Formability Investigations of High-Strength Dual-Phase Steels

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Abstract Car manufacturing is always regarded as the key industry behind sheet metal forming, and thus, the requirements of and developments in car manufacturing play a decisive role in the development of sheet metal forming. The automotive industry is faced with contradictory demands and requirements: better performance with lower consumption and less harmful emissions, more safety and comfort; these are extremely difficult to supply simultaneously with conventional materials and conventional manufacturing processes. The fulfillment of these often contradictory requirements is one of the main driving forces in the automotive industry and thus in the material and process developments in sheet metal forming, as well. In recent years, significant developments can be observed in the application of high-strength steels. In this respect, the application of various dual-phase steels is one of the best examples. However, the application of these high-strength steels often leads to formability and manufacturing problems. One formability problem is the springback occurring after sheet metal forming. In the current research, we have dealt mainly with advanced high-strength steels, primarily with dual-phase steels. When applying them, the springback phenomenon is one of the most critical issues. To reduce the tremendous amount of experimental work needed, we also applied numerical simulation using isotropic–kinematic hardening rules. The isotropic–kinematic hardening behavior of a given material in the applied AutoForm numerical package may be characterized with three independent material parameters γ , χ and K (a detailed explanation of their meaning will be given in the main part of this paper). However, we found that the material data included in simulation packages for these new high-strength steels are not fully adequate. For the determination of more reliable material parameters and to achieve better simulation results, a new testing device was developed. Numerical simulations were performed using the material parameters determined by the new device to show the sensitivity of springback behavior to these material parameters.

KEY WORDS: Springback; Large-strain cyclic deformation; High-strength dual-phase steels

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1 Introduction

Sheet metal forming is one of the most important manufacturing processes. This is particularly valid for the automotive industry, where sheet metal forming has an even more important key position. The automotive industry is the leading sector in many countries and the main driving force behind the sheet metal forming developments as well.

The competition in car manufacturing is extremely strong, leading to larger model variety and shorter model cycles. Increased competition also leads to very intense development activity to increase productivity and reduce costs. Besides the effects of this global competition, some legal requirements (e.g., safety regulations, environmental requirements, limitation of harmful emissions) as well as customer demands (e.g., more comfort, lower consumption) are significantly influencing developments in car manufacturing.

To meet these manifold requirements, the application of light-weight design principles is one of the most important trends. Obviously, the new design concepts require new materials. Among the recent material developments, the increasing application of high-strength steels should be mentioned first. During the last decades, many new grades of high-strength steel materials have been developed [1], as shown in Fig. 1. However, it is well known that the formability of steels decreases dynamically with increasing strength. This is obviously valid for the newly developed high-strength steels as well [2], as shown in Fig. 2.

Besides the significant changes in formability with increasing strength, the increased springback occurring during forming of high-strength steels is one of the major technological problems in designing and manufacturing sheet metal parts with the required shape and dimensional accuracy.

It is well known that springback is due to uneven stress distribution along the cross section of the component, and it is also known that it is in direct relation to cyclic plastic deformation during forming. In most of the forming processes, several sections of a part undergo cyclic plastic

Fig. 1 Steel development trends during the last 40 years

Fig. 2 Elongation versus tensile strength for conventional and advanced high-strength steels [2]

deformation, e.g., bending and straightening over a tool radius, passing through a drawbead, etc. Another consideration is that the hardening behavior has significant differences in forward and reverse loading due to the well-known Bauschinger effect, which inevitably occurs during such forming cases (i.e., in loading–reverse loading conditions).

Traditionally, the springback problem was handled by time- and cost-consuming trial-and-error methods. Recently, finite element simulation is used to predict the springback after forming. Reliable simulation is a precondition of determining the accurate shape and dimensions of the tools and thus those of the deformed parts. The springback phenomenon is strongly related to several physical and material properties. From the point of view of continuum mechanics, the yield strength and Young's modulus—particularly its changes during cyclic loading—are the most important mechanical properties, but many experiments indicate the importance of microstructure as well [3].

In this work, first some theoretical considerations on the springback phenomenon and then the results of experiments and numerical simulations on cyclic plastic deformation of high-strength dual-phase steel sheets will be presented and discussed.

2 Theoretical Considerations on Springback in Sheet Metal Forming

For accurate modeling of springback phenomena, it is absolutely essential to analyze the stress–strain behavior of sheet metals during loading and unloading (i.e., reverse loading). There are several investigations to study cyclic plasticity: earlier, they were mainly related to low-cycle fatigue; thus, the investigations remained in the range of

small plastic deformation. However, later more efforts were made to study the effect of the Bauschinger effect on the large-strain cyclic behavior of sheet metallic materials [3].

In several further papers [4–7], it was clearly shown that the behavior of sheet metal during loading–unloading, i.e., in the reverse loading phase, is essential for a more accurate description of springback. It is also shown in these investigations that the Bauschinger effect has a very significant effect on the cyclic plastic behavior. To illustrate it, a short analysis will be given in the next section.

2.1 Constitutive Modeling of Cyclic Plastic Deformation

On the basis of the model elaborated by Yoshida et al. [3], the following sections of the Bauschinger effect are considered: the so-called early replastification characterized by early reyielding and a smooth elastic–plastic transition, the transient softening and the permanent softening leading to work hardening stagnation and resulting in reduced yielding, as compared to isotropic hardening.

They pointed out that the classical constitutive model of mixed isotropic–kinematic hardening model elaborated by Lemaitre and Chaboche [8] cannot describe some of the deformation characteristics—e.g., the work hardening stagnation—which are experienced during cyclic plastic loading and reverse loading.

In the Yoshida–Uemori model [5, 7], the hardening is described by two bounding surfaces. One of the surfaces is defined as pure kinematic hardening (f) and given by the equation

$$f = \frac{3}{2}(\mathbf{S} - \boldsymbol{\alpha}) : (\mathbf{S} - \boldsymbol{\alpha}) - \sigma_0^2 = 0, \quad (1)$$

where $\mathbf{S}$ is the Cauchy deviator stress tensor, $\boldsymbol{\alpha}$ is the back-stress deviator tensor, and σ_0 denotes the initial yield strength. The second surface can be defined as a bounding surface with isotropic–kinematic hardening (F) and is given by the equation

$$F = \frac{3}{2}(\mathbf{S} - \boldsymbol{\beta}) : (\mathbf{S} - \boldsymbol{\beta}) - (B + R)^2 = 0, \quad (2)$$

where $\boldsymbol{\beta}$ denotes the center of the isotropic hardening surface, and B and R are its initial size and the isotropic hardening component, respectively.

He et al. [9] proposed an extended homogenous yield function to describe the Bauschinger effect and permanent softening during loading and reverse loading. Their work was based on the homogenous anisotropic hardening (HAH) model proposed by Barlat et al. [10], but with a significant improvement by considering kinematic hardening. This enhanced homogenous anisotropic hardening (EHAH) model was shown to be effective for modeling the

behavior of materials like ultra-low-carbon high-strength steels (e.g., IF-steels) and also for mild steels (e.g., DC06).

2.2 The Constitutive Model Implemented in AutoForm [11, 12]

A similar, but rather practical approach is implemented in the AutoForm FEM package which is based on the considerations depicted in the PhD thesis of Krasovsky [13]. The illustration of this model is shown in Fig. 3. The main idea of the AutoForm model is to use the same developing equations to describe the early replastification (early yielding) and the transient softening. This approach results in a smooth stress function for the entire loading–reverse loading cycle. For simplicity, the general model here will be shortly presented only for a uniaxial case, but it is also formulated for general cases. Here, we just recall that part of the model which is necessary to explain the experimental results to be discussed later.

To derive the expression describing the above-mentioned “smooth function,” the total reverse strain (ε_r) may be expressed as a sum of a linear (ε_{rl}) and a nonlinear (ε_{rn}) reverse strain. An initial tangent modulus (E_i) can be rendered to the linear reverse strain (ε_r) which characterizes the early reyielding phase. However, E_i is exponentially decreasing as the equivalent plastic strain (p) accumulates. The reduction in the tangent modulus thus may be written with the expression

$$E_i = E_0[1 - \gamma(1 - e^{-\chi p})], \quad (3)$$

where E_0 is the initial tangent modulus at zero plastic strain (i.e., the Young’s modulus), γ is a material parameter expressing the reduction in the initial tangent modulus, and χ is the saturation constant.

Fig. 3 Schematic representation of the AutoForm model concept [11]

The nonlinear reverse strain is approximated with an inverse hyperbolic tangent function, and for the sum of linear and nonlinear reverse strain, the following expression can be written

$$\varepsilon_r = \varepsilon_{rl} + \varepsilon_{rn} = \frac{\sigma_r}{E_l(p)} + K \operatorname{arctanh}^2\left(\frac{\sigma_r}{2\sigma_h(p)}\right)^2, \quad (4)$$

where $\sigma_h(p)$ is the isotropic stress depending on the reverse plastic strain and K is a material parameter representing a typical strain distance affecting the steepness of the reverse stress curve (σ_r). It can be seen from the above expressions that the tangent modulus and the total reverse strain depend on three material parameters, i.e., γ , χ and K [14]. These parameters will play an important role in the experimental part in analyzing the springback.

3 Experimental Investigations of Cyclic Plastic Deformation

3.1 Review of Experimental Methods to Study Large Cyclic Plastic Deformation

There are various methods known from the literature for measuring large-strain cyclic plastic deformation; however, there are significant differences concerning both the range of the strains and the stress–strain state. Analyzing the various applied techniques, some common principles may be summarized: As a general requirement, it can be stated that test conditions are the most favorable when the stress and strain state are more homogeneous. It is also important that the material properties characterizing cyclic plastic deformation should be determined in as wide a range as possible to reduce the measuring errors.

In their early tests, Yoshida et al. [3] applied a relatively simple device providing pure bending. In their experiments, the distribution of the bending moment was quite uniform along the tested specimen; however, such experiments involve inhomogeneous stress and strain state in the sheet specimen, and thus the material properties cannot be determined directly from the experiments. To overcome these difficulties, they applied an iterative identification procedure, which is formulated as an optimization problem where the function to be optimized is an error function expressing the differences between numerical simulation and experimental data.

A similar principle was applied in the experiments of Zhao and Lee [15], where a three-point bending system was used. During these experiments, the bending moment and punch displacement diagrams were recorded, and the material properties were determined applying the Lemaitre and Chaboche isotropic–kinematic hardening model [8]

and a genetic algorithm as a result of an optimization task. A further measuring device based on bending experiments was constructed by Omerspahic and Mattiasson [16], and they determined the cyclic plastic material properties applying an inverse FEM technique using LS-DYNA code.

A further group of methods providing large cyclic plastic strain is based on shear test investigation. Miyachi's pure shear testing method [17] can be regarded as the basic test in this group. The simplicity of this test is one of the most important advantages of this method. It can be done in a uniaxial tensile test; however, the cyclic strain usually does not exceed 5%. It is worth also mentioning that the extension of the results of shear tests to general stress state leads to significant difficulties.

One of the main reasons that recently research interest has turned toward the application of uniaxial tension–compression loads is that in both bending and shear tests, it is difficult to extend the results to a general stress state. The uniform stress and strain distribution along the cross section of the specimen may be regarded as one of the main advantages of uniaxial tension–compression cyclic loading, which results in a relatively simple method to extend these results to a general stress and strain state. A further advantage of these tests is that the strain range, depending on the material quality, can reach in some cases even 30%. However, an obvious disadvantage in testing thin sheet specimens is that during the compression load cycle the available deformation is limited due to the buckling of the sheet.

There are various proposals to avoid the buckling of the sheet specimen during the compressive loading cycle. One possible solution is to apply appropriate geometric ratio, i.e., limiting the length-to-thickness ratio of the specimen. Since in sheet metal forming, usually thin sheets are applied, this would lead to very limited length; furthermore, reducing the length of the specimen would result in significant measuring difficulties, too. During cyclic plastic deformation, the strain should be measured with high precision, which requires the application of special extensometers; however, the size of these devices cannot be reduced below a certain range. A further problem of reducing the length of the specimen is that the uniformity of the stress and strain state might change due to the geometric fixity; furthermore, in some cases, it can lead to measuring localized material properties instead of uniform global properties.

Another approach to avoid buckling of thin sheets during the compression load cycle is to apply special specimen and devices to support the sheet specimen. Boger et al. [18] applied a so-called laminated specimen system to increase the length-to-thickness ratio and thus to increase the compression cycle range up to 10–20%. They applied a special device to support the thin sheet in the compression loading cycle. The main problems in this experiment, as

Boger and his co-authors also found, is that the applied support increases the measured force due to the friction forces and the stress state proportionally changes to a biaxial stress state as the sheet thickness increases during the compression loading cycle.

Tan et al. [19] also applied solid supports in tension–compression cyclic deformation using dog-bone-type samples to prevent buckling. This hybrid approach, utilizing both small specimen size and side support, effectively improves the attainable strain range, but suffers from the same limitations of the small-scale tests, in addition to buckling in the unsupported region. Yoshida et al. [7] used a variation of the pack method, where five sheets were laminated and adhesively bonded together to provide support in addition to plates. Using this method, they were able to measure compressive strains up to 0.25 for mild steel and 0.13 for high-strength steel.

Another approach to improve the limited strain range of supported specimens was developed by Kuwabara et al. [20, 21]. They used two pairs of comb-shaped sets to support the sample. This is an improvement in solid support since as the sample is compressed, the male and female dies slide past each other, allowing the entire length of the specimen to be supported. By eliminating the interference problem between the plates and the support fixture, strains in the order of 0.15–0.20 were attainable for single sheets under compressive loading. However, this device also has some limitations: The specimen design is rather long and slender, and it is difficult to maintain axial alignment of the tensile axis for various sheet thicknesses. This misalignment leads to reductions in the compressive strain range attainable before buckling.

3.2 New Experimental Device for Tension–Compression Cyclic Test of Single Sheets

In this work, a new device will be described which was developed to overcome the limitations experienced in former experimental procedures. During the design of this device, we applied the following considerations:

1. a simple tension–compression loading cycle will be applied, which provides a relatively simple means of extension for a general stress and strain state;
2. the loading cycles should be done as continuous tension–compression cycles, which can be performed on a uniaxial testing machine applying a conventional extensometer for strain measurement;
3. to avoid buckling of thin sheet samples, a special supporting device is necessary that provides continuous full support of the specimen along its full length;
4. frictional effects should be minimized as far as possible, which is a necessary condition to minimize

the biaxial stress effect during the compression loading cycle.

When designing the experimental device, the sizes of the samples were of utmost importance. The length-to-thickness ratio of the sheet is one of the important factors strongly affecting the size of the samples. The upper limit in this sense is to avoid buckling during the loading cycles. On the one hand, the lower limit of the sample sizes is determined by the gauge length of the applied extensometer. On the other hand, the so-called head effect of the specimen should also be considered when determining the minimum size of the samples. By the head effect, we mean that different widths of the specimen head must not have an effect on the uniform stress distribution in the gauge length. The minimum gauge length was determined by a FEM analysis [22].

3.3 The Experimental Setup

Applying the above design considerations, a new experimental device was constructed. The supporting mechanism is one of the key design points. For these purposes, two rows of plates were applied. The thickness of the supporting plates was 0.5 mm. These plates supporting the specimen on both sides are positioned to each other at 1.5 mm distance and are joined in a two-part supporting frame, as shown in Fig. 4.

The experimental device was mounted in a two-column die set with the supporting frames and plates, as shown in Fig. 5. The two rows of plates are included in a clamping

Fig. 4 Supporting frame with two rows of plates (1—specimen; 2 and 3—frames with the supporting comb-shaped plates): **a** schematic diagram; **b** photo

Fig. 5 Experimental device for cyclic tension–compression test (1—two-column guided tool; 2, 3—clamping frame; 4—prestressing unit; 5—extensometer; 6—plate spring; 7—supporting pad)

frame, and the prestressing of the plates is provided by a polyurethane pressure plate moved by a precise and well-controlled screw mechanism. The whole experimental device is installed on a universal material testing machine type MTS-801.

3.4 Materials Used in the Experiments

The determination of material properties for isotropic–kinematic hardening was the primary objective of the experimental measurements. For these purpose, a group of high-strength steels was selected. In this paper, we show the results for three different dual-phase high-strength steels widely applied in the automotive industry.

The chemical composition of the selected test materials is given in Table 1. The mechanical properties (R_{eH} is the yield strength, R_m is the ultimate tensile strength, and E_0 is the initial Young's modulus) and the ratio of martensite in the microstructure in percentage value are summarized in Table 2. The sheet thickness for all tested materials was $t = 1.0$ mm.

3.5 Experimental Results

Before describing the experimental results, some general considerations will be summarized. As was mentioned before, the primary objective of these investigations is the determination of the material properties to be used in FEM

modeling in order to predict more accurately the spring-back behavior of high-strength steels. For this purpose, tension–compression cyclic loading experiments were selected with the newly developed experimental tool setup. We aimed to determine these parameters with tension–compression stress–strain hysteresis curves in a strain range as wide as possible. Performing preliminary tensile tests with the test materials, we found that the limit value of strain in tension without losing the specimens' stability is $\varepsilon_{\max} = 0.12$ for DP600 and $\varepsilon_{\max} = 0.08$ for both DP800 and DP1000. If we wish to achieve these limit values, we can follow two different loading–reverse loading strategies.

The first deformation strategy can be seen in Fig. 6a. It means that the specimens are subjected to larger and larger cyclic strain, i.e., with continuously increased total strains as shown in Fig. 6a, where $\varepsilon_1 < \varepsilon_2 < \dots < \varepsilon_{\max}$. However, applying this deformation strategy, during the compression loading cycle, the thickness of the specimen increases due to the increasing cyclic strain and the stress state changes from uniaxial toward a more and more biaxial stress state, which has an unfavorable effect on the precision of the measurements.

The second deformation strategy can be seen in Fig. 6b. Applying this measurement principle, specimens are subjected to the same value of cyclic tension–compression strain (ε_c), but the mean strain values ($\varepsilon_{\text{mean}}$) are continuously increased (i.e., $\varepsilon_{\text{mean},1} < \varepsilon_{\text{mean},2} < \dots < \varepsilon_{\text{mean},n}$), and finally the predetermined limit strains can be achieved. Preliminary experiments showed that when applying $\varepsilon_c = \pm 0.02$ cyclic strains with continuously increased prestrain values as the mean strain, the limit strain values in tension–compression cycles can be achieved reliably [22].

Since for the permissible cyclic strain $\varepsilon_c = \pm 0.02$ was found, which is less than 1/6 of the limit strain for DP600 and just 1/4 of the limit strain even for the DP1000 steel, it is obvious that at least 4–6 prestrained specimen have to be tested until the limit strain. At least 3 specimens were tested at each mean strain value. To ensure the same conditions in each specimen, we prestrained a larger specimen and then three identical specimens were cut from the prestrained specimen.

Another important aspect of experimental considerations was that these limit strain values in tension–compression cycles can be reached more reliably if different prestrained components are tested, as shown in Fig. 6, i.e., the same value of strain cycles ($\varepsilon = \pm 0.02$) will be used; however, the mean value of strain cycles is increased continuously, as can be seen in Fig. 6b. This means that determining the material properties of tested materials for isotropic–kinematic hardening requires the determination of cyclic tension–compression curves as shown in Fig. 6b.

The experiments were performed with the experimental tool setup shown in Fig. 5 on an electronically controlled

Table 1 Chemical composition of the experimental materials (in wt%)

Material	C	Si	Mn	P	Cr	Ni	Al	Co	Fe
DP600	0.118	0.217	0.785	0.022	0.023	0.040	0.051	0.015	Bal.
DP800	0.012	0.198	1.43	0.020	0.027	0.032	0.037	0.014	Bal.
DP1000	0.142	0.472	1.47	0.015	0.017	0.032	0.052	0.014	Bal.

Table 2 Mechanical properties of tested materials

Material	t (mm)	R_{eH} (MPa)	R_m (MPa)	Martensite (%)	E_0 (GPa)
DP600	1.0	351	670	18	206
DP800	1.0	555	847	32	206
DP1000	1.0	780	1004	50	206

Fig. 6 Different deformation strategies during cyclic tension–compression tests: **a** samples subjected to larger and larger cyclic strain; **b** samples subjected to the same cyclic compression–tension strain

universal material testing machine (MTS-801). For each material, several tests were done with different magnitudes of strain cycles and with changing predeformation [22].

A set of hysteresis curves is shown in Fig. 7 for DP600 dual-phase steel with $\varepsilon_{\max} = \pm 0.02$ cyclic strain with continuously increased mean strain (from $\varepsilon_{\text{mean}} = 0.0$ –0.10). The characters of the diagrams are similar for DP800 and DP1000, too, but the mean value of predeformation is different depending on the different deformation limit of the different steels [23].

As is described in Sect. 2, the variation in apparent elasticity modulus (E_{ap}) can be determined from the cyclic tension–compression curves. However, this modulus changes during the reverse loading period, as shown with a magnified section in Fig. 8. Therefore, an average value should be determined applying Eq. (3) with the following steps:

Fig. 7 Hysteresis curves for DP600 dual-phase steel determined with different prestraining ($\varepsilon_{\text{mean}} = 0.0$ –0.10; $\varepsilon_c = \pm 0.02$)

Fig. 8 Explanation of the method for the determination of apparent elasticity modulus

1. from the cyclic tension–compression curves, the section of reverse loading should be considered and the points a, b, c, d and e should be identified;
2. the upper 5% of the curve (i.e., $0.95 \sigma_0 < \sigma < \sigma_0$) should be neglected, since due to the changing of loading direction, it could lead to uncertainties;
3. four sections (i.e., points a–e as case I, a–d as case II, a–c as case III and a–b as case IV) should be linearized, and from the elasticity moduli of these sections, an average (apparent) modulus can be calculated.

Applying the above considerations, from the experimentally measured cyclic tension–compression curves, the points a to e were determined and plotted for changing prestrain values, as shown in Fig. 9.

Fitting curves on these measured points and applying the curve fitting module of the MATLAB program, the γ and χ values characterizing the changes in the elasticity modulus during reverse loading can be determined as given by Eq. (3). Analyzing Fig. 9, it can be observed that as the length of linearization sections increases, the value of the average apparent modulus decreases. Applying the same procedure, similar curves were drawn for DP800 and DP1000 material grades, too.

Applying the curve fitting method implemented in MATLAB, the γ and χ values can be determined for each section (i.e., for points a–e as case I, a–d as case II, a–c as case III and a–b as case IV), and the values for the three tested DP material grades are given in Table 3.

Table 3 shows that both the γ and the χ values change significantly in the different sections, and so does the elasticity modulus. It can also be seen that the decrease in the elasticity modulus is the largest for DP600, followed by DP800, and the smallest decrease occurs for DP1000.

Fig. 9 Variation of apparent elasticity modulus for the material grade DP600

As it is also described in Sect. 2, the isotropic–kinematic hardening behavior of a given material practically may be characterized by three material parameters (γ , χ and K): the explanation of γ and χ was given above, while it is given for the K parameter on the basis of Fig. 10. As shown in figure, the K parameter is mainly responsible for the non-linear behavior; it also follows from Eq. (4). If $K = 0$, it corresponds to fully linear reverse loading character, and as its value increases, the reverse loading curve differs more and more from the linear one.

The differences in the three material parameters (γ , χ and K) for the three tested materials (DP600, DP800 and DP1000) can be explained by the differences in the microstructures (see Fig. 11). The martensite content of the materials changes in accordance with the mechanical properties shown in Table 2. In each grade, ferrite + martensite microstructural elements can be found, but the martensite content increases from 18% for DP600 up to 50% or even more in DP1000.

4 Sensitivity Analysis of the Material Properties with FEM Simulation

Since during the experimental investigations, we found different values for different grades of DP steels, a sensitivity analysis was performed with the AutoForm package to analyze the effect of these parameters on the springback behavior, testing the parameters γ , χ and K .

To examine the effect of these parameters independently in each analysis, two parameters were fixed and the third was changed. For the sensitivity analysis, we selected the well-known Numisheet benchmark test of U-channel bending [24].

In the first test, all the three parameters (γ , χ and K) were fixed and we analyzed the effect of the yield

Table 3 γ and χ values for three different DP materials in the I–IV sections

	DP600				DP800				DP1000			
	I	II	III	IV	I	II	III	IV	I	II	III	IV
γ	0.22	0.177	0.154	0.123	0.22	0.161	0.131	0.113	0.20	0.146	0.117	0.094
χ	49	45	30	37	82	65	54	46	80	68	60	57

Fig. 10 Explanation of the meaning of K material parameter

strength differences as shown in Fig. 12. (The uniformly shaded part is the reference one.)

Then, the effect of the γ parameter was studied. In these analyses, the two other material parameters (χ and K) were kept constant. On the basis of the experimental investigations, the value of γ was changed between 0.1 and 0.2. The results for DP600 steel are shown in Fig. 13. From the figure, it can be seen that changes in the γ parameter between 0.1 and 0.2 result in significant differences.

During the next tests, the effect of the χ parameter was studied. In these investigations, the γ and the K parameters were kept constant. From the results, it may be concluded that changes in the χ parameter have no significant effect on the springback behavior in the case of identical other material properties (e.g., yield strength and Young's modulus). The results for DP600 steel are shown in Fig. 14.

Finally, the effect of the K parameter was studied. Analyzing these results, we found a similar effect on springback as was experienced when changing the γ parameter. The results for DP600 steel are shown in Fig. 15.

5 Summary

In this work, some experimental and numerical investigations of large-strain cyclic plastic deformation are introduced from the point of view of springback behavior of high-strength dual-phase steels. Starting from some theoretical considerations of large-strain cyclic deformation, it is concluded that the increased springback behavior of the tested high-strength steels is strongly affected by the Bauschinger effect.

In the experimental investigation of large-strain cyclic deformation, there are various limitations. A new experimental method and technique is proposed to overcome these limitations. The new device is used in tension–compression cyclic loading to determine the important material parameters needed to model springback behavior.

Fig. 11 Microstructure of the investigated DP steels

Fig. 12 Comparison of the springback for three different DP steels ($\gamma = 0.13$, $\chi = 40$, $K = 0.014$)

Fig. 13 Effect of the γ parameter on the springback for DP600 dual-phase steel

Fig. 14 Effect of the χ parameter on the springback for DP600 dual-phase steel

Fig. 15 Effect of the K parameter on the springback for DP600 dual-phase steel

Various sensitivity analyses were performed to study how the changes in these material parameters will affect the springback behavior of the tested material grades. From the numerical simulations, it was concluded that the effect of the γ and K parameters is more significant than that of the χ parameter.

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