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EFG METHOD USED IN DEEP DRAWING NUMERICAL SIMULATION

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Abstract: *This paper brings in front of the interested researchers using one of the most known and used meshfree method, Element-Free Galerkin (EFG) method, in modelling of a technological process. It is about the deep drawing process of thin plates made of steel or aluminium. The paper gives information both for EFG method and for deep drawing process. The modelling as well the results are presented in a comparative way towards the using of Finite Element Method (FEM). The numerical analysis is based on the Ansys/Ls-Dyna program, in which EFG method is implemented. This numerical method is less known in our country and much less used, in spite of some advantages comparatively with the FEM. Of course, the EFG method is still under developing, but it can be successfully used in many problems. This paper is a proof in this sense and an urge to use the EFG method.*

Keywords: EFG, FEM, deep drawing, numerical modelling

1. Introduction

The increase of the technological performances is surely related to the increasingly efficient use of numerical simulation. Nowadays the most used numerical method is finite element method. Next to it, many new numerical methods appeared, especially methods of meshless and meshfree types. Among these, the Smoothed Particle Hydrodynamics (SPH) method and EFG method are the best known and used. In last time, our research was focused upon using in mechanical engineering problems of the EFG method.

Unlike the FEM which uses the interpolation functions, the EFG method uses the approximation method based on weighting functions. This means that by approximation procedure do not return nodal function values. The formulation of an equation set, by one or other numerical method can be made in a strong or weak form. In a strong-form formulation, the approximate function of the unknown parameters (e.g. u, v etc.) should have sufficient degree of consistency, so that it is differentiable up to the order of the partial differential equations [1]. In a weak-form formulation, the approximate function has a weaker consistency, by introducing an integral operation to the system equations based on a mathematical or physical principle. Both a strong-form formulation and an weak-form formulation are based on global or local domain [2]. The EFG method uses a global weak-formulation.

As the technological process of deep drawing is concerned, this is described in the literature, but computational relationships are based on assumptions that often require corrections through experimental calibrations. The numerical simulations can made easier this process and can save money and time.

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The main parameters which have to be calculated are the deep drawing force and the pressure between blank and die. Next to these parameters, others like the thinning of the wall, the plastic strain aria can be also calculated. The influence of the friction coefficient upon stamping force can be calculated and many others as well.

2. Fundamentals of EFG method

The Element-free Galerkin method uses the moving least-squares (MLS) approximation of a function $u(x)$, representing a field variable. The approximated value of $u(x)$ will be denoted by $u^h(x)$ defined by expression:

$$u^h(x) = \sum_{i=1}^{n} H_i(x) \cdot b_i(x) \qquad (1)$$

In a matrix form is written:

$$u^h(x) = \mathrm{H}^{\mathrm{T}}(\mathrm{x})\mathrm{b}(\mathrm{x}) \qquad (2)$$

where, n is the order of the completeness in this approximation, the monomial $H_i(x)$ are basis functions and $b_i(x)$ are the coefficients of the approximation.

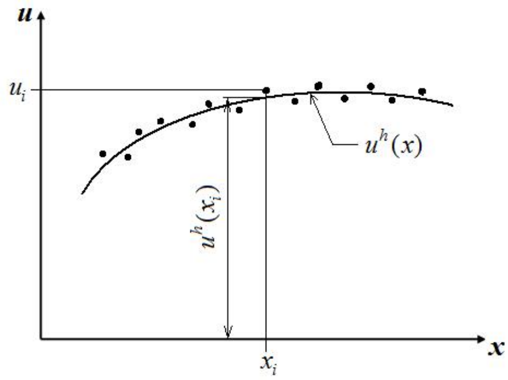

Figure 1: Nodal parameters u_i and approximate function $u^h(x_i)$

In the MLS approximation it is a difference between nodal parameter and its approximated value for a node i, as the Figure 1 shows. The coefficients $b_i(x)$ for a point $\mathbf{x}$ depend on the points $\mathbf{x_I}$ which are selected by a weighting function $w_a(\mathbf{x}\text{-}\mathbf{x_I})$.

The moving least-squares technique is based on minimizing the weighted L_2-Norm (J) defined by the relation (3).

$$J = \sum_{I=1}^{NP} w_a(x)(x - x_I)\left[u^h(x) - u_i(x_I)\right]^2 \qquad (3)$$

In a matrix form, relation (3) is represented by relation (4), where NP is the number of inside nodes of the support domain where weighting function $w_a(\mathbf{x}\text{-}\mathbf{x_I}) \neq 0$.

$$J = (\mathbf{Hb - u})^{\mathrm{T}} \mathrm{W_a}(\mathbf{x})(\mathbf{Hb - u}) \qquad (4)$$

More details about these relations can be found in [6]. Finally, the EFG approximation is obtained by relation:

$$u^h(x) = \sum_{I=1}^{NP} \Psi_I(x) u_I \qquad (5)$$

$\Psi_I(x)$ are shape functions having the expressions:

$$\Psi_{\mathrm{I}}(\mathrm{x}) = \mathrm{H}^{\mathrm{T}}(\mathrm{x})\mathrm{M}^{[\mathrm{n}]^{-1}}(\mathrm{x})\mathrm{B}(\mathrm{x}) \qquad (6)$$

The weight function (Figure 2) can be theoretically anything, as long as it has some properties. The most important conditions, which have to be fulfilled, are: to be greater zero within the support domain; to be zero outside the support domain; to be monotonically decreasing from the point of interest; to be sufficient smooth, especially on the boundary [4].

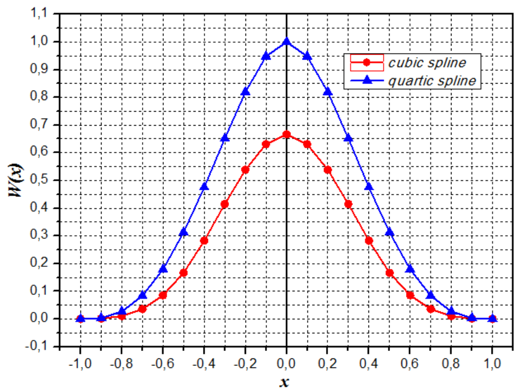

Figure 2: Weight functions

Practically, the implementing of the EFG method in the professional programs is based on the matrix form:

$$\begin{bmatrix} K & G \\ G^T & 0 \end{bmatrix} \cdot \begin{bmatrix} U \\ \Lambda \end{bmatrix} = \begin{bmatrix} F \\ Q \end{bmatrix} \quad (7)$$

where K is the global stiffness matrix, G is the global stiffness matrix resulting from boundary conditions, U is the vector of the nodal parameters of the displacements, Λ is a vector collecting the nodal Lagrange multipliers for all field nodes on the boundaries, F is the global force vector and Q is the global vector of the forces resulting from the prescribed displacement on the boundary.

3. Fundamentals of deep drawing process

The deep drawing technique is a manufacturing process which consists in shaping thin metal sheets named blank, thanks to a powerful drawing force. The process is based on the distortion of the surface, material that is not already stamped, with the punching method [3].

The deep drawing process is an important technological process based on large deformation, on appearing of plastic strain, by which a plane plate is transformed in a concave shape, useful in many activities. The resulting state of the plate can be an axisymmetric one or any other, named drawn part. The blank is a thin metal plate (sheet) as rule of steel or aluminium.

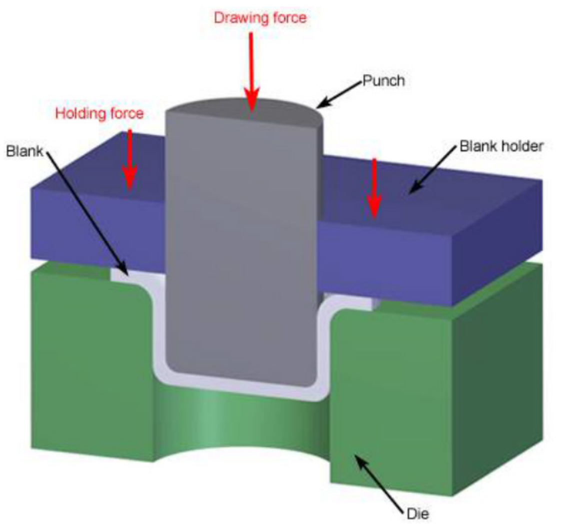

Figure 3: Components of deep drawing process

The sketch of the deep drawing process is presented in the Figure 5, which is referring to the numerical analysed problem. Blank holder helps prevent wrinkling and reduces springback. The main parameters of a deep drawing process are: the drawing force (F_s), holding force (F_r) and the gap between punch and drawing plate (die). In the deep drawing calculus other parameters are used, like drawing coefficient ($m = d/D$), friction coefficient, yielding and ultimate stress of the blank. Instead of the drawing coefficient, often the limiting drawing ratio (LDR) is used ($LDR = \max D/d$) - Figure 4.

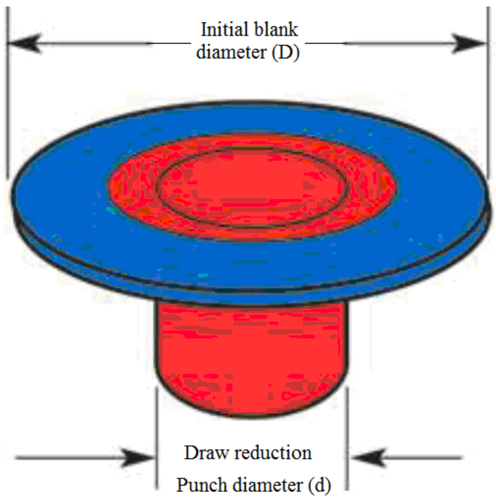

Figure 4: Defining of LDR

The deep drawing can be a hot or a cold process, as well. The deep drawing process can be made at low($v < 10m/s$) or at high ($v > 10m/s$) punch velocity.

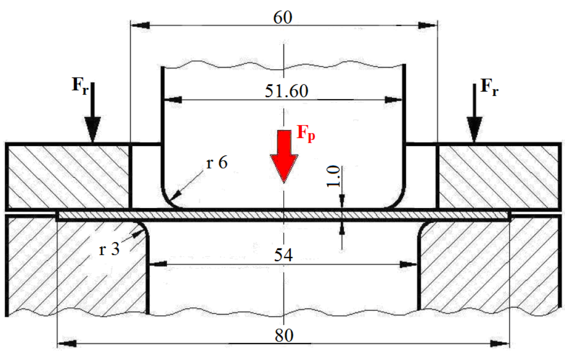

Figure 5: Deep drawing sketch

The deep drawing process can also be made with or without thinning of the walls, depening the gap size between punch and die. All these parameters and working conditions were taken into account in our numerical simulation, at the recommended values by the technical literature.

3.1 Analytical deep drawing calculus

The analytical calculus is referring to the deep drawing force and to the holding force as well. For calculus of the deep drawing force is used the relation [6]:

$$F = 2\pi \cdot r \cdot g \cdot \sigma_c \left(\frac{2}{\sqrt{3}} \ln \frac{R}{r} + \frac{\mu Q}{\mu r g \sigma_c} + \right.$$

$$\left. + \frac{g}{2 r_{pl} + g} \right) (1 + 1.6\mu) \quad (8)$$

where r is the punch radius, g is the plate thickness, σ_c is the yielding stress of the blank, R is the initial blank radius, μ is friction coefficient, Q is the blank holder force (F_r) and r_{pl} is punch front radius. The holding force $(F_r = Q)$ is calculated by the holding pressure q [6]:

$$q = (2...2.5) \cdot 10^3 \cdot \left[(\beta - 1)^2 + \right.$$

$$\left. + 0.005 \frac{d_0}{s_0} \right] \cdot R_m \quad (9)$$

where β is the drawing coefficient, d_0 is the blank diameter, s_0 is the blank thickness and R_m is the ultimate stress of the blank material.

4. Problem formulation

Our researching was aimed at the numerical simulation, using EFG method and FEM as well, of the deep drawing process illustrated in the Figure 3 and 5. The plastic-kinematic material model was used for the blank. The material characteristics (1018 steel) are: density = $7865\, kg/m^3$, Young modulus = $2 \cdot 10^{11} Pa$, Poisson coefficient = 0.27, yield stress= $310 MPa$, tangent modulus = $763\ MPa$, the coefficients $C = 40 s^{-1}$, $P = 5$, and failure strain = 0.75.

5. Numerical model

The same numerical model was used for both EFG and FEM model. We also used 2D and 3D models presented in below figures.

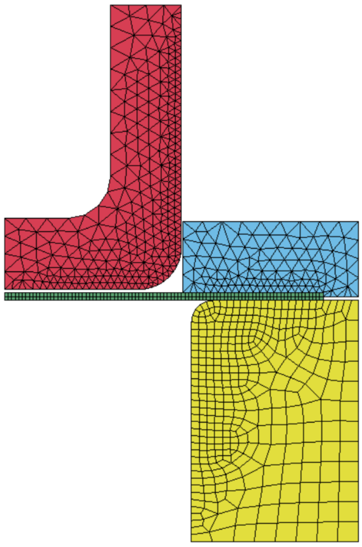

Figure 6: The 2D axisymmetric model

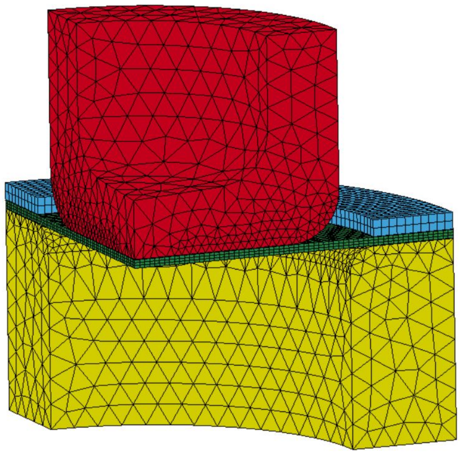

Figure 7: A quarter of the 3D model

Table 1. The model characteristics

Components	F.E. number	Nodes number
2D model		
Punch	184	218
Blank holder	20	33
Blank	345	464
Die	149	173
3D model (quarter)		
Punch	12937	19442
Blank holder	1100	1848
Blank	9216	12676
Die	16511	24844

Of course, other models could be used, by practically we used only these two models for EFG method and FEM.

The numbers of finite elements (FE) and nodes of the models are presented in the Table 1. The FE size is variable between 0.33 to 4.0 mm, as can be seen in the Figures 6 and 7.

For the punch, blank holder and the blank, a steel rigid material model was used. The calculus has taken into account the gap size of 1.41 mm between punch and die, the friction coefficient of 0.10 and defining the contact during working process. The blank holder being considered a rigid material perfectly blocked, no pressure was applied; so, the retaining force was calculated by simulation. Of course, is about a variable blank holder force.

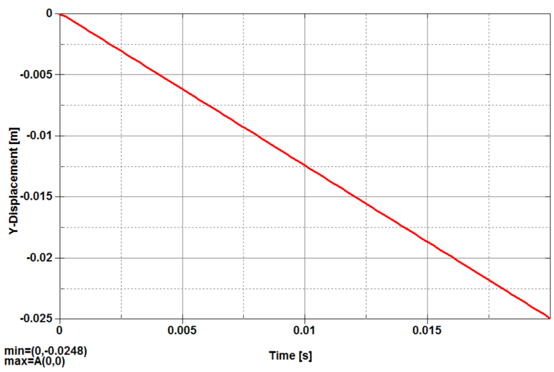

Figure 8: Punch displacement

No constraints were taken into account, referring to the thinning of walls. Simulation time was choosen at 0.02 seconds, at a punch average velocity of 1,24 m/s. As the Figure 8 shows, the punch displacement was 25 mm.

6. Results

The deformed state of the blank in presented in Figures 8…10, for 2D and 3D models. The Figure 11 shows the result of the embossing process, a cup instead a plane plate. The pictures presented in the Figures 8…11 are the same for FEM and EFG method. By numerical simulation, the contact forces automatically were determinated. The contact force between punch and blank versus deep drawing (punch) displacement is presented in the Figures 12 and 13, for the quarter model, using FEM and EFG method respectively. Practically, the values has to be multiplied by 4.

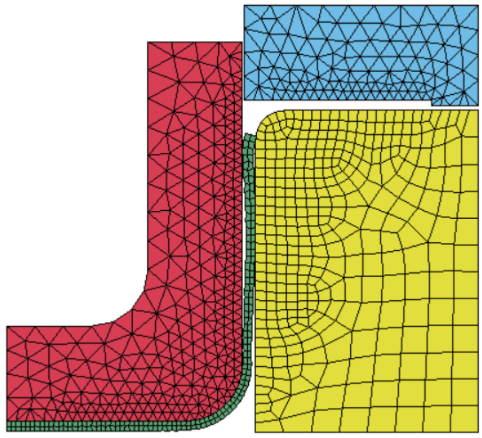

Figure *8. Final state of 2D model*

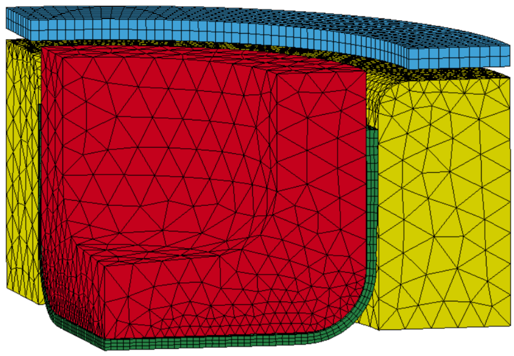

Figure 9: Final state of 3D quarter model

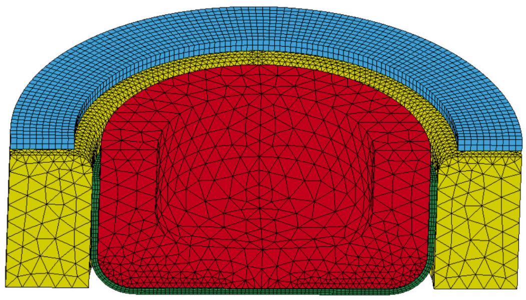

Figure 10: Final state of 3D half model

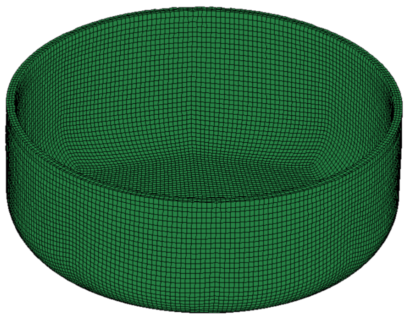

Figure 11: The cup – final result

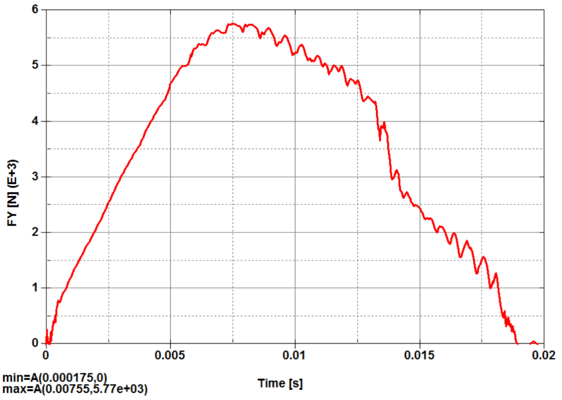

Figure 12: Punch-blank contact force, by FEM, for a quarter model

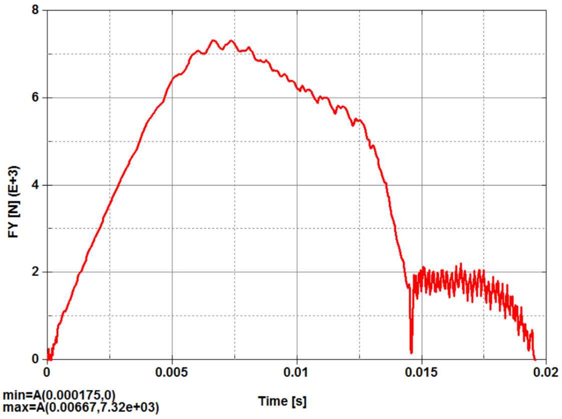

Figure 13: Punch-blank contact force, by EFGM, for a quarter model

Any curve regarding contact forces can be presented versus time or versus punch displacement (UY). Such representation is presented in the Figure 14. Of course, the curve has the same allure like in technical literature.

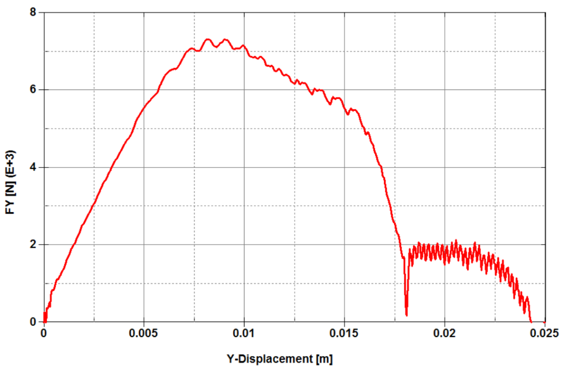

Figure 14: Punch-blank contact forc versus punch displacement, by EFGM, for a quarter model

The disturbances, that occur at a certain time (0.0135 seconds), are caused by that special position of the blank, when this goes out from the blank holder as we can see in the Figure 15.

Using of the FEM is less sensitive to this aspect as it can be seen in the Figure 12.

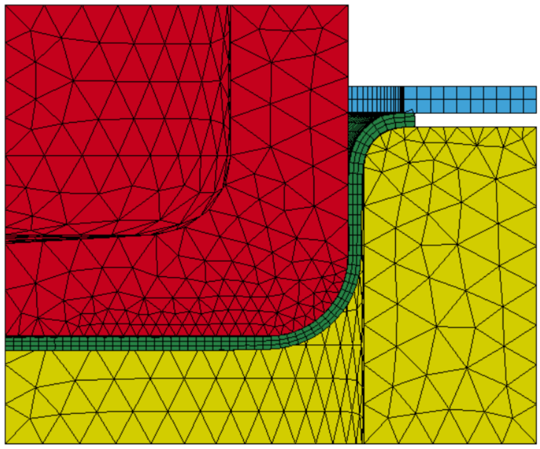

Figure 15: The state of process at 0.0135 seconds

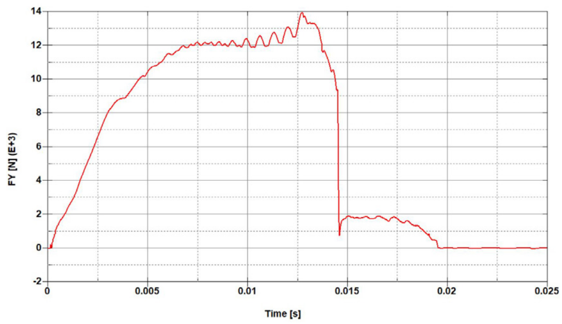

Figure 16: Contact force between blank and die, by EFGM, for a quarter model

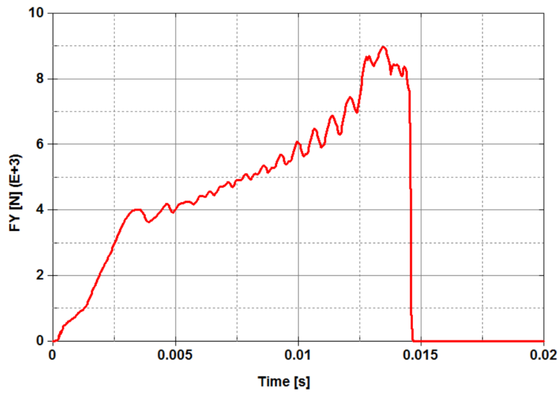

Figure 17: Contact force between blank and die, by EFGM, for a quarter model

The contact force between the blank holder and blank versus time is presented in the

Figure 16; the time evolution of the contact force blank-die is presented in the Figure 17, for the quarter model, both are performed using EFG method. The curves presented in the Figures 16 and 17 have the theoretical allure described in technical literature.

As the Figure 3 shows, the sum of drawing force with blank holder force must be equal with the contact force between blank and die. This is the deep drawing force, which can be calculated by analytical way using the relation (19).

For our problem for numerical simulation, this result has the value of 69.2212 kN; in applying of the relation (19) the value of the force Q was calculated as average value of maximum blank holder force, numerical calculated, by FEMand EFG method. So, we have got the value of 47 kN. This value is calculated for entire model, not a quarter.

Because the relation (19) gives a value not depending of time, for comparison the analytical value with numerical value, the sum of drawing force with blank holder force was made with their maximum values, although their maximum values does not occur in the same time (Figures 12, 13, 16, 17).

The result of comparison of the numerical results with analytical result is presented in the Table 2.

Table 2. Comparative results of the deep drawing force.

Analytical method	FEM	EFGM
69.2212 kN	81.08 kN	65.24 kN
Err. [%]	*17.13*	*-5.75*

Another aspect, investigated in our research, is referring to the thinning of the cup walls. The 2D model is the most expressive from this point of view.

In the Figures 18 and 19, the percentage reduction of wall thickness is presented by the numerical simulation based on 2D FEM model and 2D EFG model, respectively.

In the Table 3, the thickness of the cup wall and the percentage reduction are presented.

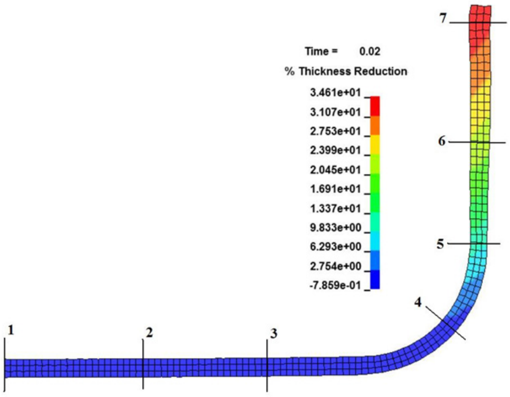

Figure 18: Percentage reduction of wall thickness, by FEM

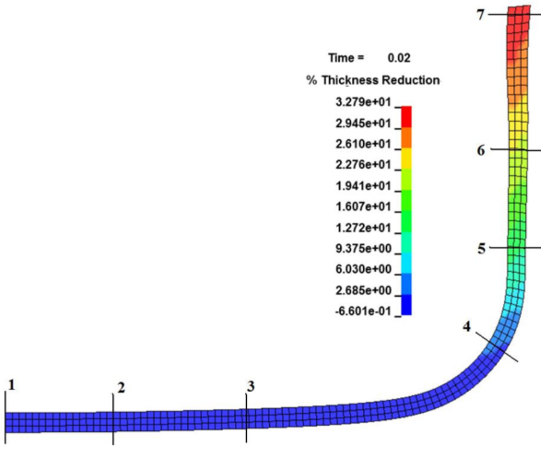

Figure 19: Percentage reduction of wall thickness, by EFGM

Table 3. The thinning of the cup walls

Section	Thickness [mm]		Percentage reduction [%]	
	FEM	EFG	FEM	EFG
1	1.032	1.020	3.20	2.00
2	0.990	0.999	-1.00	-0.10
3	0.990	0.998	-1.00	-0.20
4	0.953	0.947	-4.70	-5.30
5	0.894	0.916	-10.60	-8.40
6	1.030	0.977	3.00	-2.30
7	1.152	1.140	15.20	14.00

As we can see, the values presented in the Table 3 are obtained by FEM and by EFGM as well. Those 7 sections, chosen for thickness determination are those sections upon which the technical literature gives information regarding to thinning process.

Such general information are presented in the Figure 20, where *g* is the blank thickness.

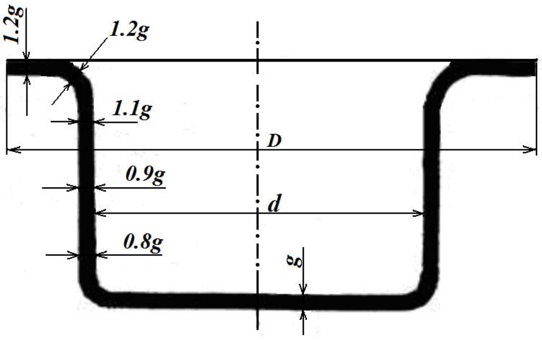

Figure 20: The wall thickness of the cup

Comparing the simulation results presented in the Table 3 with the values from Figures 20, we can see not only a good concordance but even better results by EFG method.

7. Conclusions

The deep drawing technology is a very difficult and complex process, but very important in industrial activity.

Our researching in this field intends to bring more information about numerical simulation of this technological process. Knowing about some advantages of the Element-Free Galerkin method, we used this mesh-free method.

The results of the numerical simulation of the deep drawing process are comparatively presented with Finite Element Method.

As the presented results in Figures, in Tables, by conclusions and by discussions lead to main conclusion: Element-Free Galerkin Method is not only a valid but also an efficient method, suitable for simulating such a dynamic complex process.

Our numerical models can be examples of good practice in numerical simulation, using 2D and 3D models as well.

The lack of experiments is replaced by the numerical experiment by FEM, which fully validates this mesh free method –EFGM.

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