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Study of hydroforming by implementing necking criterion in FEM code

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1. Introduction

The aim of modelling using numerical methods is to develop material treatment processes. Lately this is tried to be done not only by selecting technological parameters, but also by evaluating these failure phenomenona.

- In the first case, this can be done by estimating failure formation and observing its progress during material deformation; by changing some parameters (reology, load, etc.). Undesirable failure processes are observed in stamping, hydroforming, etc.
- In the second case, this can be done by optimizing the failure process itself in such procedure as cutting, stamping, etc.

The failure is the outcome of instability of plastic deformation during material forming [1]. Necking analysis will be discussed in this paper.

One of the limitations in sheet metal processing is the appearance of local necking. This corresponds to the formation of a restricted band where the sheet is locally and excessively thinned [2]. The neck also is considered as an unacceptable aspect by default. The neck can also be expressed by major strains and stresses, which compose Forming Limit Curve (FLC) of available deformations allowing the sheet to deform without any necking.

So, the geometric neck formation is visual expression of the processes developing in material, such as plastic flow causing material failure.

One of the methods for material failure investigation in sheet metal processing is comparing of FLC predicted by numerical methods and FLC determined by bulge test.

This paper concerns necking models, which were implemented in FEM code and numerical simulation results of simple sheet metal processing. Further the technology of metal hydroforming is shortly presented.

2. Sheet metal deformation technologies

Usually stamping technologies and currently developing hydroforming technologies are used for sheet metal deforming. As can be seen in Figs. 1,2, cutting operations and strict geometric shapes are typical for stamping technology. Using hydroforming, complex 3D curvilinear shapes can be obtained. Hydroforming technology also lets to avoid welding operations when producing assembled parts. Talking about disadvantages of these technologies, the wear of stamping tools and expensiveness, complexity of hydrofoming equipment should be mentioned. New hydroforming technology attains an increasing interest in the industrial environment, particularly due to the weight reduction and uniform thickness distribution that can be achieved by this technology if compared to the standard stamping technologies.

Fig. 1 Examples of the stamped parts

Fig. 2 Part, manufactured by hydroforming [1]

According the material feeding to matrix, there are two main material hydroforming technologies:

1) when the water pressure load is nonlinear – it is controlled with special pistons, this technology is used in tubes hydroforming;
2) when water pressure load is linear, sheet metal is fixed between two matrixes which form a gap, this gap controls material feeding to the matrix.

The material feeding to the matrix phenomenon is very interesting in the case of double sheet hydroforming (a new variety) which offers a substantial improvement in cycle time production since two parts are formed simultaniuosly [1-3].

Basically, the hydroforming process can be classified into three groups according to the different process features and the usage of different original blanks as follows [4]:

1) shell hydroforming;
2) sheet hydroforming, which includes two technologies:
    a) when the punch pushes the sheet metal into the die cavity, within which oil or other liquids are contained;
    b) the liquid can be used as a punch;
3) tube hydroforming using seamless tube or welded tube, the blank can be formed into the shape of the die cavity by internal pressure and when the side punches move in.

In the course of this paper the investigation of simple sheet hydroforming will be discussed. As can be seen in Fig. 3, sheet hydroforming technology is presented.

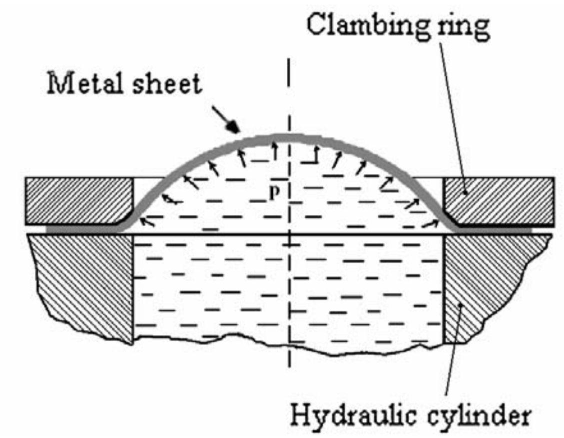

Fig. 3 Hydroforming process [5]

3. Material hydroforming technology and its investigation using finite element method

The scheme of free hydroforming scheme symmetric to the axis is presented in the Fig. 4. The critical points of the deformed metal are chosen:

a) the sheet is deformed because of tangential compression and radial stretch at the point A;
b) the stresses are affected by matrix radius, i.e. geometry of the matrix at the point B;
c) the zone of the stress is related to the height of the deformed sheet at the point C;
d) the zone of peak stresses is at the point P. In this zone failure occurs after the maximum decrease of metal thickness. The failure in this zone occurs while deforming the sheet in an open matrix. If the matrix is closed, the failure can turn up in another critical state point.

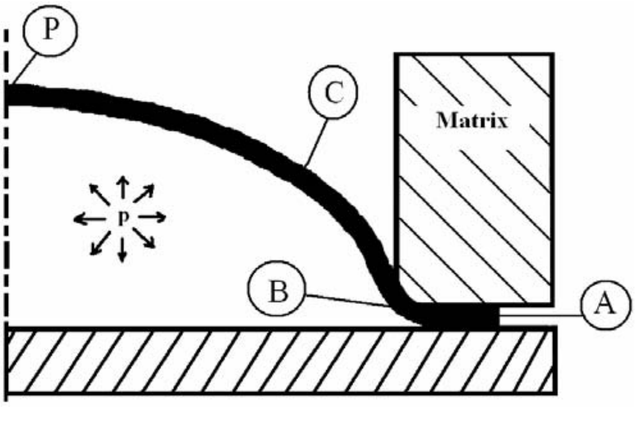

Fig. 4 The example of free hydroforming scheme [1]

When modelling by finite element method, the task was simplified to the minimum, i.e. it was solved in 2D environment and only half of symmetric deformation scheme has been modelled. Such simplification of the task allows to decrease the calculation time.

The material behaviour was described considering reological properties such as elastically plastic material flow and hardening law [6]. This could be expressed by

$$\sigma = K\left(\varepsilon_0 + \varepsilon\right)^n \tag{1}$$

where σ is equivalent stress, pre-strain ε_0, the material consistency K, hardening exponent n.

General equivalent strain takes the form

$$\varepsilon = \varepsilon_p + \varepsilon_e \varepsilon \tag{2}$$

where ε_p is plastic strain, ε_e is elastic strain.

As the sheets for hydroforming were manufactured using laminated way, giving the anisotropic features, so plastic deformation could be evaluated by Von Mises [7] criterion. The simplified form of this criterion is

$$\sigma_{eq}^2 = 1/2\left[\left(\sigma_{xx} - \sigma_{yy}\right)^2 + \left(\sigma_{yy} - \sigma_{zz}\right)^2 + \left(\sigma_{zz} - \sigma_{xx}\right)^2\right] + \\ +3\left(\sigma_{xy}^2 + \sigma_{yz}^2 + \sigma_{zx}^2\right) \tag{3}$$

here σ_{eq}^2 is equivalent stress, $\sigma_{xx}, \sigma_{yy}, \sigma_{zz}, \sigma_{xy}, \sigma_{yz}, \sigma_{zx}$ are stresses in the signed directions.

The friction processes are described, evaluating Coulomb law [6]

$$\tau = \mu \sigma_n \tag{4}$$

With this relation, the friction shear stress τ is equal to the normal stress σ_n multiplied by the friction coefficient μ.

During bulging tests, the major and minor strains at the top of bulged part are recorded in real time. We can find the values of material behaviour, which exceed limit strain at rupture (it is not possible to determine these values by tensile test). In another way, the curve of material flow behaviour also can be found by calculating current stress [8]

$$k_f = \frac{p\rho}{2s} \delta \sqrt{\delta^2 - 3\delta + 3} \tag{5}$$

here p is the pressure; ρ is the radius of the deformed material on the top; δ is the ratio of deformed material on its top; s is the material thickness during experiment on the top of deformed material.

4. Evaluation of necking in hydroforming

In order to investigate physical processes, which occur when deforming materials using water pressure, mathematical models, created by several authors were evaluated and implemened into finite elements method software package Forge2® [6].

In the calculation of the FLC diagram, the following assumptions are taken:

- the material is orthotropic,
- yielding is described by Hill's anisotropic plasticity theory,
- sheet metal is strain hardening.

Storen and Rice [8] derived the following relation for the major strain at the instant of instability, using a Von Mises

[7] yield function and a power law stress-strain relation to define the incremental strain rates

$$\varepsilon_1 = \frac{3\beta^2 + n(2+2\beta)^2}{2(2+\beta)(1+\beta+\beta^2)} \tag{6}$$

n =0.25 is hardening factor established experimentally [1]; $\beta = \frac{\varepsilon_3}{\varepsilon_1}$ is the strain ratio, where $\varepsilon_1, \varepsilon_3$ are the major and minor principals strains.

Fig. 5 [1] presents the expression of the analytical Storen-Rice necking criterion by metal sheet FLC considering major strains.

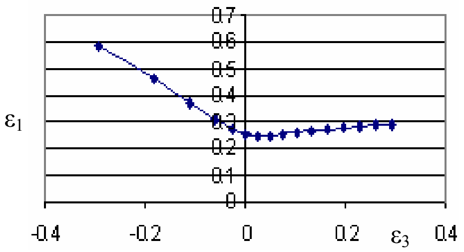

Fig. 5 Strain based view of Storen-Rice instability model used to describe sheet metal forming limit behaviour [1,4]

Hill-Swift criterion or load bifurcation and tension bifurcation analysis is expressed using power law and applying Von Mises [7] plasticity criterion, the Swift [1,9] analysis takes the following form

$$\varepsilon_p = \frac{4n\left(1-\alpha+\alpha^2\right)^{\frac{3}{2}}}{4-3\alpha-3\alpha^2+4\alpha^3} \tag{7}$$

where $\alpha = \frac{\sigma_3}{\sigma_1}$

here ε_p is effective strain; σ_1, σ_3 are the major and the minors principals stresses.

To simplify analysis of laminated sheet metal it is assumed, that $\sigma_2 = 0$.

The solution of neck formation solution is developed using a Von Mises yield function under the associated flow rule [8]

$$\sigma_y = \sqrt{\sigma_1^2 + \sigma_3^2 - \sigma_1\sigma_3} \tag{8}$$

which leads to the following relation between α and β [9]

$$\beta = \frac{2\alpha - 1}{2-\alpha} \tag{9}$$

where σ_y is effective stress.

The major strain is expressed like

$$\varepsilon_1 = \frac{\varepsilon_p}{\frac{2}{\sqrt{3}}\sqrt{1+\beta+\beta^2}} \tag{10}$$

Swift analysis expresses the positive part of the FLC: $0 \le \beta \le 1$.

Evaluating material behaviour during deformation using power law and having linear load, Hill analysis can be expressed as follow [9] and the negative part of the FLC is expressed by Hill analysis: $-\frac{1}{2} \le \beta$.

$$\varepsilon_1 = \frac{n}{1+\beta} \tag{11}$$

Fig. 6 [1] presents the expression of the analytical Hill-Swift necking criterion by metal sheet FLC considering major strains.

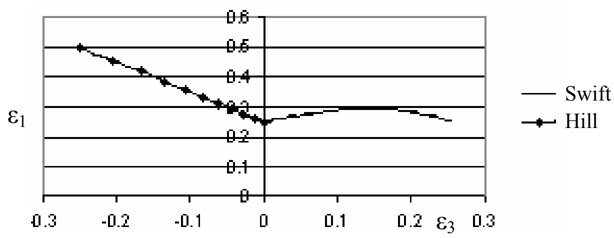

Fig. 6 Strain based view of Hill-Swift instability model used to describe sheet metal forming limit behaviour [1,4]

In order to evaluate Ramaekers criterion [1, 9] the calculation scheme for sheet deformation is provided. The expression of the major strain could be written as

$$\varepsilon_1 = n(1+\beta)^q - \frac{\varepsilon_0}{\varepsilon_p} \tag{12}$$

with $q = -1$, if $\beta \le 0$ and $q = 1$, if $\beta \ge 0$; $\varepsilon_0 = 0.0059$ - initial strain established experimentally [1]

$$\varepsilon_p = \frac{R+1}{\sqrt{2R+1}}\sqrt{1+\frac{2R}{R+1}\beta+\beta^2} \tag{13}$$

here ε_p is effective strain.

If R =1, then effective strain takes the expression

$$\varepsilon_p = \frac{2}{\sqrt{3}}\sqrt{1+\beta+\beta^2} \tag{14}$$

When $\beta \le 0$, the major principal strain is obtained as

$$\varepsilon_1 = \frac{n}{1+\beta} - \frac{\sqrt{3}\varepsilon_0}{2\sqrt{1+\beta+\beta^2}} \tag{15}$$

When $\beta \le 0$, the major principal strain is obtained as

$$\varepsilon_1 = n(1+\beta) - \frac{\sqrt{3}\varepsilon_0}{2\sqrt{1+\beta+\beta^2}} \tag{16}$$

Fig. 7 [1] presents representation of the analytical Ramaekers necking criterion expression by metal sheet FLC considering major strains.

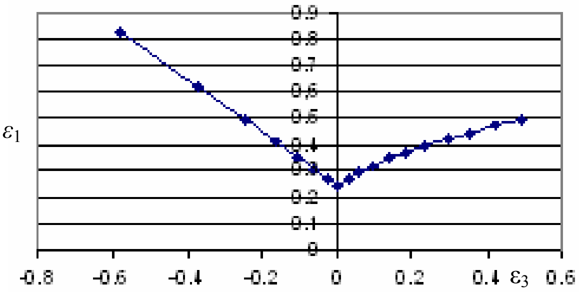

Fig. 7 Strain based view of Ramaekers instability model used to describe sheet metal forming limit behaviour [1,10]

Criterion of maximum modified force [1,3,11] allows describing two phenomena of such metal forming:

- distributed phenomena of the neck,
- localised neck.

In fact, the formation of localized neck is described by sudden deformation change. In this case the plane deformation level is chosen again.

When $dF_1 = 0$ (F_1 is effort along the direction of the major strains [3]), we have the beginning of neck formation and the describing necking criterion

$$\frac{\partial\sigma_1}{\partial\varepsilon_1} + \frac{\partial\sigma_1}{\partial\beta}\frac{d\beta}{d\varepsilon_1} = \sigma_1 \tag{17}$$

Taking the hypothesis of local linearity [3]

$$\frac{\partial\beta}{\partial\varepsilon_1} = -\frac{\beta}{\varepsilon_1} \tag{18}$$

The material behaviour is described using material hardening law, expressed by material consistency K, hardening factor n, initial deformation ε_0, and deformation rate m [3]

$$\sigma = K\left(\varepsilon_0 + \varepsilon\right)^n \dot{\varepsilon}^m \tag{19}$$

The criterion of maximum modified force can be written as

$$\frac{n}{\varepsilon_p} = g\left(1 + \frac{\dfrac{\partial f(\Omega)}{\partial\Omega}}{f(\Omega)} \frac{1}{\dfrac{\partial\beta}{\partial\Omega}} \frac{\beta}{\varepsilon_1}\right) \tag{20}$$

The following coefficients are introduced to simplify this expression [3,]

$$\left.\begin{array}{l} \Omega = \dfrac{1+2\beta}{2+\beta},\ f = \dfrac{1}{\sqrt{1-\Omega+\Omega^2}} \\ \dfrac{\partial f}{\partial\Omega} = \dfrac{1}{2}\left(1-2\Omega\right) f^3 \\ \dfrac{\partial\beta}{\partial\Omega} = \dfrac{3}{\left(\Omega-2\right)^2},\ g = \dfrac{1}{f\left(1+\beta\Omega\right)} \end{array}\right\} \tag{21}$$

Fig. 8 [1] presents the expression of the analytical Maximum Modified Force necking criterion by metal sheet FLC considering major strains.

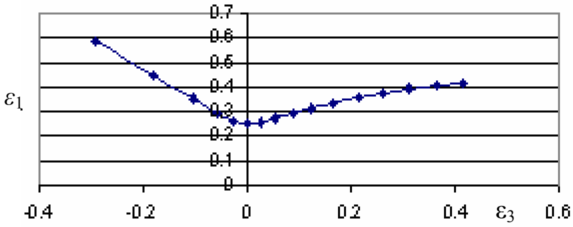

Fig. 8 Strain based view of Maximum Modified Force instability model used to describe sheet metal forming limit behaviour [1,3]

Figs. 5-8 [1] presents the expression of the analytical necking criterion by metal sheet FLC considering major and minor strains. It can be seen, that the failure according to the Ramaekers criterion would occur at the latest.

4. Calculation results

Necking criterions (Storen and Rice, Hill-Swift, Ramaekers, Maximum modified force) were implemented into FEM software package original version of which is created in ENSMP (France). In Figs. 9 - 10 [1] the images are presented, when numerical experiments of laminated steel deformation by hydroforming were preformed, with already integrated into the FEM code failure criteria. The major strains of integrated criteria were coded using different colours to distinguish their localization and other parameters. After this attempt the simulation can be stopped. In another hand, the physical phenomenon of failure can provide the non-convergence of solution. As can be seen in these figures, such experiment allows to test if the failure localisation conforms to the real physical phenomenon. The performed experiments confirmed that the results of numerical experiments are coincident with the results of experiments.

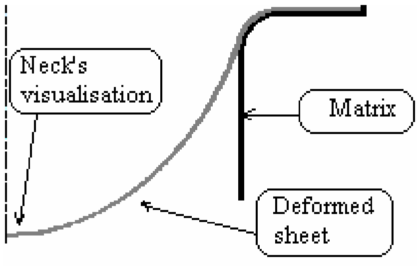

Fig. 9 Laminated sheet metal in matrix, deformed in an open matrix

Table 1 presents the results of the simple sheet hydroforming process stopped by failure, when the deformation is performed in an open matrix. Table 2 presents the results of the simple sheet hydroforming process stopped by failure, when the deformation is performed in an closed matrix. All experiments were performed using linear load (0.5 Bar/s). In tables 1-2 are listed such results: exact position of failure appearance, time, equivalent deformations and stress, deformation rate and also sheet thickness at the moment of failure.

During the bulge tests material deformations are evaluated using 3D deformation measurement system. Numerical experiments were performed, using grid of two finite elements in thickness of the sheet. To test the influence of finite element, the simulation has been performed, using grid of four finite elements in thickness of the sheet. And in our case, the results of this simulation were coincident with the results of numerical experiments, performed using grid of four finite elements in thickness of the sheet [1], so the size of the elements does not have any influence to the results.

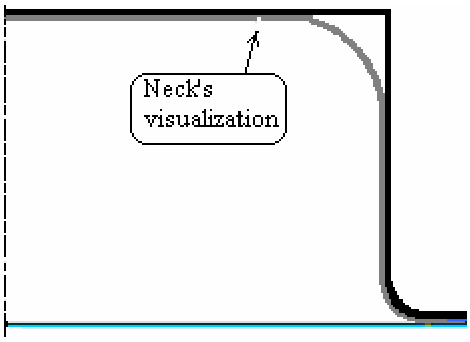

Fig. 10 Laminated sheet steel, deformed by hydroforming in closed matrix until visualisation of deformation criteria

Table 1

The results, which express failure occurrence by deforming material in an open matrix, according to the criteria integrated into finite element method software package. (Material - steel, 1 mm: E =2.1GPa; Poisson factor=0.3; K =318 MPa)

Implemented criterions in simulation (open matrix with gap 0.005 mm)	Time, s	Height from intial position, mm	Equiv. deformation	Deformation rate	Equiv. stress, Pa	Sheet thickness, mm
Storen_Rice	38.6	-43.8	0.628	0.202	483	0.535
Hill-Swift	38.5	-43.1	0.603	0.165	477	0.549
Ramaekers	38.8	-59.7	1.3	0.033	599	0.278
Modified forces	38.8	-53	0.979	0.025	550	0.377

Table 2

The results, which express failure occurrence according to the code of finite elements when the grid of 2 elements was selected (for the sheet of 1 mm thickness). (Material - steel, 1 mm: E =2.1 GPa; Poisson factor = 0.3; K =318 MPa)

Implemented criterions in simulation (closed matrix with gap 0.005 mm)	Time, s	Height, mm	Equiv def.	Deformation rate	Equiv. stress, Pa	Sheet thickness, mm	Notes about failure's moment
Storen-Rice criterion	136	53.4	0.614	0.101	481	0.538	before touching matrix
Hill-Swift criterion	135	49.7	0.516	0.063	461	0.594	before touching matrix
Ramaekers criterion	146	60.6	1.03	0.0107	548	0.36	after touching matrix
Criterion of maximum modified force	137	60.6	0.88	0.467	527	0.416	after touching matrix

4. Conclusions

1. The obtained numerical results enable the determination of location of upcoming failure, deformation speed of various material and deformation speed depending on technological mode (ex, gap dimension). The experiments were performed using linear water load (0.5Bar/s) and using different gaps (0.25 mm; 0.05 mm; 0.005 mm) between matrix and metal sheet.

2. Using numerical methods, the results of sheet metal failure due to hydroforming were obtained, which confirm the results of experiments.

5. Acknowledgments

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V. Gylienė, V. Ostaševičius

DEFORMAVIMO VANDENS SLĖGIU TECHNOLOGIJOS TYRIMAS, INTEGRUOJANT DEFORMAVIMO KRITERIJUS Į BAIGTINIŲ ELEMENTŲ PROGRAMŲ PAKETĄ

Reziumė

Straipsnyje pateikiamas metalo lakštų deformavimo vandens slėgiu technologijos tyrimas, į baigtinių elementų programų paketą integruojant kakliuko susidarymo kriterijus. Yra žinoma, kad prieš medžiagai suyrant suirimo vietoje susidaro deformacijų lokalizacijos. Siekiant nustatyti plastinių nestabilumų zonas, į baigtinių elementų programų paketą buvo integruoti keturi kakliuko susidarymo kriterijai. Pateikiami suirimo nustatymo skaitinių eksperimentų rezultatai.

V. Gylienė, V. Ostaševičius

STUDY OF HYDROFORMING BY IMPLEMENTING NECKING CRITERION IN FEM CODE

Summary

The paper contains an investigation of hydroforming technology, by implementation local necking criterion in finite element code. It is known that even for expansion deformations a local necking takes place before failure. Four necking criteria were implemented in FEM code to predict plastic instabilities in hydroforming technology and the results of numerical experiments of failure prediction are presented.

В. Гилене, В. Осташявичюс

ИССЛЕДОВАНИЕ ДЕФОРМИРОВАНИЯ ВОДЯНЫМ ДАВЛЕНИЕМ, ИНТЕГРИРУЯ КРИТЕРИИ ДЕФОРМИРОВАНИЯ В ПАКЕТ КОНЕЧНЫХ ЭЛЕМЕНТОВ

Резюме

В данной статье описывается исследованные процессов гидроформирования с учетом критериев деформирования в методе конечных элементов.

Известно, что местные деформации проявляются перед разрушением. Четыре критерии деформирования были интегрированы в пакет конечных элементов с целью предсказания зон нестабильности пластичных деформаций.

Представлены численные данные о прогнозируемом разрушении.

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