NUMERICAL ANALYSIS OF FREE UPSETTING CYLINDER USING FEM WITH EXPERIMENTAL VERIFICATION

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Abstract - *This paper describes numerical simulation of upsetting process of cylindrical specimen by flat die performed by Finite Element Analysis on the bases of results of experimental research. Software CATIA V5 R18 is used for modeling and simulation. Having in mind that during the upsetting process large deformation occurred, nonlinear analysis is performed. It is needed to take into consideration large displacement and contact friction, as well as large pressure cylinder and rigid die. Results gained by Finite Element Analysis and by experiment show high degree of similarity, so this way of modeling could be used for even more complex technology of plasticity.*

Key words: *Simulation, FEM, Nonlinear analysis, Experiment, Upsetting of cylindrical*

1. INTRODUCTION

Upsetting cylindric specimen with flat closed-die is elementary operation in the plastic metal forming processes. Besides upsetting method with flat closed-die there are more complicated methods with spheric or conic shape of closed-die. Upsetting process is important part in the heat and cold metal forming processes. Based on upseting process we can research material formability, analize its ductile fracture and form flow curve for material. Large plastic straines and large contact friction betwen closed-die and specimen occur during all kind of upseting processes. This two phenomenon are racily nonlinear and extremely complicate modeling and numeric analysis of upseting process [1]. Numerous analytic methodes for analysis of upsetting process are developed. Unfortunately they enable solutions for few cases due to complicated geometry and complicated contour conditions. Unlike from analytic methods, numeric methods enable substantially larger possibilities in analysis complicated upsetting processes. Finite element method (FEM) is proved as efficient specialy in the analysis of nonlinear problems. Today FEM is applying very efficient in stress and strain analysis in mechanics of deformable body, for determinition of temperature field and thermal flux in stationary and nonstationary heat transfer processes, for determination of velocity, preasure and stress in the fluid mechanics [2]. Numeric analysis of upsetting process, as a extremely nonlinear process, is one of the severest tasks in FEM appliance. Special finite elements are developed for appliance in nonlinear analysis which are able to simulate big plastic strains and contact friction. Unlike from numeric analysis, using FEM in elastic domain during nonlinear analysis it is harder to obtain appropriate accuracy of solution. Obstacles in determination of reliability model for numeric analysis are particulary noticable in metal forming technology due to large plastic strains and contact friction. Therefore it is very important based on more primitive experimental research develop reliable numeric models which are accurate enough in order to based on them we can carry out simulation of more complicated metal forming technologies. When we achieve satisfactory accuracy of numeric simulation then we can take the same dimension of finite elements and coefficient of friction to carry out simulation of more complicated processes with adequate reliability. That means that we can directly start simulation of technology process from CATIA program enviroment after generating appropriate assemble, where are noticable all essential parametars of tehnology with appropriate accuracy. All of that is possible due to integration of nonlinear solver ABAQUS into software enviroment of CATIA V5 R18. That solver is named AFC V2.5. In this paper, based on simple upsetting process of cylinder with flat dies, we shown that represented software combination can very exactly simulate metal forming technology.

2. ANALYSIS OF CYLINDER UPSETTING PROCESS USING FINITE ELEMENT METHOD

Dimensions of cylinder are Ø 20 X 25 mm. Model are generated in software CATIA V5 R18. Because of symmetry we are modeled just one-eighth of the cylinder, where we should pay attention on geometric limits. Cylinder is made of steel (EN: 100Cr6). Analytical form of flow curve for this material represents aproximation expressed as Ludwik dependency $K=423{,}5+658{,}06\varphi_e^{0{,}3412}$ [MPa] [3].

Material are modeled based on analytical form of flow curve so we have certain deviation comparing with behaviour of specimen material in domain of large plastic deformation. Material are modeled as elasticity-plastic with izotropic hardening in plastic domain.

Before forming process specimen was lubricated with mineral oil so on the contact place we have adopted Coulomb friction coefficient $\mu = 0.15$ [4].

Because of symmetry we are generated just one-eighth of the model which is sectionalized in 6606 tetrahedral linear elements type C3D4. Flat die is modeled as solid body which is significantly simplified analysis. Flat die is specified displacement of 10 mm as contour condition and it is equal to vertical displacement of die during experiment. Entire nonlinear analysis was completed after 213 increments.

Based on distribution of displacement which is shown in figure 1 we can notice displacement on place of highest diameter 13.1 mm, which means that highest diameter value according FEM is 46.2 mm, while diameter of specimen obtained using the expetiment is 46.72 mm. It can be stated very good matching results.

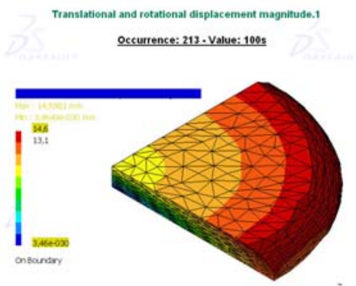

Figure 1 – Distribution of displacement

In experimental research displacement of flat die is 10.09 mm and in that moment the crack observed by the whole amount of compressed cylinder. In figures 2 and 3 distribution of stress is shown for 8 and 10 mm die displacement. It can be observed that already during 8 mm displacement in big part of volume we obtained stress amount 109.6 kN/cm^2, which is the highest stress value and there are already conditions for apperance of crack on contour.

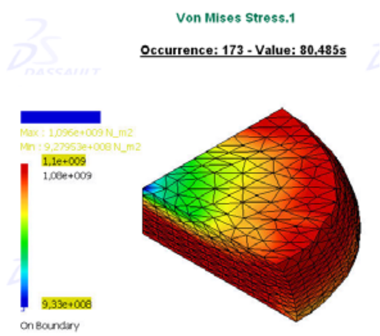

Figure 2- Distribution of Von Mises`s stress (displacement of die 8 mm)

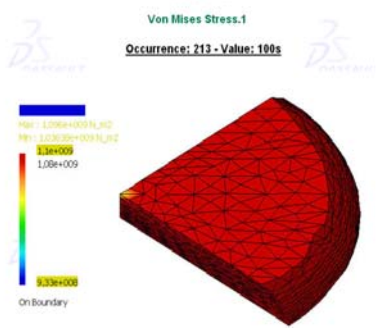

Figure 3 - Distribution of Von Mises`s stress (displacement of die 10 mm)

When given the maximum displacement of flat solid die 10 mm, which corresponds to the end of the upsetting process, it is evident that the maximum stress reached in almost the whole volume. Figures 4 and 5 show the distribution of equivalent plastic strain.

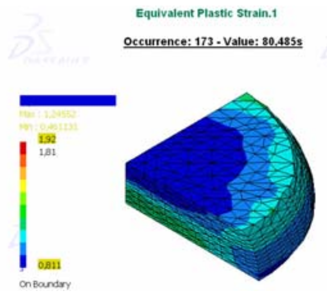

Figure 4 - Distribution of equivalent plastic strain (displacement of die 8 mm)

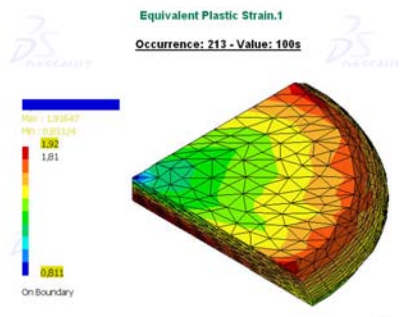

Figure 5 - Distribution of equivalent plastic strain (displacement of die 10 mm)

It can be concluded that the zone of the largest deformation properly distributed and that at the end of the process is well match the results of numerical analysis and experiment. In the numerical analysis we have value φ_e=1.5, and in experiment φ_e=1.6024

Figure 6 show dependence of the largest diameter of the displacement flat plate. It can be seen excellent agreement of numerical and experimental results.

s	0	1	2,5	5	8	10
FEM-D	20,00	21,14	22,74	26,68	34,50	46,20
Exp.-D	20,30	21,24	22,83	26,65	35,10	46,72

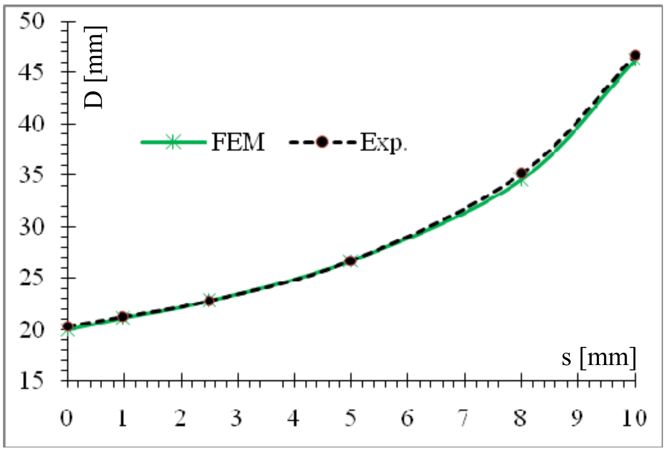

Figure 6 - Dependence of the diameter (D) of the displacement (s)

3. EXPERIMENTAL RESEARCH

Eksperimental research were realized on specimen that are made of steel (EN: 100Cr6). The specified material is chrome steel, and given that the balanced hardness value achieved by the total cross section, is primarily intended for making balls, rollers and roller bearing rings. Table 1 gives the chemical composition.

Table 1 - Chemical composition 100Cr6 [%]

C	Si	Mn	P	S	Cr
≈ 1	0,25	0,35	0,025	0,025	1,5

Generally, experimental research, whose results are presented in this paper, can be divided into two parts: the determination of flow curve and upseting of cylindrical specimen with flat dies.

3.1 Flow curve

Due to the lack of unique analytical connection between the size of strain and specific deformation resistance, flow curves can be determined only by experiment. For this purpose, can be used large number of methods.

The main advantage in defining the flow curves using method of upsetting cylinder is the possibility of achieving a relatively high values of strains of the specimen (over 100 %). However, applying this method, due to the occurrence of friction on contact surfaces, there is the problem of generating bulk state of stress in of workpiece. Therefore, many authors use different ways to reduce the impact of friction force on the contact sheet to the scheme of workpiece state of stress. One of the often encountered possibility is the use of specimen with special shapes and adequate means for lubrication, thus the impact of friction is reduced to negligible measure. In such circumstances the scheme of work-piece state of stress is very close linear form.

In this paper for defining the flow curves Rastegajev methodology is used, which is based on upsetting cylindrical specimens with specific geometry between flat dies.

We used three specimens whose shape is shown in figure 7 with dimensions: d_0 = 20 mm, h_0 = 20 mm, u = 0,6 mm, t = 0,3 mm.

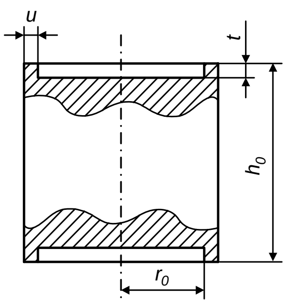

Figure 7 – Specimen with skin front cavity

The process of free upsetting of cylinder using method of Rastegajev is incremental realized in several stages. From the figure 8, where we can see pictures of specimens in different upsetting phases, it can be noticeable that specimen refrain cylindrical shape from start to the end of upsetting process, which represents experimental verification of hypothesis about strain equability of this specimen. Therefore, it can be concluded that we obtained state of stress in specimen very close to axial state of stress, which was necessary condition for experimental determining of flow curve in sense minimization of contact friction impact.

Figure 8 – Pictures of specimen in typical phases during cylinder upsetting using method Rastegajev

Forming of specimen is realized on hydraulic press HP-6.3 MN Sack & Kiesselbach. Stearin are used as means for lubrication. In figure 9 we can see pictures of specimen before and after upsetting process in contact with tool with precisely noticable means for lubrication.

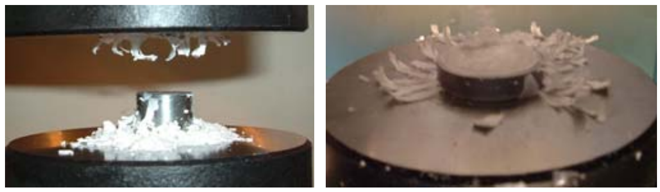

Figure 9 – (a) Picture of specimen before upsetting process, (b) Picture of specimen after upsetting process [3]

Principle of specific forming resistence determining is very simple. Namely, starting from real assumption that axial state of stress is obtained, specific forming resistence and current area of specimen can be determined using following expressions:

$$K = \frac{F}{A}; \quad \mathrm{A} = \frac{d_0 \cdot \pi}{4} \cdot \frac{h_0}{h} \tag{1}$$

When we know specimen height and its appropriate forming force we can calculate specific forming resistence. However, in order to define flow curve (K-φ), it is nesesery to know values of effective strain too. Effective strain, in that case, are determined using following expression:

$$\varphi_e = \ln \frac{h_o}{h} \tag{2}$$

Based on determined paired values of specific forming resistence and efective strain, using statistic processing of results we obtain functional dependence K = K(φ) whose graphic interpretation represents flow curve. We have various approximate forms of flow curve in dependence on strain degree. In this paper flow curve is approximated as Ludwik´s dependence:

$$K = K_0 + A \cdot \varphi_e^b \tag{3}$$

Approximation of flow curve as shows expression (3) is carried out accordingly values of specific forming resistance K was coded by substraction value of K_0 from each value of K. Thus we obtained pairs ($K-K_0$, φ_e) which were approximated in resumption by exponential regresive dependence in following form:

$$\ln(K - K_0) = \ln A + b \ln \varphi_e \tag{4}$$

Coefficients A and b are determined according following expressions:

$$b = \frac{\sum_{i=1}^{n}\left[\ln(K_i - K_0)\cdot \ln \varphi_{ei}\right] - \frac{\sum_{i=1}^{n}\ln \varphi_{ei} \cdot \sum_{i=1}^{n}\ln(K_i - K_0)}{n}}{\sum_{i=1}^{n}\ln^2 \varphi_{ei} - \frac{\left(\sum_{i=1}^{n}\ln \varphi_{ei}\right)^2}{n}} \tag{5}$$

$$A = \frac{\sum_{i=1}^{n}\ln(K_i - K_0) - b\cdot \sum_{i=1}^{n}\ln \varphi_{ei}}{n} \tag{6}$$

Finaly, analytic form of flow curve for steel (EN: 100Cr6) is: $K=423{,}5+658{,}06\varphi_e^{0,3412}$ [MPa].

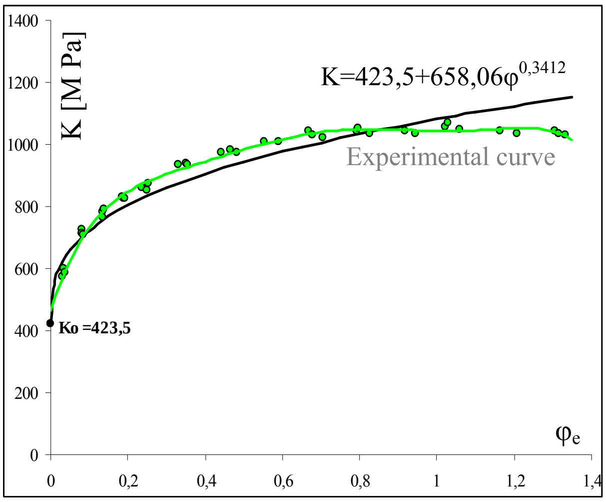

Figure 10 – Flow curve for steel (EN: 100Cr6) [3]

Approximative form of flow curve graph for steel (EN: 100Cr6) in mathematical sense is monotonous increasing function, and shows an increase of forming resistance (K) with increasing degree of strain (φ). However, the experimental flow curve (Figure 10) shows that after the achieved degree of strain $\varphi \geq 0.8$ comes to the fall of the value of this parameter. Such behavior of materials at the experimental research suggests certain changes in structure that lead to a reduction in forming resistance when we have increasing the degree of strain.

3.2 Upsetting of cylinder with flat dies

The second part of experimental research refers to the process of upsetting cylindrical specimen with flat dies. In this sense we used three sample sizes Ø 20 x 25 mm. In figure 11 we can see the view of a specimen before and after crash with a clearly visible crack that marked the end of the upsetting process.

Free upsetting of cylinder with flat dies belongs to a group of plastic forming processes which aren't monotonous. However, using the incremental procedure of upsetting, it is possible to upsetting certain phases considered monotonous process and applying the theory of plasticity to obtain expressions for determining the components of stress.

Figure 11 - Specimen with initial dimensions Ø 20 x 25 mm before and after crash [3]

The deformation processes in cylindrical specimens in free upsetting processes, the identification of stress components in the critical zone (outer surface of equatorial cross section of the specimen) is much easier, because in this case we have plane state of stress. As the component of the radial stress on the outer surface is zero ($\sigma_r = 0$), it follows that the r-axis direction at the same time and direction of the principal stress. Direction, which determines θ axis is also the direction of the principal normal stress because it is considered that the flow of metal during upsetting process is symmetrically in relation to the longitudinal axis z, which in these circumstances must represents a third direction of the principal normal stresses. In this paper, the identification of state of stress and strain was carried out by applying forming theory, based on established geometry of the specimen in upsetting process stages.

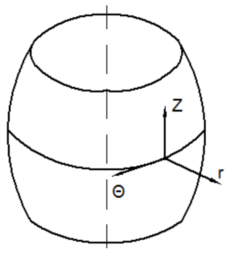

Figure 12 – Scheme of specimen during free upseting process

Components of stress on the free surface of equatorial cross section of the specimen were determined on the basis of forming theory [4]:

$$\sigma_z = -\sigma_e \left[1 - \left(\frac{1+2\cdot\alpha}{2+\alpha}\right) + \left(\frac{1+2\cdot\alpha}{2+\alpha}\right)^2\right]^{-\frac{1}{2}} \tag{7}$$

$$\sigma_\theta = \sigma_z \left(\frac{1+2\cdot\alpha}{2+\alpha}\right) \tag{8}$$

where α represents the ratio of increase of logarithmic strain in the direction *z* i θ axis.

Equivalent strain for the case of incremental upsetting process of the cylindrical specimen is determined by the form (9):

$$\varphi_e = \frac{2}{\sqrt{3}}\sqrt{1+\alpha+\alpha^2}\,\varphi_z \tag{9}$$

The average values of the characteristic geometric sizes of the specimen and stress and strain components in stages of upsetting process for the set of specimens with same starting geometry are given in table 2.

Table 2 - Displey of exprimental results [3]

N_0	h_i [mm]	d_i [mm]	φ_{hi}	$\varphi_{\theta i}$	α_i	φ_{ei}	$\sigma_{zi/K}$	$\sigma_{\theta i/K}$
0.	25,160	20,300	0,0000	0.0000	--------	0,0000	-1.0000	0.0000
1.	24,190	20,720	-0,0393	0,0205	-0,5209	0,0393	-0,9858	0,0278
2.	23,080	21,240	-0,0863	0,0453	-0,5246	0,0863	-0,9832	0,0328
3.	22,170	21,745	-0,1265	0,0688	-0,5435	0,1267	-0,9698	0,0579
4.	20,200	22,830	-0,2196	0,1175	-0,5349	0,2198	-0,9759	0,0465
5.	18,360	24,020	-0,3151	0,1683	-0,5340	0,3153	-0,9766	0,0454
6.	16,720	25,335	-0,4086	0,2216	-0,5422	0,4091	-0,9707	0,0562
7.	15,130	26,645	-0,5086	0,2720	-0,5348	0,5090	-0,9760	0,0463
8.	13,650	28,020	-0,6115	0,3223	-0,5270	0,6118	-0,9815	0,0360
9.	12,460	29,460	-0,7027	0,3724	-0,5299	0,7032	-0,9794	0,0399
10.	11,200	31,130	-0,8093	0,4276	-0,5283	0,8098	-0,9806	0,0377
11.	10,030	32,865	-0,9197	0,4818	-0,5239	0,9200	-0,9837	0,0318
12.	8,880	35,100	-1,0415	0,5476	-0,5258	1,0419	-0,9824	0,0344
13.	7,900	37,075	-1,1584	0,6023	-0,5200	1,1587	-0,9864	0,0266
14.	7,030	39,305	-1,2751	0,6607	-0,5182	1,2754	-0,9877	0,0243
15.	6,120	42,130	-1,4137	0,7301	-0,5165	1,4139	-0,9888	0,0220
16.	5,070	46,720	-1,6019	0,8336	-0,5203	1,6024	-0,9862	0,0271

4. CONCLUSIONS

In the application of FEM to model the processes, in which plastic deformation are dominant, special attention should be paid to the modeling of contact conditions between tool and specimen. At the end of the process when large deformation occurs, the coefficient of friction is not constant. This is the main reason for discrepancies in results compared to experiment, in addition variations of material model in the analysis using FEM. In the simulation processes that are nonlinear, the impact of finite element size on accuracy and convergence of solutions is increased. Applying a smaller size of finite element to the model of these processes, computer calculations time for analyses is rapidly increases. This process often takes a few hours at the best performance computers, and often is the case of divergence of the solutions.

However,in the numerical analysis of free upsetting cylinder, the model is divided into 6066 tetrahedral elements, which allowed a very good agreement between numerical and experimental results. Discrepancies of results during the process are constant and approximately about 1%.

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