.

The anisotropic yield model of type 36-Dynaform, developed by Barlat et al. [16], was used defining the anisotropic yield criterion Φ corresponding to plane stress hypothesis as:

$$\Phi = a|K_1 + K_2|^m + a|K_1 - K_2|^m + c|K_2|^m - 2\sigma_Y^m \quad (2)$$

where σ_Y represents the yield stress and $K_{i=1,2}$ are given by:

$$K_1 = \frac{\sigma_x - h\sigma_y}{2}$$

$$K_2 = \sqrt{\left(\frac{\sigma_x - h\sigma_y}{2}\right)^2 + p^2\tau_{xy}^2}. \quad (3)$$

The anisotropic material constants a , c , h and p are obtained from R_{00} , R_{45} and R_{90} :

$$a = 2 - 2\sqrt{\frac{R_{00}}{1 + R_{00}} \frac{R_{90}}{1 + R_{90}}}$$

$$c = 2 - a \quad (4)$$

$$h = \sqrt{\frac{R_{00}}{1 + R_{00}} \frac{1 + R_{90}}{R_{90}}}.$$

The anisotropy parameter p is computed implicitly and in the case of steels (BCC materials) it can be chosen a power coefficient $m = 6$.

5 Results and discussion

This section is devoted to the comparison of the numerical results performed for both types of the deep drawing process using draw beads respectively for a conventional one and for a sheet stamping with punch rotations.

5.1 Thickness distribution

The sheet thickness distribution of the two types of parts are taken for comparison in the edge and in the middle of the long side, perpendicular to the parts bases, as is depicted in Figures 9 and 10.

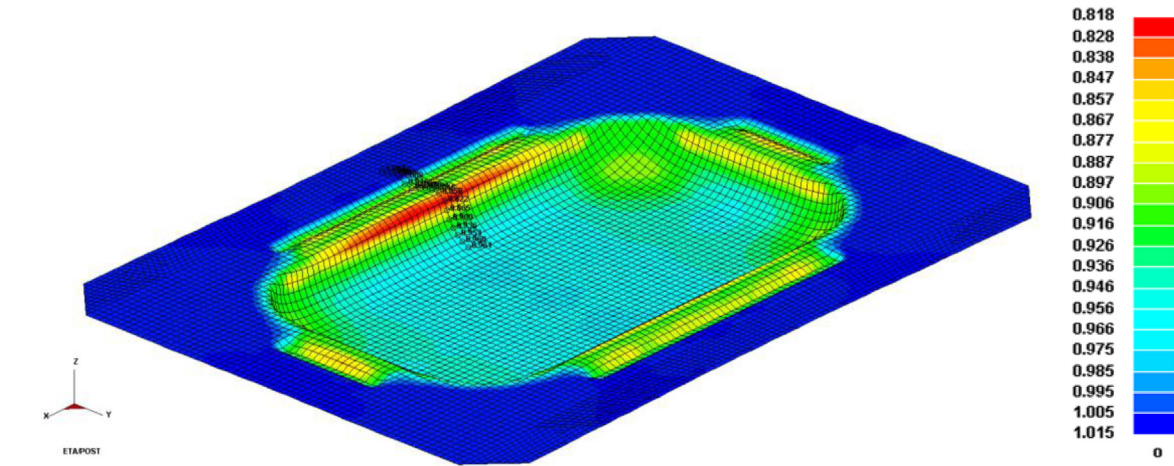


Fig. 10. Chart of thickness iso-values along whole sheet corresponding to the conventional drawing and selected computed points on the long side of the part.

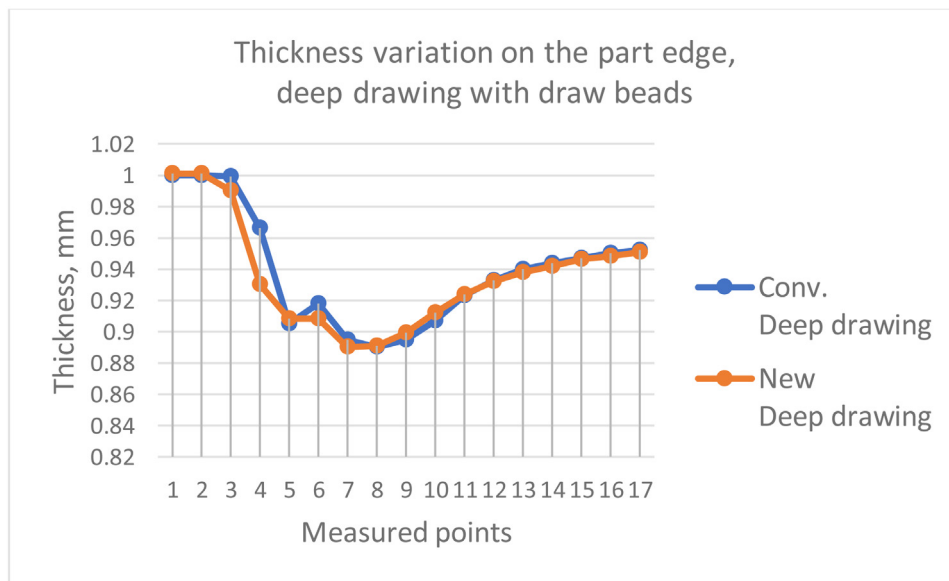


Fig. 11. Numerical thickness distribution on the part edge for both types of deep drawing (Conv. – Conventional and New – Proposed).

Figure 11 pictures the thickness variations on the edge of the two parts for a conventional deep drawing and respectively for the new proposed sheet forming with punch rotations. The comparison shows that if small differences occur between the two types of sheet deformation, a more continuum thickness distribution is obtained in the case the deep drawing with punch rotations.

Figure 12 pictures the thickness variations of the two parts corresponding to the middle long side, for conventional deep drawing and for the new proposed sheet forming. The comparison shows that between the two types of deformation the distribution of the thickness is practically the same.

Figure 13 shows the qualitative images of the conventional deep drawing with draw beads respectively of the new process using draw beads and two punch

rotations. The values of the thinning appear to be uniform in the second case where a smaller thinning appears in the wall of the piece simultaneously with a stronger thickening in the flange area.

5.2 Punch load

Globally, the loads predicted by the numerical models can be find along Figure 14. In the case of the conventional deep drawing (with draw beads), the maximum force is 400 KN while concerning the new forming process (with draw beads) using two sequential punch rotations of 2°, the maximum force value decreases to 350 KN. Concerning the first punch rotation the value of the force becomes 83 KN and after the second rotation the force decreases to 50 KN. From this point of view the deep drawing

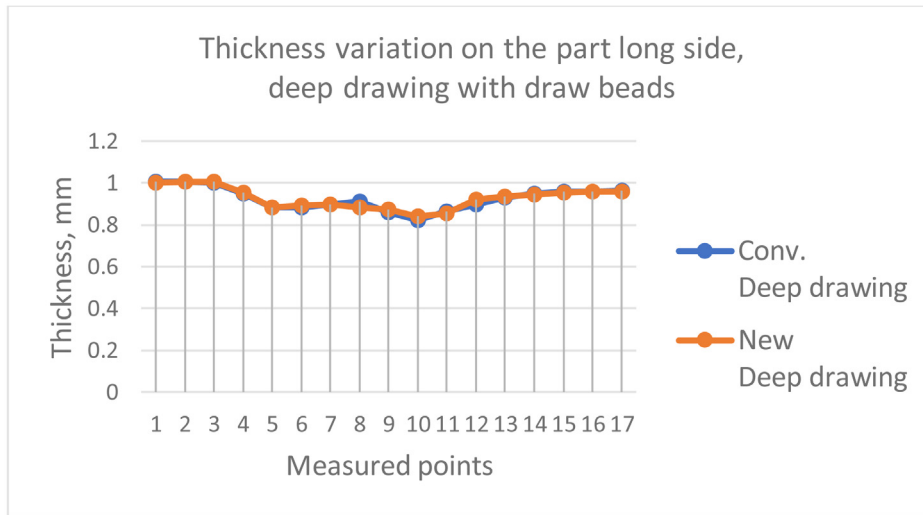


Fig. 12. Numerical thickness distribution on the part long side for both types of deep drawing (Conv. – Conventional and New – Proposed).

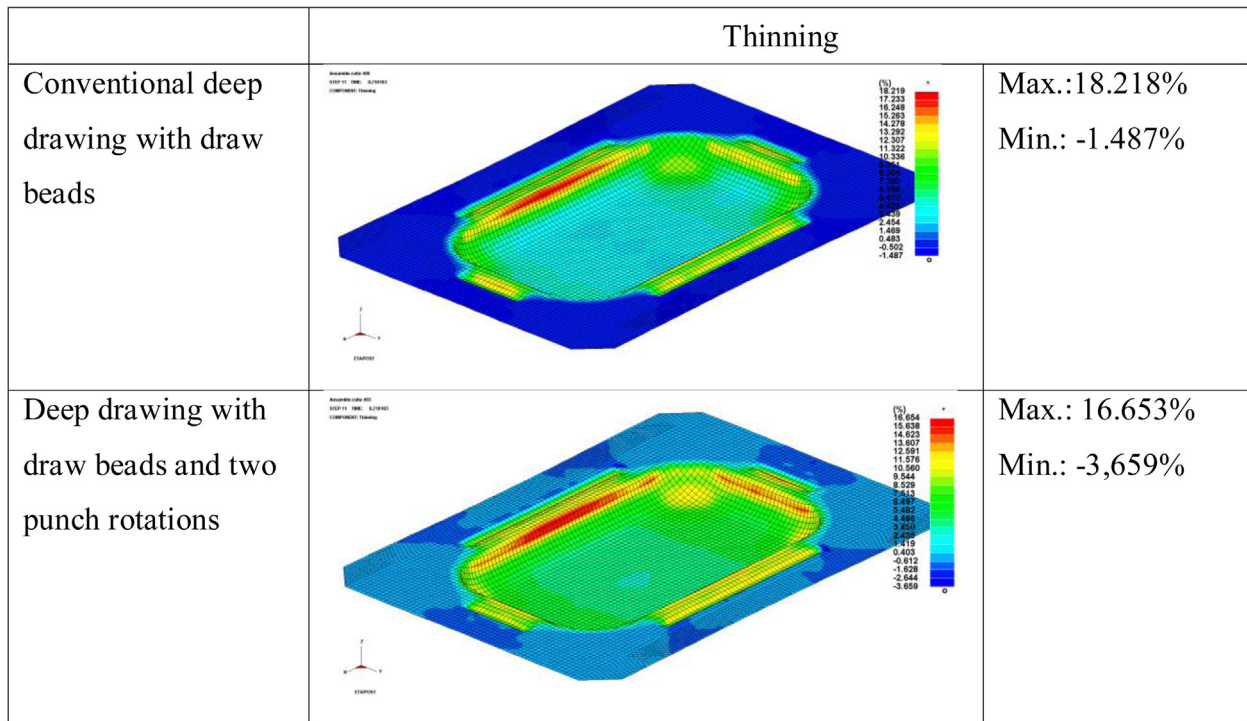


Fig. 13. Thinning distribution of the part for both types of deep drawing.

with draw beads and two punch rotations is more advantageous, reducing energy consumption in a ratio of 12,5%.

5.3 Forming limit diagram – FLD

FLD diagrams are generally employed to evaluate the deep drawing process on both the wrinkles appearance and fracture points of view. In all performed numerical simulations the fracture did not occur, while a wrinkle

tendency is identified always in the same areas (see Fig. 14). It should be specified that the rotation simulated by tilting the punch right-left, carried out only in one direction at an angle of arbitrarily chosen value. No connection has been made with the diagram of maximum and minimum plastic strains variation, the presented FLD curves being the result of the total deep drawing of the blank. As can be pictured in Figures 13 and 14 during FE simulations the choice of punch angle rotation has been make following a manual interactive-graphical interaction

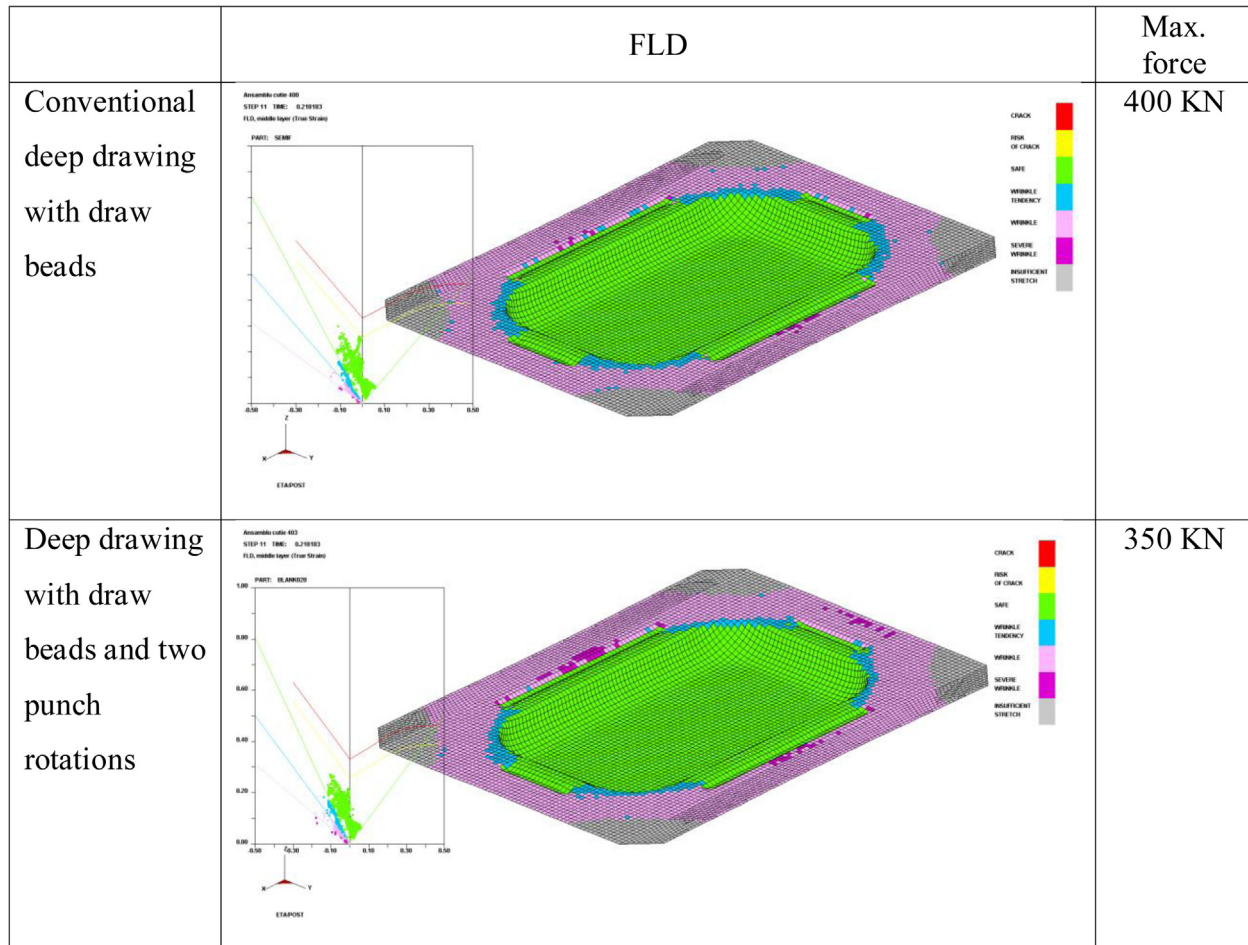


Fig. 14. Forces and FLD distribution of the part for both types of deep drawing.

between the numerical results concerning strains and sheet thickness values and FLD curve points. Moreover, using numerical simulations results coupled to FLD information can be find the optimal range of punch rotations angle together with the corresponding design of mobile punch holder subassembly (2) pictured in Figure 5 and then to search to prevent during the punch kinetic control the risk of collision between punch, back holder and some area of the sheet.

6 Conclusions

Implementing the presented new technology concept of a sheet deep drawing using a specific punch kinematics control it can be anticipating the following benefits:

- The combination of the two movements allows to an increased flexibility during the plastic deformation process, ensuring that the active elements occupy positions that minimize resistance during pressing.
- The gradual application of pressing force on the semi-finished product reduces the required total pressing force, extending the operational lifespan of the active elements and minimizing energy consumption.

- Improvement of material plasticity leads to a higher degree of plastic deformation and of corresponding drawing ratio.
- The vertical movement of the punch, complemented by the two sequential rotational movements in the vertical plane, reduces the impact and noise resulting from the contact between the active tools elements and the material.

In conclusion, the proposed kinematic solution can be applied for any hydraulic press that meets necessary strength requirements. The process design is relatively simple and does not involve lengthy assembly or disassembly times. Future work will be focus on design and manufacturing of new die, automatic rotation angle choice based on coupling of numerical simulations and FLD diagram with hydraulic punch command, followed by development of a digital manufacturing technique and automatic process control.

Acknowledgements

The research presented in this paper has been developed under the Romanian Ministry of Research and Innovation, CCCDI – UEFISCDI, project number PN-III-P1-1.2-PCCDI-2017-0446 /

Intelligent manufacturing technologies for advanced production of parts from automobiles and aeronautics industries (TFI PMAIAA) – 82 PCCDI/2018, within PNCDI III.

Funding

The Article Processing Charges for this article are taken in charge by the French Association of Mechanics (AFM).

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data and results, especially concerning the numerical ones are found under all authors' responsibilities based on cross discussions and quantitative analysis.

Author contribution statement

Prof. V. PAUNOIU – Paper structure and content especially concerning use of plunge principles starting from discrete drawing process idea and design of plunge work diagrams together with make of a lot of Finite Element Simulations and Numerical Results using DYNAFORM software, **Prof. V. TEODOR** – die kinematics definition and a part of kinematic punch control and driving, **Assoc. Prof. N. BAROIU** – complete hydraulic system and hydraulic control together with coupling concerning plunge drivers, **Drd. Georgiana-Alexandra MOROSANU** – validation of experimental design and numerical simulations together with result's extraction and first paper versions redaction, **Prof. A. EPUREANU** – novel idea to build a hydraulic system to control punch kinetics across different punch orientations angles during a deep drawing process to obtain uniform plastic strains and sheet thickness variations with general conceptualization and support for all paper content, **Assoc. Prof. A. GAVRUS** – validation of Finite Element Simulation using general DYNAs software package including DYNAFORM and FLD diagram data with perspective to automatically control the punch orientation angle from plastic strains limits, quantitative analysis of input and output numerical data, successive revisions of paper content by add of detailed elements concerning the presented idea and all results comments/analysis.

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Cite this article as: V. Paunoiu, V. Teodor, N. Baroiu, G.-A. Morosanu, A. Epureanu, A. Gavrus, Contribution to the formability improvement in sheet metal stamping by a novel technique to control press kinetics, *Mechanics & Industry* **25**, 19 (2024)