SPRING-BACK PREDICTION FOR STAMPINGS FROM THE THIN STAINLESS SHEETS

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The metal forming technology is (mainly due to the automotive industry) one of the most dynamically developing branch of the engineering industry. Continuous effort to achieve the top technological level and car´s safety factor at keeping the low price level means necessity to still implement into the own production process the newest mathematical models of these technological processes. Thus these days represents utilization of the numerical simulations an essential part for the car shape lay-out design, for determination the basic technological operations and also e.g. for stamping tools shape optimization. Alongside such implementation of the newest materials into production reveals necessity to develop new and more precise computational models of materials deformation behavior as well as models designed for spring-back prediction. Nowadays, in the branch of the metal forming technologies, there are several truly top software among which also belongs software PAM-STAMP 2G. In this article is evaluated influence of the computational model on the numerical simulation accuracy by PAM-STAMP 2G at the spring-back prediction. For the deformation analysis it was chosen stainless sheet material DIN 1.4301 and for the spring-back prediction were used two anisotropic computational models termed as Hill-48 and Vegter in combination with the kinematic hardening model termed as YOSHIDA UEMORI. Accuracy of the measured results from the individual computational models is evaluated by the compliance of the carried out experiment and results from the numerical simulations. For the own experiment was chosen test where material is drawn over the drawbead and drawing edge.

KEYWORDS

spring-back, numerical simulation, computational model, stainless sheet

1 INTRODUCTION

Nowadays are on the sheet stampings posing quite strict claims mainly in light of their strength, surface quality and dimensional accuracy. Stiffness and strength of produced part is essentially influenced by its shape and selection of material. Thus as a necessary condition for the technological process proposal is there resolution of the chosen material deformation to achieve final shape of stamping at the required quality (allowed sheet thinning, sufficient strain of sheet in areas with the low deformation, wrinkling of stamping, elimination of surface defects occurrence and so on) [Dobransky 2015].

Achieving the shape and dimensional accuracy of the formed part in bending is closely connected mainly with the material spring-back. Such truly very undesirable effect (spring-back) is possible to be eliminated by the suitable proposal of the technological operations and shape correction of the stamping tool. Design changes at the new types of the car-bodies quite markedly increase the requirements for shape and dimensional accuracy of sheet stampings and it also forces the processors of sheet to implement the newest methods which can fulfill these targets. Among such methods belongs mainly increasing of the technological processes mathematical modeling ratio in the pre-producing and producing phases because they enable to make quite flexible reaction on the solving problem.

Spring-back of the drawn stampings differs by its technological principle from products produced only by bending. Difference rests mainly in the deformation evolution and stress state on the drawing and bending edge of tool. At the conventional types of bending is major stress direction in the cross-section area tensile (on the outer side) and compressive one (on the inner side). Important is fact that during the bending process is changed magnitude but not sense of these stresses. Thus there is not influence of the Bauschinger effect. However, at the drawing process is material on the drawing edge bended in the first phase and then it is straightened in the second phase. Thus here occurs Bauschinger effect during the material hardening. This paper is focused into the area of utilization mathematical modelling for spring-back prediction at sheet stampings and to determine influence of the individual computational models on the results of performed tests. To evaluate the exercise of the Bauschinger effect influence at spring-back prediction by the mathematical modelling there were selected two anisotropic yield criterions termed as the Hill-48 and Vegter in combination with isotropic and kinematic hardening of formed material. Due to the high magnitude of spring-back, there was for this test chosen stainless material DIN 1.4301 because there was strong presumption to prove the influence of individual computational models on the test results.

2 METHODOLOGICAL BASES AND EXPERIMENTAL PART

2.1 *Static tensile test*

To define the material model Hill-48 was necessary to carry out the static tensile test and determined the normal anisotropy coefficients in the directions 0°, 45°and 90°regarding the rolling direction. Conditions of tests were chosen to be comfortable with the standard EN ISO 6892-1 and EN ISO 10113. From the measured values of static tensile test in the individual directions were subsequently computed the hardening curves of true stress σ in dependence on true strain ε. With respect to mathematical definition of hardening curves in model Hill-48 was made their approximation by power-law function as:

$$\sigma = K.(\varepsilon + \varepsilon_0)^n \qquad (1)$$

where:

K	- strength coefficient	(MPa)
n	- strain hardening exponent	(-)
ε_0	- offset of strain	(-).

Computed fitting constants acc. to equation (1) are, together with values of the normal anisotropy coefficients, summarized in table 1. Hardening curves for the tested material DIN 1.4301 regarding the individual directions are shown in fig. 1.

Table 1. Values of the fitting constants and normal anisotropy coefficients in dependence on temperature

Rolling direction	K (MPa)	n (-)	ε_0 (-)	R (-)
0°	1469,5	0,498	0,0403	0,871
45°	1372,8	0,512	0,0473	1,139
90°	1415,7	0,532	0,0522	0,787

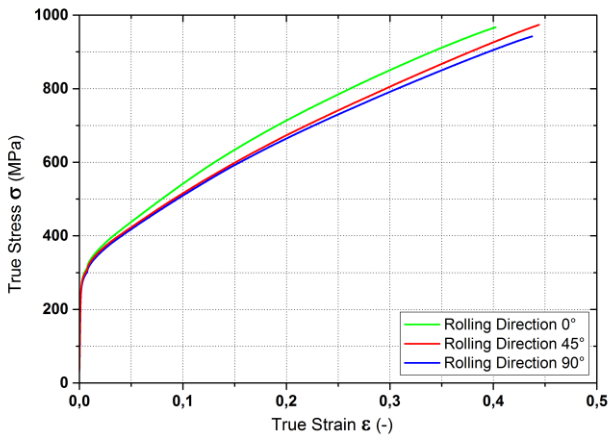

Figure 1. Hardening curves from the static tensile test – DIN 1.4301

2.2 Hydraulic bulge test (HBT)

For proper definition of the Vegter yield criterion is especially necessary to carry out the so-called hydraulic bulge test (HBT). The hydraulic bulge test represented the second major part of the experiment. For this test is very important fact that there is bi-axial stress state cause it is very important "point" for the future utilization in the different yield criterions. Due to the different stress state in comparison to the static tensile test, for its stress-strain curve it is necessary to compute so-called effective stress σ_{EF} (MPa) and effective strain ε_{EF} (-). Computation of all important values is summarized by means of equation (2), (3) and (4) [ASM HANDBOOK].

$$\sigma_{EF} = \frac{pR}{2t} \tag{2}$$

$$\varepsilon_{EF} = \frac{2\sqrt{3}}{3}\sqrt{\varepsilon_1^2 + \varepsilon_1\varepsilon_2 + \varepsilon_2^2} = \varepsilon_3 \tag{3}$$

$$t = t_0 e^{\varepsilon_3} \tag{4}$$

where:

σ_{EF}	effective stress	(MPa)
p	pressure	(MPa)
ε_{EF}	effective strain	(-)
R	radius of curvature	(mm)
$\varepsilon_{1,2,3}$	true strains	(-)
t, t_0	actual and initial thickness	(mm).

For the own measurement of the hydraulic bulge test there was used the contact-less optical system ARAMIS. The principle of such measurement is shown in Fig. 2. Measured material is placed between upper and lower blank-holders and two scanning cameras are added right before the tested material (stainless steel DIN 1.4301).

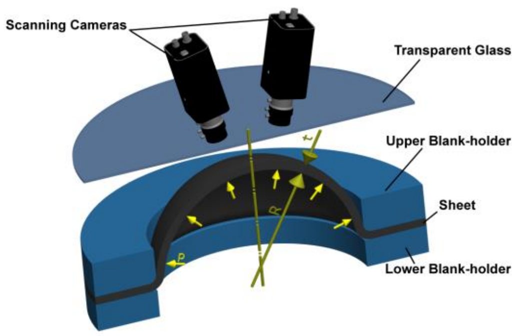

Figure 2. Principle of the hydraulic bulge test with contact-less optical system ARAMIS

As the whole evolution of the hydraulic bulge test was scanned by the contact-less optical system ARAMIS, subsequently it was possible to compute distribution of both major strain ε_1 and minor strain ε_2 within the required area (top of the sphere). Due to that was also possible to compute strain in the thickness direction ε_3 which is important to know for computation actual thickness - see equation (4). Finally by fitting best-fit sphere over computed part it was possible to find out required radius of curvature R [mm]. After that it was possible with equations (2), (3) and (4) to compute effective stress σ_{EF} and effective strain ε_{EF} and to plot stress-strain curve for the bi-axial stretching state of stress (the hydraulic bulge test). From these values was subsequently created the scatter plot - see Fig. 3. It is not possible to use continuous increasing of pressure due to time delay in sensor and hoses. After that was also used (as in the case of the static tensile test) the power-law equation acc. to Swift-Krupkowsky and via fitting (nonlinear curve fit) was computed the hardening curve and all constants (K, n, ε_0). Values of these constants for the hydraulic bulge test were as following: K = 1676 MPa, n = 0.6617 and ε_0 = 0.06219. Such values are truly very important to compute the very significant bi-axial point in the advanced computational models in numerical simulations (e.g. for Vegter yield criterion). Beside values of uni-axial tensile (eventually compression) point and normal anisotropy coefficients are these values the crucial for proper computation of required yield criterion.

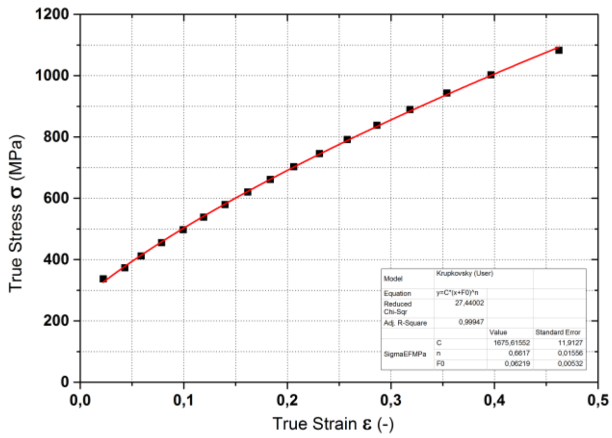

Figure 3. Results from the HBT – stainless steel DIN 1.4301

2.3 Cyclic test

To define the material model termed as Yoshida-Uemori there is needed to carry out such cyclic test under that can take effect the change in sense (+, -) of the tested sample loading [Yoshida 2003, Hassan 2016]. Due to the compressive stress states is carrying out of this test for sheet samples very demanding and there is loss of stability resulting as sample buckling. Because of these reasons was at Department of Engineering Technology designed the testing jig which enables to carry out cyclic test for sheet sample on the device for the static tensile test. Such testing jig was designed as additional device of the clamping grips. Testing jig consists of four subdivided supporting grips that are hydraulically controlled and prevent the sheet sample from buckling during the compression. Strain magnitude is recorded by the contact length-gauge with high accuracy. As a result from test there is cyclically repeating course of tensile and compressive stress in dependence on deformation. The offset of individual measured curves from monitored cycles rests in the magnitude of Bauschinger effect for tested material [Shun-lai 2009]. Own lay-out arrangement of the cyclic test is clearly shown in Fig. 4. Results for the measured magnitudes are evident from the graph which is shown in Fig. 5.

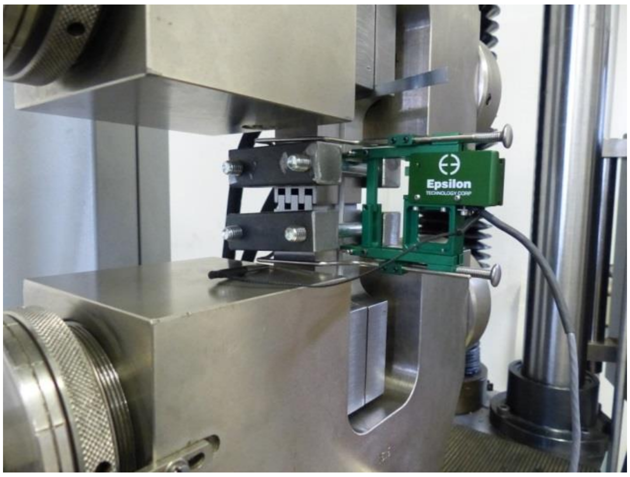

Figure 4. Arrangement of the cyclic test on the device TIRA Test 2300

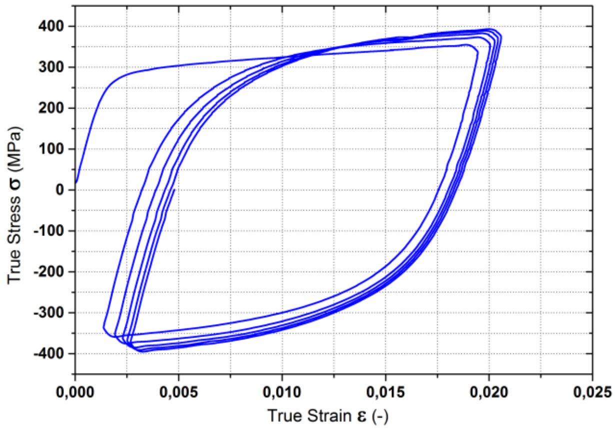

Figure 5. Cyclic test results for the stainless material DIN 1.4301

2.4 *Experimental measurement of the spring-back*

For experimental determination of the spring-back it is suitable to choose such test when change of stress state occurs in the bending area because in this case can be fully developed the so-called Bauschinger effect [Taherizadeh 2009]. Regarding the labs equipment of the Department of Engineering Technology was for spring-back analysis chosen test when sheet sample is drawn over the drawbead and drawing edge of the testing jig. Thus such procedure simulates the process which occurs in the drawing tools. During test is sheet sample bended 4x and always with the opposite sense (+, -) then in the previous case. Principle of test is obvious from Fig. 6.

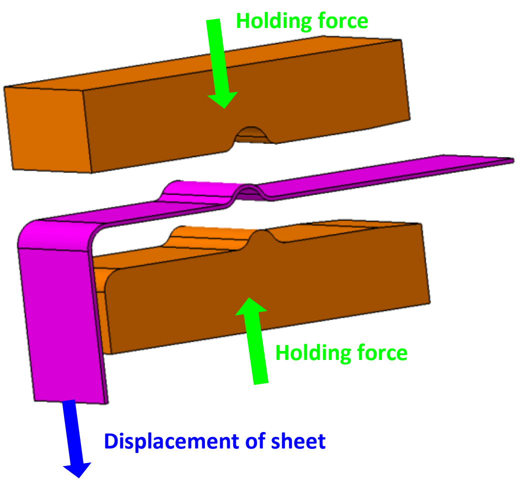

Figure 6. Strip drawing test over the drawbead and drawing edge

The magnitude of the blank-holder force was necessary to set so that testing clamps were closed fully and there were created bends in drawbead. Conditions of test were as following: magnitude of normal holding force 12 kN, feed rate 10 mm·s^{-1} and sample displacement was 200 mm. After termination of test was sheet sample subjected to dimensional and shape analysis on 3D coordinate measuring device SOMET XYZ 464 with relevant software TANGO !3D for their evaluation. As a result of the experimental measurement there is array of points in the step format that copies the real shape of sample. Sheet contour is defined by 70 measured points among which is finally fit the SP_line curve. Measuring and result from experiment is evident from Fig. 7. The obtained contour of sheet is subsequently used as comparative criterion to verify matching between experiment and numerical simulation in the environment PAM-STAMP 2G.

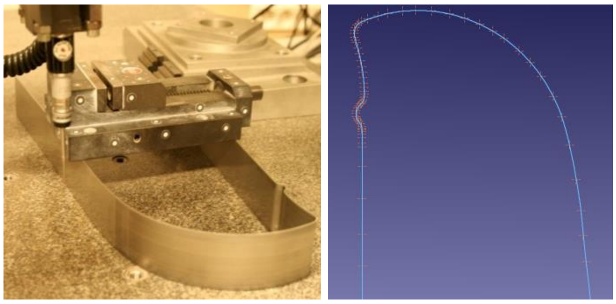

Figure 7. Measurement of the shape after spring-back

3 NUMERICAL SIMULAION OF THE SPRING-BACK

For numerical simulation of the spring-back was used software PAM-STAMP 2G. For its mathematical computation was applied yields criterions termed as Hill-48 and Vegter and these yield criterions were combined always both with the isotropic and kinematic hardening model. That is why there were used four computational models and their results were compared with the results measured from the real experiments.

3.1 *Definition of the material models*

To define the Hill-48 yield criterion in software PAM-STAMP 2G is firstly needed to enter into the material card the following values: Young´s modulus, Poisson´s ration, density of material, normal anisotropic coefficients in directions 0°, 45°and 90° and average yield strength magnitude. Thus for its definition it is enough to make static tensile test in three directions. Advanced yield criterion (termed as Vegter one) enables at its definition to take into account individual tested directions and beside the static tensile test to use also results from tests carried out at the multi-axial stress state. These are mainly results from the bi-axial test (hydraulic bulge test), shear test and the plane strain test. Material cards of the tested material DIN 1.4301 for both used yield criterions in software PAM-STAMP 2G are shown in fig. 8. In the plastic deformation area there were used two hardening models. The first one is termed as an isotropic hardening model and in the software PAM-STAMP 2G is defined by equation (1). Fitting constants that are used in this equation (1) are given as directionally average from measured values in the individual directions 0°, 45° and 90°. The second deformation behavior model termed as Yoshida uses results from the cyclic test. Thus in the second case there is a kinematic hardening model which is able to measure the Bauschinger effect influence that occurs in the area of the drawbeads and drawing edge in testing jig. Deformation hardening models used for the finite element analysis (FEM) are illustrated in Fig. 9.

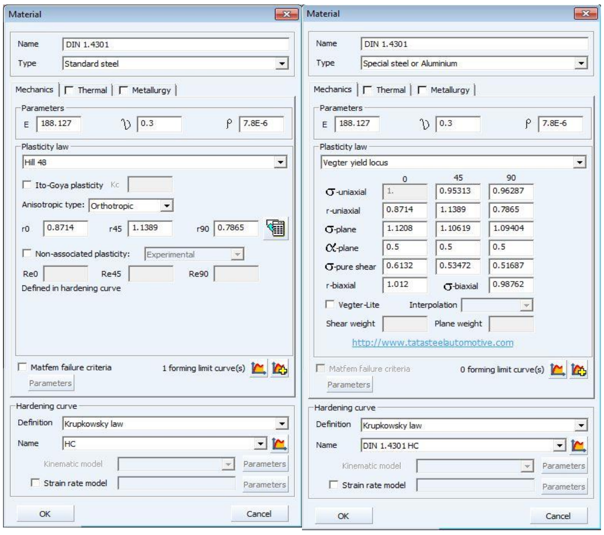

Figure 8. Definition of the Hill-48 and Vegter yield criterion

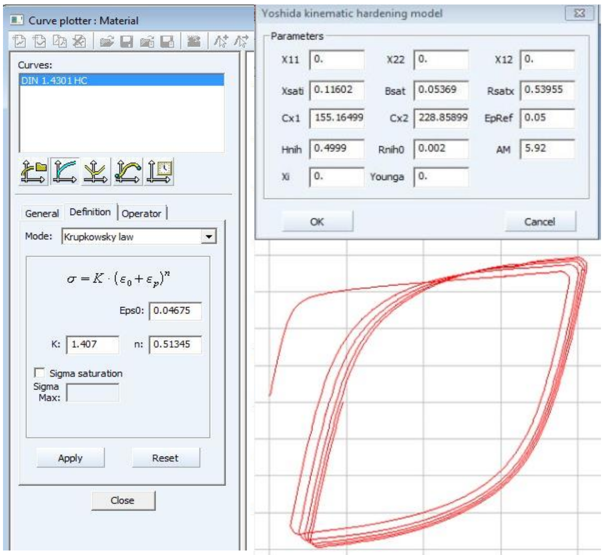

Figure 9. Isotropic and kinematic hardening models (Yoshida)

3.2 Problem setting in the environment PAM-STAMP 2G

Boundary conditions for the numerical simulation were set in such manner so that they corresponded to the performed test. Tools with the drawing material in the PC environment are shown in Fig. 10. Before the own sheet displacement in tool, there was necessary to close the virtual clamps by defined force 12 kN and to bend sample by 90° over the drawing edge. For this purpose was needed to create the auxiliary bending tool - in Fig. 10 is marked in green. Subsequently there was only sheet displacement by the distance 200 mm.

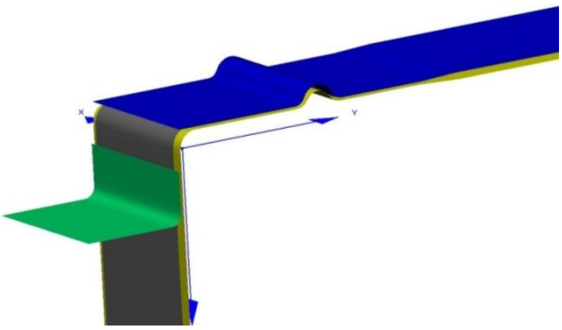

Figure 10: Virtual model in the environment PAM-STAMP 2G.

After drawing of the sample there was own computation of the spring-back and its results were compared with the experiment. In Fig. 11 (left) is shown result from the numerical simulation without spring-back when the sample was just drawn over the drawbead and drawing edge. Same sample after spring-back computation in PAM-STAMP 2G is in Fig. 11 (right). There is evident big influence of the spring-back on the sample shape.

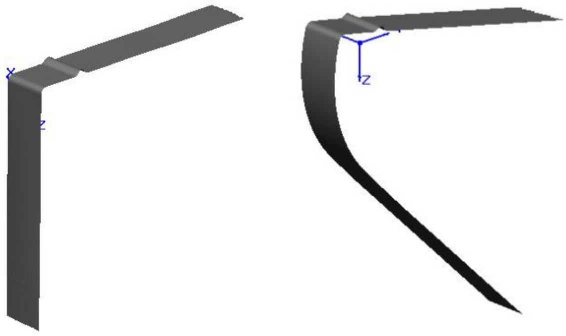

Figure 11. Sample without spring-back computation (left) and with the spring-back computation in the environment PAM-STAMP 2G (right)

3.3 Comparison of results from the experiment and the numerical simulation (PAM-STAMP 2G)

As a criterion for comparison suitability of the computational model for the monitored problem there was used the shape matching between the real sample shape and shape of the sample from the numerical simulation. There were evaluated all four used mathematical models regarding the real sample shape. With respect to fact that selection of Hill-48 or Vegter yield criterion didn´t strongly influence results and regarding the length of paper is in Fig. 12 and 13 shown only fundamental difference between tested deformation hardening model (isotropic and kinematic hardening model termed as Yoshida). In Fig. 12 is illustrated the result comparison of the experiment and computational Vegter model in combination with the isotropic material hardening. Almost the same result was observed for the computational model Hill-48 in combination with the isotropic hardening.

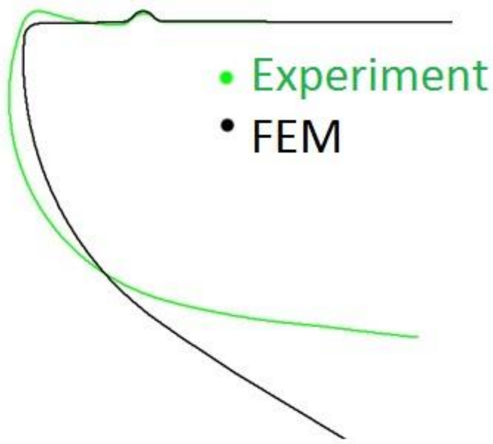

Figure 12. Comparison of result (in light of shape) for the experiment and for the numerical simulation for Vegter model in combination with the isotropic hardening

From Fig. 12 it´s obvious that selected computational model with the isotropic hardening isn´t able, with sufficient accuracy, to simulate processes which occur just beyond the drawbead.

Compared to reality when spring-back occurs also beyond the drawbead, numerical simulation reveals spring-back as far as beyond the drawing edge of the testing jig.

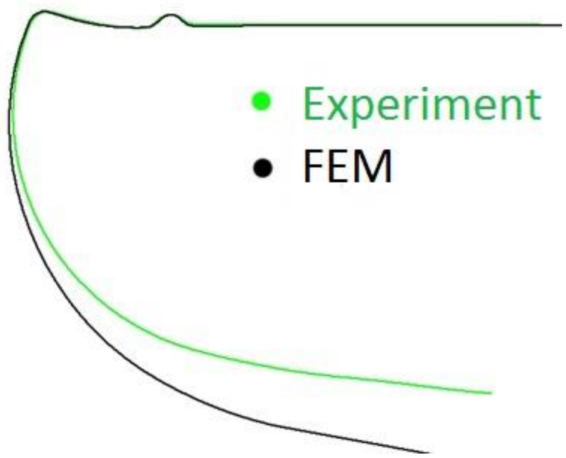

Figure 13. Comparison of result for the experiment and the numerical simulation for Vegter model in combination with kinematic hardening

4 CONCLUSIONS

Selection of the proper mathematical model for solving all types of technological problems is a basic factor that influences the quality of achieved output. Thus creation of mathematical model and obtaining all necessary data inputs represents mostly very time-consuming phase in mathematical modelling. However at selection mathematical model it is important to take into account that individual factors which enter into FEA don´t influence results in the same manner. It is very suitable to qualify their influence ratio already at the beginning of FEA. In this paper was tested mathematical model influence on the accuracy of prediction stamping spring-back. There were tested and evaluated 2 yield conditions termed as Hill-48 and Vegter in combination with isotropic and kinematic hardening. For FEA was used software PAM-STAMP 2G. Suitability of the individual tested mathematical models for given problem was made by the comparison of results from the experiment and numerical simulation. As a criterion for evaluation such mathematical model suitability, there served the shape matching of samples. From the measured and computed results arises that tested Hill-48 and Vegter yield criterions do not strongly influence the result of mathematical problem. This is probably due to the character of this problem when there aren´t big deformation in the strain area. Quality of the selected yield criterion would take bigger effect at the most complicated problems. On the other hand, truly very important influence on the spring-back magnitude has selection of the deformation behavior model. The kinematic hardening model reveals much better matching with experiment than isotropic deformation behavior model. The highest matching between FEA and experiment was achieved by the Vegter yield criterion and kinematic hardening model termed as Yoshida. Nevertheless, also results of mathematical model Hill-48 in combination with the kinematic hardening model revealed quite good matching with the experiment. Regarding much shorter time that is necessary to gain input data for model Hill-48, there should be carefully considered whether to use Vegter yield criterion for the simpler problems. For complicated stampings with presumed big deformation is recommended to use the advanced yield criterions. Presented results proved that the crucial influence on the spring-back prediction rests in selection of the deformation hardening model and that the yield criterion doesn´t influence result as much.

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