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NUMERIC SIMULATION OF HYDROFORMING DEFORMATION PROCESS FOR T-SHAPED PIPE CONNECTIONS

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Abstract*: Finite element method (FEM) is currently the most used method for numeric analysis of engineering problems. FEM has the following advantages: flexibility; possibility to model bodies not homogenous as regards their physical properties; easy implementation into general calculation programs etc. The software market currently provides several calculation programs using finite element method to solve problems related to plastic deformation of metal sheets and parts. These programs are used to address the following issues: reduce time to devise plastic deformation technologies; reduce products manufacturing costs; increase quality of products manufactured by plastic deformation.*

Key words*: hydroforming, connections, FEM, plastic deformation, simulation, T-shaped connection.*

1. INTRODUCTION

Simulation, by generating a substantial reduction of development time, as well as the cost of a product, is recommended to be applied to hydroforming pipe parts.

Currently, DYNAFORM [ETA08a, ETA08b, ETA08c] is one of the applications most used in the field of finite element simulation of hydroforming. Among the features of this application, the following should be mentioned:

- possibility to import geometric models of parts and/or tools designed in the most usual CAD programs (CATIA, SolidWorks, SolidEdge, AutoCAD etc.)
- automated discretisation into finite elements of the parts and tools;
- assistance in preparing process models (defining deformation steps, positioning tools against the part, defining variation diagrams for process parameters, such as the pressure acting inside the tubes);
- using high performance plasticity models, which take into account the anisotropic properties of laminated or pulled tubes (e.g. Hill 1948, Barlat 1989, Barlat 2000 etc. models);
- availability of library containing mechanical properties of most frequent industrial materials;
- modelling the contact with friction between the part and the tools;
- availability of a post-processor providing detailed graphic presentations of simulation results (distribution of part's thickness, analysis of breaking risk, folding risk, as well as the material stretching status etc.).

Using numeric simulation of connection hydroforming has a double motivation. First, the purpose is to confirm that the tubular part with exterior diameter of 51 mm and wall thickness of 2 mm would not reach breaking point. Another purpose is to certify the correctness of process parameters determined in chapter 2 with an empiric formula (e.g. maximum value of hydroforming pressure – 1700 bar). Analytic modelling of hydroforming a connection part is difficult and would require the application of a simplifying hypothesis. The accuracy of results obtained from such models is low. Simulation by finite element method is a more convenient alternative, both regarding the quality of results and the efficiency.

Advantages of numeric simulation are numerous. Using this method allows for correction of geometry of the part or the tools since the stage of technical design, without passing repeatedly through the adjustment stages characteristic to the traditional design method. Thus the expenses related to tools manufacturing are reduced. In addition, a better sizing of the part usually improves the material usage coefficient. It should be mentioned that the numeric simulation applications allow for comparing multiple technical alternatives and selecting the optimal solution as regards the quality and the financial aspects.

2. TECHNOLOGY FOR OBTAINING THE HYDROFORMED PART, T-SHAPED CONNECTION

Hydroforming is an attractive technology for manufacturing parts of complex geometric forms with tubular shapes. Compared to alternative technologies, this technology presents significant potential advantages, such as: complex geometry parts, easy design, high accuracy, relatively simple construction tools.
Fig. 1 presents the cinematic of obtaining a T-shaped connection from a tubular part.

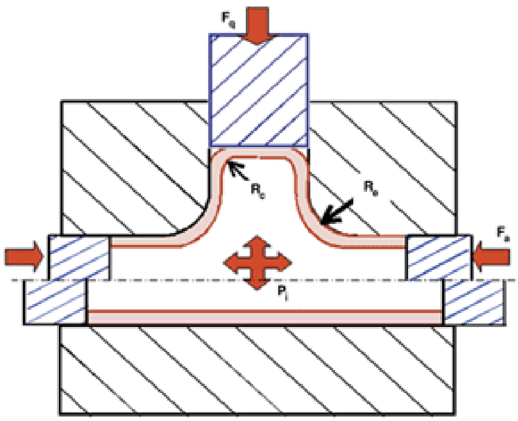

Fig.1. Principle of a modern installation for hydroforming with independent control of axial feeding, internal pressure, and counter-pressure

Portal presses are special destination installations, namely: hydroforming connections. These types of presses have good rigidity and are equipped with computer controlled hydraulic pumps which provide technology parameters as per figure 1.

3. NUMERIC SIMULATION OF HYDROFORMING PROCESS

3.1 General aspects

An elastoplastic material model has been adopted to describe the mechanical behaviour of the tube. This model describes the elastic part of the deformation through a Hooke type linear law, which includes two material constants: Young's modulus (E) and Poisson's ratio (ν). To describe the irreversible part of the deformation, the material model uses a Barlat 1989 plasticity criterion and a Hollomon hardening law:

$$\sigma = K\cdot(a + \varepsilon_p)^n \, , \qquad (3.1)$$

where: K is the strength index;

n – strain hardening exponent;

a – plastic deformation (expressed in logarithmic form), for which the material's limit flow is determined experimentally.

Table 1 presents the values of material constants defining the elastoplastic model for stainless steel X2CrNi19-11.

Hydroforming of T-shaped connections is usually performed in three steps [Koc08, Neu07, Sin03]:

- Bringing the tubular piece to plastic flow (achieved by moving the horizontal plungers, without applying internal pressure);
- Suddenly increasing pressure inside the tube to form a flattened cap in the rising area of the vertical branch (during this entire stage the vertical plunger has to exert sufficient pressure to prevent the formation of a spherical cap[1]);

Table 1.Mechanical characteristics of stainless steel X2CrNi19-11 (SR EN 10088-1: 2005)

Elastic constants	E	$2.1\cdot10^5$ N/mm²
	ν	0.3
Constants from the hardening law (1) – Hollomon law	K	1094.429 N/mm²
	ε_p	0.00198
	n	0.290

[1] In general, the cap's evolution towards a spherical shape determines a significant thinning of the part and early breaking.

- continue increasing pressure inside the tube up to maximum level to form the full vertical branch of the connection (during this stage, the pressure exerted by the vertical plunger continues to increase, but gradually lags behind the resultant associated to hydrostatic effect of pressure inside the piece).

Considering that the flow limit of metallic materials is experimentally measured for a remnant deformation of 0.2%, it is considered that the first stage of the hydroforming process (bringing the tube to plastic state) is completed when the sum of displacement of horizontal plungers is:

$l_{sf} \cdot 0.2 \cdot 10^{-2} = 145 \cdot 0.2 \cdot 10^{-2} = 0.29$ mm.

Equally dividing this value to the two plungers, resulting axial displacement is around 0.15 mm. As stated before, as long as the tube is being plasticized, the walls are not subject to load from the hydroforming liquid or from the vertical plunger.

To determine the level of the first pressure impulse (second stage of hydroforming) several numeric simulations were performed. Unfortunately the bibliography does not provide quantitative indications regarding this aspect. Following repeated numeric tests, it was determined an optimal pressure value for the first impulse of 1000 bar. Liquid pressurization has to be very quick. After performing simulations, the conclusion was that the 1000 bar level should be achieved after a displacement of 0.1 mm of the horizontal plungers. The analysis of simulation results revealed that the flat cap forming ends for a 1.5 mm displacement of the said plungers. In this stage of hydroforming, the flat area at the top of the cap has an approximate diameter $d_c = 35$ mm. With this value, the maximum force exerted by the vertical plunger during the second stage of the process can be determined:

$$F_{v,max,1} = p_{max,1} \cdot \pi \cdot d_c^2 / 4 = 100 \cdot \pi \cdot 35^2 / 4 = 96211.28 \text{ N} \qquad (3.2)$$

In the equation above, $p_{max,1} = 1000$ bar $= 100$ N/mm^2 is the related maximum pressure. Since the force exerted by the vertical plunger should allow for a small rise of the cap, a slightly lower value was adopted, namely $F_{v,max,1} = 95000$ N = 95 kN.

During the third stage of hydroforming, the pressure rises uniformly from 1000 bar up to the maximum level of 1700 bar. The force exerted by the vertical plunger is also uniformly increasing. By maintaining the diameter of flat area at the cap's top at $d_c = 35$ mm, the top limit of the said force can be determined:

$$F_{v,max,2} = p_{max,2} \cdot \pi \cdot d_c^2 / 4 = 170 \cdot \pi \cdot 35^2 / 4 = 163559.16 \text{ N} \qquad (3.3)$$

In the equation above, $p_{max,2} = 1700$ bar $= 170$ N/mm^2 is the maximum pressure corresponding to the final stage of hydroforming. Once again, such as the pressure exerted by the vertical plunger to not prevent the rise of the tube wall, a value slightly lower than the calculated limit was adopted, namely $F_{v,max,2} = 160000$ N = 160 kN.

Table 2 summarizes the previous results. Based on the table data, the variation cyclograms of pressure inside the tube, as well as of the opposing force exerted by the vertical plunger, have been traced. (Fig. 2).

The stages of numerical simulation of hydroforming process are presented in short, below.

3.2 Preparing the geometrical models of the tubular part and of the tools

The tubular part, as well as the active surfaces of the semi-moulds and plungers have been modelled using the assisted design application SolidWorks 2007. Geometric representations have been exported to DYNAFORM as IGES files (fig.3).

Table 2.Specific levels of pressure inside the tube and of opposing force applied to the vertical plunger

Horizontal plunger displacement [mm]	Pressure inside the tube [bar]	Force applied to vertical plunger [kN]
0	0	0
0.15	0	0
0.16	1000	95
1.50	1000	95
18.50	1700	160

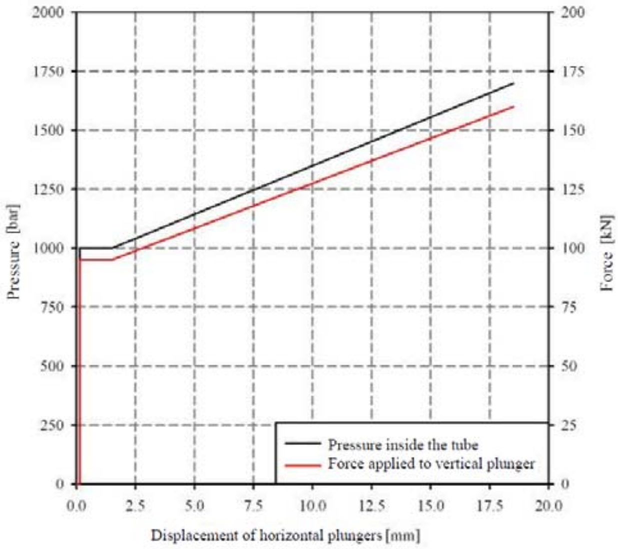

Fig. 2. Variation diagram of pressure inside the tube and opposing force applied to the vertical plunger

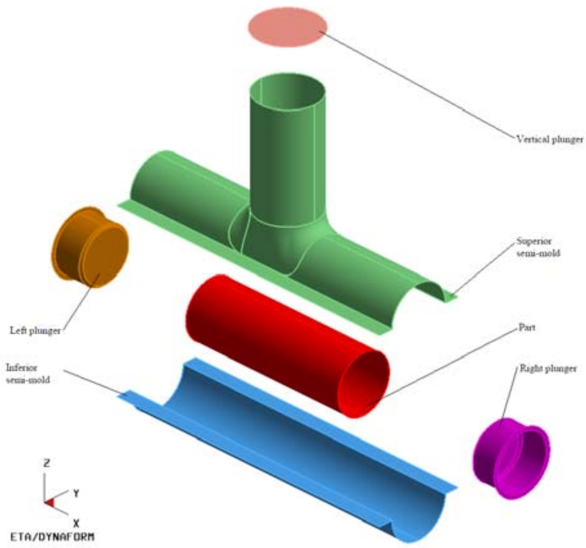

Fig. 3. Importing geometric models of the part and of tools active surfaces into DYNAFORM

3.2 Discretisation of geometric models of the part and tools

Median surface of the part has been discretized into finite elements as a flexible envelope (fig. 4). Since the tools are subject to negligible deformations as compared to the part, rigid face elements have been used for their discretisation (Fig. 5).

Description of process subject to numeric simulation

DYNAFORM application provides the users with the specialized module AutoSetup, where all parameters of the hydroforming process can be set [ETA08a, ETA08b].

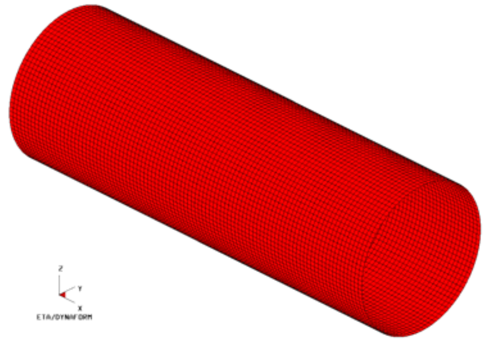

Fig. 4. Discretisation of the median surface of the tubular part into finite elements as a flexible envelope

Graphic interface of the AutoSetup module is structured into several dialog boxes. The information input in the fields of the respective dialog boxes is presented below.

- General characteristics of the process to be analysed:
  - class of the process – in this case, deformation of a tubular part;
  - nominal wall thickness: 2 mm;
  - type of process: hydroforming.

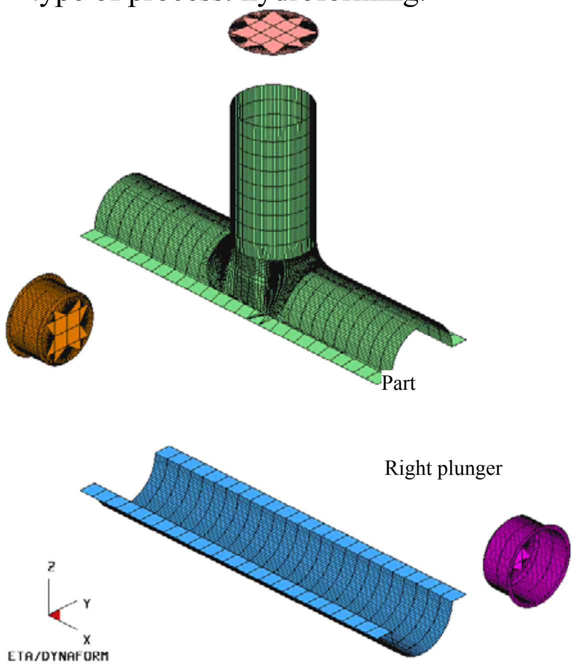

Fig.5. Discretisation of tools active surface into finite elements as a rigid face

- Give a title to identify the results of numeric simulation;

- Define mechanical properties of the tubular part:
- – Select mechanic model as envelope (ELFORM = 2 – model proposed by Belytschko, Lin and Tsai [ETA08b]
- – Specify parameters defining the elastoplastic model associated to the part (fig. 6 and fig. 7).
- Specify tools cinematic and parameters defining the friction interaction between the part and their surfaces:
- – define direction of movement for each tool included in the process model;
- – define Coulomb's friction coefficient associated to the surface of each tool (in this case the adopted value was μ = 0.125
- – recommended in DYNAFORM's documentation for steel/steel contact [ETA08a, ETA08b]).
- Automated positioning of tools in relation with the part (fig. 8)

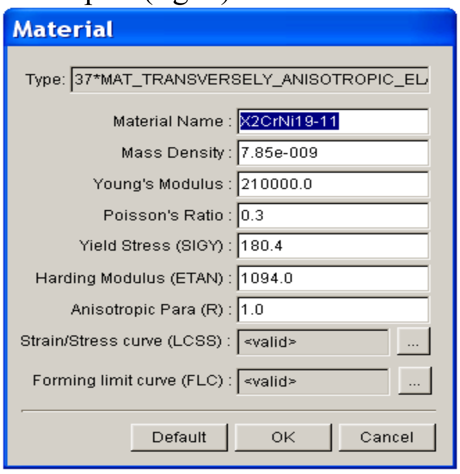

Fig. 6. Values for parameters defining the elastoplastic model associated to the part (stainless steel X2CrNi19-11)

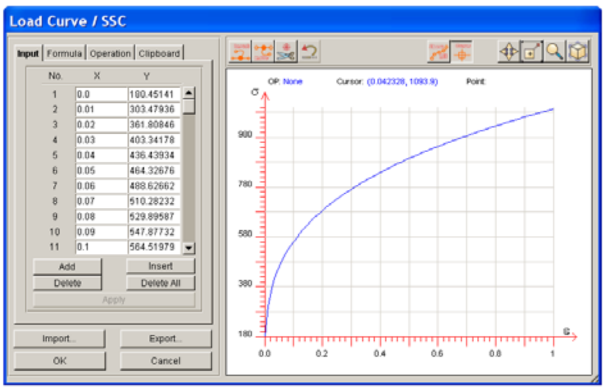

Fig. 7. Hardening graph for stainless steel X2CrNi19-11

(described by a Hollomon type empirical law)

- Specify parameters defining the stages of hydroforming process:
- – Status of each tool included in the model (active / inactive), type of tool control (applied force / pressure or imposed displacement), as well as total duration of simulated process
- – Tabular descriptions of variation of parameters defining the tool control (in this case, the law defining the travel of horizontal plungers – fig. 9, law of pressure variation inside the tube – fig. 10, and the law of variation for the force exerted by the vertical plunger – fig. 11).

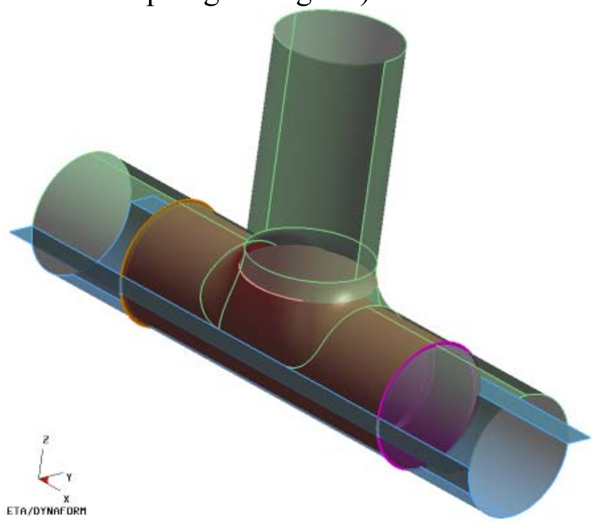

Fig. 8. Automated positioning of tools in relation with the part

- Run the numeric simulation program;
- Visualise and interpret the simulation results;

In order to facilitate the analysis of numeric simulation results, DYNAFORM provides the users with the eta/POST postprocessor module [ETA08c]. This module graphically presents the distribution of status parameters of the part in various stages of deformation (thickness, deformation, tension etc.), as well as of parameters defining the whole process (e.g. variation diagrams of forces exerted by each tool). From the information provided by the postprocessor, the most significant from the technological point of view are the following:

- – Evaluation of risk for deformation in the final stage of the process (Fig. 12);

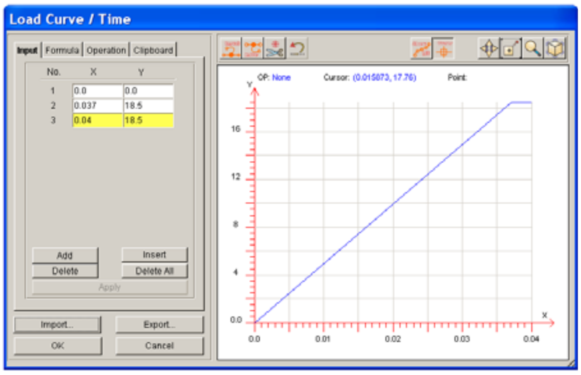

Fig. 9. Horizontal plungers displacement curve

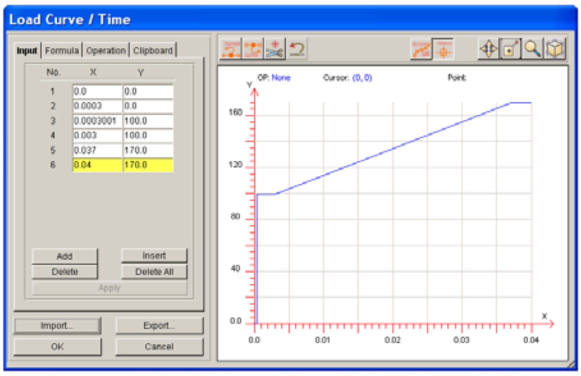

Fig. 10. Variation curve of pressure inside the tubular part

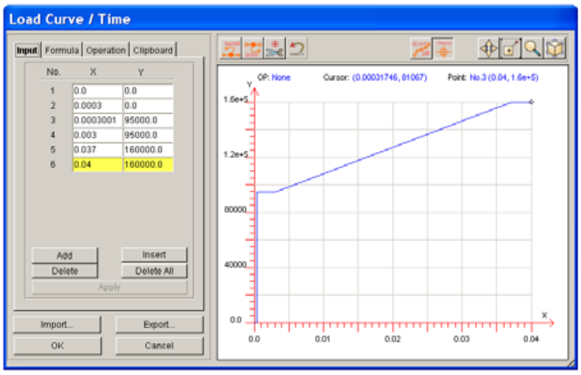

Fig. 11. Variation curve of force exerted by vertical plunger

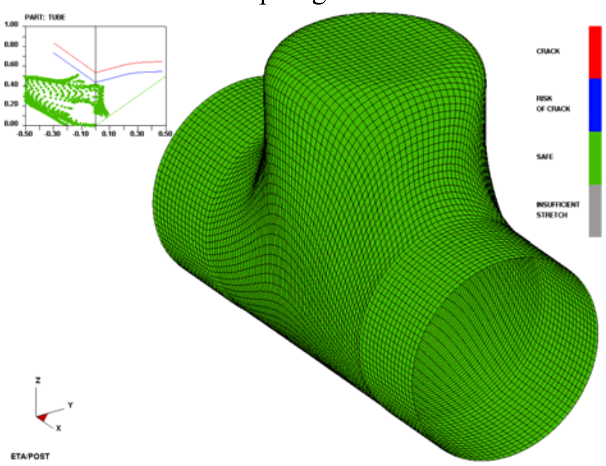

Fig. 12. Analysis of risk for final deformations

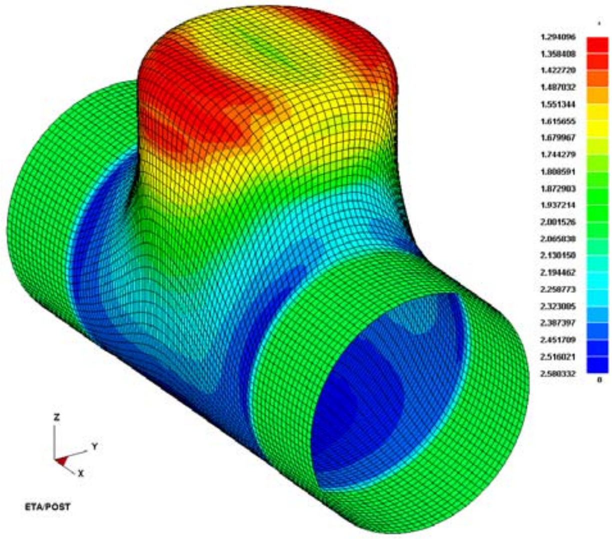

Fig. 13. Thickness variation of the hydroformed part

– thickness variation of the part in the final stage of hydroforming (Fig. 13);

– variation diagrams of forces exerted or supported by the rigid elements of the mould (Fig. 14 and Fig. 15).

For evaluating the risk of strangulation or breaking occurring in the part, the eta/POST postprocessor uses a limit deformation curve [Ban92]. This is a diagram using pairs of main deformations (ε_1, ε_2) to define the total amount of strangulation or breaking occurrences in the material. In the case of eta/POST postprocessor, the limit curve is generated with an empiric formula proposed by Keeler [ETA08c].

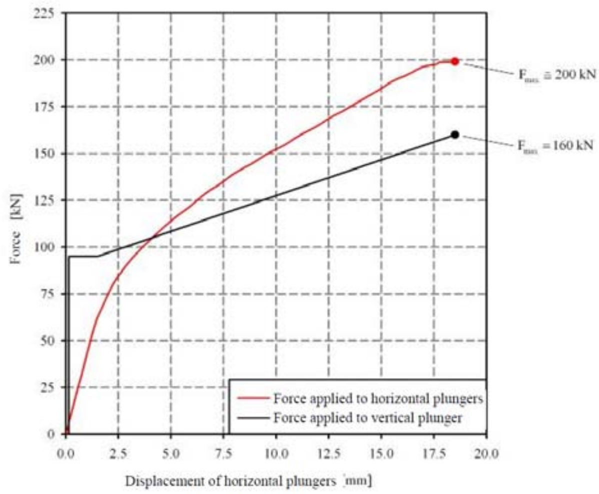

Fig. 14. Variation diagram of axial forces applied to the plungers of hydroforming mould

The box in the top left of the diagram in figure 12 contains two limit deformation curves. The red curve corresponds to material breaking conditions. The blue curve is equidistant traced 0.1 lower. It represents the conditions where the risk of strangulation is already present. The gap of 0.1 between the two limit curves was determined empirically by researchers, by observing the behaviour of materials frequently used in industry.

Obviously, most of the times, the occurrence of strangulation causes the rejection of parts. In the specific case of hydroformed tubes, the areas with severely reduced thickness due to strangulation have a lower mechanical strength and present a potential risk in the operation stage. Therefore, the simulation results may be considered as acceptable only if all surface deformations are in the area below the inferior limit curve.

As seen in the diagram in figure 12, the entire area of the hydroformed part is green. This colour code corresponds to the safe zone of deformations located below the strangulation limit curve. Also to be noticed that the gap between the largest deformations and the inferior limit curve is quite small. This situation presents an optimal usage of deformability of stainless steel X2CrNi19-11.

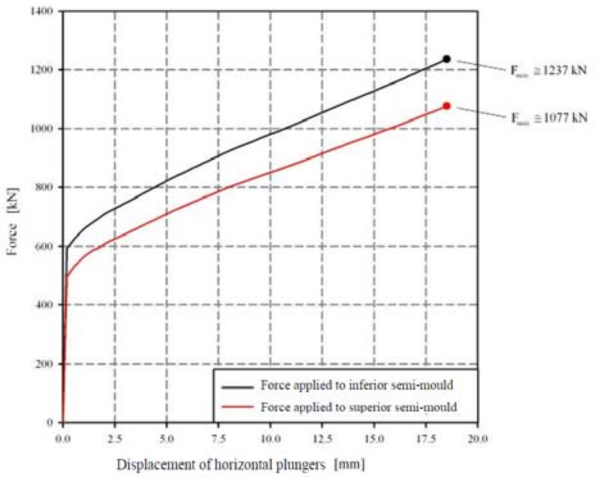

Fig. 15. Variation diagram of vertical forces applied to the semi-moulds

The diagram in figure 13 presents significant variations of tube wall thickness. As expected, the vertical branch wall is thinned. The most reduced thickness is in the top cap area (approximately 1.29 mm). Horizontal branches are less affected by thickness variations. This is due to the guiding sections of the horizontal plungers, which drastically limit the radial deformation of the wall. However, the branches joining area is not affected by the horizontal plungers. During hydroforming, the walls in this area are subject to significant thickening (up to approximately 2.58 mm), due to significant axial compression. Despite their magnitude, the thickness variations noticeable in the diagram in figure 13 comply with the limit deviations of ±0,75 mm specified on the part's execution drawing. Consequently, the result of hydroforming process may be considered as satisfactory from the quality point of view.

Diagrams in figures 14 – 15 present a very significant increase in the forces exerted by the horizontal plungers and in the forces supported by the semi-moulds respectively. This situation is mainly due to the extremely hardening characteristic of the steel X2CrNi19-11. As practical aspects, the most important are the maximum levels of forces in the diagrams. These values allow for proper selection of the plant to be used for hydroforming the T-shaped part.

4. CONCLUSIONS

Advantages of numeric simulation are multiple. By using this method, the geometry of the part or of the tools may be corrected since the stage of technical design, without requiring repeated adjustment stages which are specific to traditional design methods. This way, the expenses related to production of tools are reduced. Furthermore, a better sizing of the part usually has the benefit of improving the material usage coefficient. To be mentioned that numeric simulation applications allow for analysing several technical alternatives and selecting the optimal solution as regards the quality and the financial aspects.

The geometrical 3D model of the mould was made with SolidWorks application. The 2D technical documentation was made with AutoCAD, by importing views and sections directly from the SolidWorks model.

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SIMULAREA NUMERICĂ A PROCESULUI DE DEFORMARE PRIN HIDROFORMARE A RACORDURILOR PENTRU ȚEVI IN FORMĂ DE T

Rezumat: Metoda elementelor finite (MEF) este, la ora actuală, cel ma răspândit procedeu de rezolvare numerică a problemelor inginereşti. Principalele avantaje ale MEF sunt următoarele: flexibilitate; posibilitatea de a modela corpuri neomogene din punct de vedere al proprietăților fizice; uşurința implementării în programe de calcul generale , etc. Pe piața software există la ora actuală mai multe programe de calcul cu elemente finite pentru rezolvarea problemelor de deformare plastică a tablelor şi profilelor metalice. Prin utilizarea acestora, se urmăreşte rezolvarea următoarelor probleme : reducerea timpului de elaborare a tehnologiilor de deformare plastică; reducerea cheltuielilor de fabricație a produselor; creşterea calității produselor fabricate prin deformare plastică.

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