Laboratory of Applied Mathematics and Mechanics

Technology of EHIS (stamping) applied to the automotive parts production

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Motivation (1)

The discharge in water was examined experimentally in the end of 50 of 20th century in the Soviet Union and the USA.

After that moment this technology has been developed mostly in our country for the purpose to produce small series of items.

Nowadays, GM is interested in industrial application of Electro Hydraulic Impulse Stamping (EHIS) to put out small automotive parts.

Motivation (2)

The electric discharge in water can be effectively used for stamping flat-pattern parts. The additional investigation is needed including:

1. Research of the EHIS process physics;
2. Measurements of a number of parameters that determine the deformation process;
3. Development of a mathematical model capable to interpret the experimental results.

Aims and tasks for complete research

1. Develop and validate numerical methodology that is capable to simulate the EHIS process;

2. Test EHIS process on model hydro-pulse plant;

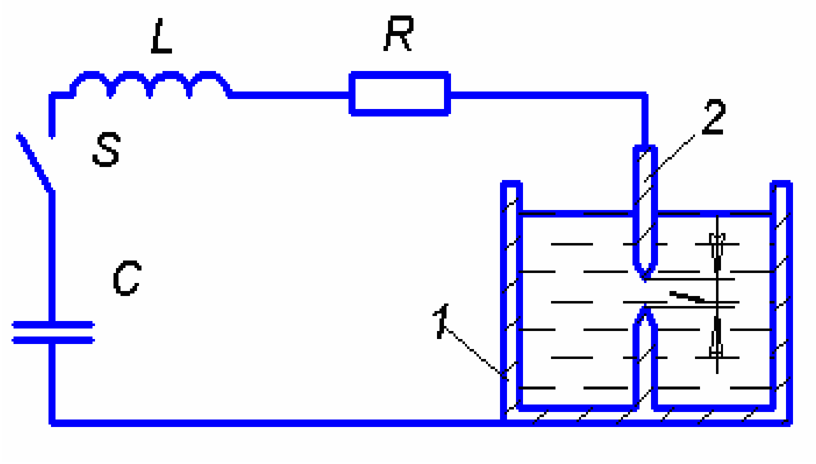
   (pressure field forming, characteristics of the process, similarity conditions)

3. Develop a EHIS technological model for given object (part).

   (verification of numerical models and similarity conditions for realization of full scale technological process)

Description of technological process (1)

Traditional scheme of the spark discharge experiment in water:



after closing of switch S voltage from the charged capacitor C is applied to electrodes 2 located in the discharge chamber 1, the chamber is filled with water

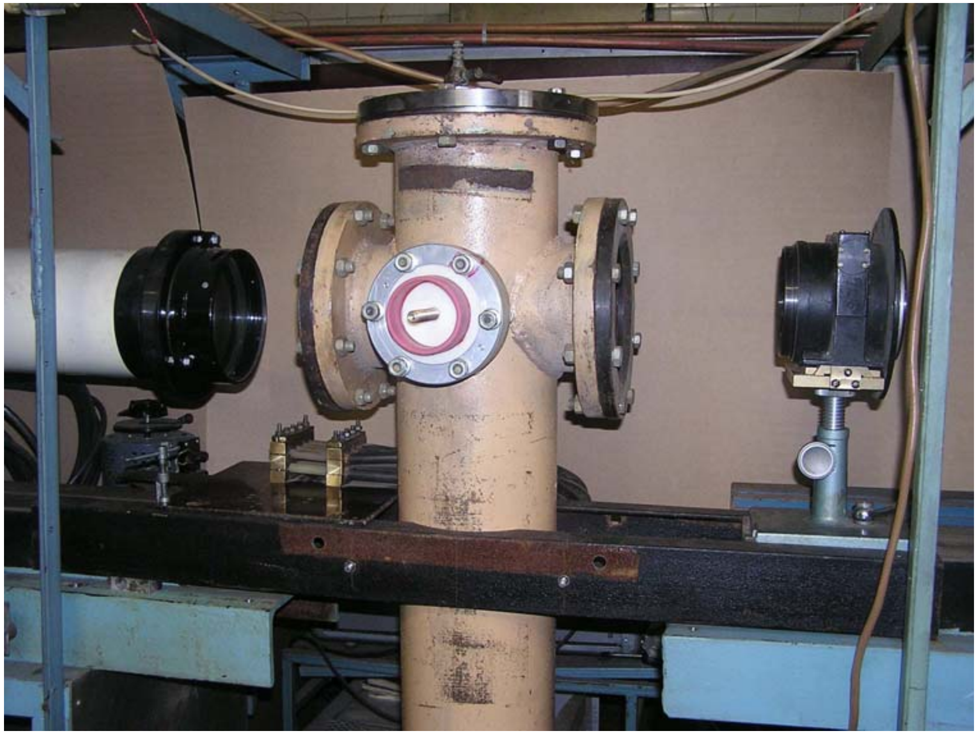
time of discharge development is about $10^{-5} - 10^{-4}$ seconds

Description of technological process (2)

Experimental plant

The chamber is provided with two sight holes with diameter 130 mm. Two electrodes are inserted into the same volume through insulators. Electrodes form the discharge gap in which energy necessary for deformation releases.

In the upper part of the chamber along its axis there is the metal sample that is being deformed during discharge in fluid.



Our place in investigation (1)

1. Review of mathematical models to be used for fast processes analysis;

2. Development of a mathematical model and computational method for thin sheet dynamic deformation under specified pressure on its surface;

3. Test computations (based on reported data and model experiment results);

4. Analysis and matching of experimental and computational results.

Our place in investigation (2)

In particular:

- Determination of constitutive relationships for the materials to be used;
- Adaptation of the computational model in accordance to the specific material characteristics;
- Estimation of influence of possible inaccuracy in the computational model characteristics on the difference between computational and experimental results;
- Selection of computational model characteristics based on experimental results.

Investigation method (1)

The electrohydraulic stamping of metals is a complicated process, which is characterized by development in time and interaction of several physical phenomena. An additional complexity in simulation of such process is related to the fact that the deformation of a blank may lead to significant changes in the model geometry.

Capabilities of modern engineering software (ANSYS, LS-DYNA, etc.) for providing accurate and adequate simulations to the process of elastoplastic metal deformation are wide.

Investigation method (2)

It is well known that LS-DYNA is able to provide accurate results for simulation of fast processes, but there are only few articles, where such an approach is described in application to electrohydraulic forming of metals.

In our opinion, usage of LS-DYNA for simulation with comparison to experimental data is a
right way of constructing methods for mathematical

modeling of electro-hydraulic metal stamping.

Physical phenomena of metal deformation which are necessary to take into account

- *Plasticity*

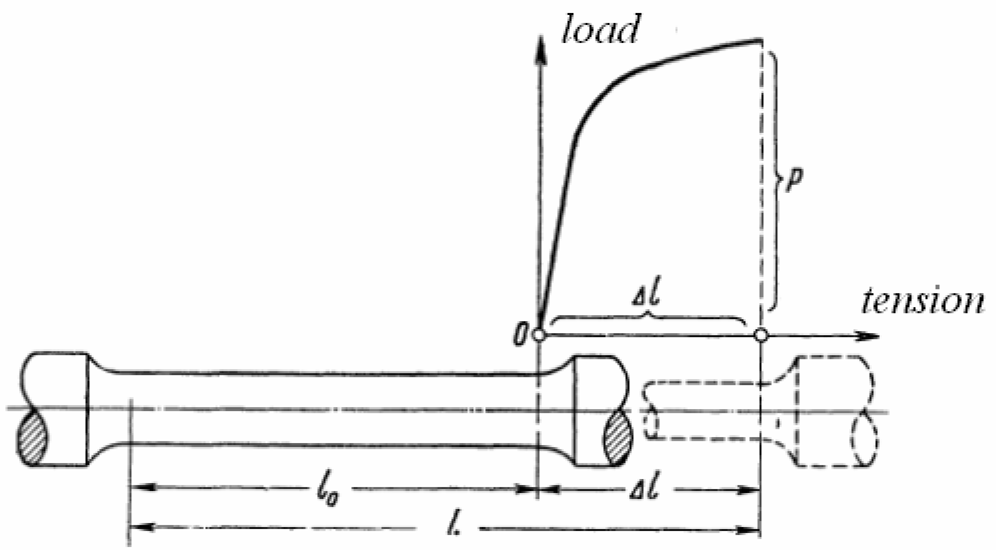
  There are two types of deformation – elastic and plastic, elastic deformations are recoverable but plastic are not. For successive stamping it is necessary to achieve plastic deformations.

- *Elastic behavior specified by equation of state*

  Relationship between pressure, internal energy and volumetric change.

Plasticity (1)

A one type of tests to analyze the behavior of a material is the tension of a rod.



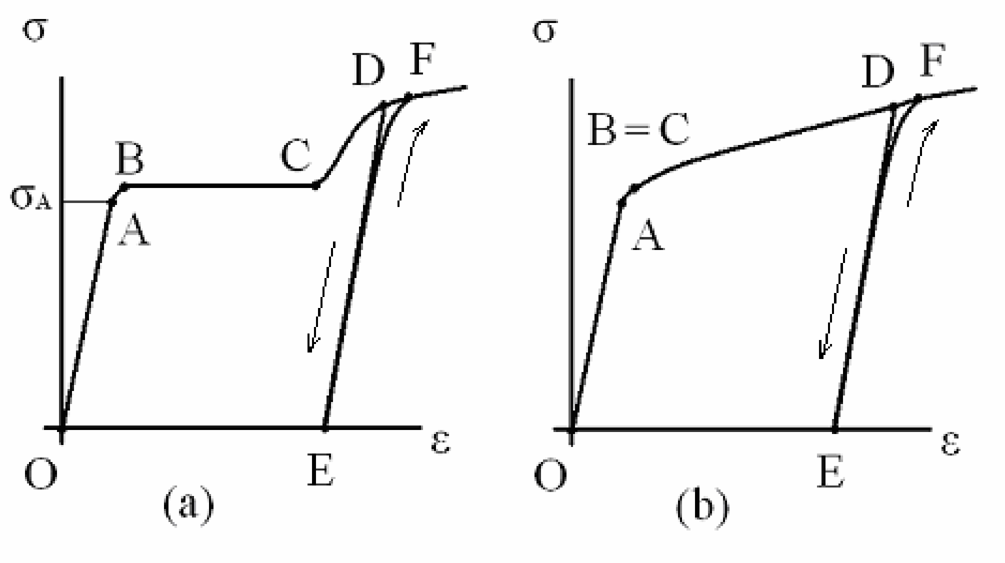
The result of such test is represented by plotting the ratio of tensile stress σ to the initial cross-sectional area, against some measure of the total strain.

The amount of deformation can be measured as $\varepsilon = \ln(l / l_0)$ (called logarithmic or natural strain)

or as $\varepsilon = (l - l_0) / l_0$ (engineering or conventional strain)

Plasticity (2)

Typical stress-strain relationships for metals



(a) – soft metal (like copper), (b) – hard metal (like steel)

A – proportional limit

B – yield point

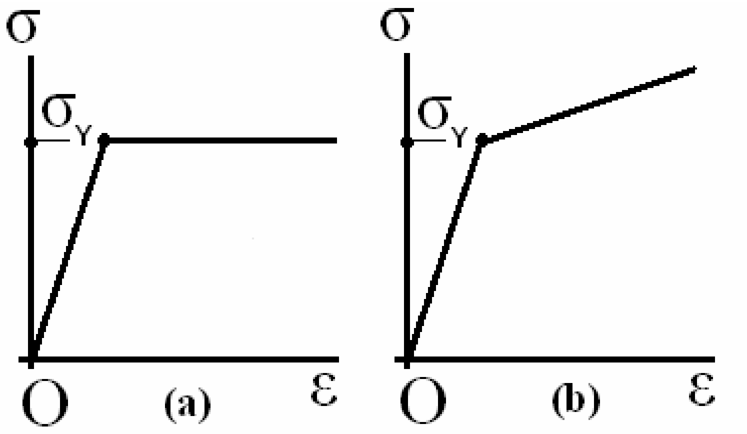
C – point where hardening starts

DE – unloading, EF – repeated loading

Yield criterion

The yield criterion determines the stress level at which yielding is initiated. For multi-component stresses, it is represented by a function $F(\sigma)$ of the stress vector (or tensor) σ, which can be interpreted as an equivalent stress $\sigma_E = F(\sigma)$.

Stress-strain relations for the simplest mathematical models of plasticity are depicted below.



Case (a) corresponds to the perfect plasticity (no hardening), and case (b) represents behavior with linear hardening, where there are two linear parts of the stress-strain curve.

Yield surface (1)

Yield function: $F(\sigma)$

Acceptable stress: $F(\sigma) \leq 0$

A material element is said to be in an elastic state if $F(\sigma) < 0$, and in a plastic state when $F(\sigma) = 0$.

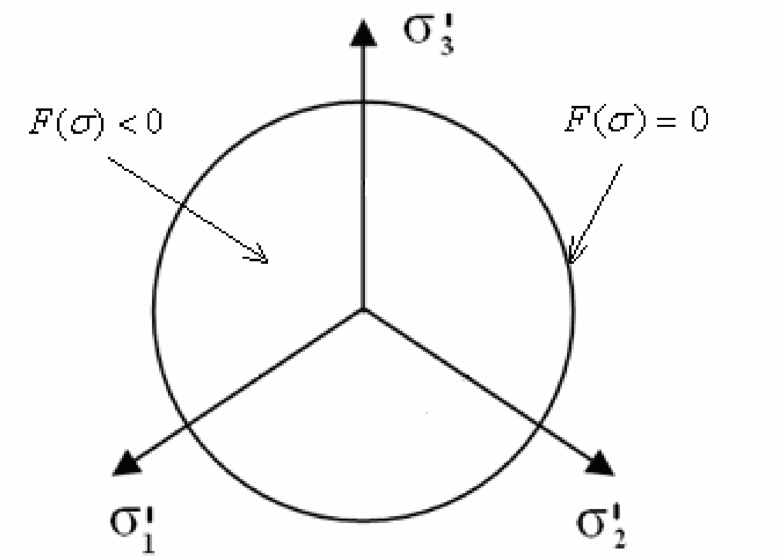
For plastic yielding, the element needs to be in a plastic state ($F = 0$), and to remain in a plastic state ($\dot{F} = 0$); otherwise the plastic strain rate vanishes.

Hence $\dot{\varepsilon}^{plast} = 0$ for $F < 0$ or ($\dot{F} < 0$ and $F = 0$) otherwise there is yielding. First condition corresponds to the case when element is in elastic state, second – element passes from a plastic state to an elastic state (unloading).

Yield surface (2)

For metal under moderate pressure yield function depend not on stress tensor but on its deviator $\sigma^D = \sigma - \overline{\sigma}\mathrm{I}$

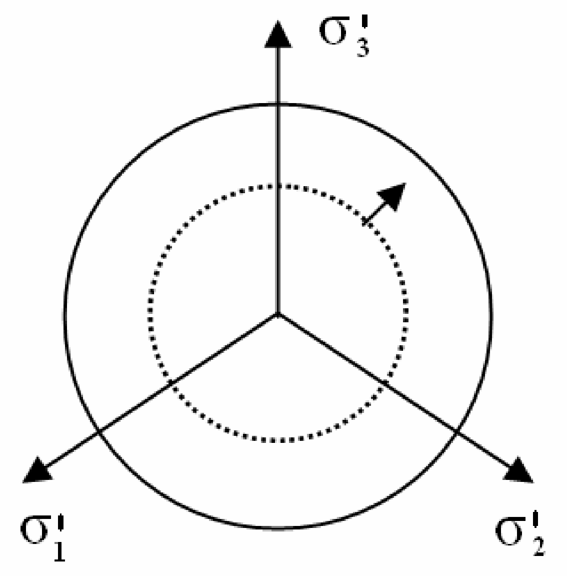
where I is the identity tensor and $\overline{\sigma} = tr\sigma / 3$ (so called hydrostatic pressure)



In this case yield surface can be defined with equation $\left|\sigma^D\right|^2 - k^2 = 0$
In principal stress space $\sigma_1, \sigma_2, \sigma_3$ yield surface will look like a cylinder with axe $\sigma_1 = \sigma_2 = \sigma_3$ which is perpendicular to the deviatoric plane (where $\overline{\sigma} = 0$). In projection to a deviatoric plane yield surface looks like a circle with center in the origin.

Hardening

For metals under plastic deformations yield limit may increase with deformation growth. Metal is gaining additional elastic properties and loses ability to deform plastically. This phenomenon is called hardening.



The hardening rule describes how the yield surface changes with progressive yielding.

In the so-called work hardening (isotropic hardening) the yield surface remains centered about its initial centerline and expand in size as the plastic strains develop.

LS-DYNA plasticity models (1)

Bilinear Isotropic Model (BISO)

This classical strain rate independent bilinear isotropic hardening model uses two slopes (elastic and plastic) to represent the stress-strain behavior of a material.

Stress-strain behavior can be specified at only one temperature. Input elastic parameters are elastic modulus, Poisson's ratio and density of a material. The program calculates the bulk modulus automatically.

Input parameters for the simulation of a plastic behavior are the yielding limit and the tangent slope.

LS-DYNA plasticity models (2)

Johnson-Cook model

Johnson and Cook express the yielding limit as

$$\sigma_Y = (A + B(\varepsilon^{plast})^n)(1 + c\ln\dot{\varepsilon})(1 + T^{*m}) \qquad T^* = \frac{T - T_{room}}{T_{melt} - T_{room}}$$

where A, B, c, n, m, T_{melt} are material constants

ε^{plast} - effective plastic strain

$\dot{\varepsilon}$ - ratio of effective plastic strain rate to initial strain rate

Input parameters for the simulation are the elastic modulus, Poisson's ratio, density of a material and all material constants

This model, also called the viscoplastic model, is a strain-rate and adiabatic (heat conduction is neglected) temperature-dependent plasticity model. In our case temperature dependence is neglected.

Equation of state (1)

Equations of state describe relationship between pressure P, internal energy E and specific volume $V = 1/\rho$ where ρ is a material density. If E and V are independent thermodynamic functions it is sufficient to write the equation of state as one function:

$$P = P(V, E)$$

There is a suitable type of EOS in LS-DYNA – linear polynomial

Equation of state (2)

The linear polynomial equation of state:

$$P = C_1\mu + C_2\mu^2 + (C_3 + C_4\mu)E$$

where P is pressure and E is specific internal energy, $\mu = \rho/\rho_0 - 1$ is a dimensionless parameter where ρ/ρ_0 is the ratio of a current density to the initial one.

For expansion process $(\mu < 0)$ term $C_2\mu^2$ is set to zero and equation transforms into

$$P = C_1\mu + (C_3 + C_4\mu)E$$

Required data for simulation

1. Geometrical model;

2. Material model;

3. Material properties for a selected material model (density, Poisson's ratio, elastic modulus, plastic properties and other material constants);

4. Finite Element model based on a selected type of element;

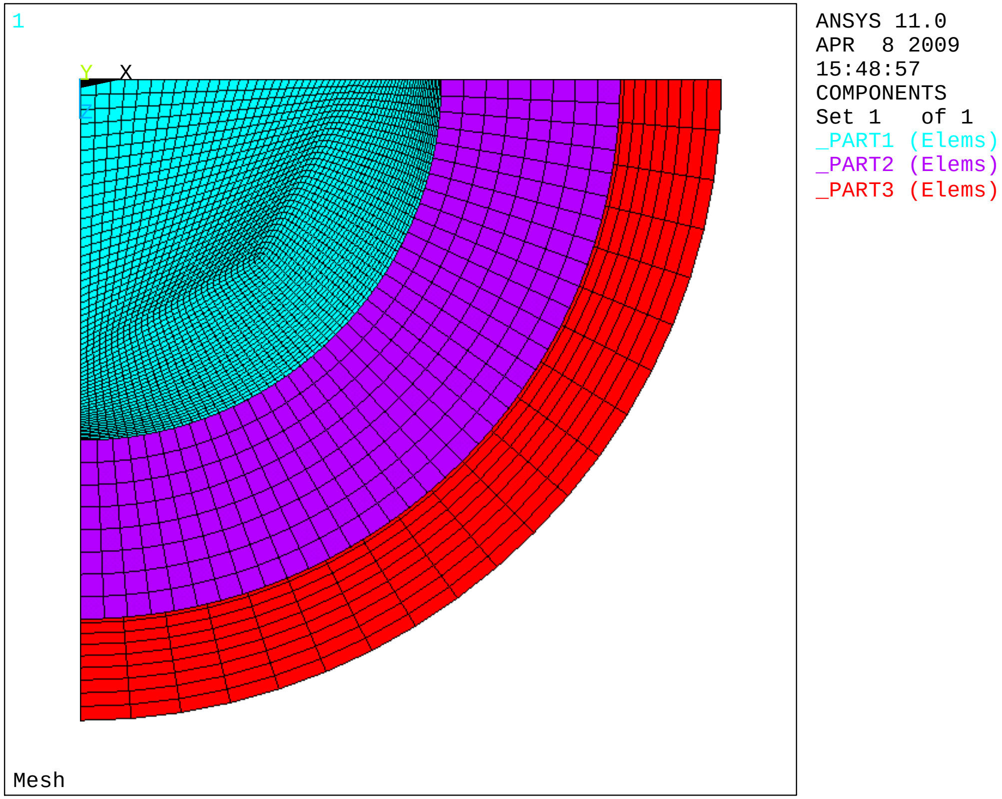
5. Boundary conditions;

6. Loading as a function of time and spatial coordinates;

7. The termination time for simulation.

Geometrical and finite element model (1)

The model consists of tree parts – the deformable metal blank (blue), rigid holder (purple) and rigid die (red), 1/4th symmetry was used to reduce the amount of calculations.



Blank size:
thickness 0.5 mm
radius 20 mm

The SOLID164 element is used

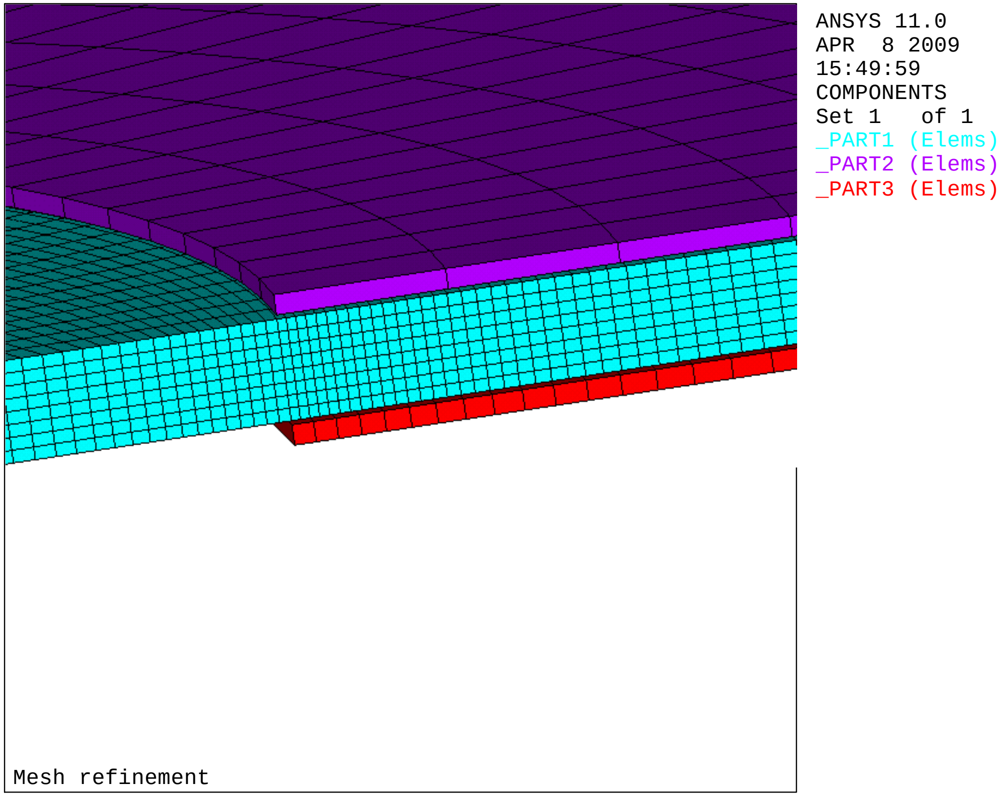
Geometrical and finite element model (2)

Near the die edge mesh was refined for accurate computations in area where plastic deformations mostly occur.

Mesh:

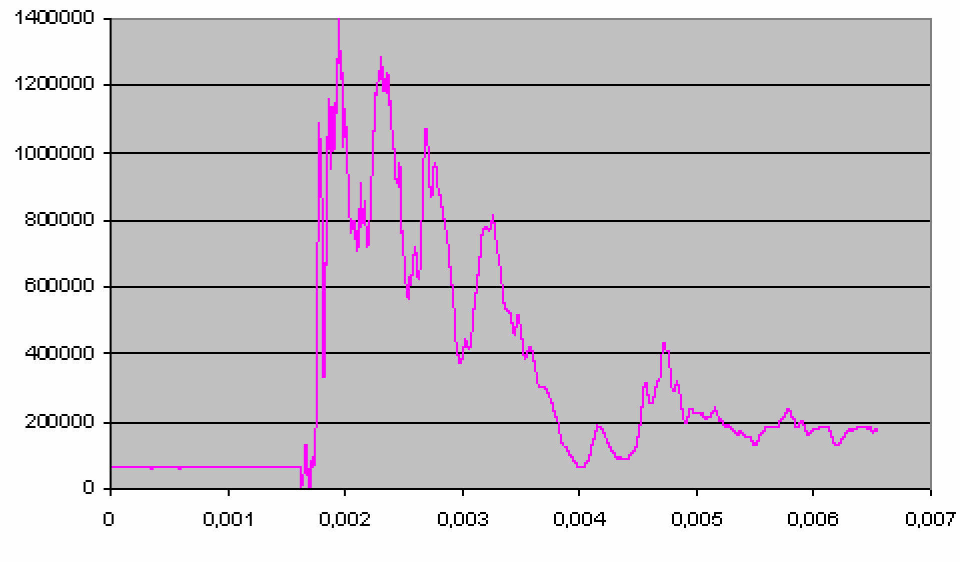
59 349 nodes

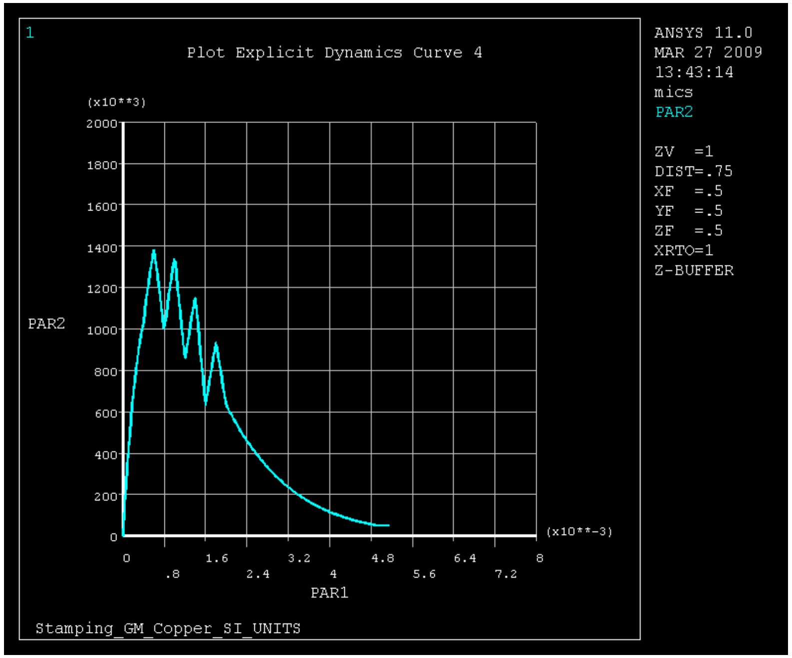
50 528 elements



Loading (1)

Pressure on the deformable metal blank was measured experimentally and then approximated.

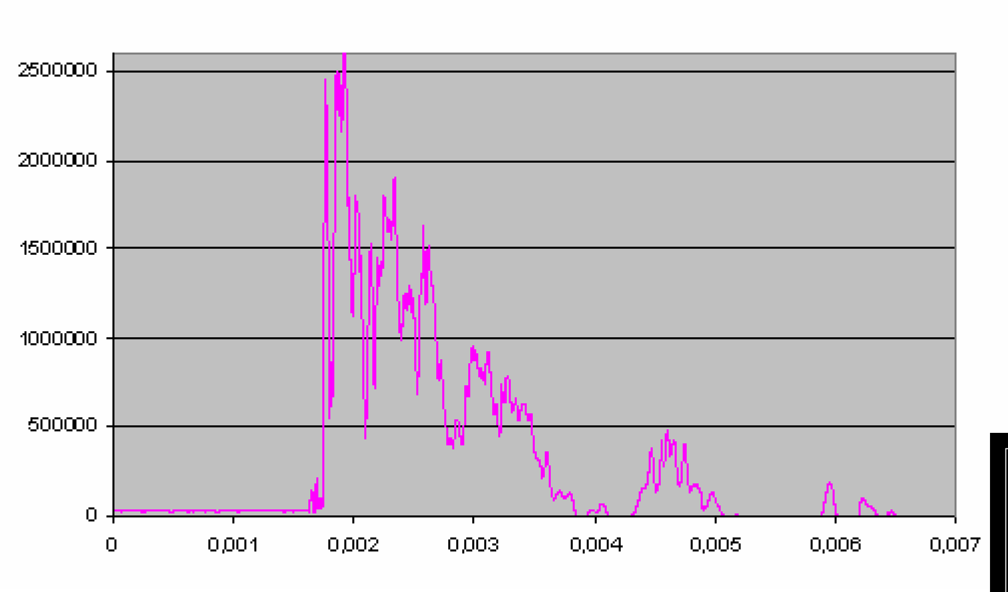




Maximum pressure:

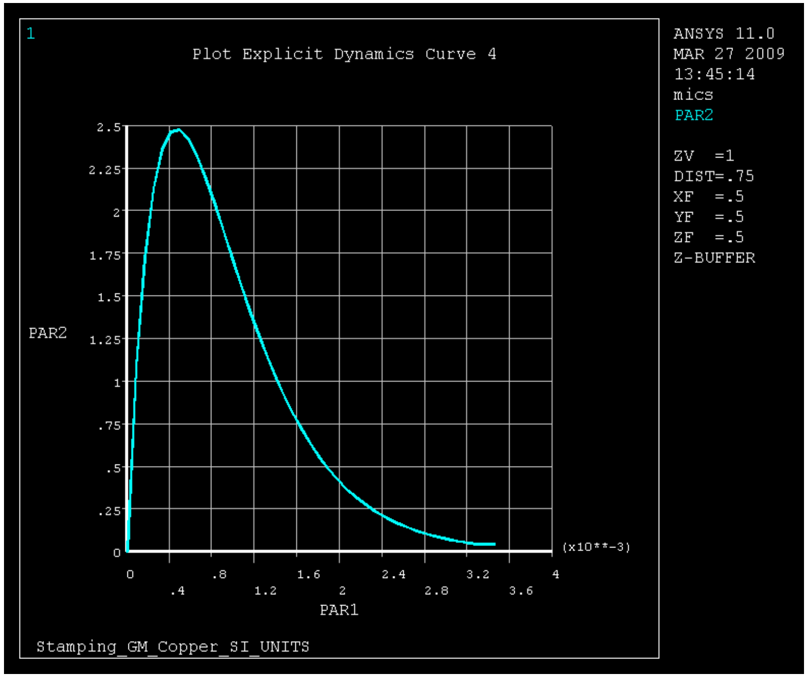
1.4 MPa

Loading (2)

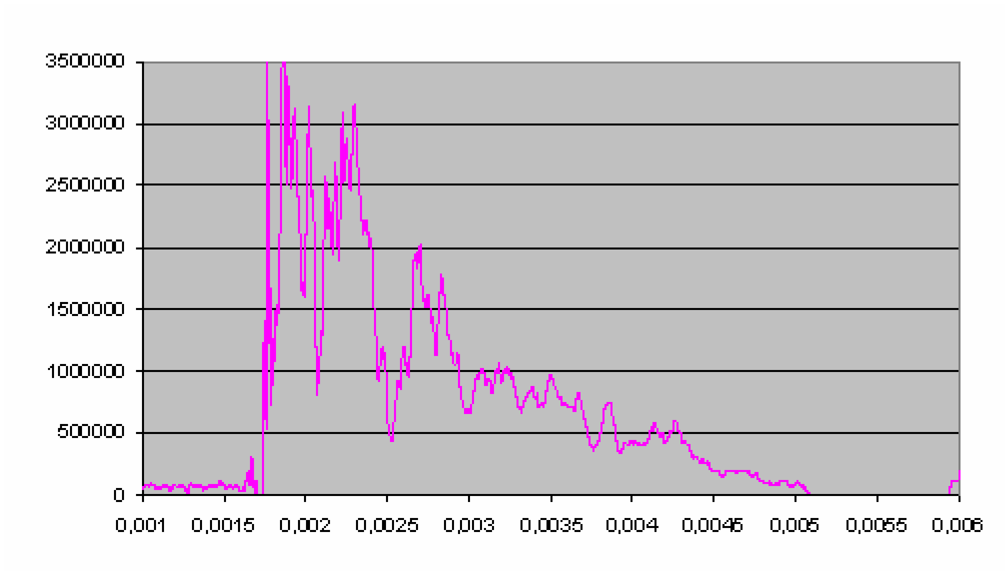


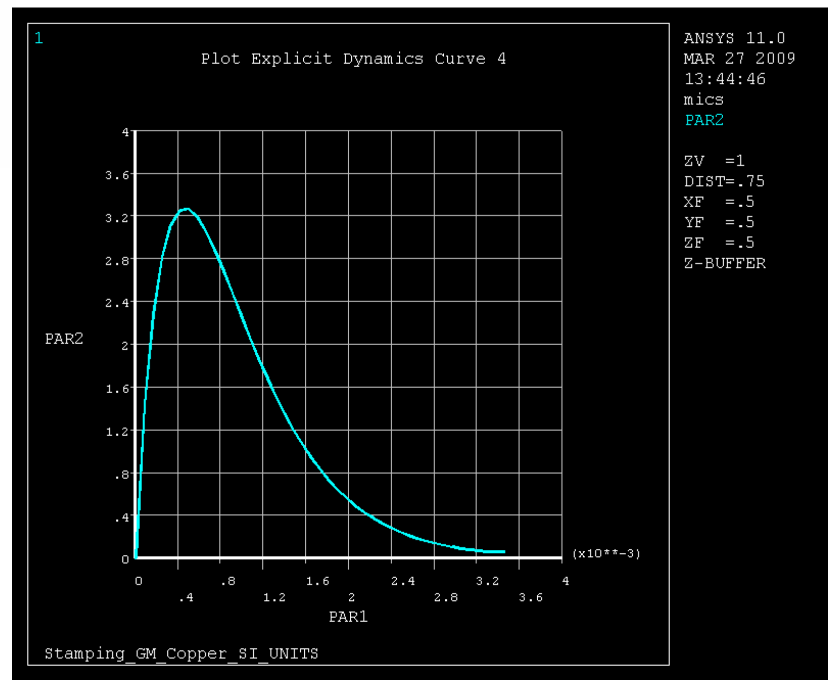
Maximum pressure:

2.5 MPa



Loading (3)





Maximum pressure:

3.3 MPa

Material constants for copper

Elastic modulus	120.0e9	N/m^2
Poisson’s ratio	0.343	
Density	8930	kg/m^3

Constants for BISO model

Yielding limit	70.0e6	N/m^2
Tangent slope	2.0e9	N/m^2

Constants for Johnson-Cook model

Room temperature	27 $^{\circ}C$	
A	89.63e6	N/m^2
B	291.64e6	N/m^2
n	0.31	
c	0.025	

Constants for EOS

C_1	140e9	N/m^2
C_2	2.8e9	N/m^2
C_3	1.96	
C_4	0.47	

Results

Maximum deflection, mm for copper blank:

max pressure, MPa	experiment	Time of calculation	BISO model	Johnson-Cook model
1.4	1.60	4.9e-3	1.48	0.78
2.5	3.00	3.3e-3	2.85	
3.3	3.50	3.3e-3	3.40	

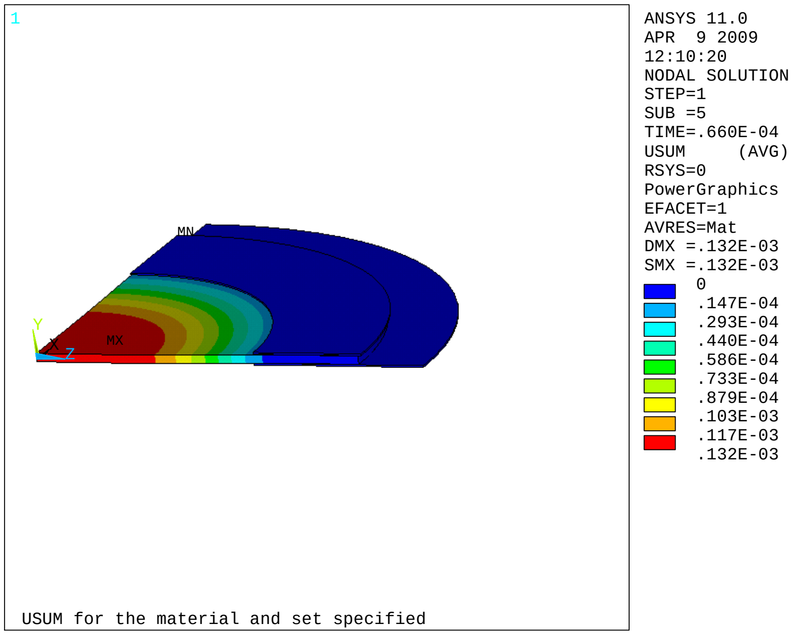
Time of a typical computation – about 15 hours

(AMD Athlon(tm) 64x2 Dual Core Processor 6000+
3.00 GHz, 3 Gb RAM)

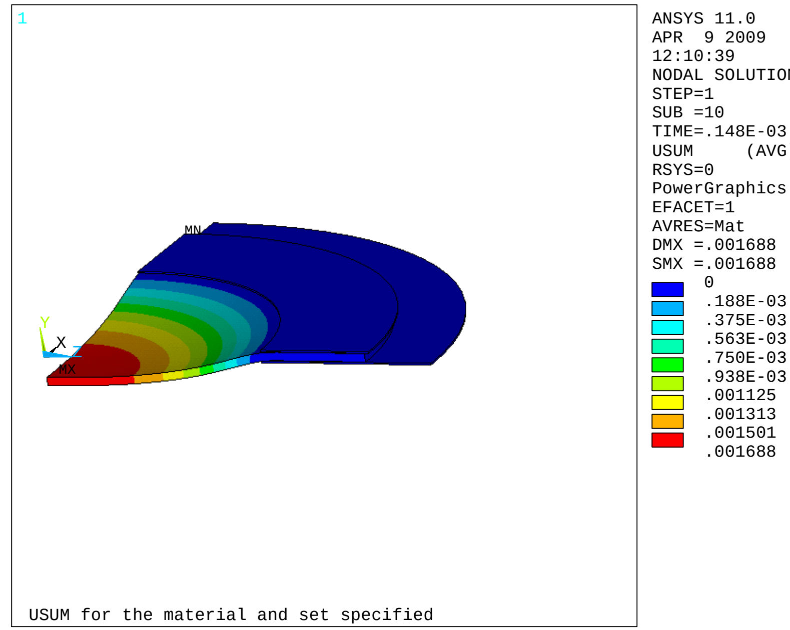
The average accuracy for BISO model is 5.1%

Results for maximum pressure 3.3 MPa (1)

Total displacement via time



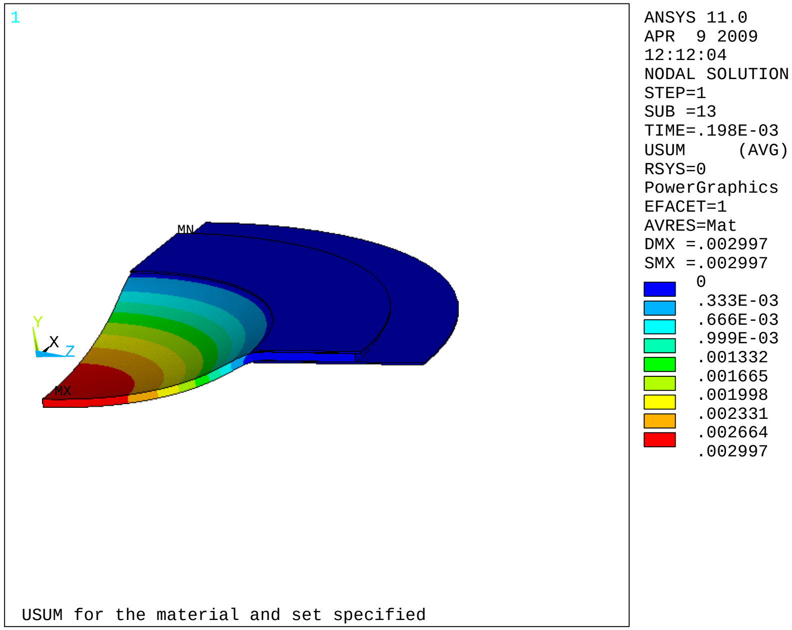
Step 5 Time 0.660e-4 sec



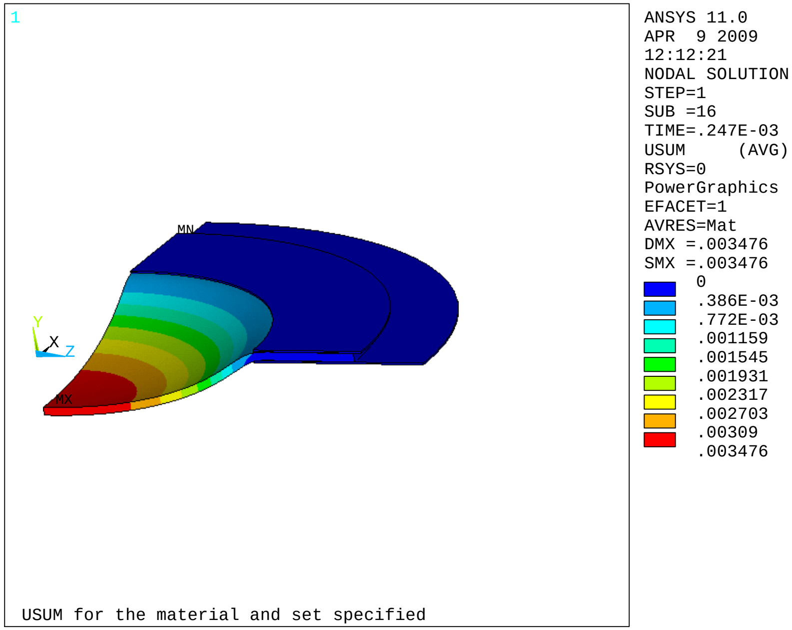
Step 10 Time 0.148e-3 sec

Results for maximum pressure 3.3 MPa (3)

Total displacement via time



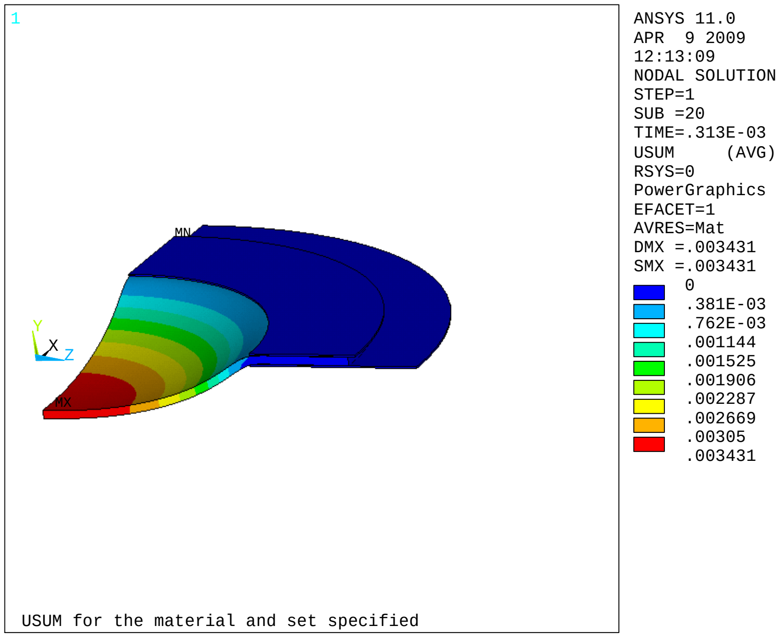
Step 13 Time 0.198e-3 sec



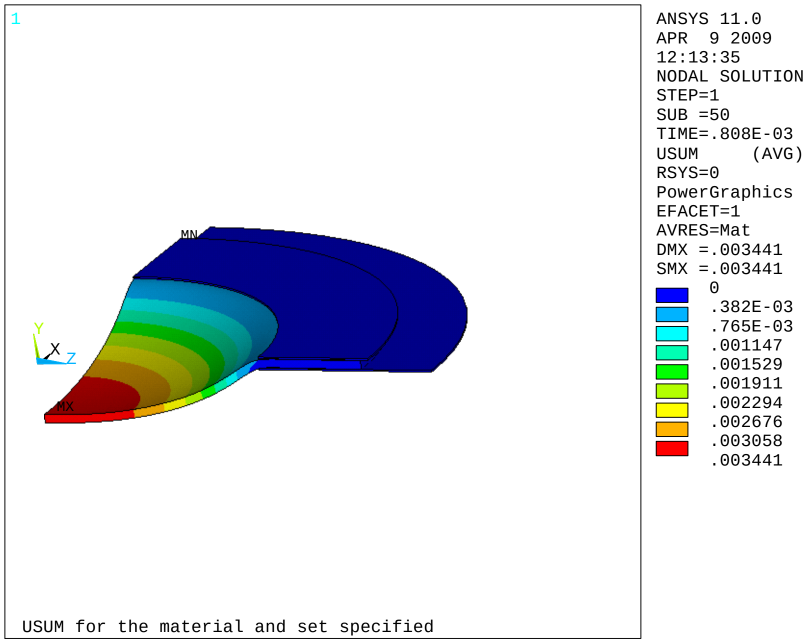
Step 16 Time 0.247e-3 sec

Results for maximum pressure 3.3 MPa (2)

Total displacement via time



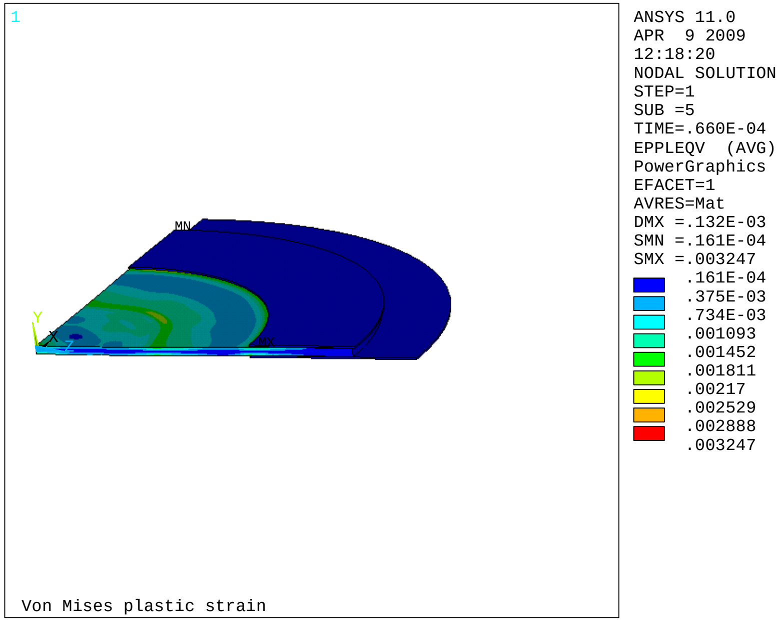
Step 20 Time 0.313e-3 sec



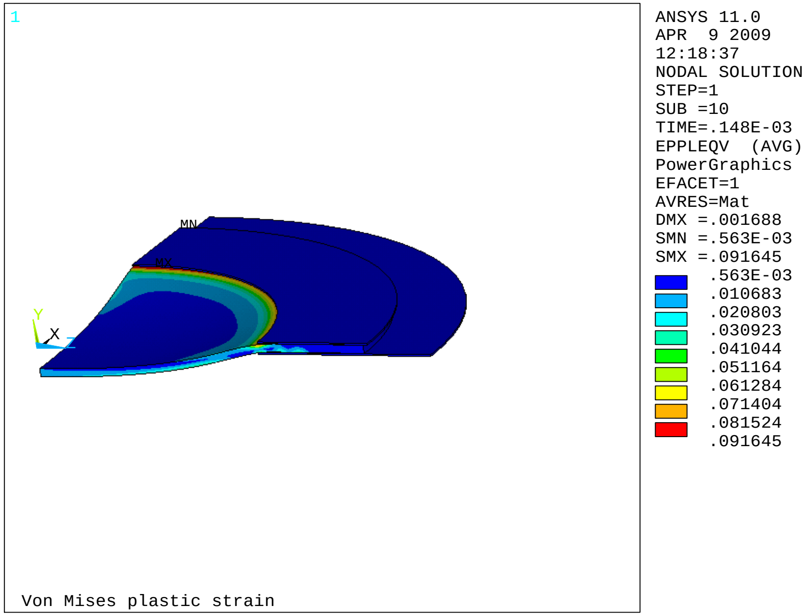
Step 50 Time 0.808e-3 sec

Results for maximum pressure 3.3 MPa (4)

Von Mises plastic strain via time



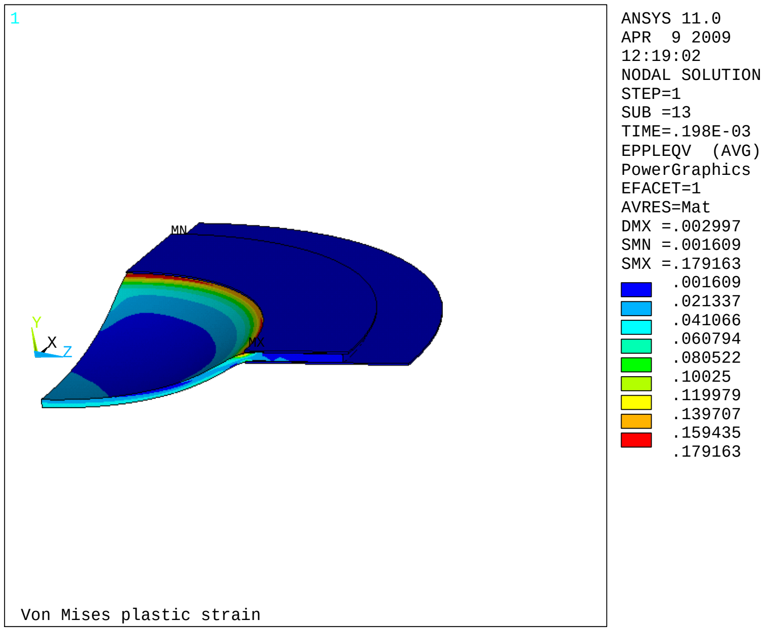
Step 5 Time 0.660e-4 sec

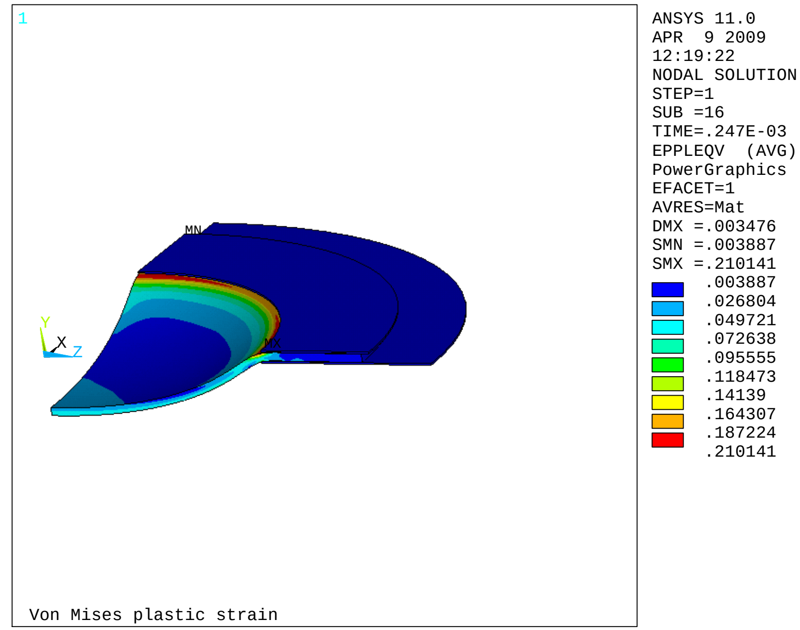


Step 10 Time 0.148e-3 sec

Results for maximum pressure 3.3 MPa (5)

Von Mises plastic strain via time



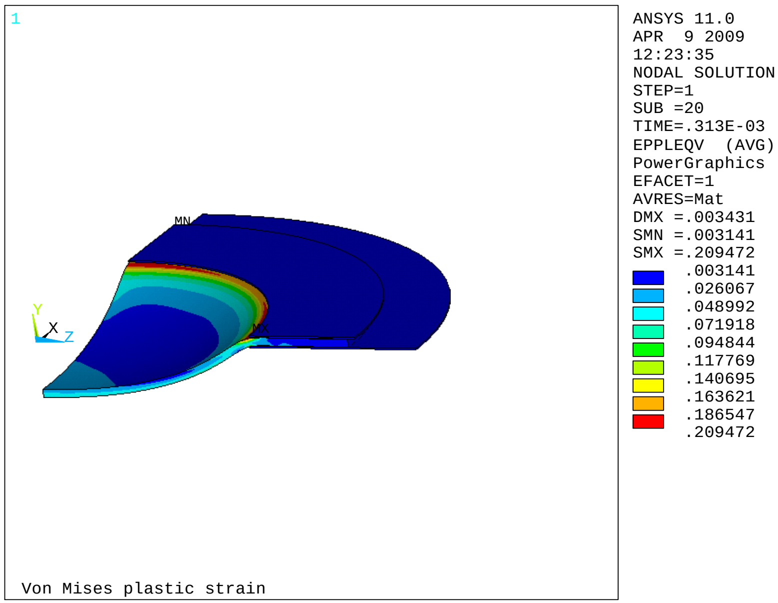


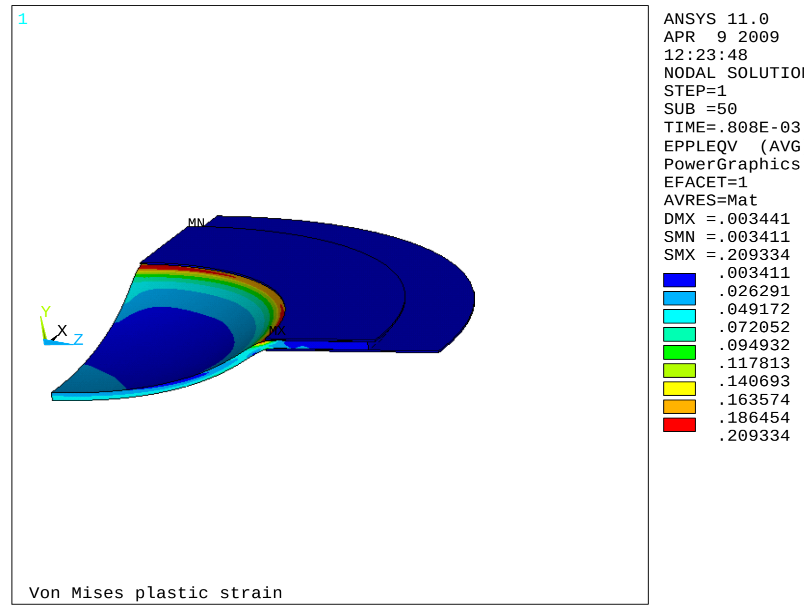
Step 13 Time 0.198e-3 sec

Step 16 Time 0.247e-3 sec

Results for maximum pressure 3.3 MPa (6)

Von Mises plastic strain via time





Step 20 Time 0.313e-3 sec

Step 50 Time 0.808e-3 sec

Conclusions

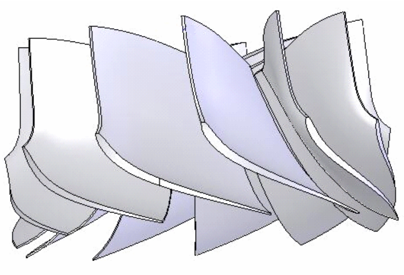
- BISO model is more adequate for description of “slow” processes. (For an industrial application our process is slow and pressures are not high).

- Mean error of the computations with BISO model is about 5%. Plastic deformations occur where they were expected theoretically.

- Deformation of a blank in small-scale experimental plant is well simulated by BISO model.

- The Johnson-Cook model is more complicated and gives poor results in our case.

Laboratory of Pulsed Power Energy



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Thank you for your attention!