

Strain path changes in Reverse Redrawing of DP Steels

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Abstract. There has been a longtime and steady interest for the influence of strain path changes on the forming and formability of metallic sheets. First from an experimental point of view, leading to a classification of strain path changes according to their severity, related to the microstructural changes at the grain scale and stress stagnation or even decrease at the macroscopic scale. And secondly, from a modeling point of view, with the development of dedicated constitutive equations to represent various behaviors ranging from strain path reversal to abrupt (or orthogonal) strain path change. However, apart from path reversal, there is still a need, out of validation's sake, to design forming tests at the laboratory scale that are sensitive to strain path changes, and particularly to orthogonal ones. Reverse redrawing of cylindrical cups is considered in this study. Indeed, during the second stage, strain path changes are expected to occur and the load prediction and the residual stresses should be dependent on the mechanical model. Though the study is purely numerical in a first step, a dual phase steel DP 980 is considered, and its sensitivity to strain path change made of tension followed by simple shear is first checked. The occurrence of strain paths occurring during the two stages of reverse redrawing are then investigated numerically and a comparison of two indicators is performed.

1. Introduction

Within the framework of virtual forming, there is a growing interest for the analysis and numerical prediction of the influence of the residual stresses stemming from forming on the service life of industrial parts. Such residual stresses are highly dependent on the mechanical model and its ability to represent the real material under the various strain paths occurring in forming. Though the external shape of the part can be rather well predicted, residual stresses are more difficult to capture accurately, as can be evidenced with the split ring test performed on cylindrical drawn cups [1]. Moreover, similar shapes can be obtained with different strain paths; indeed, a previous numerical study [2] compares, for the same final cup dimensions, a two-stage process consisting of a first cup drawing followed by reverse redrawing with a single stage drawing; the strain paths are different, as exhibited in Figure 1, though strain path changes are not investigated. Therefore, residual stresses after forming should be rather different in the two cases and should influence differently the service life of the drawn part.

The field of sheet metal forming has been rather vastly investigated for several decades, fueled by industrial concerns about the formability of the materials and hence the validation of process parameters. Experiments at the laboratory scale have been performed to be representative of



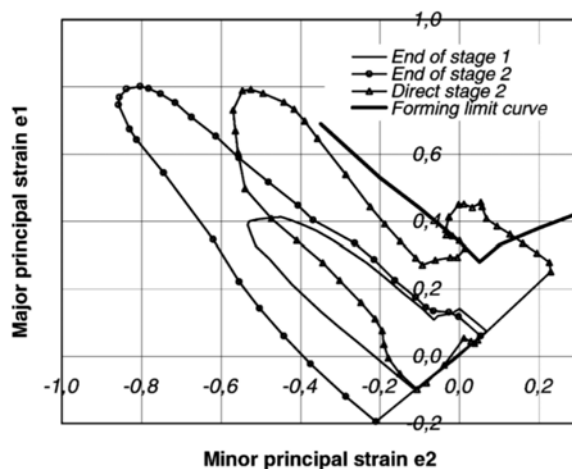


Figure 1. Strain paths during two-stage redrawing of cylindrical cups [2]. Direct stage 2 corresponds to the direct drawing in a single step, for the same final dimensions of the cup.

forming conditions, characterised by large strains and non-linear strain path, with more or less smooth/abrupt strain path changes. Indeed, though the strain path are non-linear for most forming processes such as deep drawing, they are reproduced by sequential tests, made of two, even three paths involving unloadings in-between. Several sequences such as tension followed by another tension at different orientations, rolling than tension, tension followed by simple shear have been considered and three main categories are classically sorted out: quasi-continuous strain path, reversed strain path change (related to the Bauschinger effect) and abrupt or orthogonal strain path change. The macroscopic behavior during the second stage is significantly influenced by the prestrain, relatively to the status of the new slip systems, that could have been activated, activated but in the reverse direction or latent during the prestrain respectively. Different macroscopic indicators are proposed in the literature to quantify the magnitude of the strain path change, based either on strain or stress tensors. Schmitt's factor [3] is the oldest one, based on a geometrical meaning of the indicator related to the angle, in the strain space, between two strain rate tensors. A modification of Schmitt's factor is performed by introducing a second-order tensor representative of the plastic strain history [4], motivated by smoothing the evolution in the case of forming. From a modeling point of view, an equivalent idea but expressed with the help of stress tensors, is introduced in the Homogenous Anisotropic Hardening (HAH) model [5]. Finally, an indicator limited to orthogonal strain path change (or cross-hardening indicator) [6] is also introduced. In this study, only the two first ones, strain-based are considered.

After evidencing such influence at the sample scale, the next step is to analyse the strain path changes occurring during forming. The use of numerical simulation has led to the evaluation of several indicators during forming, e.g. the reverse redrawing test using Schmitt's factor [3], the cross-die deep drawing test with van Riel's strain path change indicator [4, 7] and channel forming with twist springback [8]. Therefore, it is concluded that strain path changes are clearly evidenced in forming. However, they do not occur simultaneously over the blank and can concern a rather limited area. Therefore, their influence on the macroscopic behavior, i.e. load evolution is still to be ascertained. Moreover, residual stresses after forming are highly influenced by the strain paths and therefore by the ability of the mechanical model to represent them.

This study deals with a numerical investigation of strain path changes in the reverse redrawing of dual phase steel DP980. Such a test was proposed as a Benchmark at the international

conference Numisheet 1999 [9]. Reverse redrawing is a two-step process used for some deep drawn part, such as gas cylinder, as the formability is enhanced. A first part focuses on the strain-based indicators proposed in literature to evaluate strain path changes. Then, the mechanical behavior of DP 980 sheets is characterised to exhibits its sensitivity to strain path changes and finally, such changes are evaluated in the case of the reverse redrawing of DP980 cylindrical cups, using two indicators, in order to highlight and discuss their stability and reliability.

2. Evaluation of strain path changes

2.1. Schmitt's factor

The purpose is to define a parameter able to represent the evolution of the direction of the strain vector in the tensor space. The definition of this parameter is a cosine of the angle between the two directions, presented in Eq. (1).

$$\Theta = \frac{\dot{\epsilon}_1^p : \dot{\epsilon}_2^p}{\|\dot{\epsilon}_1^p\| \|\dot{\epsilon}_2^p\|} \quad (1)$$

where $\dot{\epsilon}_i^p, i = 1, 2$ are the plastic strain rate tensors of two successive strain paths. This definition, very intuitive and understandable, is very well suited to clearly distinct variation of strain paths, as imposed at the sample scale at the laboratory scale. Indeed, the values range between -1 and 1, and three particular values can be distinguished:

- $\Theta = 1$: continuous (or monotonic) loading, which is not a strain path change,
- $\Theta = -1$: reverse loading, corresponding to the Bauschinger effect,
- $\Theta = 0$: orthogonal loading, also known as cross-loading.

2.2. Modification of Schmitt's factor: a better evaluation of continuous strain path change

Schmitt's factor is effective when the change of strain path is abrupt because it considers two sequential strain increments. For example, it works very well when the second strain path is applied on a sample cut out of the first sample submitted to the prestrain. However, when the change of strain path is more continuous and occurs rather smoothly over several strain increments, large variations can be recorded. A stabilizing procedure is proposed via the definition of a tensorial internal variable \mathbf{G} , that takes into account the strain path history [4]. The evolution law is presented in Eq. (2).

$$\dot{\mathbf{G}} = \dot{\epsilon}^p - c \|\dot{\epsilon}^p\| \mathbf{G} \quad (2)$$

The strain path indicator ξ is then defined by Eq. (3):

$$\xi = \frac{\mathbf{G} : \dot{\epsilon}^p}{\|\mathbf{G}\| \|\dot{\epsilon}^p\|} \quad (3)$$

The parameter c quantifies the weight of the strain path history, it controls the rate at which ξ returns to a monotonic state. The three particular cases of monotonic, reverse and orthogonal loading are equally described by the respective values 1, -1 and 0. The use of ξ reduces oscillations of the indicator value that could be misinterpreted as strain path changes and can deal with multiple strain path changes [7].

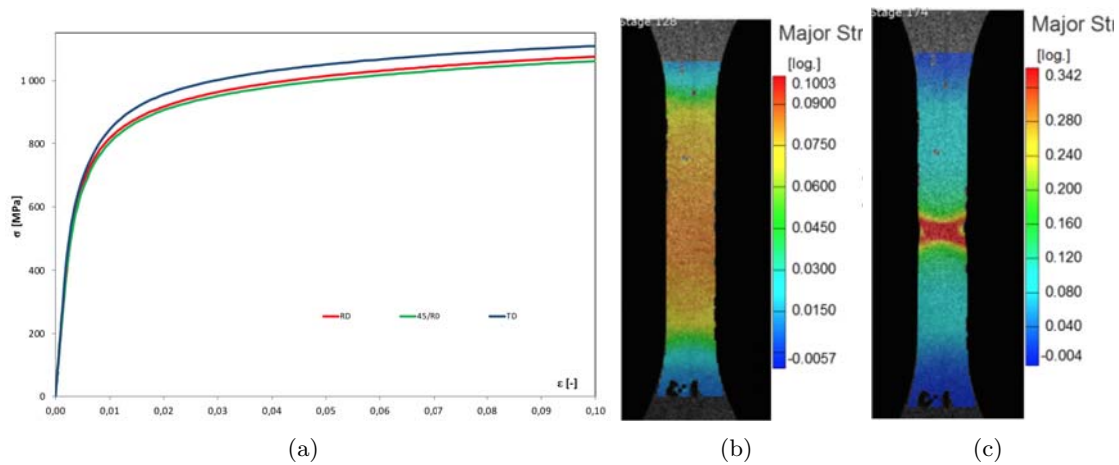


Figure 2. (a) Cauchy stress versus strain curves at several orientation to the rolling direction. The strain range is limited to 0.1 corresponding to the onset of necking (b) Major strain isovalue showing the very good homogeneity of the strain distribution before necking (c) Stage just before rupture in the specimen center.

3. Mechanical behavior of dual phase steel DP980

The material is provided as sheets of thickness 1.75 mm [10]. Tensile tests at several orientations to the rolling direction are performed in order to characterize the initial anisotropy. Moreover, simple shear tests are done on the material without any prestrain and also prestrained in tension; in this latter case, the shear direction is the same as the tensile direction, both parallel with the rolling direction. The aim of this investigation is to characterize the magnitude of strain paths for $\Theta = 0$. In a first step, and as only strain-based definitions for the strain path indicator are used, only isotropic hardening associated with von Mises yield criterion are used. The next step (not presented here) is to identify material parameters of more advanced mechanical models that take account of the specific characteristics associated to strain path changes.

Figure 2 shows the evolution of Cauchy stress with the longitudinal strain (logarithmic definition), measured as an average value over a central area using digital image correlation system. It is worth noting that due to a specific tensile device, with a sample free to rotate under the grips, the strain field is homogeneous in the gauge area (Figs. 2(b) and 2(c)). The normalised yield stress $R_{p0.2\%}$ lies within the range [674 MPa, 724 MPa] and exhibits a slight anisotropy (gap of 50 MPa). The same gap is recorded on the ultimate tensile strength, with a minimum value of 1002 MPa. The plastic anisotropy coefficients also vary, within the range [0.62, 1.01]. Simple shear tests, as described in [11], are performed on sample without pre-strain and also after a tensile pre-strain. They are not easy to perform, due to the very high mechanical properties and the relatively high thickness, and a rotation of the specimen under the grips is evidenced. The deformed area is no longer strictly parallel to the shear direction and a finite element analysis is necessary to output accurately the shear stress; therefore, these results are not presented here. However, it is observed, in a qualitative way, that DP980 is sensitive to orthogonal strain path change consisting of a tensile pre-strain followed by a simple shear along the same direction. These results are consistent with a previously published investigation of dual phase steels under complex loadings [12].

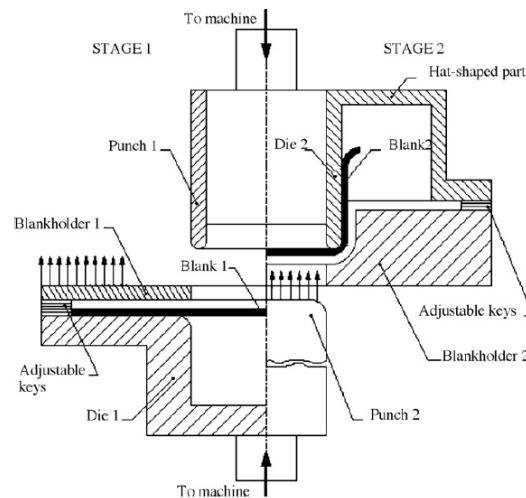


Figure 3. Schematic drawing of the deep-drawing device. The first-stage process is represented on the left hand-side and the second stage on the right hand-side [2].

4. Two-stage forming process of cylindrical cups

The first two strain path indicators previously introduced give the intensity of path changes occurring during the deformation. A further step is to use mechanical models able to reproduce the associated specific behaviors. However, these models generally include a large number of material parameters and necessitate an extensive experimental database for their identification. There is therefore an industrial interest to evaluate a priori the amount of strain path changes in a forming process, to adjust the complexity of the constitutive equations. However, to validate the model, it is necessary to develop forming tests at the laboratory scale which are sensitive to strain path changes. In this study, reverse redrawing of cylindrical cups is considered using DP980 as the material and a numerical investigation is carried out to highlight strain path changes, their intensity and their importance.

4.1. Geometry of the blank and tools

Reverse redrawing test consists in drawing a cylindrical cup in two stages. A previous study shows that such a multi-stage process involves orthogonal strain path change during the second stage [2, 13]. The geometry comes from a benchmark at the international conference Numisheet 1999 [9]. The experimental device is represented in Figure 3.

The first stage is represented on the left-hand side of the figure. The blank is positioned on a die which is fixed during all the stage. The blank-holder is also fixed at a constant distance to the die via adjustable keys (as far as the elastic deformation of the tools can be neglected). A displacement is imposed to the punch to deep-drawn the blank. In the second stage, represented on the right-hand side of the figure, the punch of the first stage become the die. The die and the blank holder of the first stage are removed. They are replaced by a new punch and a new blank-holder. As in the first stage, the gap between the die and the blank-holder is fixed by adjustable keys during all the stage and the punch is also controlled in displacement to deep-drawn the cylindrical cup a second time, to form another cylindrical cup of smaller internal diameter. The maximum stroke in the first stage is 54 mm and 80 mm in the second stage. The main dimensions are summarised in Table 1.

A finite element analysis of the test is performed assuming von Mises yield criterion and

Table 1. Characteristic dimensions of the reverse redrawing test.

	Dimension (mm)
Blank sheet initial diameter	170
Die 1 internal diameter	104.5
Die 1 drawing radius	8
Punch 1(die 2) internal diameter	100
Punch 1 (die 2) drawing radius	5.5
Punch 2 diameter	73.4
Punch 2 drawing ratio	8.5

isotropic hardening. The symmetry of the problem is taken in account and only half the blank is meshed. Three integration points are taken in the blank thickness and a in-plane mesh size of around 0.3 mm is considered. The plastic strain tensor is output at each time increment, as well as the equivalent plastic strain. The parameter Θ (Eq. 1) is then calculated. As already discussed, it is very sensitive to the time increments and several calculations are performed, for different increments of the punch displacement, either 1 mm, 2 mm or 5 mm. The evolution of the parameter with the punch displacement is investigated. To remove the calculation of Θ when the equivalent plastic strain does not evolve (elastic loading/unloading), a condition is added on the increment of the equivalent plastic strain, that must be above a given threshold (here equal to 1×10^{-3}).

Moreover, the parameter ξ (Eq. 3) is also calculated using an explicit time integration based on the same spatial discretisation as the finite element analysis, of Eq. 2, to compare with Θ . The parameter $c = 5$ is fixed in a first step, in order to smoothen the evolution of ξ .

5. Results and discussion

Several nodes are considered, one located at a radial distance of 77 mm and two at 58 mm, either at the bottom or top surface. Figure 4 displays the evolution of Θ and ξ with time, that is directly related to the punch displacement, for the 2 stages. Whatever the increment considered, it appears clearly that strain path changes occur during the first stage, but with a limited intensity, i.e. $\Theta \geq 0.6$, whereas a zero value is reached during the second step. The value of Θ is however largely influenced by the increment of displacement, and a value of 5 mm leads to nearly a nul value, though lower values are calculated for 1 mm and 2 mm. These results are consistent with previously published ones [2, 13]. The evolution of ξ is similar to the one of Θ , for a displacement increment of 2 mm. It should be emphasized that the return to the value of 1 in-between the two stages is forced by a specific condition, that is $\xi = 1$ when the increment of equivalent plastic strain is below a threshold of 1×10^{-3} in-between two increments.

Figure 5(a) shows the evolution of ξ at a different node, located at a radial distance of 58 mm, at the top surface in contact with the punch of the first stage. The influence of the condition on the variation of the equivalent plastic strain is emphasized. Several strain path changes are detected without this conditions (yellow curve), corresponding to evolution of the strain path direction without any plastic strain. When the condition is used, the indicators returns to 1 (green curve). It is difficult to conclude on the importance of these specific path changes and whether they alter the macroscopic behavior such as the load. Further investigation with mechanical model taking account of path changes will be performed. Finally, Figure 5(b) exhibits the influence of the value of parameter c (Eq. (2)) on the prediction of strain path change. It

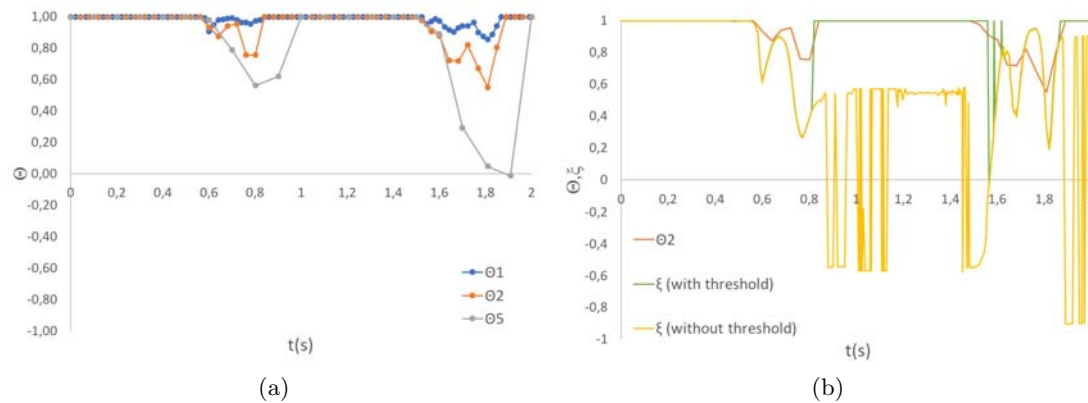


Figure 4. Strain path change indicators (a) Θ and (b) ξ . The time t is used for the abscissa axis. The punch displacement is linearly related to it, and is equal to of 54 mm at 1 s and 80 mm at 2 s. The node is located at a radial distance of 77 mm.

shows that the occurrence of strain path changes is predicted at the same instants, though the value of the parameter ξ depends strongly on c .

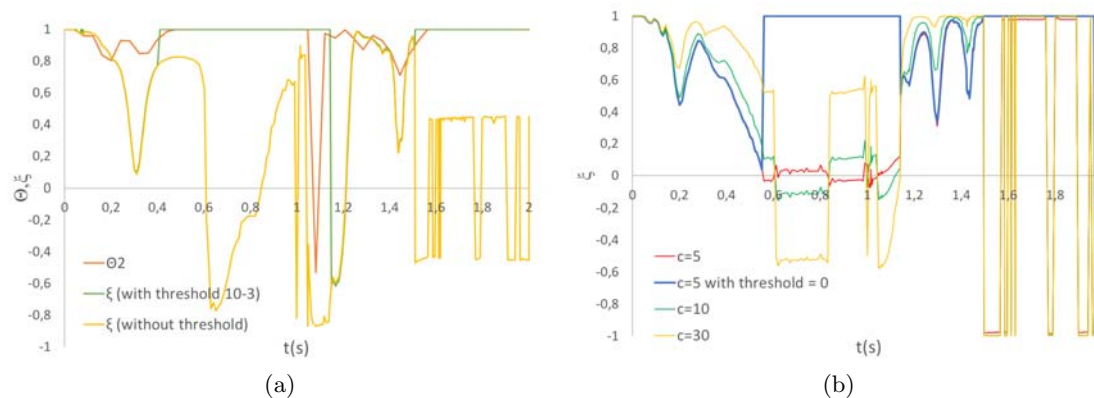


Figure 5. ξ evolution at nodes located at a radial distance of 58 mm, at the (a) top surface in contact with the punch of the first stage and (b) bottom surface. The threshold corresponds to a condition on the variation of the equivalent plastic strain between two successive time increments.

6. Conclusion

This study is dedicated to the evaluation of strain path during the reverse redrawing of cylindrical cups. In a first part, a brief overview of previous investigations is presented, to highlight two different strain path change indicators, based on strain tensors. Then, the mechanical behavior in tension and simple shear of DP980 steel sheets, of thickness 1.75 mm, is investigated at room temperature and it is concluded that this material is sensitive to orthogonal strain path changes. Finally, a numerical investigation of the reverse redrawing of DP980 blank is presented, and two different strain-based path change indicators are calculated and compared. It is shown that they are consistent on the displacement range corresponding to path changes. However, the value by

itself may vary significantly. Orthogonal strain path changes are calculated during the second stage. However, path changes are less significant during the first stage.

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