ANNALS OF THE ORADEA UNIVERSITY
Fascicle of Management and Technological Engineering
ISSUE #3, SEPTEMBER 2013, http://www.imtuoradea.ro/auo.fmte/

# FINITE ELEMENT ANALYSIS OF A SUPERPLASTIC FORMING PROCESS, USING ANSYS SOFTWARE

**Gavril GREBENISAN**[1]
[1]University of Oradea, grebe@uoradea.ro

***Abstract***—Superplastic forming of metals and alloys is known as a technological process of deformation, of those materials which are characterized by a structure well defined and uniform as grain size around of 10 micrometers, at medium temperature, and with very low strain rate. All of these conditions makes the process unattractive, but the benefits are quite major and valuable. The complexity of shapes deformed and obtained, the large and uniform dimension of parts, are some of these major benefits of this kind of deformation process. Although of these benefits, the superplastic forming process are quite difficult for simulating and analysis process. The finite element method comes to facilitate the analysis and simulation of the flow and forming process. The present work is focused on this objective: to show a method for simulation and finite element analysis of superplastic forming, using the unconventional software ANSYS.

***Keywords***—Superplastic Forming(SPF), finite element analysis, strain rate sensitivity exponent, strain hardening exponent, constitutive material equations.

## I. INTRODUCTION

SUPERPLASTICITY reflects a scientific recognized process that consists by a large deformation, almost exclusively plastic range of deformation, at very low deformation speed, at medium temperature, about 0.5 $T_{melt}$ and a quite low pressure of forming process, [1], [4]- [6]. This is not a completely definition because any characteristics of material wasn't included, because of widely properties involved, and grains dimensions, as well. It is well known that a large deformation, these materials manage to undergo an elongation of 1000-2000%, and this was obtained on aluminum and zinc bronze. The requirements of superplastic behavior of materials are: first-grain size; the second- temperature and the third are the strain rate. These deformation conditions are associated with low flow stresses (the pressure of forming process, in term of technological parameter), generally <10 MPa and this, combined with the relatively high uniformity of plastic flow, has led to increasing commercial interest in superplastic forming (SPF) . Commonly the grain size should be less than 10 μm; the deformation speed should be on 0.001- 0.0001 $s^{-1}$, and the temperature should be less than half of melting point, and the pressure of forming process to be into the range of 5- 20 Mpa.

## II. MATERIAL AND CONSTITUTIVE MODEL

The specially processed superplastic FORMALL 545 aluminum sheet alloy used in this work was received from FormTech GmbH Company, Weyhe, Germany, with a nominal thickness of 1.22 mm. The constitutive model used to describe the flow stress–strain rate–strain relationship was the power law equation, [2]:

$$\sigma = k \cdot \dot{\varepsilon}^{m} \cdot \varepsilon^{n} \qquad (1)$$

where $\sigma$ is the solution of the equation (and the analysis, as well), and denotes the effective flow stress, k is a material constant, $\dot{\varepsilon}$ is the effective strain- rate, m is the strain rate sensitivity coefficient, $\varepsilon$ is the effective strain, and n is the strain hardening exponent. The most important parameter, the strain rate sensitivity exponent, m, is defined by the following equation, [3]:

$$m = \frac{d\log\sigma}{d\log\dot{\varepsilon}} \qquad (2)$$

This is the reason because the strain rate sensitivity is obtained determined from the slope of the double logarithmic plot of flow stress against strain rate. Although the strain-rate sensitivity (m) determines the ability of a material to resist necking during tensile straining. Based on the assumption that m is constant over a limited range of strain rates associated with a small diffuse neck, one can write by expressing stress and strain rate in terms of load and area, [1]:

$$\dot{A} = -\sqrt[m]{\frac{P \cdot A^{m-1}}{k}} \qquad (3)$$

where $\dot{A}$ is the change rate of cross section area A of the specimen subjected to the force P. Other coefficients are previously defined.

Rate dependent plasticity, the case of superplastic forming process, describes the flow rule of materials, which depends on time, such as the deformation of materials is assumed to develop as function of the strain rate, which depends on time. On a logical rule, an important class of applications of this theory is high temperature creep. ANSYS provides several options to characterize the different types of rate-dependent material behaviors. The creep option is used for describing material creep over a relative long period or at low strain. This option should be very precisely defined, using Engineering Data Toolbox option, from Workbench Project. In crystalline materials, such as metals, creep mechanism is linked to diffusional flow of vacancies and dislocation movement. The creep deformation, and superplastic forming, as well, by an analogy of process occurs, depends on stress, strain, time, and temperature and is modeled with a form similar to the following:

$$\dot{\varepsilon} = f_1(\sigma)\cdot f_2(\varepsilon)\cdot\ f_3(t)\cdot f_4(T)\cdot f_5(d) \qquad (4)$$

Where $f_3(t)$ means time dependency (not quite directly), $f_4(T)$ ·means temperature dependency (most of time this dependency is described by an Arhenius law, $\dot{\varepsilon} \propto e^{-\frac{Q}{RT}}$, where Q is activation energy, R is the universal gas constant, and T is absolute temperature), and $f_5(d)$ ·denote the grain size dependency.

## III. FINITE ELEMENT FORMULATION

In the finite element analysis of superplastic forming process inertia effects are usually neglected which permits to establish an equilibrium equations in a quasi-static framework. On the classical mechanics principle of virtual work established over a limited domain V with boundary surface A, it may be verified by equations, [3]:

$$\delta W(x,\delta v) = \delta W_{int}(x,\delta v) - \delta W_{ext}(x,\delta v) = 0 \qquad (5)$$

In the incremental formulation, the rate of deformation based material law which describes the phenomenon of superplasticity is approximated by a geometry based constitutive equation. The traditional formulation of any deformation process consists on a cinematic variable such as velocity field, instead of superplasticity which is more reliable for using as primary variable the displacement field. In such idea, considering the initial domain $V_0$ at two consecutive time steps $t_n$ and $t_{n+1}$ are $V_n$, and $V_{n+1}$ respectively, the incremental motion between two steps previously nominated, is represented by a general mapping law, to be Φ, with an associated deformation gradient tensor F, the formulation are:

$$x_{n+1} = \Phi(x_n); \quad F = \frac{\partial\Phi}{\partial x_n} = \nabla_n F; \ J = detF \qquad (6)$$

On the Fig. 1. Is represented a mapping law, on an initial stage, and on an intermediate stage of superplastic forming simulated on ANSYS.

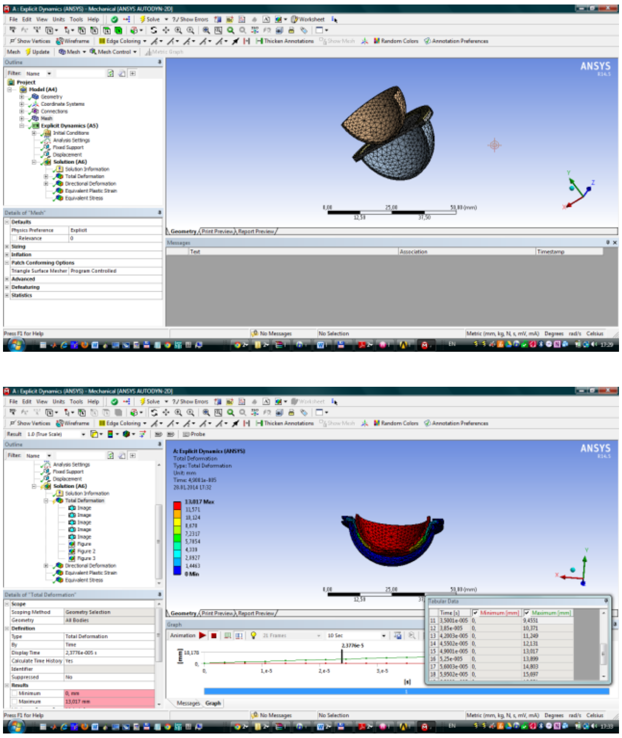

Fig. 1. – The mapping, Φ, on a superplastic forming process

The constant flow of deformation, on a superplastic forming process is attained by a detailed pressure of work cycle algorithm adopted. A numerical algorithm consists on a law of flow, written as mathematical model in which the pressure is treated as an unknown variable, included on an equation, a constraint equation, as well, with the target strain rate, for example. On an incremental flow formulation, tensorial written, one may formulate:

$$R(x_{n+1}^{k+1}, p_{n+1}^{k+1}) = T(x_{n+1}^{k+1}) - p_{n+1}^{k+1}\cdot G(x_{n+1}^{k+1}) = 0 \qquad (7)$$

where the symbols are generally stated as: the assembled residual equilibrium equations **R** ;the assembled equivalent internal force vector **T**, and **G** is the assembled external equivalent force vector corresponding to a normalized unit pressure. The spatial coordinates and forming pressure will be obtained iteratively updated as follows:

$$\begin{aligned} x_{n+1}^{k+1} &= x_{n+1}^{k} + \Delta u \\ \Delta u &= \Delta u_R - \Delta p \Delta u_G \\ p_{n+1}^{k+1} &= p_{n+1}^{k} + \Delta p \end{aligned} \qquad (8)$$

Where the components $\Delta u_R$ and, $\Delta u_G$ of the incremental vector are formulated as:

$$\begin{aligned} \Delta u_R &= -[K|_{n+1}^{k}]^{-1} R|_{n+1}^{k} \\ \Delta u_G &= -[K|_{n+1}^{k}]^{-1} G|_{n+1}^{k} \end{aligned} \qquad (9)$$

And the incremental pressure will be obtained by:

$$\Delta p=\frac{\mathcal{F}\Big|_{n+1}^{k}+\frac{\partial\mathcal{F}}{\partial x}\Big|_{n+1}^{k}\Delta u_R}{\frac{\partial\mathcal{F}}{\partial x}\Big|_{n+1}^{k}\Delta u_F-\frac{\partial\mathcal{F}}{\partial p}\Big|_{n+1}^{k}} \qquad (10)$$

## IV. RESULTS

A simple sheet metal is clamped on external diameter, around its periphery, and deformed superplastically into a spherical bulge. The die is closed and warmed at 510 °C, and maintained at this temperature in order to obtain an uniform structure of the material, [7]. After the regim temperature was obtained and the process can be stated, the procedure is numerical controlled. Forming temperature: 490 - 540 °C, logarithmic strain rate: $10^{-3}$ $s^{-1}$, mechanical properties: $R_{p0,2}$=150 N/mm$^2$, $R_m$=300 N/mm$^2$, $A_5$=20 %. The pressure cycle is represented on Fig. 2.:

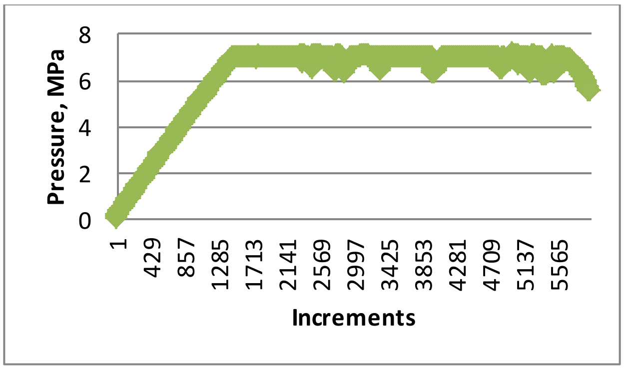

Fig. 2.- Pressure vs Time cycle (5565 increments)

The simulation results are presented in the next tables and figures:

**TABLE I**
**Model (A4) > Geometry**

| *Object Name* | *Geometry* |
|---|---|
| *State* | Fully Defined |
| *Definition* | |
| *Source* | D:\ANSYS_Superplasticitate\Matrita_superpl\Poanson fara capac_b_files\dp0\SYS\DM\SYS.agdb |
| *Type* | DesignModeler |
| *Length Unit* | Millimeters |
| *Display Style* | Body Color |
| *Bounding Box* | |
| *Length X* | 40, mm |
| *Length Y* | 32,2 mm |
| *Length Z* | 40, mm |
| *Properties* | |
| *Volume* | 4989,6 mm³ |
| *Mass* | 3,1456e-002 kg |
| *Scale Factor Value* | 1, |
| *Statistics* | |
| *Bodies* | 5 |
| *Active Bodies* | 5 |
| *Nodes* | 3865 |
| *Elements* | 10118 |
| *Mesh Metric* | None |
| *Basic Geometry Options* | |
| *Parameters* | Yes |
| *Parameter Key* | DS |
| *Attributes* | No |
| *Named Selections* | No |
| *Material Properties* | No |
| *Advanced Geometry Options* | |
| *Use Associativity* | Yes |
| *Coordinate Systems* | No |
| *Reader Mode Saves Updated File* | No |
| *Use Instances* | Yes |
| *Smart CAD Update* | No |
| *Attach File Via Temp File* | Yes |
| *Temporary Directory* | C:\Users\admin\AppData\Local\Temp |
| *Analysis Type* | 3-D |
| *Decompose Disjoint Geometry* | No |
| *Enclosure and Symmetry Processing* | Yes |

**TABLE II**
**Model (A4) > Geometry > Parts**

| *Object Name* | *Epruveta* | *Matr_inf* | *Matr_sup* | *Suport_inf* | *Suport_sup* |
|---|---|---|---|---|---|
| *State* | Meshed | | | | |
| *Graphics Properties* | | | | | |
| *Visible* | Yes | | | | |
| *Transparency* | 1 | | | | |
| *Definition* | | | | | |
| *Suppressed* | No | | | | |
| *Stiffness Behavior* | Flexible | | | | |
| *Coordinate System* | Default Coordinate System | | | | |
| *Reference Temperature* | By Environment | | | | |
| *Reference Frame* | Lagrangian | | | | |
| *Material* | | | | | |
| *Assignment* | AL5083H 116 | STNL.STEEL | | STEEL 1006 | |
| *Bounding Box* | | | | | |
| *Length X* | 40, mm | 33,978 mm | 30, mm | 39,778 mm | 39,837 mm |
| *Length Y* | 1,2 mm | 16,424 mm | 15, mm | 0,49105 mm | 0,63986 mm |
| *Length Z* | 40, mm | 33,978 mm | 30, mm | 39,778 mm | 39,837 mm |
| *Properties* | | | | | |
| *Volume* | 1508, mm³ | 1649,5 mm³ | 1321,6 mm³ | 216,53 mm³ | 294,04 mm³ |

| | | | | | |
|---|---|---|---|---|---|
| ***Mass*** | 4,0715e-003 kg | 1,2965e-002 kg | 1,0387e-002 kg | 1,7097e-003 kg | 2,3217e-003 kg |
| ***Centroid X*** | 4,7991e-016 mm | 3,3437e-005 mm | 5,552e-009 mm | 1,5206e-015 mm | -1,3176e-015 mm |
| ***Centroid Y*** | 0,6 mm | -8,5378 mm | 7,9582 mm | -0,36635 mm | 1,5636 mm |
| ***Centroid Z*** | 0, mm | -2,2631e-004 mm | -5,2676e-004 mm | -1,2204e-015 mm | -9,7153e-017 mm |
| ***Moment of Inertia Ip1*** | 0,40352 kg·mm² | 1,4191 kg·mm² | 0,90474 kg·mm² | 0,27538 kg·mm² | 0,37195 kg·mm² |
| ***Moment of Inertia Ip2*** | 0,80607 kg·mm² | 2,2931 kg·mm² | 1,4463 kg·mm² | 0,5507 kg·mm² | 0,74375 kg·mm² |
| ***Moment of Inertia Ip3*** | 0,40352 kg·mm² | 1,4191 kg·mm² | 0,90466 kg·mm² | 0,27538 kg·mm² | 0,37195 kg·mm² |
| ***Statistics*** | | | | | |
| ***Nodes*** | 674 | 948 | 892 | 889 | 462 |
| ***Elements*** | 1831 | 2637 | 2552 | 2092 | 1006 |
| ***Mesh Metric*** | | | None | | |

## TABLE III
## Model (A4) > Mesh

| **Object Name** | *Mesh* |
|---|---|
| **State** | Solved |
| **Defaults** | |
| **Physics Preference** | Explicit |
| **Relevance** | 0 |
| **Sizing** | |
| **Use Advanced Size Function** | On: Proximity |
| **Relevance Center** | Medium |
| **Initial Size Seed** | Active Assembly |
| **Smoothing** | High |
| **Transition** | Slow |
| **Span Angle Center** | Coarse |
| **Proximity Accuracy** | 0,5 |
| **Num Cells Across Gap** | Default (3) |
| **Proximity Min Size** | Default (1,6222e-002 mm) |
| **Max Face Size** | Default (1,62220 mm) |
| **Max Size** | Default (3,24440 mm) |
| **Growth Rate** | Default (1,20 ) |
| **Minimum Edge Length** | 87,9650 mm |
| **Inflation** | |
| **Use Automatic Inflation** | Program Controlled |
| **Inflation Option** | Smooth Transition |
| **Transition Ratio** | 0,272 |
| **Maximum Layers** | 5 |
| **Growth Rate** | 1,2 |
| **Inflation Algorithm** | Pre |
| **View Advanced Options** | No |
| **Patch Conforming Options** | |
| **Triangle Surface Mesher** | Program Controlled |
| **Advanced** | |
| **Shape Checking** | Explicit |
| **Element Midside Nodes** | Dropped |
| **Straight Sided Elements** | |
| **Number of Retries** | 0 |
| **Extra Retries For Assembly** | Yes |
| **Rigid Body Behavior** | Full Mesh |
| **Mesh Morphing** | Disabled |
| **Defeaturing** | |
| **Pinch Tolerance** | Default (1,46e-002 mm) |
| **Generate Pinch on Refresh** | No |
| **Automatic Mesh Based Defeaturing** | On |
| **Defeaturing Tolerance** | Default (8,111e-003 mm) |
| **Statistics** | |
| **Nodes** | 3865 |
| **Elements** | 10118 |
| **Mesh Metric** | None |

## TABLE IV
## Model (A4) > Explicit Dynamics (A5) > Analysis Settings

| **Object Name** | ***Analysis Settings*** |
|---|---|
| State | Fully Defined |
| **Analysis Settings Preference** | |
| Type | Custom |
| **Step Controls** | |
| Resume From Cycle | 0 |
| Maximum Number of Cycles | 1e+07 |
| End Time | 7,e-005 s |
| Maximum Energy Error | 0,1 |
| Reference Energy Cycle | 0 |
| Initial Time Step | Program Controlled |
| Minimum Time Step | Program Controlled |
| Maximum Time Step | Program Controlled |
| Time Step Safety Factor | 0,9 |
| Characteristic Dimension | Diagonals |
| Automatic Mass Scaling | No |
| **Solver Controls** | |
| Precision | Single |
| Solve Units | mm, mg, ms |
| Beam Solution Type | Bending |
| Beam Time Step Safety Factor | 0,5 |
| Hex Integration Type | Exact |
| Shell Sublayers | 3 |
| Shell Shear Correction Factor | 0,8333 |
| Shell BWC Warp Correction | Yes |
| Shell Thickness Update | Nodal |
| Tet Integration | Average Nodal Pressure |
| Shell Inertia Update | Recompute |
| Density Update | Program Controlled |
| Minimum Velocity | 1,e-003 mm s^-1 |
| Maximum Velocity | 1,e+013 mm s^-1 |
| Radius Cutoff | 1,e-003 |
| Minimum Strain Rate Cutoff | 1,e-010 |
| **Euler Domain Controls** | |
| Domain Size Definition | Program Controlled |
| Display Euler Domain | Yes |
| Scope | All Bodies |
| X Scale factor | 1,2 |
| Y Scale factor | 1,2 |
| Z Scale factor | 1,2 |
| Domain Resolution Definition | Total Cells |
| Total Cells | 2,5e+05 |
| Lower X Face | Flow Out |
| Lower Y Face | Flow Out |
| Lower Z Face | Flow Out |
| Upper X Face | Flow Out |
| Upper Y Face | Flow Out |
| Upper Z Face | Flow Out |
| Euler Tracking | By Body |
| **Damping Controls** | |
| Linear Artificial Viscosity | 0,2 |
| Quadratic Artificial Viscosity | 1, |
| Linear Viscosity in Expansion | No |
| Hourglass Damping | AUTODYN Standard |
| Viscous Coefficient | 0,1 |
| Static Damping | 0, |
| **Erosion Controls** | |
| On Geometric Strain Limit | Yes |
| Geometric Strain Limit | 1,5 |
| On Material Failure | No |
| On Minimum Element Time Step | No |
| Retain Inertia of Eroded Material | Yes |
| **Output Controls** | |
| Save Results on | Equally Spaced Points |

| | |
|---|---|
| Number of points | 20 |
| Save Restart Files on | Equally Spaced Points |
| Number of points | 5 |
| Save Result Tracker Data on | Cycles |
| Cycles | 1 |
| Output Contact Forces | Off |
| **Analysis Data Management** | |

TABLE V
**Model (A4) > Explicit Dynamics (A5) > Solution (A6) > Total Deformation**

| *Time [s]* | *Minimum [mm]* | *Maximum [mm]* |
|---|---|---|
| 0, | 0, | 0, |
| 3,5012e-006 | | 1,418 |
| 7,0014e-006 | | 2,3713 |
| 1,0502e-005 | | 3,253 |
| 1,4003e-005 | | 4,1146 |
| 1,7503e-005 | | 4,9663 |
| 2,1e-005 | | 5,8441 |
| 2,4501e-005 | | 6,7544 |
| 2,8001e-005 | | 7,647 |
| 3,1502e-005 | | 8,5487 |
| 3,5001e-005 | | 9,4551 |
| 3,85e-005 | | 10,371 |
| 4,2003e-005 | | 11,249 |
| 4,5502e-005 | | 12,131 |
| 4,9001e-005 | | 13,017 |
| 5,25e-005 | | 13,899 |
| 5,6003e-005 | | 14,803 |
| 5,9502e-005 | | 15,697 |
| 6,3002e-005 | | 16,351 |
| 6,65e-005 | | 17,266 |
| 7,0002e-005 | | 18,178 |

TABLE VI
**Model (A4) > Explicit Dynamics (A5) > Solution (A6) > Results**

| **Object Name** | *Total Deformation* | *Directional Deformation* | *Equivalent Plastic Strain* | *Equivalent Stress* |
|---|---|---|---|---|
| **State** | Obsolete | Solved | | |
| | **Scope** | | | |
| **Scoping Method** | Geometry Selection | Geometry Selection | | |
| **Geometry** | All Bodies | All Bodies | | |
| | **Definition** | | | |
| **Type** | Total Deformation | Directional Deformation | Equivalent Plastic Strain | Equivalent (von-Mises) Stress |
| **By** | Time | | Time | |
| **Display Time** | 2,3776e-005 s | 7,0014e-006 s | 1,0502e-005 s | 7,e-005 s |
| **Calculate Time History** | Yes | | Yes | |
| **Identifier** | | | | |
| **Suppressed** | No | | No | |
| **Orientation** | | X Axis | | |
| **Coordinate System** | | Global Coordinate System | | |
| | **Results** | | | |
| **Minimum** | 0, mm | -0,47425 mm | 0, mm/mm | 0, MPa |
| **Maximum** | 13,017 mm | 0,50097 mm | 0,20377 mm/mm | 993,59 MPa |
| **Minimum Occurs On** | Matr_inf | Matr_sup | Epruveta | Suport_inf |
| **Maximum Occurs On** | Epruveta | Matr_sup | | Matr_inf |
| | **Minimum Value Over Time** | | | |
| **Minimum** | 0, mm | -3,0236 mm | 0, mm/mm | 0, MPa |
| **Maximum** | 0, mm | 0, mm | 0, mm/mm | 0, MPa |
| | **Maximum Value Over Time** | | | |
| **Minimum** | 0, mm | 0, mm | 0, mm/mm | 0, MPa |
| **Maximum** | 18,178 mm | 2,9879 mm | 1,2744 mm/mm | 993,59 MPa |
| | **Information** | | | |
| **Time** | 4,9001e-005 s | 7,0014e-006 s | 1,0502e-005 s | 7,0002e-005 s |
| **Set** | 15 | 3 | 4 | 21 |
| | **Integration Point Results** | | | |
| **Display Option** | | | Averaged | |

TABLE VII
**Model (A4) > Explicit Dynamics (A5) > Solution (A6) > Directional Deformation**

| *Time [s]* | *Minimum [mm]* | *Maximum [mm]* |
|---|---|---|
| ***0,*** | 0, | 0, |
| ***3,5012e-006*** | -0,32611 | 0,34583 |
| ***7,0014e-006*** | -0,47425 | 0,50097 |
| ***1,0502e-005*** | -0,43384 | 0,455 |
| ***1,4003e-005*** | -0,41249 | 0,50844 |
| ***1,7503e-005*** | -0,42937 | 0,55574 |
| ***2,1e-005*** | -0,52099 | 0,59426 |
| ***2,4501e-005*** | -0,72485 | 0,78396 |
| ***2,8001e-005*** | -1,0661 | 1,0581 |
| ***3,1502e-005*** | -1,4011 | 1,4075 |
| ***3,5001e-005*** | -1,6869 | 1,6874 |
| ***3,85e-005*** | -2,0307 | 2,0273 |
| ***4,2003e-005*** | -2,2388 | 2,3098 |
| ***4,5502e-005*** | -2,543 | 2,4011 |
| ***4,9001e-005*** | -2,6518 | 2,4375 |
| ***5,25e-005*** | -2,8326 | 2,6639 |
| ***5,6003e-005*** | -2,9139 | 2,8473 |
| ***5,9502e-005*** | -2,9509 | 2,9501 |
| ***6,3002e-005*** | -2,9747 | 2,9879 |
| ***6,65e-005*** | -2,9928 | 2,9504 |
| ***7,0002e-005*** | -3,0236 | 2,9597 |

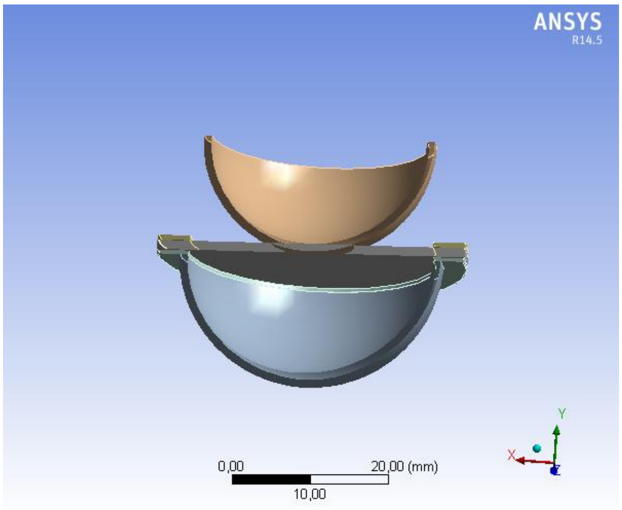

Fig. 3. –The starting gauge

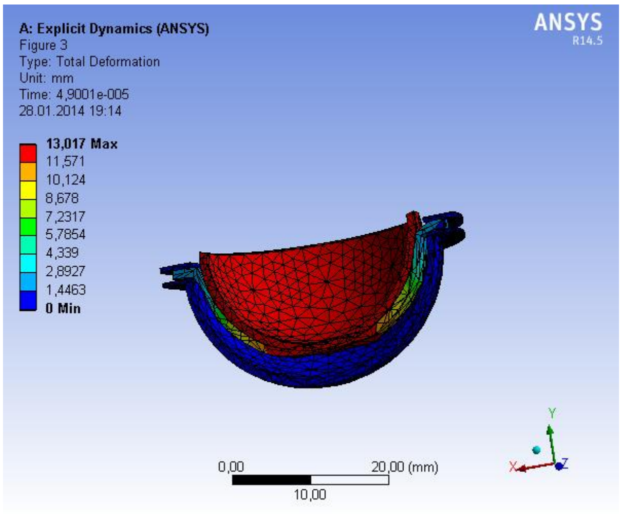

Fig. 4.- The final stage of finite element analysis

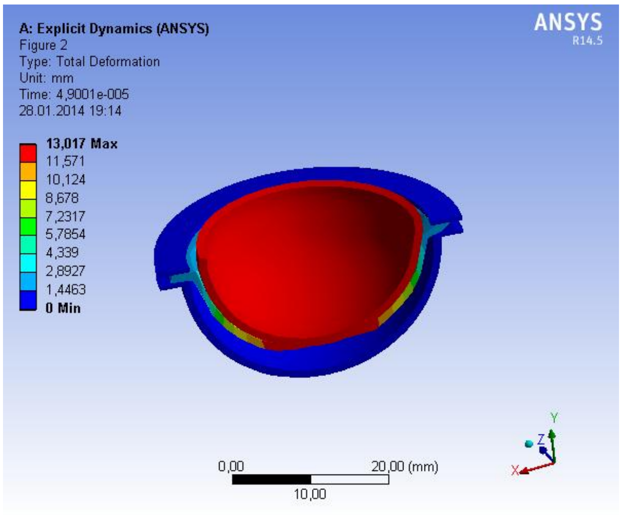

Fig. 5. – Total deformation of the part

## V. CONCLUSION

The complexity of the materials superplastic forming is consists on the complexity of phenomenon which are a material's one, and a parameters of deformation, the second one. The material's behavior consists on the grain size stability, and on the uniformity of this. The parameters of deformation, as pressure, temperature and strain rate should be well constructed as mathematical model and equations. The constitutive equations of the superplastic forming are in continuous changing. Any of analysis results may be used for progress and develop the superplastic forming simulation.

## REFERENCES

[1] ASM Handbook, Volume 22A: Fundamentals of Modeling for Metals Processing, D.U. Furrer and S.L. Semiatin, editors, p 472-477, www.asminternational.org.

[2] J. BONET - Numerical Simulation of the Superplastic Forming ofThin Sheet Components Using the Finite Element method, "International Journal for Numerical Methods in Engineering", vol. 30,pag. 1719- 1737, 1990.

[3] G. Giuliano, Superplastic forming of advanced metallic materials. Methods and applications, Cambridge , Woodhead Publishing Limited, 2011.

[4] G. GREBENIŞAN-*Analysis Approach of Superplastic Deformation and Gasostatic Forming*, The Journal of Strain Analysis for Engineering Design, ISSN 0309-3247, Edited by Professional Engineering Publishing Limited, London;

[5] S. KOBAYASHI- Metal Forming and the Finite Element Method, Oxford University Press, New York, 1989.

[6] J. PILLING Superplasticity in crystalline solids, The Institute of Metals, London, 1989.

[7] T.Y. YANG - Experimental and Finite Element Simulation Methods for Rate-Dependent Metal Forming Processes, " International Journal for Numerical Methods in Engineering " , vol. 31, pag. 345- 367, 1991.