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MODELLING AND EXPERIMENTAL INVESTIGATION OF LARGE-STRAIN CYCLIC PLASTIC DEFORMATION OF HIGH STRENGTH DUAL-PHASE STEELS

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Abstract. The springback is an important practical and theoretical issue for the recently developed high strength steels. It is well-known that the springback occurring during sheet metal forming is strongly connected to large-strain cyclic deformation. The more accurate handling of springback during numerical modelling of sheet metal forming processes is of utmost importance particularly in the automotive industry where new high strength steels are more and more widely applied. In this paper, first the theoretical background of springback will be shortly analyzed, and then a new experimental device for studying large-strain cyclic deformation will be described presenting some experimental results on dual-phase steels obtained by these experiments and verified by numerical modelling.

1 INTRODUCTION

Springback of formed components is one of the main problems in sheet metal forming. In most of the forming processes several part sections are undergoing cyclic plastic deformation, e.g. bending and straightening over a tool radius, or passing through a drawbead, etc. The hardening behaviour has significant differences for forward and reverse loading due to the well-known Bauschinger effect.

Traditionally, the springback problem is handled by time and cost consuming trial and error methods. Recently, finite element simulation is used to predict the springback after forming: good simulation is the precondition of determining the accurate shape of the part. The springback phenomenon is strongly connected to several physical and material properties. From the point of view of continuum mechanics the Young-modulus and particularly its changes during cyclic loading, as well as the yield strength are the most important mechanical properties, but many experiments indicate the importance of microstructure as well.

In the followings, some theoretical considerations on springback phenomena and some experimental results on cyclic plastic deformation of high strength dual phase sheets will be discussed.

2 THEORETICAL CONSIDERATIONS ON SPRINGBACK

For more accurate modelling of springback phenomena, it is absolutely essential to analyse the stress-strain behaviour of sheet metals during loading and unloading (i.e. reverse loading). There are several investigations to study the so-called cyclic plasticity: earlier they were mainly related to low-cycle fatigue thus the investigations remained in the range of small plastic deformation, however recently more efforts were done to study the effect of the Bauschinger effect on large-strain cyclic behaviour of sheet metallic materials [1].

In the recent papers, it is clearly shown that the behaviour of sheet metal during loading-unloading and reverse loading phase is very essential for 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 behaviour. To illustrate it, a schematic stress-strain curve determined in uniaxial tension-compression loading is shown in Figure 1. On the basis of this Figure, the following sections of the Bauschinger effect are considered: the so-called early replastification characterized by the early re-yielding and smooth elastic-plastic transition, the transient softening and the permanent softening leading to the work hardening stagnation and resulting in reduced yielding as compared to isotropic hardening (see also in Figure 1.).

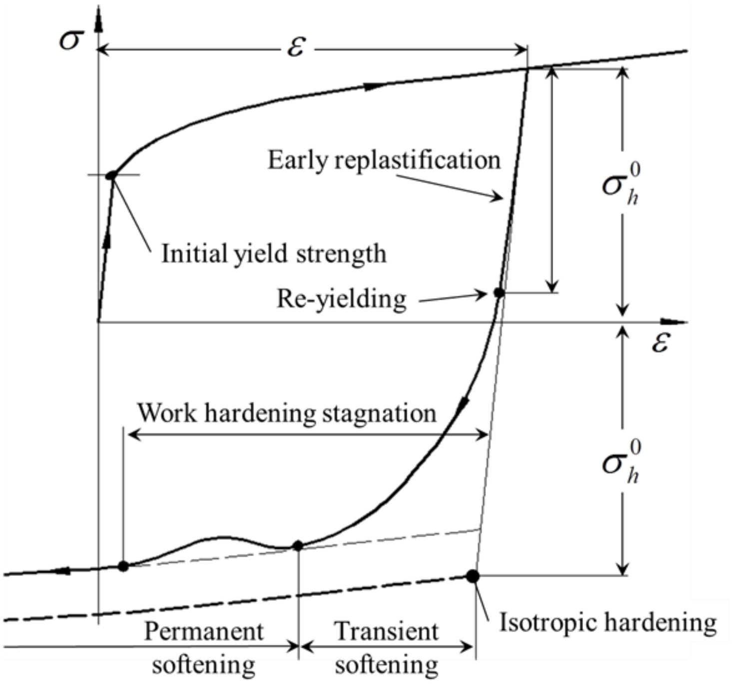

Figure 1. Schematic illustration of loading-unloading cycle [1]

One of the most widely applied models for this tension-compression stress-strain was elaborated by Yoshida and Uemori [1]. In this model the hardening is described by two bounding surfaces. One of the surfaces is defined as pure kinematic hardening and given by

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

where $\mathbf{S}$ is the Cauchy deviator stress tensor, α is the so-called back-stress deviator tensor and σ_o denotes the initial yield strength. The second surface can be defined as a bounding surface with isotropic-kinematic hardening and given by the equation

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

where β denotes the centre of isotropic-hardening surface, B and R are its initial size and isotropic hardening component.

A similar but rather practical approach is implemented in the AutoForm FEM package. The main idea of the AutoForm model is to use the same developing equations to describe the early re-plastification (early yielding) and the transient softening. A detailed description of this model can be found in several publications [2], [3]. 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 case. 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 non-linear (ε_{rn}) reverse strain. An initial tangent modulus (E_l) can be rendered to the linear reverse strain (ε_r) which characterizes the early re-yielding phase. However, E_l is exponentially deceasing as the equivalent plastic strain (p) accumulates. The reduction of the tangent modulus thus may be written with the expression

$$E_l=E_0\left[1-\gamma\left(1-e^{\chi p}\right)\right] \tag{3}$$

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 of the initial tangent modulus and χ is the so-called saturation constant.

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

$$\varepsilon_r=\varepsilon_{rl}+\varepsilon_{rn}=\frac{\sigma_r}{\mathrm{E}_l(\mathrm{p})}+\mathrm{K}\,\mathrm{arctanh}^2\left(\frac{\sigma_r}{2\sigma_h(\mathrm{p})}\right)^2 \tag{4}$$

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

3 EXPERIMENTAL INVESTIGATIONS

There are various methods known from the literature to measure 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 those 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 range as possible to reduce the measuring errors.

Yoshida and Urabe [4] in their early tests 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 Yoshida and Urabe 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.

Similar principle was applied in the experiments of Zhao and Lee [5] where a three-point bending system was used. During these experiments the bending moment and punch displacement diagrams were recorded and applying the Chaboche isotropic-kinematic hardening model and a genetic algorithm the material properties were determined as a result of an optimization task. A further measuring device based on bending experiments was constructed by Omerspahic and Mattiasson 0 and they determined the cyclic plastic material properties applying inverse FEM technique using LS-DYNA code.

A further group of methods providing large cyclic plastic strain is based on shear test investigation. Miyauchi's pure shear testing method [7] 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 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 the research interest turned towards the application of uniaxial tensile-compressive loads that both in bending and in shear tests, it is difficult to extend the results to 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 tensile-compressive cyclic loading which results in a relatively simple method to extend these results to general stress and strain state. A further advantage of these tests 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 that during the compressive 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, it 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 needs 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 that the uniformity of 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 ones.

Another approach to avoid buckling of thin sheets during the compressive load cycle is to apply special specimen and devices to support the sheet specimen. Ramberg and Miller [8] 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%. Boger and coworkers [9] 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 revealed that the applied support increases the measured force due to the friction forces and the stress state proportionally changes to biaxial one as the sheet thickness increased during the compression loading cycle.

Tan et.al [10] 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 and co-authors [11] used a variation of the pack method, where 5 sheets were laminated together to provide support in addition to plates. This method was 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. [12]. They used two-pairs of comb-shaped sets to support the sample. This is an improvement of solid supports 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 has also 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.

4 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 [13]. During the design of this device we applied the following considerations:

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

During designing the experimental device, the sizes of the samples are 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. Under the head-effect we mean that the different width of the specimen head must not have effect on the uniform stress distribution in the gauge-length. The minimum gauge-length was determined by a FEM analysis [14] as shown in Figure 2. (The two black lines on the Figure denote the gauge length.)

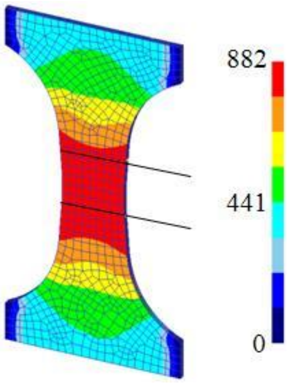

Figure 2. FEM analysis of the sample head effect on the gauge length

4.1 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 comb-shaped plates were applied. The material of the plates was DC04 mild steel with 0.5 mm thicknesses. These plates supporting the specimen on both sides are positioned to each other by 1.5 mm distance and are joined in a two parts frame as shown in Figure 3.

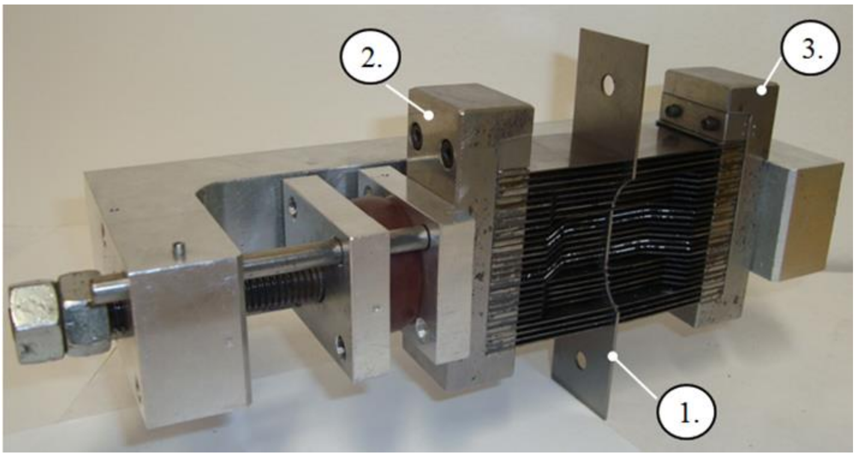

Figure 3. The supporting frame with two rows of plates
1-specimen; 2 and 3-frames with the supporting comb-shaped plates

The experimental device mounted in a two-column die-set with the supporting frames and plates can be seen in Figure 4. The two rows plates are included in a clamping frame, the pre-stressing 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 system (MTS-801).

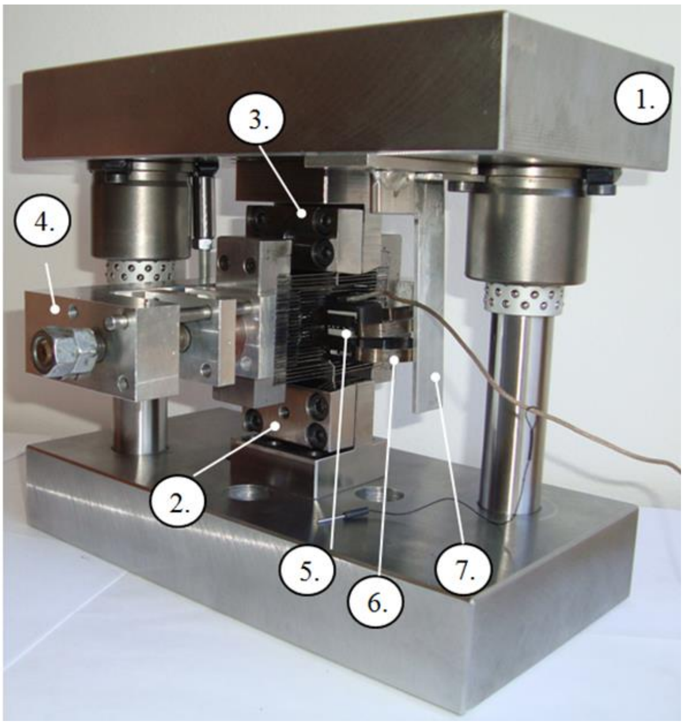

Figure 4. The experimental device for cyclic tension-compression test
1-two column guided tool; 2,3-clamping frame; 4-prestressing unit; 5-extensometer; 6-plate spring; 7-supporting pad

4.2 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.

Table 1. Chemical composition of the experimental materials

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	rest
DP800	0,012	0,198	1,43	0,020	0,027	0,032	0,037	0,014	rest
DP1000	0,142	0,472	1,47	0,015	0,017	0,032	0,052	0,014	rest

The mechanical properties (R_{eH}: the yield strength, R_m: the ultimate tensile strength, E_0: the initial Young 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.

Table 2. Some mechanichal properties of tested materials

Material	Lv. [mm]	R_{eH} [MPa]	R_m [MPa]	Martenzit %	E_0 [GPa]
DP600	1	351	670	18	206
DP800	1	555	847	32	206
DP1000	1	780	1004	50	206

5 EXPERIMENTAL INVESTIGATIONS

Before describing the experimental results some general considerations can be summarized. As it was mentioned before, the determination of the material properties to be used in FEM modelling to predict more accurately the springback behavior of high strength steels can be regarded as the primary objectives of these investigations. 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 as wide strain range as possible. Performing preliminary tensile tests with the test materials, we found that the limit value of strain in tension without losing the stability is ε_{max}=0.12 for DP600 and ε_{max}=0.08 for both DP800 and DP1000. Another important aspect of experimental considerations was that to achieve these limit strain values in tension-compression cycles, it can be realized more reliably if different pre-strained components are tested as shown in Figure 5., i.e. the same value of strain cycles (ε=±0.02) will be used however the mean value of strain cycles is increased continuously.

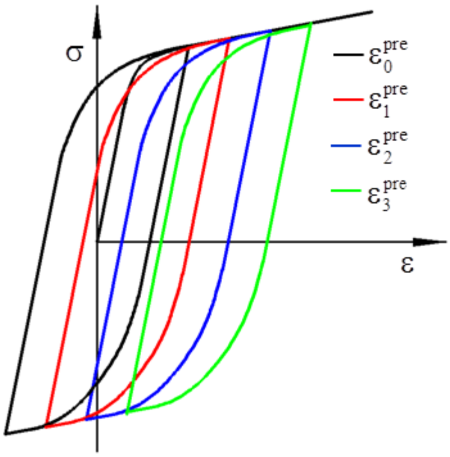

Figure 5. Deformation strategy to achieve the strain limits in cyclic tension-compression tests

5.1 Experimental results

The experiments were performed with the experimental tool setup shown in Figure 4. on an electronically controlled universal material testing machine (MTS-801). For each material several tests were done with different magnitude of strain cycles and varied pre-deformation.

A set of hysteresis curves are shown in Figure 6. for DP1000 dual phase steel with $\varepsilon_{max} = \pm 0.02$ cyclic strain with continuously increased mean strain (from $\varepsilon_{mean} = 0.0$ to 0.06). The characters of the diagrams are similar for DP600 and DP800, too, but the mean value of pre-deformation is different depending on the higher uniform deformation of the different steels.

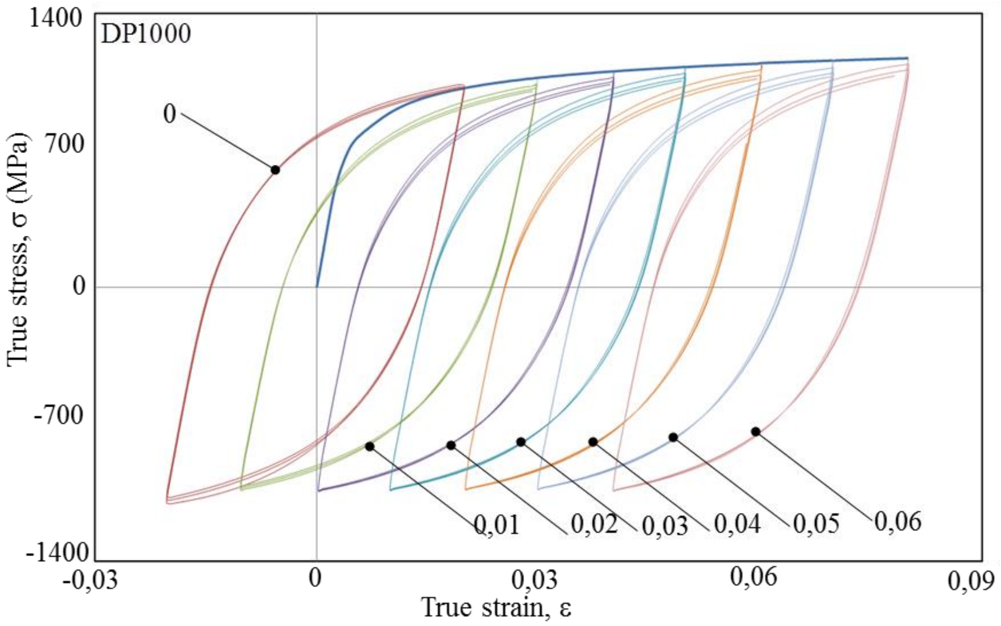

Figure 6. Hysteresis curves for DP1000 dual-phase steel with (cyclic strain $\varepsilon_{max} = \pm 0.02$, pre-deformation values: $\varepsilon_{mean} = 0.0$ to 0.06)

On the basis of the experiments, the material parameters (γ, χ and K) necessary for the springback simulation were determined as described in section 2. and the variation of apparent elasticity modulus (E_{ap}) was determined. The variation of apparent elasticity modulus is shown in Figure 7. for DP1000 material quality.

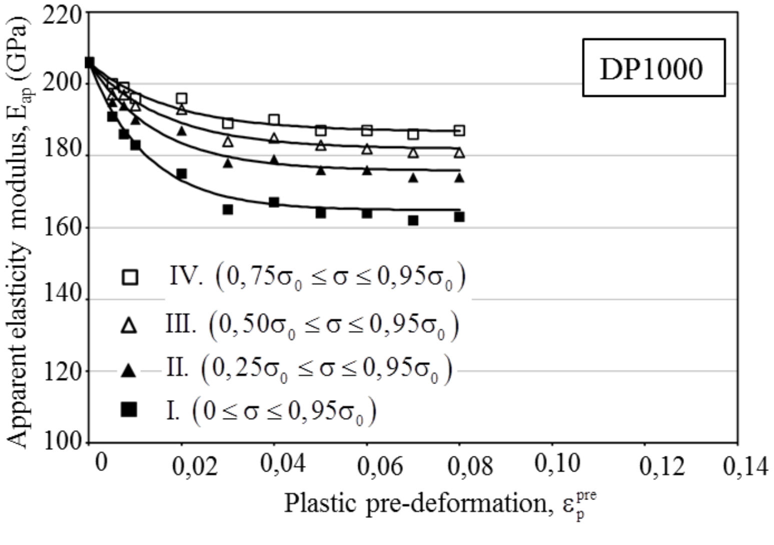

Figure 7. Variation of apparent elasticity modulus for DP1000

6 SENSITIVITY ANALYSIS OF THE MATERIAL PARAMETERS BY FEM SIMULATION

Various numerical simulations were performed to analyze the effect of material parameters changes on the springback behavior of the tested materials. In Figure 8. the springback of three DP grades are shown compared to the reference geometry for given material properties.

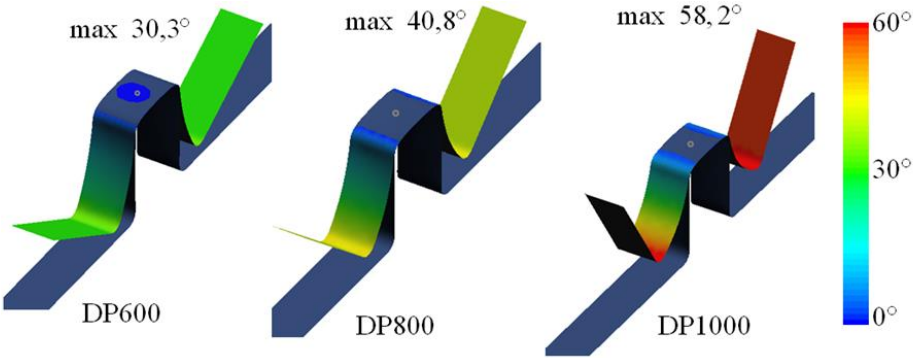

Figure 8. Numerical simulation of DP600, DP800 and DP100
(γ = 0.13, χ = 40 and K = 0.014)

We also tested the effect of the variation of the various parameters on the springback behavior. In Figure 9, the effect of the γ, whilst in Figure 10, the effect of the K parameter on the springback behaviour is shown for the DP600 material [15].

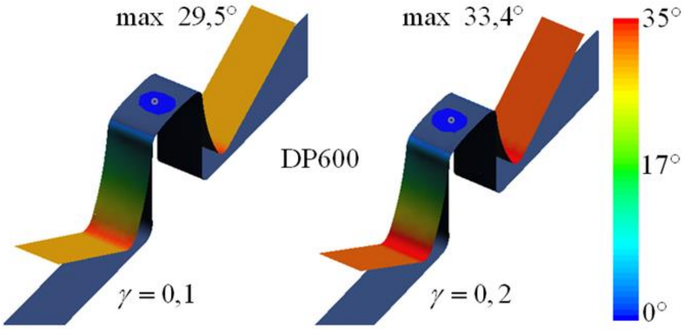

Figure 9. The effect of the γ parameter on the springback behaviour for DP600 material grade

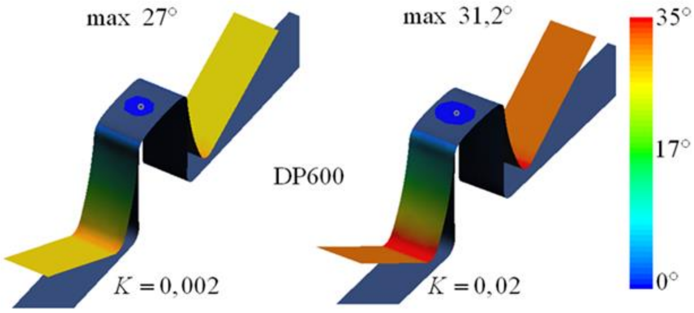

Figure 10. The effect of the K parameter on the springback behaviour for DP600 material grade

7 SUMMARY

In this paper, some experimental and numerical investigation of large strain cyclic plastic deformation is 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 the springback behavior.

Various sensitivity analyses were performed to study how the changes of 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.

8 ACKNOWLEDGEMENT

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