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# On the definition of an kinematic hardening effect graph for sheet metal forming process simulations

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ABSTRACT

The objective of this work is to develop a kinematic hardening effect graph (KHEG) which can be used to evaluate the effect of kinematic hardening on the model accuracy of numerical sheet metal forming simulations and this without the need of complex material characterisation. The virtual manufacturing process design and optimisation depends on the accuracy of the constitutive models used to represent material behaviour. Under reverse strain paths the Bauschinger effect phenomenon is modelled using kinematic hardening models. However, due to the complexity of the experimental testing required to characterise this phenomenon in this work the KHEG is presented as an indicator to evaluate the potential benefit of carrying out these tests. The tool is validated with the classic three point bending process and the U-channel width drawbead process. In the same way, the capability of the KHEG to identify effects in forming processes that do not include forming strain reversals is identified.

## 1. Introduction

The increasing use of higher strength materials for weight reduction in the automotive industry has motivated the development of new high strength alloys with complex microstructures such as the dual phase (DP), the transformation induced plasticity steels (TRIP) and the complex phase (CP) steels [1]. Those steel can show significantly higher springback compared to conventional grades due to their high material strength and a stronger Bauschinger phenomenon [2].

The finite element method has been established as an efficient tool to analyse, design and optimise manufacturing processes [3,4]. Nevertheless, the complex behaviour of these multiphase grades has led to the necessity of more accurate constitutive material models to correctly represent their material behaviour in forming. In recent years, new material models have been developed to improve the representation of the yield condition [3,5–8], material hardening [4,9,10] and the change in elastic modulus with plastic strain [11,12]. Most of the process parameters in forming are stress related, e.g. springback issues, process forces and torque. Therefore, for forming simulations accurately representing material hardening through advanced hardening laws is vital. The Bauschinger phenomenon is associated with a strain path reversal and this is common in sheet metal stamping processes, which generally involve the bending–unbending of the material on the die shoulder or the reverse bending–unbending at the punch corner radius [1]. Fig. 1 shows characteristic strain path reversal behaviour. The dashed line represents the material behaviour as predicted by a material model that does not account for Bauschinger effects, while the continuous line shows the material response if the Bauschinger effect is accounted for. The Bauschinger effect is associated with an early re-yielding together with the transient behaviour characterised by a rapid change of hardening rate [4,9]. In some cases the reversal behaviour converges to the tensile behaviour and in other materials a permanent softening can be observed [3].

Several models have been proposed in recent years to model material hardening [4,13–16]. The isotropic hardening model supposes an expansion of the yield surface due to the increase in dislocation density during forming [13] but does not accurately represent material hardening during strain reversal. This material behaviour can be captured by the kinematic hardening model which assumes the translation of the yield surface during material hardening [16]. In Fig. 2 combined hardening behaviour (the combined hardening assumes the expansion and translation of the yield surface during forming) in the biaxial space is shown. The continuous line represents the initial yield surface before forming while the dotted line stands for the yield surface after

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plastic deformation. In this case, the kinematic hardening model predicts a translation of the centre of the surface (defined by the back stress tensor $\overrightarrow{X}$) while the isotropic hardening predicts an expansion of the surface ($\Delta\sigma_y = \sigma_y - \sigma_{y0}$).

The early kinematic hardening model presented by Prager [17] was subsequently modified by Ziegler [18] in order to accurately represent the Bauschinger effect. Amstrong and Frederick [19] modified the Prager hardening model introducing a memory recall term to be able to represent the transient behaviour. The combination of both isotropic and kinematic hardening (Fig. 2) was proposed by Hodge [20]. In order to improve the capability of the hardening law to represent both initial transient behaviour as well as long term behaviours (multiple cyclic loading behaviours), Chaboche and Lemaitre [21] proposed the concept of multiple back stress tensors. Recent studies have focused on the correct representation of the reverse strain path behaviour by slightly modifying the hardening expressions proposed by Prager, Ziegler, Amstrong and Frederick as well as the isotropic hardening expression. Among these studies, Zhang et al. [2] and Chun et al. [22] proposed the superposition of a non-linear kinematic hardening rule and a linear kinematic hardening rule to improve the prediction of the transient material behaviour as well as of permanent softening. Similar modifications were proposed by Yoshida [23] and Ahn et al. [24] to represent multiaxial strain conditions.

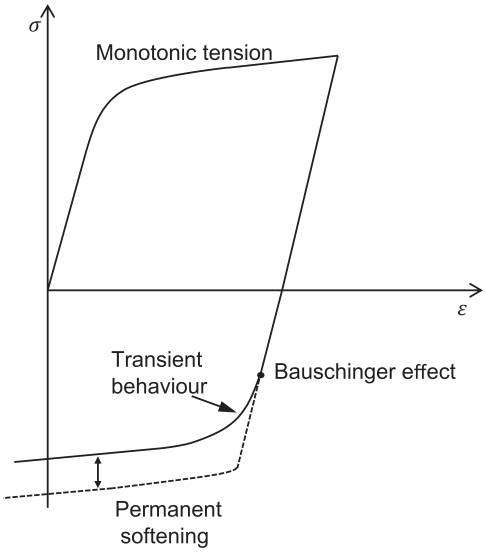

**Fig. 1.** Characteristic strain path reversal behaviour. The Bauschinger effect can be observed in the form of early re-yielding and permanent softening.

The material models introduced above often require complex programming for their incorporation in commercial software packages. Additionally to that the identification of the model parameters can be difficult and time consuming depending on the model complexity and the number of parameters required.

The test procedure generally applied to investigate the material behaviour during strain path reversal is the tension compression test. However, due to the tendency of metal sheet to buckle in compression the test is difficult to perform and is often limited to low strain ranges [4,25,26]. Alternative testing methods based on shear and bending deformation have been introduced to enable the identification of material hardening parameters at higher strains and to avoid buckling effects. While the shear reversal test [2,13,14] allows the analysis of material hardening parameter up to 30% of shear strain the bending test is limited to 6–8% of forming strain [1,16,27–29] significantly easier to apply. Due to the complex material deformation in both the bending and shear test inverse analysis techniques have to be applied for model parameter identification.

Due to the large effort required for model parameter identification and for integrating complex material models in commercial FEA codes the industrial application of advanced material hardening models is limited to some specific cases that show clear forming strain path reversals. However, even without a clear reversal in strain path some forming processes may require the

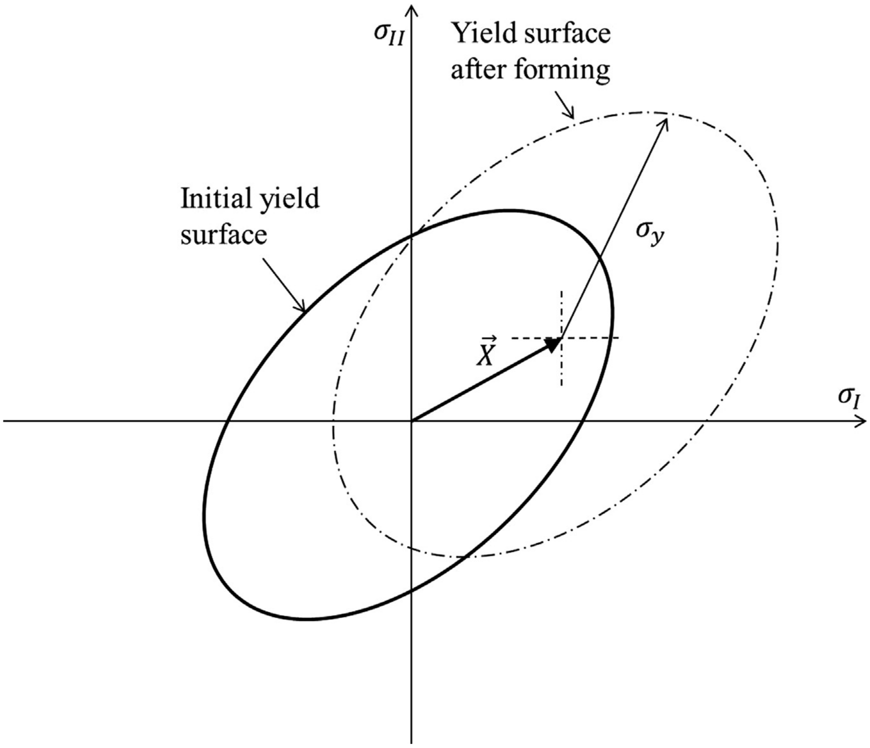

**Fig. 2.** Yield surface translation and expansion under plastic deformation (combined hardening model).