

Material Parameters Sensitivity on Springback Modelling of Simple Bending Process

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Abstract. Springback is one of the major defects that continuously concerns the sheet metal experts' community. It has long been known that the sheet thickness, the bending angle and the yield stress of the material primarily affect the angle change after the tools' release. Besides, the consideration of the kinematic hardening (*KH*) model has powerful influence on the modelling results, too. In this study, we overviewed several possible factors on the springback with finite element modeling of a simple V-die bending operation, highlighting the effect of the material variables on the final shape. AutoForm® R7 software and the built-in theory of kinematic hardening were used for the material characterization, coupled with the Hockett-Sherby isotropic hardening rule as well as the Yld89 yield criterion. The material data for modeling kinematic hardening behavior were obtained by cyclic tension-compression tests, whilst the isotropic hardening and the yield surface parameters were acquired by simple uniaxial tension tests. The simulation results were compared to the experimental springback observations obtained by a CNC bending machine, without using springback compensation. A detailed parametric study was also carried out to highlight the level of criticality of the applied material variables on the final angle change.

Introduction

Springback of thin sheets that means the bending angle's change after the tools' release (i.e. in the unloading stage) is an extensively researched topic in the sheet metal forming industry. The proper springback evaluation and thus its suitable correction are relevant questions of the process planning, thanks to its powerful influence on the product's geometric compliance.

During bending, an elastic region develops in the thickness direction near to the neutral axis, which takes an elastic moment into the opposite direction relative to the deformation. On the other hand, the total strain is the sum of the elastic and plastic strains in the bent region, and the reversibility of elastic strain tries to restore the workpiece to its initial geometry [1]. As a result, the extent of the springback angle (θ^*) is primarily influenced by the yield strength (Y) over elastic modulus (E) ratio and the thickness (t) if considering clearly the material parameters. The features of the bending geometry, such as the punch corner radius (R) and the bending angle (θ) are counted as technological conditions, which also have their own effect [2, 3, 4, 5]. From these, the conclusion can be made that the materials' strength increase following the current trends in the structural engineering, further strengthens the role of springback correction recently.

According to the mentioned circumstances, a strain reversal takes place during the springback, resulting in changes in the microstructure, too. As a direct consequence of the contrary movement of dislocations, the role of the Bauschinger effect becomes more emphasized in this process. To consider it, kinematic hardening formulas were developed in previous research. One pioneer in this field was Chaboche [6], whose model has been incorporated into the Simufact Forming® software. In the sheet metal forming industry, the Yoshida-Uemori model [7] is maybe the most widespread theory, which has been even developed further by them [8]. In this study, we used the AutoForm® *KH* model (discussed and referred later) to unfold how strong the impact of each material parameters is on the

results of springback modelling. Its importance is explained by the reduction demand of the difficulty implemented physical tests and shifting the focus to the most relevant variables.

Material Characterization

Applied materials. Three types of commercial, un-coated dual phase steels, namely Docol DP600, DP800 and DP1000 were investigated during this research. The DP abbreviation refers to the dual phase microstructure of the sheets, in which hard martensite particles are distributed in the ferrite matrix. These phases together provide the high strength and the relative good formability for this material family [9, 10].

Material data identifying. The basic mechanical properties, which served as input parameters for the yield surface and the isotropic hardening definition were obtained by uniaxial tensile tests. The averages of the yield strength, the ultimate tensile strength (*UTS*), the uniform- and the total elongation (A_g and A_{80}) as well as the *r*-values are listed in Table 1. The tensile experiments were carried out in 0°, 45° and 90° to the rolling direction, in accordance with the EN ISO 6892 standard's prescriptions at room temperature, with constant cross-head speed on three parallel specimens. The *r*-values were defined at A_g -1(%) engineering strain for all steels, using touchless AVE video-extensometer. The sheets had 1 mm nominal thickness (*t*) uniformly.

Table 1. The basic material properties of the applied steels

	Y [MPa]	UTS [MPa]	Ag [%]	A₈₀ [%]	r₀	r₄₅	r₉₀
DP600	444	656	12.8	20.6	0.803	0.910	1.010
DP800	570	879	10.2	16.0	0.654	0.786	0.767
DP1000	758	1099	6.7	10.6	0.752	0.730	0.811

The kinematic hardening parameters were defined by cyclic tension-compression tests, in connection with which, the authors refer their own work. The details of the measurement method and the results are described in [11].

Bending experiments. The bending investigations were performed three times on initially flat blanks with constant 20 mm/min stroke by an AMADA HFE 50-20 CNC bending machine. The side view sketch of the bending tools (punch and V-die) can be seen in Fig. 1. All the samples were bent to 90°, which angle value was controlled by the punch motion, excluding springback corrections.

The specimens had 120 mm width and 600 mm length, in which the length direction was coincided with both the rolling direction and the axis of the bending line.

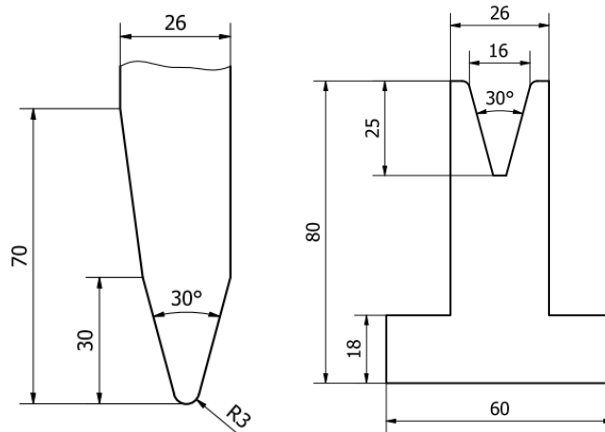


Fig. 1. Schematic view of the applied bending tools: punch with 3 mm radius (left) and die (right)

Numerical Simulations

AutoForm® R7 code was used to investigate the springback phenomenon in the model space. The die and the punch were specified as non-deformable, rigid elements. The blank was built up by elasto-plastic shell elements, with 693 initial element number in the plane of the sheet and with 11 integration points in the thickness direction. The re-mesh object was defined in six levels of refinement. The modelled bending process, prior- and after the deformation can be seen in Fig. 2.

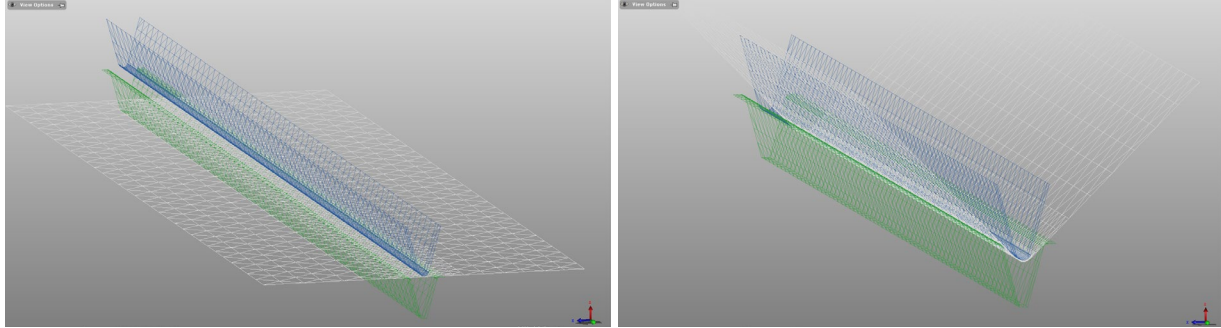


Fig. 2. The arrangement of the tools and the workpiece in the bending model

The strain hardening of the material was described by the Hockett-Sherby equation [12], as

$$\bar{\sigma} = \sigma_s - \exp(-a\bar{\epsilon})^p(\sigma_s - A), \quad (1)$$

in which A is equivalent to uniaxial yield stress (Y in Table 1.), σ_s is the saturation stress and a and p are further material constants. The constants were determined based on the least squares method approximation from the tensile tests' results and the values are summarized in Table 2, indicating the R^2 value, too.

Two yield functions, the Yld89 [13] and the Hill'48 [14] were also examined with the aim of monitoring those effect on the springback results. Both yield functions' parameters were obtained by the r -values. However, the results got by the different yield surfaces were somewhat different, we primarily put the hardening parameters into the focus in this study. Due to the limited content of the paper, we will illustrate the model results using the Yld89 theory uniformly, in the rest of the paper.

The kinematic hardening was described by the AutoForm® model according to the theory of Kubli, Krasovskyy and Sester [15]. Since this model is compatible to any hardening theory, it can be interpreted as a supplement of the isotropic hardening phenomenon with four added parameters: Young's reduction factor (γ), Young's reduction rate (χ), transient softening rate (κ) and stagnation ratio (ξ). These parameters determine the three typical stages of the stress-strain curve during reverse loading, the early re-plastification (i), the transient softening (ii) and the hardening stagnation (iii).

The model describes the connection between the reverse stress (σ_r) and reverse strain (ϵ_r) with a smooth function in the early re-plastification (linear part) and the transient softening (non-linear part) stages. It can be followed in Eq. (2), in which $\sigma_h(\bar{\epsilon})$ is the plastic strain dependent isotropic hardening stress, $E_l(\bar{\epsilon})$ is the initial tangent modulus at the beginning of the load reversal and κ is a material parameter representing the steepness of the non-linear part of the stress reversal curve.

$$\epsilon_r = \epsilon_{rl} + \epsilon_{rn} = \frac{\sigma_r}{E_l(p)} + \kappa \cdot \operatorname{arctanh}^2\left(\frac{\sigma_r}{2\sigma_h(p)}\right)^2 \quad (2)$$

In the linear part, the tangent modulus is responsible for defining the material behavior predominantly, which decreases with the accumulated plastic strain, in the following form (Eq. (3)):

$$E_l = E_0[1 - \gamma \cdot (1 - e^{-\chi\bar{\epsilon}})]. \quad (3)$$

Here γ and χ parameters are responsible for the description of the elastic modulus's reduction and the steepness of the early re-yielding period. In the possession of the stress-strain curves obtained by

the cyclic tension-compression tests, the γ , χ and κ parameters were determined, and be collected in Table 2. Here, the default values advised by the AutoForm® for high strength steels (HSSs) are also indicated. According to our experiences, the fourth added parameter (ζ) that indicates the amount of the workhardening stagnation has the least effect on this type of springback, therefore it has been ignored in this study.

Table 2. The parameters of the Hockett-Sherby equation and the AutoForm® KH model

	σ_s	a	p	R^2	γ	χ	κ
DP600	780	21.0	0.812	0.9995	0.123	37	0.012
DP800	991	38.1	0.765	0.9991	0.113	46	0.014
DP1000	1160	102.0	0.785	0.9969	0.094	57	0.014
AF® def HSS	-	-	-	-	0.130	40	0.014

Results and discussion

‘EXP’ notation indicates the springback angles determined on the edges of the sheets by a workshop angle meter with 15’ preciseness in Fig. 3. The validation of the measurements results is in progress by a coordinate measuring equipment. Generally, no higher than $\pm 1.0^\circ$ average deviation occurred for all materials during the experiments. Since the representation of all three mentioned DP materials’ results needs an extensive discussion, only the results of DP600 fit into this manuscript.

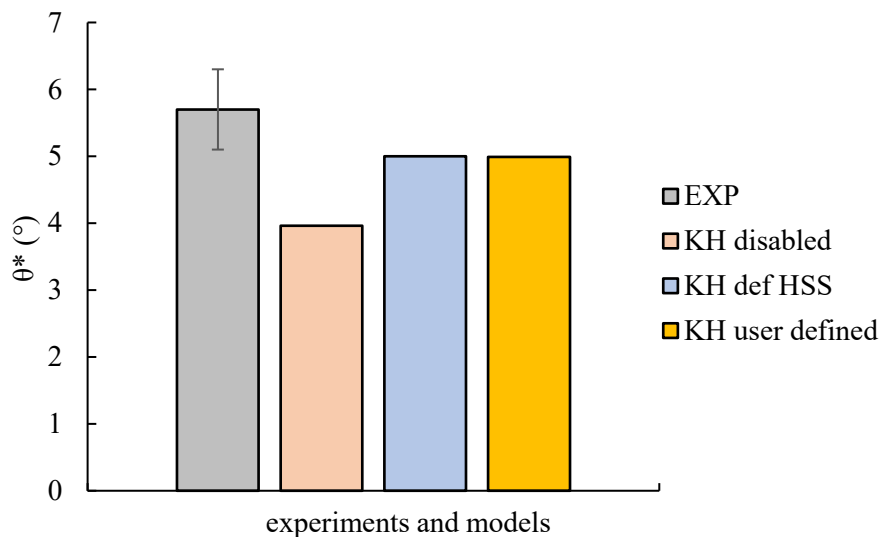


Fig. 3. The measured and the modeled springback angles with and without using *KH* parameters (DP 600)

Blue and yellow columns belong to the simulation results obtained by the default (blue) and the user-defined (yellow) *KH* parameters in the figure above. Red column shows the simulated springback value without using *KH* model. It can be stated that using *KH* parameters suits the model results better to the experiments and there is no outstanding difference between the application of default and user defined parameters at this material. Note that the material parameters of DP600 is quite similar to the default ones. Nevertheless, the impact of each material *KH* parameters on the modelled results is still in the background, which is worth looking behind.

Sensitivity analysis. To assess the sensitivity of the simulation results to the material data, a parametric study was performed in the AutoForm R7® software on the user-defined variables. The sheet thickness, the elastic (Young) modulus, the isotropic and the kinematic hardening parameters were systematically changed to reveal the influencing intensity of the applied material parameters.

The effect of the yield surface definition was also studied, but due to its less impact on the springback, only the results obtained by the Yld89 yield theory is discussed here.

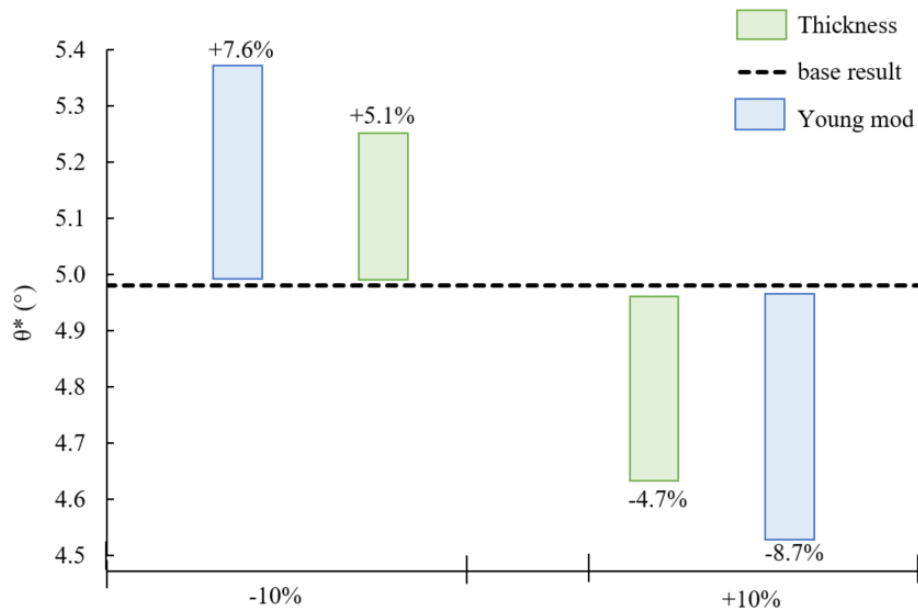


Fig. 4. The effect of 10% change in the sheet thickness and the Young modulus on the springback

As shown in Fig. 4, the changing of both the sheet thickness and the elastic modulus cause a relatively symmetrical deviation of the springback. A 10% increasing or decreasing of these variables result approx. 5-8% change in the opposite direction. Compared these to the effect of the isotropic hardening parameters' change (see next figure), it is well visible that the thickness and the elastic modulus represent a more significant influence on springback, except for the saturation stress parameter.

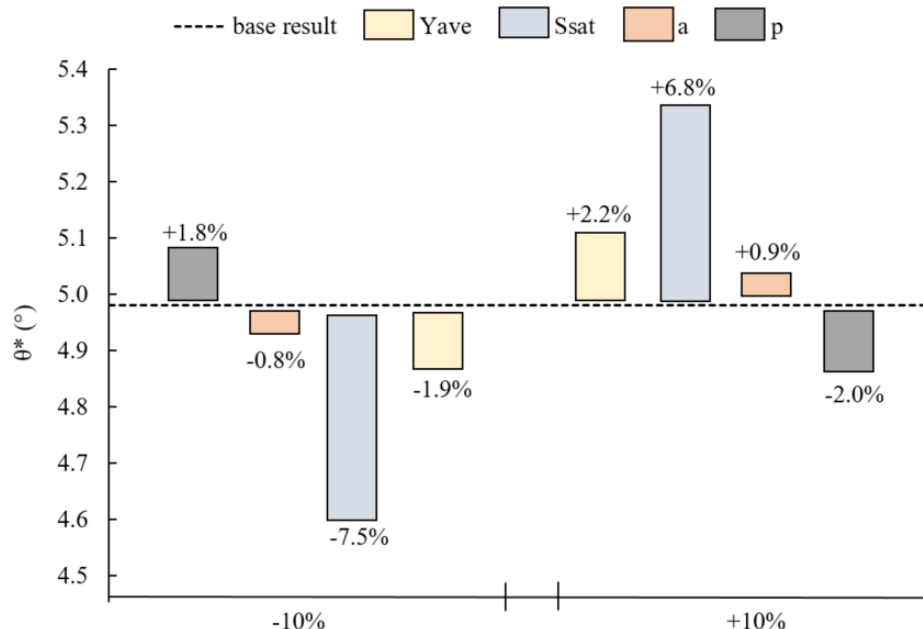


Fig. 5. The effect of 10% change in the Hockett-Sherby equation parameters on the springback

Fig. 5 indicates that a 10% change of the isotropic hardening parameters leads to generally a lower deviation than the thickness and the elastic modulus have. Only, the effect of the saturation stress is in a similar magnitude. Since the saturation stress increase leads to the strength increase of the material, it shows changes in the same direction, just like the average yield stress (i.e. A parameter).

Interestingly, the p exponent behaves on the other way than the rest parameters. It is also visible that the a parameter has the least effect on modelled springback.

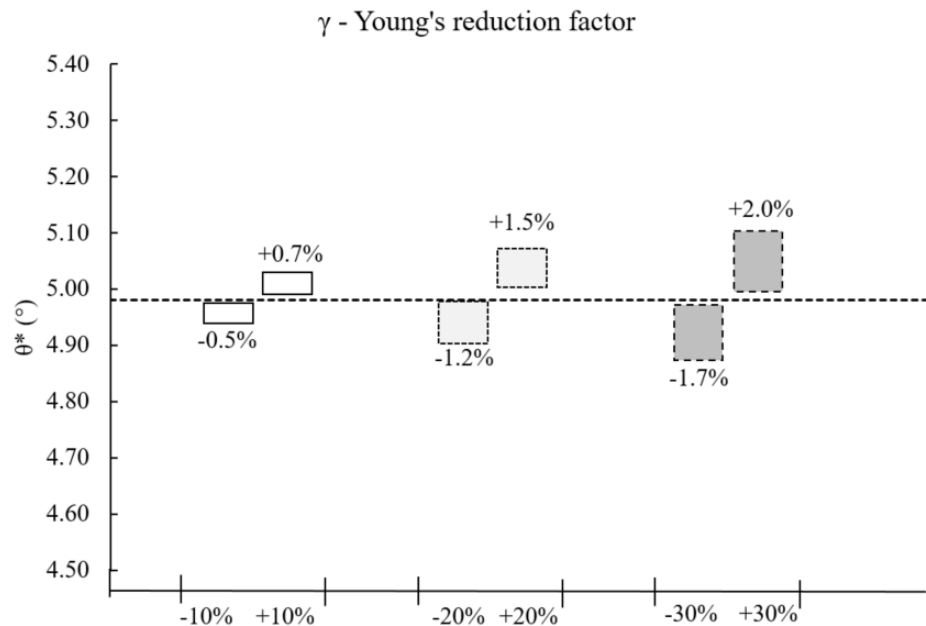


Fig. 6. The effect of 10-30% change in the Young's reduction factor on the springback

The cases of the kinematic hardening parameters are described in Fig. 6 – 8. It can be observed that the most powerful influence on the springback is represented by the transient softening rate, i.e. the steepness of the non-linear part in the reversal stress-strain curve. The impact of the parameters, which affect the change of the Young modulus are similar, and a little stronger effect can be realized by the Young's reduction factor. All three parameters cause symmetrical intervention and monotonous growth in the springback results.

The effect of the stagnation ratio is almost negligible and not discussed here.

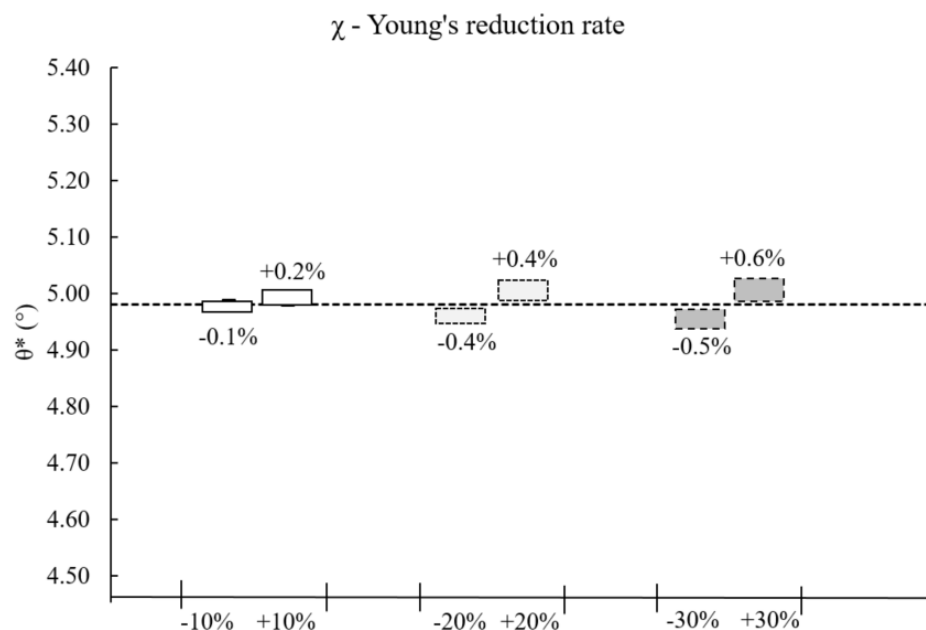


Fig. 7. The effect of 10-30% change in the Young's reduction rate on the springback

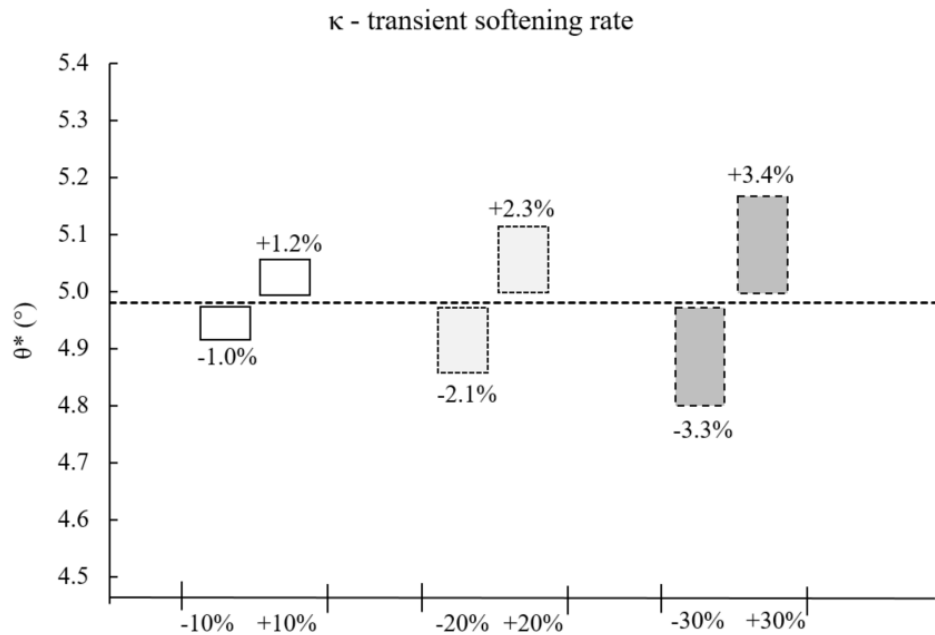


Fig. 8. The effect of 10-30% change in the transient softening rate on the springback

Conclusion

We have focused on the material parameters' sensitivity of springback modelling using the AutoForm® model at simple V-die bending. Taking KH behavior into consideration has moved the simulation results closer to the experiments, and an exact impact analysis was carried out on the most emphasized input variables, in the same time. Based on the results it can be observed that most of the investigated parameters cause symmetric deviations in springback, i.e. decreasing or increasing of each parameters have roughly the same effect in the angle change tendency. It is worth mentioning that the saturation stress and the transient softening rate parameters caused the highest deviation on the modeled springback values, among the isotropic and the kinematic hardening parameters respectively. Besides that the Young's reduction factor has approx. two times stronger effect than the Young's reduction rate has, both of their impact is almost negligible, and the default parameters can be used safely for DP600.

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