EXPERIMENTAL AND NUMERICAL APPROACHES TO IMPROVE SPRINGBACK PREDICTION AND COMPENSATION

Mihael Deželak[1*]*, Andrej Stepišnik*[1]*, Ivo Pahole*[2]*, Mirko Ficko*[2]*,*
[1]*Emo -Orodjarna d.o.o., Slovenia*
[2]*University of Maribor, Faculty of mechanical engineering, Slovenia*

ABSTRACT

Striving after passenger´s safety, reduced fuel consumption and environment protection tendency lead automotive industry to development and use of new materials with higher strength. However, higher values of strength usually lead to reduced formability and increased sensitivity of springback. Today, springback is one of the most important factors that influence the quality of sheet metal forming products. We separate the following types of springback considering the geometry of the product and the forming regime: angular change, sidewall curl and twist. During the forming process, sheet metal undergoes a complicated deformation history, which is why the accurate prediction and consequently the compensation of the springback can be very difficult. In this paper the procedure for springback prediction and compensation of car body parts is presented.
Key words: *sheet metal forming, machine learning, springback compensation, FEM simulation*

1. INTRODUCTION

The springback phenomenon is the result of the stress state in the material following the forming process and means a change of shape in the sheet metal forming product after the removal of the forming forces. Steel sheets with high strength and aluminium alloys are more sensitive to the springback effect due to the greater degree of elastic deformation than conventional mild steels. There are three general types of springback considering the geometry of the product and the forming regime: angular change, sidewall curl and twist (Fig. 1) [1]. During the deep drawing process, sheet metals show a combination of angular changes and sidewall curls which usually occur in the walls of the products, while the effect of torsion springback deviation (twist) is visible in the entire area of the product with changeable cross-sections.

* Corresponding author E-mail address: mihael.dezelak@emo-orodjarna.si

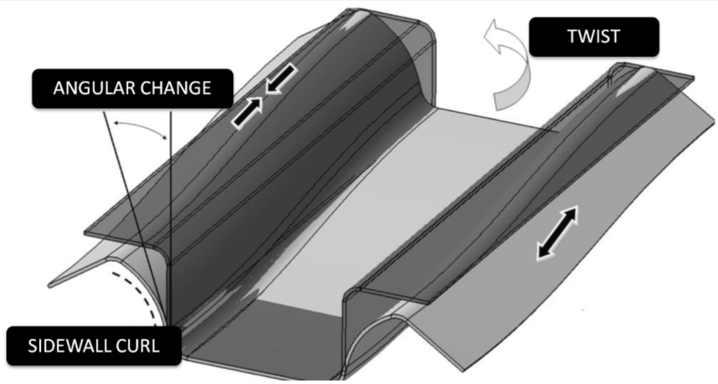

Fig. 1 *- General types of springback*

Angular change follows the sheet metal bending in plain strain, when a sheet metal strip is bent over a punch radius. The stress gradient in the thickness direction causes the residual bending moment after tool withdrawal. This bending moment is the reason for the geometrical errors in the shape of the part angle deviation compared to the punch angle after the bending operation. The key to eliminate the angular change is to eliminate or minimize this residual bending moment.
Sidewall curl occurs when the sheet metal is drawn over the die radius or through the drawbead. Sheet metal undergoes a bending and unbending process and both cause uneven stress distribution through the thickness direction. Sidewall curl is seen as a drawing part wall curvature deviation compared to the geometry of the forming tools.
Torsional springback or twist is defined as two-cross sections rotating differently along their axis caused by torsion moments [1]. They occur because of the unbalanced elastic residual stresses in the flanges and walls of the sheet metal part. The geometrical parameters of the sheet metal part have the biggest influence on the twist springback. Maximizing the torsional stiffness of the part by adding geometrical stiffeners (ribs) or by redesigning to avoid long, thin sections is a common strategy for twist springback minimization.

2. SPRINGBACK MODELLING METHODS

2.1 Numerical Simulations with FEM Approach

Finite element method (FEM) simulations are nowadays the most important tool for springback behaviour prediction of sheet metal parts in the process design step [2]. Presented below are several examples of FEM springback simulations compared to measured experimental values. In all cases special software for sheet metal processes (PamStamp) simulation was used.
Springback after bending (angular change) is the simplest case of geometrical deviation after the forming punch removal. For pure bending of dual phase sheet metal strips (thickness 1.2mm, tensile strength 780MPa) we can see the comparison between the FEM simulation and the experimental data (Fig. 2). The effects were analysed of the sheet metal rolling direction on springback after bending with a 5mm punch radius. Although we can see some deviation between the simulation and the experiment results, the tendency of springback according to the rolling direction is comparable.

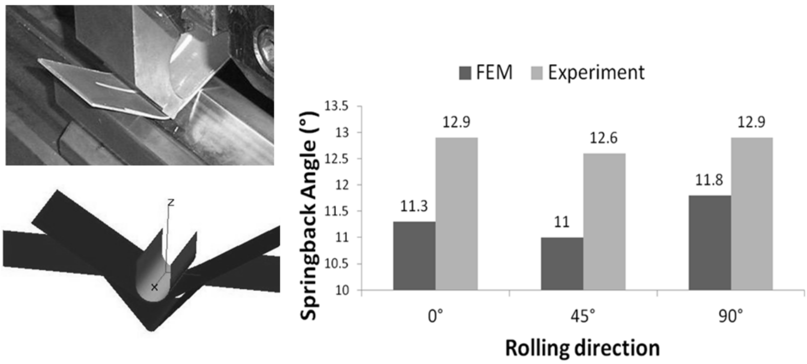

Fig. 2 *- Springback after the pure bending test*

The next case of springback is presented in an experiment called the draw/bend test. This is a simplified method of the deep drawing process, where the sheet metal is pulled over the radius. After the experiment progression, springback occurred. It is the result of flexible angular changes and sidewall curl. Their sum is expressed in $\Delta\theta$ angle. Details of the experiment and the results were summarized by source [3]. Figure 3 demonstrates the comparison of the experimental springback results and the results of FEM simulations for the HSLA material.

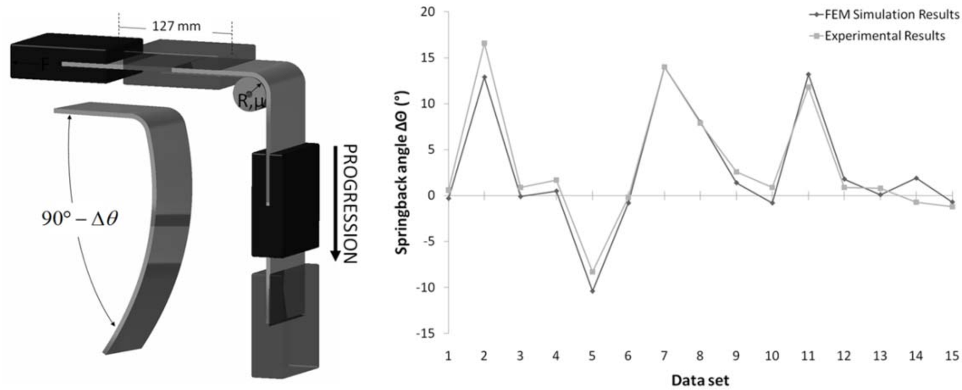

Fig. 3 *- Draw/bend test*

The next example [4] presents the prediction of springback of an industrial case (Fig. 4), as calculated using numerical simulations and compared to experimental measurements. Comparison of the simulation and the experimental results show some deviation. The main reason could be in using a relatively simple material-model (Hill 48), which is good enough for forming simulations, but has some disadvantages in springback modelling. This yield criterion is today widely used and for this reason, the accuracy of the springback simulations is still limited. In spite of the deviation, the springback tendency is clearly seen and this data are very useful in forming process design.

It is necessary to know and understand the influence of numerical parameters on the simulation results for the successful application of the finite element method to predict springback. Plenty of numerical parameters in each simulation step (tool closing, forming, springback) can have a significant impact on final springback prediction results. Careless determination of the numerical parameters can cause additional errors in the FEM approach.

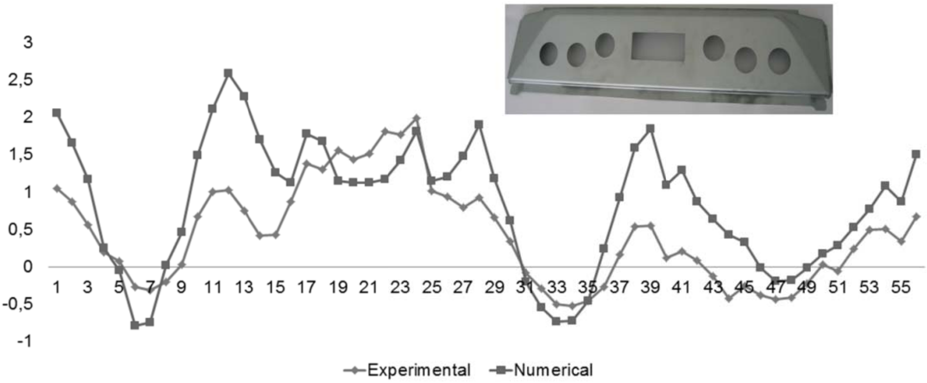

Fig. 4 *- Springback results (experimental and numerical) after deep drawing the industrial part.*

Springback is calculated with the FEM software based on implicit or explicit algorithms. One of the most important parameters when using explicit algorithms is defining the velocity of the forming tools. It is usually overestimated, because this reduces the CPU time of the whole forming simulation. We checked the influence of the prescribed die velocity for a simple forming case of a U- drawing part and found some connections (Fig. 5 right). The starting velocity was defined as a growing function up to 5m/s and multiplied by the reduction factor *k*. The effect of the latter was analysed. When *k* = 1 (the highest velocity) simulations show less springback compared to values of 0.5 and 0.1.

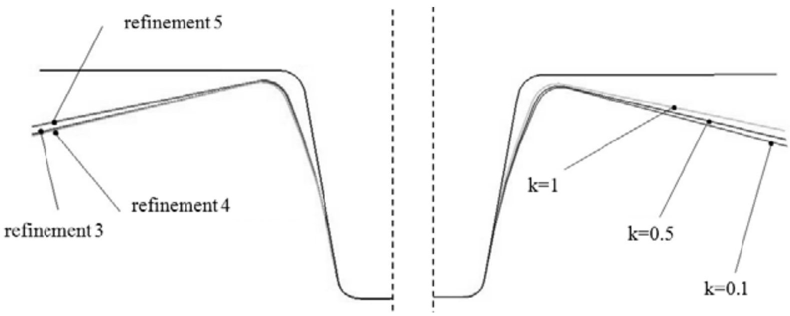

Fig. 5 *- The effect of the blank mesh refinement and die velocity on springback.*

The blank mesh refinement during the forming process is also a very important numerical parameter. The adaptive meshing automatically refines the mesh in the blank areas where it is important relating to the die or punch geometry.

According to the same size of the mesh elements on the start of simulation we can see (although in our case it is not so clear) the effect of the different meshing parameters on the FEM springback prediction. The more fine mesh is used the more the springback appears (Fig. 5 left).

The preliminary condition of a successful springback prediction is therefore a more precisely prepared numerical simulation. This means better tool mesh quality, advanced contact definition, lower forming velocities, sufficient number of integration points through the thickness [5].
In view of the above-presented comparisons between the FEM and the experimental springback results we can see some degree of unreliability in the FEM springback predictions. We think that the reasons lie in the sheet metal forming process being too simplified when it is modelled. In other words: it is hard to make a representative model of such a complicated process. Besides complexity, a problem of the robustness of the sheet metal parts' production can play an important role in the geometrical deviations and for this reason a stochastic analyses of springback should be integrated into the design chain.

2.2 Machine Learning Models

Using machine learning methods, branches of computational intelligence, has flourished in recent years in many areas [6, 7], as computers become more powerful and accessible to a wider circle of researchers and users in industry. Sometimes artificial intelligence methods are used for improving springback prediction, mostly for academic examples. They can be used as optimization algorithms or as an evaluation method. Combining the FEM methods and artificial intelligence can improve our springback prediction to better reflect the measured data [8].
In the following case for improving the FEM springback results a Weka workbench was used [9]. The Weka workbench is a collection of ML algorithms and data preprocessing tools. It includes methods for all the standard data mining problems: regression, classification, clustering, association rule mining, and attribute selection. We used classification methods under the function category, because the "new knowledge" can be written down as a mathematical equation in a reasonably natural way. In our case, the ML system based on experiments and the simulation draw/bend test, and six different algorithms were used: *Linear Regression, Isotonic Regression, Least Medium Square, SMO, Gaussian Processes and Multilayer Perceptron* [9].
The attributes (inputs) for each case of sheet metal material were radius, normalized holding force or back force, the coefficient of friction, sheet thickness, yield stress, factor of normal anisotropy, elastic module and the result of the FEM simulation. The regression variable as a measured angle value in the experiment we assume to be absolutely correct.

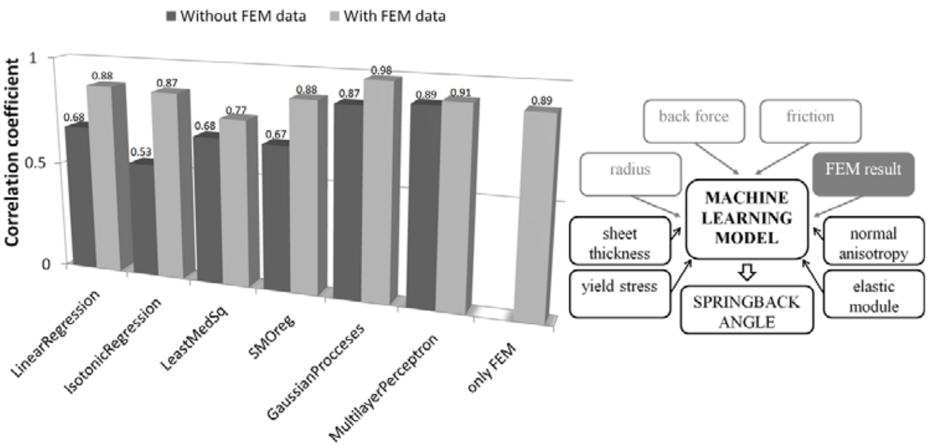

Fig. 6 *- Finite element method combined with machine learning for springback prediction*

If we take a look at the results (Fig. 6) of the correlation coefficients we can see that the last three tested methods (SMO, Gaussian Processes and Multilayer Perceptron) are more suitable for springback prediction. One of the reasons is definitely in the nonlinearity of the complex springback phenomenon and these methods are able to model these kinds of phenomena. However, in combination with the FEM it raises the correlation coefficient to a higher level compared to the solely FEM method.

3. COMPENSATION STRATEGIES FOR SOLVING GEOMETRICAL DEVIATIONS AFTER FORMING PROCESS

We realize that it is impossible to completely overcome springback but it can be limited and monitored by setting the optimal forming parameters to reach a higher level of sheet metal plastic deformation. The invention of the *Displacement Adjustment (DA)* method [10] was an important progression in the area of springback compensation.
In papers [11, 12] there are presented two on DA based methods: *Smooth displacement adjustment (SCA)* and *Surface Controlled Overbending (SCO).* Their main purpose is the DA method application on complicated sheet metal parts from the automotive industry. All the stated methods are a significant progression in springback compensation although there are lots of applicability limitations at the moment. The main limitation is due to too few reliable FEM springback results because of not using advanced material models for sheet metal modelling in industry. There is a cost-benefit conflict in material modelling. Models that are appropriate for forming simulations usually lack the final part geometry prediction after the tool elements withdrawal.
A few software packages for sheet metal forming simulation contain modules for automatic springback compensation. These kinds of tools are very useful, but their drawback is currently the problem of mesh robustness when the compensation of an auto body part is done. Excessive local solving of the geometrical deviation (wrinkles) can cause a corruption to the die and punch shape. However, in the near future, the software for automatic springback compensation will reach a satisfactory level for industrial applications.

3.1 Introduction of GCM Method

In the last link of the sheet metal forming design chain, when optimal technological parameters for springback minimization are found (blank holder force, drawing radii, drawbeads construction...) the springback compensation can only be completed with geometrical changes to the die shape. This can be conducted with the *Guide Curve Method (GCM)* based on the DA philosophy (Fig. 7). This relatively simple method showed positive efficiency according to the invested work and costs and the final result.
Because of the GCM implementation, the simulation and validation time of the complete forming process is extended but in this way physical tryouts are started with an initial geometrical correction which usually reduces the number of tool shape adaptations. The GCM is applicable not only in forming the planning process but also when tryouts on real tools are performed and corrections are implemented.
The groundwork of the GCM is the FEM springback simulation result. The exported mesh in the stl file is inserted into a 3D environment tool (Catia V5) and the deviation analysis between the FEM result and the reference CAD geometry is done. The reference curves (guide curves) of both the FEM result and the CAD reference are created and they are elements for drawing the tool

surface reconstruction. New iterations start the FEM simulation with the adapted die shapes. If the geometry of the part after springback is suitable within the tolerance allowance this is the end of the springback compensation in the planning phase and the physical tool is then manufactured. A single iteration (surface adaptations) is made inside a 3D environment tool and for this reason the surfaces keep their quality.
A similar compensation process is also executed in the physical tryouts and tool corrections phase, with the exception that for the springback evaluation in spite of the FEM results, real measurements are used.

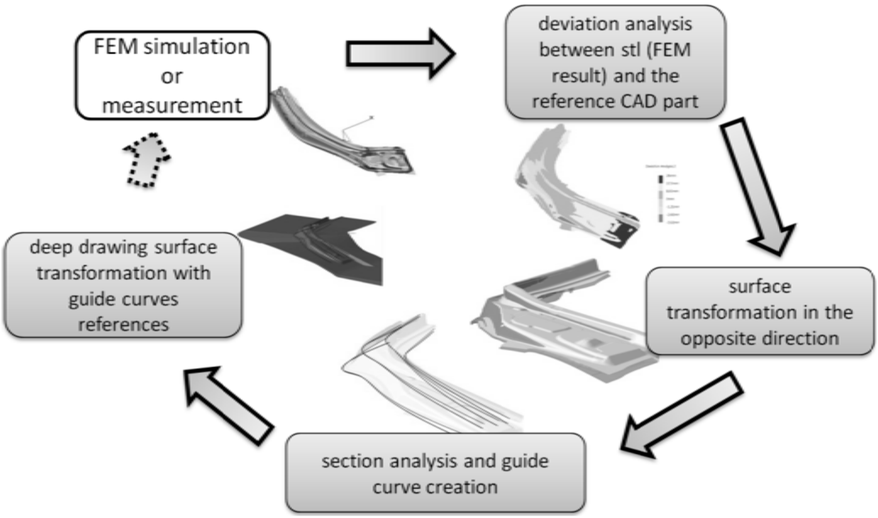

***Fig.** 7 - Guide Curve Method -GCM*

3.2 Performing Springback Compensation of an Industrial Product

The special shape of the A-pillar (Fig. 8) causes twisting of the part after the forming operation. For the actual auto body part the GCM based on FEM simulations was used. Although physical tool corrections were needed, their number was reduced by a half. Measurements based on the GCM enabled quicker, more precise and controllable adaptations of the forming tools.

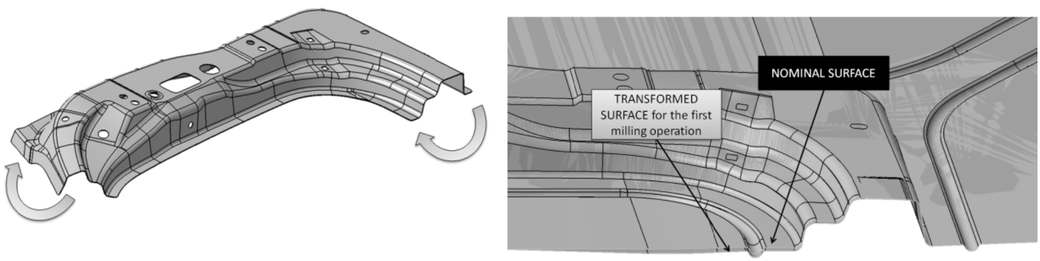

***Fig. 8** - The twisting tendency of the A-pillar after forming, and the springback compensation in the first forming operation*

5. CONCLUSION

This paper presents a few approaches for springback prediction and compensation. The conclusions obtained in this study were as follows.

1) In spite of the limited reliability of the FEM springback results this method is very useful. Even if there are problems with accuracy, the springback tendency (direction of a part area deformation) is well predicted.

2) There is a cost-benefit conflict in sheet metal material modelling. With advanced (costly) material models better springback prediction is possible.

3) Combination of the FEM and the Artificial Intelligence Methods allows a more accurate springback prediction.

4) Performing geometrical springback compensation in the first tryout significantly reduces the time for physical tool modification.

5) In the springback prediction and compensation process it will be soon necessary to take into account the stochastic nature of the sheet metal material.

Acknowledgements

"Operation part financed by European Union, European Social Fund."

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EKSPERIMENTALNI I NUMERICKI PRILAZ POBOLJŠANJU PREDVIĐANJA ELASTIČNOG VRAĆANJA I KOMPENZACIJE

Mihael Deželak[1], Andrej Stepišnik[1], Ivo Pahole[2], Mirko Ficko[2],
[1]Emo -Orodjarna d.o.o., Slovenia
[2]University of Maribor, Faculty of mechanical engineering, Slovenia

REZIME

Težnja ka što većoj bezbednosti putnika, redukovana potrošnja i zaštita životne sredine vode auto industriju ka razvoju i primeni novih materijala koji imaju veću čvrstoću. Međutim, veće vrednosti čvrstoće obično vode ka smanjenu deformabilnosti i povećanju osetljivosti na elastično vraćanje. Danas je elatično vraćanje jedan od najvažnijih faktora koji utiču na kvalitet proizvoda od lima. Tipovi elastičnog vraćanja se dele u zavisnosti od geometrije proizvoda i režima obrade: promena po uglu, bočni pregib i uvijanje. U toku procesa deformisanja, lim je podvrgnut kompleksnoj istoriji deformisanja što izuzetno otežava predviđanje elastičnog vraćanja. U ovom radu je prikazana procedura predviđanja elastičnog vraćanja i kompenzacije auto delova.

Ključne reči: *Obrada lima, programiranje mašine, elastično vraćanje, simulacije metodom konačnih elemenata*