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ORIGINAL ARTICLE

Prediction of press/die deformation for an accurate manufacturing of drawing dies

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Abstract In this work a methodological scheme for a reduction of both the try-out and lead-time of complex dies is presented. The finite element simulation of the system press/tool behaviour along the stamping process results in criteria for the best design of high-cost dies/punches. Modifications of the main geometry, components and functional parameters are so recommended. Die deflection during the pressing process is in this work investigated. With the proposed methodology die manufacturers are able to avoid errors coming from die deformation due to their asymmetrical shape. At the same time, time of manual adjustment and polishing is reduced in a 30%. Examples are deeply explained as well as experimental evidences.

Keywords Try-out · Stamping dies · Numerical simulation · Finite element · Press elasticity

1 Introduction

The problem analysed in this work is the extra deformation that appears in the die, which is necessary to polish manually, during the try-out phase. It is also necessary to perform this manual operation in the large presses for the final process. In this work the structural behaviour of the tool and the press is considered, and a methodology for their calculation is developed.

Sheet metal forming is an important production process based on deep experience and involves several trial and error loops. Tekkaya [1], analyses the industrial requirements for simulating sheet metal forming, the various approaches in finite element methodologies, that is, element types, and commercial programs for sheet metal simulations, including expensive commercial software packages used by industry in the simulation of sheet metal forming processes. Nowadays the main software packages have specially oriented tools for die makers and automotive. In these software packages the forming process with rigid dies is analyzed, but the deformation of the dies and the forming presses are not taken into account [1].

To date, much of the research using FEM applied to the analysis of metal deformation has focused on the simulation of material flow sequence; however, the die is assumed to be perfectly rigid to enable the computation [2]. Chodnikiewicz et al. [3] expressed a method and measurement system for the calibration of metal-forming presses, since practitioners of metal-forming operations know that the necessary force to produce the parts additionally results in a deformation in the press; although this is relatively small compared to the size of the machine, it is bigger than the allowed tolerance for the final part. Jian Cao et al. [4] proposed another approach for sheet metal forming, by means of design and control of variable binder force for the next generation of stamping dies [5]. Rosochowski [6] used a procedure for taking into account the die deflection and part springback, mainly in net-shape forming processes. R. Lingbeek et al. [7] presented a method for springback compensation in the tools for sheet metal products, concluding that for industrial deep drawing products the accuracy of the

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results has not yet reached an acceptable level. Thomas et al. [8] recommended procedures for obtaining accurate and reliable results from FE simulations for process simulation in stamping. Hernández et al. [9] discussed an approach combining the use of numerical simulation with the design-aid system CAETROK.

López et al. [10] have experimentally studied the use of newly developed utilities in the preparation stage, and the elaboration of CNC programs using CAM software to solve the special changes related to the forming tools due to the advanced high-strength steels (AHSS) used for car body parts currently. In [11] a similar treatment for forge presses is done particularized for a screw press. Chen and Liao [12] have reported an optimum die design for the purpose of eliminating the wrinkles in the stamping of tapered square cups and stepped rectangular cups, using finite-element analysis by examination the effect of process parameters, such as the die gap and blank-holder force. Tor et al. [13] applied a knowledge-based blackboard framework for stamping process planning in progressive die design in spite of KBE's lack a proper architecture for organizing heterogeneous knowledge sources in a cooperative decision making environment. Dequan et al. [14] analyzed a knowledge-based system for intelligent stamping process planning: feasibility of the stamping process, an optimal algorithm for blank layout, intelligent strip layout and force calculation. Tang et al. [15] addressed an intelligent feature-based DFS (design for stamping) system for implementing the stampability evaluation oriented to part shape analysis and cost estimation, based on features, and a knowledge-based system enable designers to carry out the stampability evaluation automatically. Pilani et al. [16] found a hybrid intelligent systems approach for die design in sheet metal forming, as an integrated decision support environment for simulation and analysis of the forming process, both during the initial die design phase and during the tryout phase.

Some experimental tests carried out in three local companies have verified that the tools deformation due to these effects can reach the size of tenths of millimetre. A process for producing mold is presented in the patent [17], considering the press deformation in an empirical way, with range of values of millimetres.

In this work, a global methodology [18] in order to take into account the structural behaviour of the tools in the mechanical group press-die is presented, assuming that both components are not rigid solids, and that the deformation of the press, although small, is in the order of magnitude of the manufactured part tolerance. This method has been proposed as a utility for the try-out of dies by stamping die-makers [19].

Section 2 describes the deformation of large dies in working. The proposed scheme for simulation of the press die working behaviour is developed in Sect. 3. Section 4 explains how this deformation affects the machining of the dies. In Sect. 5 this methodology is also tested with a sample in an industrial application, where the calculated deformation is proposed to machine the die surface. Finally the conclusions are explained in Sect. 6.

2 Deformation of large dies in working

Due to the recent techniques for high speed machining (HSM), it is possible to reach a great precision on the manufacturing of dies. Nevertheless, due to the big loads in the stamping process (400–1500 T), the deflection of dies is suffered during the bending process, but it is not taken into account.

A part of that deflection results from the deformation experienced by the die material as a consequence of its characteristics; however, most of the deformation is due to the die structure and to its lack of rigidity. The combination of both factors is what defines the total deflection of the die.

The magnitude of deformation experienced by the die is considerable. Therefore, it is necessary to proceed to manual operations with the purpose of modifying the shape of the die surface in order to compensate the deflection. This process of manual work-in-bench requires specialized manpower, resulting in higher prices for the die.

In preliminary studies, the variation of parameters in die design has been considered to obtain useful design criteria, which allows the design of dies with maximum rigidity and minimum deformation from the initial conceptual design phase (see Table 1).

Results, shown in Fig. 1 are in the range of millimeters. The hypotheses of this simulation contemplates that the base die contact with the press is completely rigid. In this case the range of values of the deformations is in the order of millimeters.

According to DIN 55189, protocols of press geometric verifications used for sheet metal forming are: the parallelism between bolster and slider, the looseness in the guides of the slider, the deflection of bolster. This latter measuring protocol for a hydraulic press of 1200 T, reaching to 75% of the load, gives values of 0.85 mm. This problem can be compared to the flexion of a doubly supported beam under the pressure of a load. This value has been calculated by the finite element (FE) method.

With these premises it has been proposed the method of simulating the behaviour of die in the press, because it has been demonstrated that this effect has enormous influence, and it is the sum of both deformations: die and press.

Table 1 Influence of parameters for die design in deflection

Die parameter / Impact in variation	High	Medium	Low
Diameter of the fasten screws			X
Application form of the load	X		
Height of the punch	X		
Increase the width of the punch		X	
Number of ribs in the inferior base die	X		
Ribs in lateral walls of the die		X	
Reinforcements in punch		X	
Curve forms in lateral walls			X

3 Proposed scheme for simulation of the press/die working behaviour

This section explains the process shown in Fig. 2, regarding the proposed scheme for simulation of the press/die working behaviour.

On the column left of Fig. 2 the global flow in a typical die manufacturing company is shown, and the proposed methodology with their relations is shown on the right side.

The process in a typical die manufacturing company is initiated with a 3D part model, and it ends with a test or try-out of the tool and the acceptation of the pre-series of the final part [20]. The process steps are:

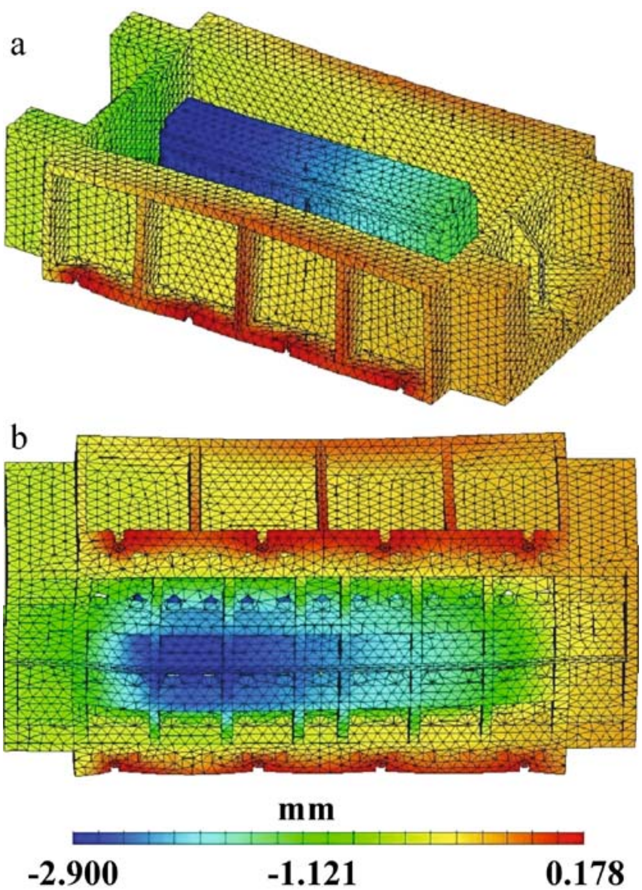


Fig. 1 Preliminary results: (**a**) 3D general view, (**b**) 3D bottom view

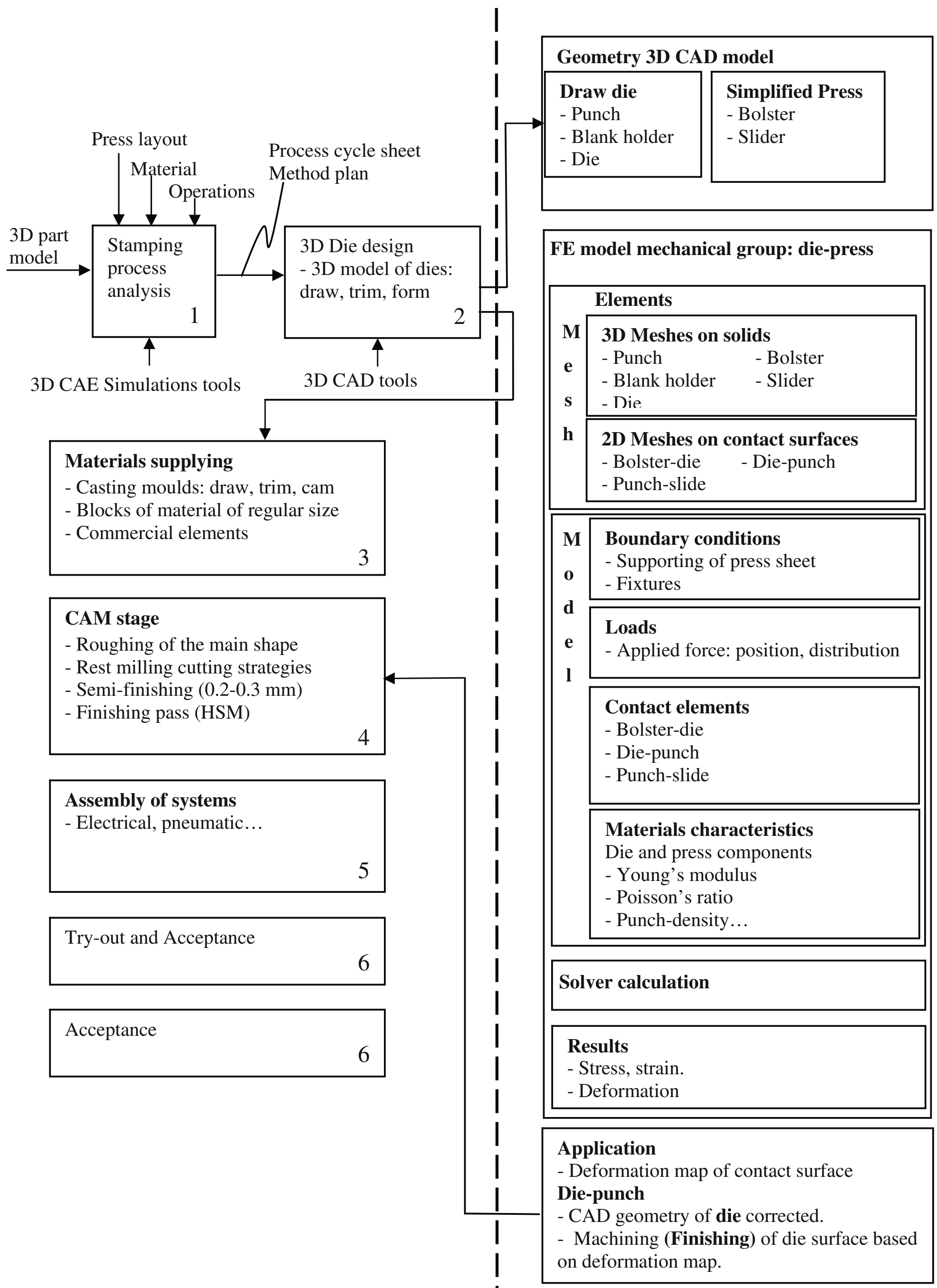
1. The definition of the “method plan” or stamping process is realized in the stamping process analysis. The analysis is validated by the simulation of the stamping process in order to check formability. Simulation tools (3D CAE) are used, taking into consideration the press layout, the material of the desired part and the number of operations. The output is the process cycle sheet.
2. The complete die design is realized in the 3D design system. The complete and detailed design of full set of dies is realized for the production of casting moulds and specific parts and elements of the system. This set of dies is designed for all the operations (draw, trim, conform, ...) defined in the method plan. Design (3D CAD) tools are used. The output is the 3D design of operations and the bill of materials.
3. The supply of material, which is related to three main types of items: casting parts, blocks of material of regular size and commercial elements.
4. The CAM stage, where the work is concentrated in the surfaces machining process. Probably the main problem when machining stamping dies is the generation of sculptured surfaces. Software tools (3D CAM) and CNC machines are used. The sequence [21] are as follow: previous work material set-up and preparation of the blank, roughing of the main shape of the stamping die, leaving an allowance ranging from 1.5 up to 5 mm, using bitangential tool path and rest milling cutting strategies, semi-finishing with the objective of leaving a nearly constant allowance of about 0.2–0.3 mm, finishing pass with the objective of machining of the previous allowance.
5. The assembly of systems where all elements coming from material supplying are assembled to operate mechanically in the press. This stage is realized for the full set of dies defined in the method plan.
6. Try-out and acceptance, where manual polishing operation is realized until the part is achieved, and the dies are accepted by the customer.

The proposed methodology assumes that the two first steps are realized [22]. In this way the start point is the draw die with the surface of the target part and the 3D design of the die elements: die, punch and blankholder. The following are the steps for the methodology:

1. CAD 3D geometry of the draw die: die, punch and blankholder, positioned according to their operation (CATIA V5, Ideas, etc.). 3D geometry of the simplified press including bolster and slider also performed in the same CAD.

2. Based in the CAD geometry, a finite element (FE) model for a static structural analysis is created with the following items:
3. Mesh. The mesh is composed of two types: 3D meshes on solids and 2D meshes for contacting surfaces. The 3D mesh is composed of tetrahedral elements with four nodes created from the components of the mechanical group die-press: die, punch and blankholder; bolster and slider. The 2D mesh is composed of thin shell elements with three nodes created from the contact surfaces: bolster-die, punch-slide, die-punch. This latter surface is the objective and thereafter the target contacting surface.
4. The boundary conditions considers the supporting of press and fixtures (see Fig. 6), where the press is considered as a doubly supported beam.
5. The loads is the applied force by the press through the corresponding cylinders in their position.
6. The contact elements defined by the 2D meshes of the contact surfaces, as created in step 2.

Fig. 2 Proposed methodology for the simulation



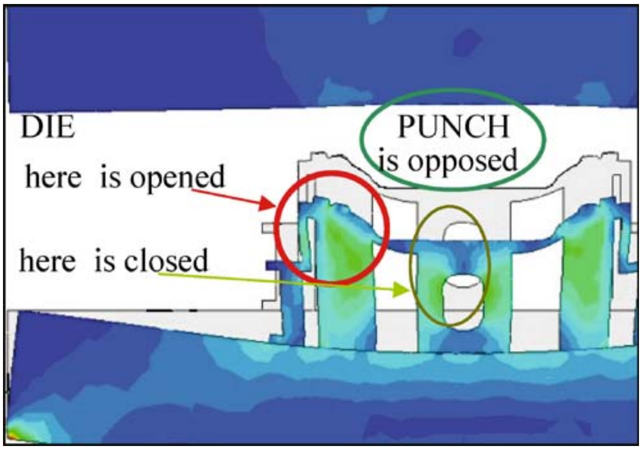


Fig. 3 Die-punch behaviour

7. The material characteristics based on the die and press components for the elements of the model: modulus of elasticity, Poisson's ratio, density, etc.
8. Solver. The solver for computation could be Ideas, CATIA V5, NASTRAN, ANSYS, etc.
9. Results. The results from computation are the stress, strain and deformation of the complete group. By postprocesing the deformation results in the contacting surface between die and punch, the predicted deformation map of die surface is obtained.
10. Application. There are two possibilities of application of this deformation map: the corrected geometry can be obtained by applying the deformation map of contacting surface to the CAD geometry of the die, or by applying to it the machining process, in the finishing step, for the initial surface of the die, based on this predicted deformation.

The first solution is not accepted by the customers, that is, the modification of the punch and die CAD design. Therefore the only way to solve the deformation problem is to make modifications of the CAM tool parts, according to the deformation predicted value.

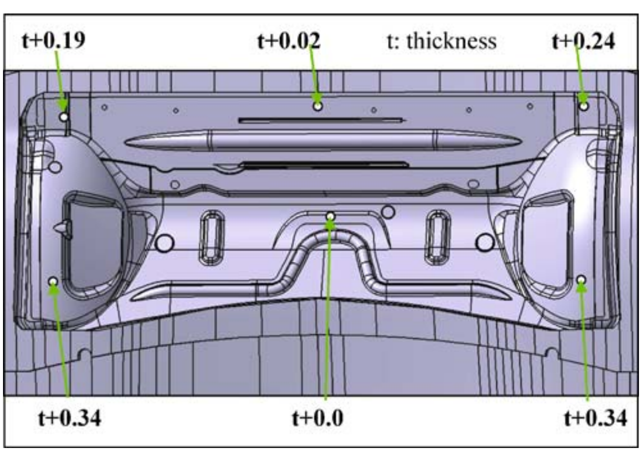


Fig. 4 Measurements of deflection between die-punch

The idea is to eliminate by machining the previously explained deformation, since generally the punch surface is machined reproducing exactly the manufactured part, and the die surface is machined to an offset equal to the thickness of the blank. The die-punch behaviour, due to the flexion of press, shows that the punch is opposing to the close of the die (see Fig. 3). At the moment, the only way to avoid this problem of lack of matching is by manual polishing. This is why the procedure is so labour intensive and expensive.

4 Influence of the deformation on machining

Some measurements can be performed on the die-punch, after the part is successfully obtained. In this way the distance between die and punch (part thickness plus tolerance) in its operating position can be obtained, this

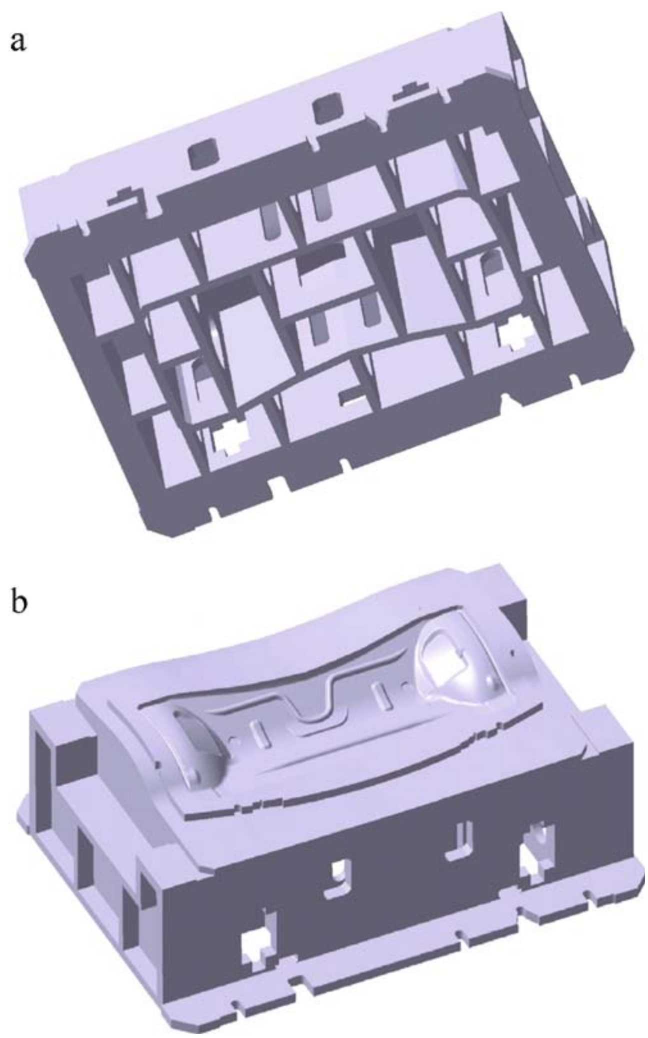


Fig. 5 Geometry CAD of die: (**a**) 3D-down (bottom view), (**b**) 3D-up (general view). The bottom view shows the cavities and ribs for lightweight die

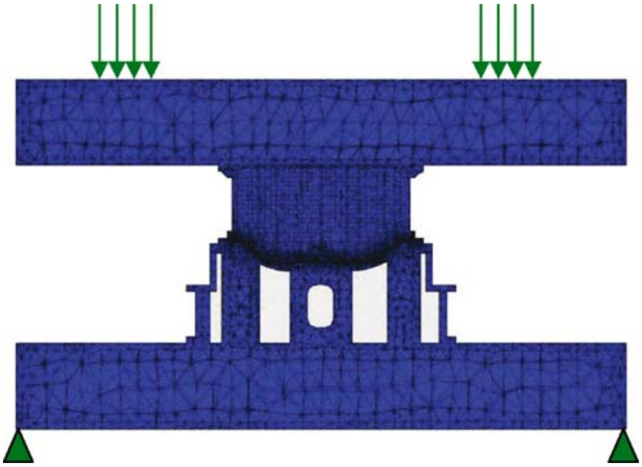


Fig. 6 Complete 3D mesh model

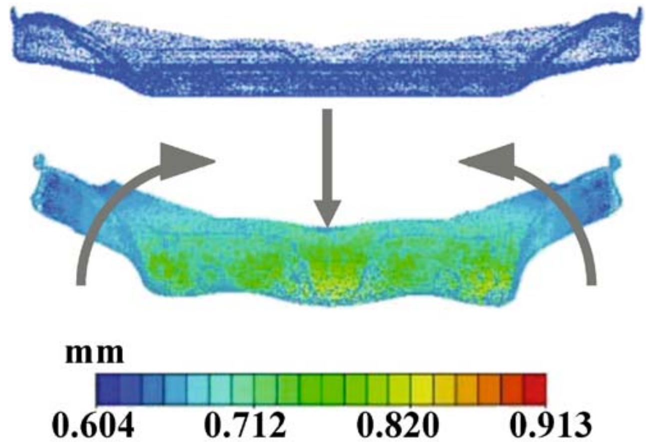


Fig. 8 Deformation of die surface and behaviour, arrows show the main deformations

distance is due to deflection, and is called “clearance/allowance” (see Fig. 4). The clearance between die-punch shows that, although the part is symmetrical, its values are not constant and they are asymmetrical. This is due to the ribs structure applied to the die-punch in order to lightweight.

The measurement process is performed using plumb pins with a defined dimension length. These plumb pins are fixed with plasticine in points located in quasi-horizontal zones of the die surface. The press is activated without force until the ram touches all the plumb pins, and after the press is opened the length of plumb pins can be measured with a coordinate measuring machine (CMM). The difference between the initial value of the length and the measured length of the plumb pins shows the clearance between die and punch, after the manual polishing operation. This method has the following disadvantages: the measurements are realized “a posteriori”, when the part’s shape is achieved, only a few points can be measured in the surface because the plumb pins require a quasi-horizontal area. The deviations between the measured values and the predicted ones by the proposed methodology are very small and in the range of hundredths of millimetre.

5 Industrial application

In order to validate the methodology this section shows an industrial sample case according to the previously described steps. The press was a hydraulic one with a nominal force of 1200 T. The bolster dimensions are 5,000×2,500 mm. The material was ASTM60 [23]. The applied force in the process, based in the plan-method, was: punch 500 T, and holding 120 T. The contacting surface (die-punch) was 0.84 m^2 (1,275×850 mm).

3D CAD model of the geometry of the die includes all the elements: ribs, holes, exact surface of the part modelled with CATIA V5 in solids (see Fig. 5).

The complete 3D mesh of the mechanical group in Ideas Master Modeler, includes the holes and ribs made in the

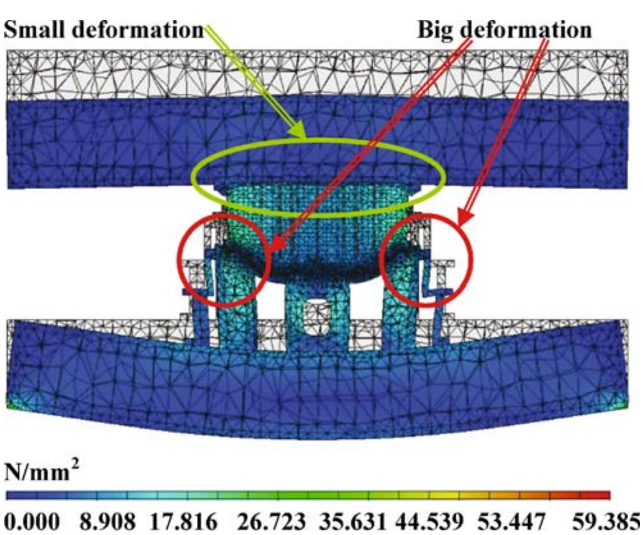


Fig. 7 Comparison of tools deformations

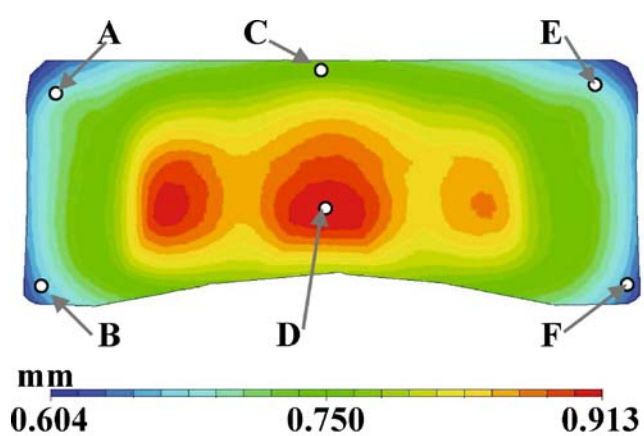


Fig. 9 Contacting surface deformation (z direction)

Table 2 Deflection in z direction measured in possible points

Point	Deflection measured (mm)
A	0.19
B	0.34
C	0.02
D	0.00
E	0.24
F	0.34

die, punch and blankholder in their operational position (see Fig. 6).

Once the analysis is completed the comparison of the deformation in the press can be seen: bolster and slider; and draw die components: die and punch. The upper part of the die (in this case the punch) shows a small deformation, but the central part of the group shows a big deformation, the contacting surface between die and punch (see Fig. 7).

In addition, the analysis results show the deformation of the die surface and its behaviour during process in a front view (see Fig. 8). Arrows show the main deformations as explained in Section 3.

Finally the deformations map shows that these deformations are not equals or proportional in the contacting surface. In this case, they depend on the location of ribs. The value range is in term of tenths of millimetre, 0.3 mm for this industrial case, calculated as the difference between the maximum (0.9 mm) and the minimum (0.6 mm) deformation in the contacting surface (see Fig. 9 and Table 2).

Table 3 shows four industrial cases corresponding to large draw dies where the use of the methodology has been considered due to the part's complexity and large dimensions of them. The table summarizes parameters in the process for the press and for the die. The press parameters are bolster dimensions (mm), nominal load (T) and applied force (T). The die parameters are die dimensions (mm), area of contacting surface (mm^2), predicted deflection (mm) and measured deflection (mm). The material of the dies was ASTM60. The nominal force of each press is 2000 T, 1200 T, 650 T and 1200 T, respectively. The applied force

Table 4 Table load-deformation

Press load (Tm)	Max. deformation z (mm)
100	0.053
200	0.105
300	0.157
400	0.210
500	0.262
600	0.313
700	0.369
800	0.414
900	0.470
1000	0.530

in each case is 1200 T, 1200 T, 650 T and 650 T. The die dimensions are 3940×2380×670 mm, 3,780×1,700×668 mm, 2,370×1,650×700 mm and 2,210×1,300×750 mm, of which the area of contacting surface is 4.33 m^2, 1.9 m^2, 0.9 m^2 and 0.84 m^2. The predicted maximum deflection was 0.6 mm, 0.4 mm, 0.3 mm and 0.3 and the measured maxima deflection using plumb pins was 0.637 mm, 0.47 mm, 0.35 mm and 0.34 mm, respectively. The predicted results obtained from the model range from 0.3 mm to 0.7 in these experimental cases, and confirm that the deflection is not constant in the contacting surface. The predicted results are checked with the measured plumb pins.

6 Conclusions

A new methodology for an accurate manufacturing of drawing dies has been presented. Real deformation of punch/dies bolt on the press machines are usually bigger than tenths of millimeter, that is similar to the part tolerance.

One simply approach could be use the estimated values of the maximum deformations in a very simplified model (symmetrical distribution of ribs, constant relation of holes, homogeneous dimensions of holes and thickness of ribs, similar sizes of dies). Results values are those of Table 4. However this would lead to the need to a long and hard

Table 3 Experimental and predicted deformation in industrial large draw dies

	Part 1	Part 2	Part 3	Part 4
Bolster press [mm]	4,200×2,500	5,000×2,500	3,000×1,800	5,000×2,500
Nominal Press Load [T]	2,000	1,200	650	1,200
Applied force [T]	1,200	1,200	650	650
Die dimensions [mm]	3,940×2,380×670	3,780×1,700×668	2,370×1,650×700	2,210×1,300×750
Contacting surface [m^2]	4,33	1,9	0,9	0,84
Predicted deflection [mm]	0.6	0.4	0.3	0.3
Measured deflection [mm]	0.637	0.47	0.35	0.34

hand polishing. To avoid this, a FEM simulation of the draw die real geometry and punch can be performed. The deformation estimated values can be introduced at the CAM stage to modify the finishing tool paths. As result, a punch and die shape which stamp the desired part are directly machined, needing only little manual polishing. Examples show some figures of the benefits of the proposal approach.

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