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Comparison of the hardening behaviour of different steel families: From mild and stainless steel to advanced high strength steels

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ABSTRACT

Although steel has been used in vehicles from the automotive industry's inception, different steel grades are continually being developed in order to satisfy new fuel economy requirements. For example, advanced high strength steel grades (AHSS) are widely used due to their good strength/weight ratio. Because each steel grade has a different microstructure composition, they show different behaviours when they are subjected to different strain paths in forming processes. Materials with high yield strength tend to be influenced by phenomena of cyclic plasticity such as the Bauschinger Effect, while low yield strength materials tend to harden when they are subjected to cyclic loading.

Different steel grades are used in different forming processes, which are usually optimised by numerical tools such as Finite Element Models. This method requires proper hardening rules in order to correctly predict the real behaviour of the materials. For instance, AHSS are usually well modelled by means of mixed isotropic–kinematic hardening models.

The methodology for developing a mixed hardening model to be implemented in finite element codes and simulate sheet forming processes requires three steps: (i) an appropriate experimental test to obtain stress–strain curves, (ii) a model able to predict accurately the behaviour of the material and (iii) a parameter identification method. Currently, there are few studies which analyse and model the hardening behaviour of different steel families following the same methodology. In this work, a wide range of steels from low to high yield strengths were characterised and their hardening behaviour modelled with the same methodology so as to provide comparative data.

In particular, the Chaboche and Lemaitre hardening model was successfully fitted to the experimental stress–strain curves obtained from a tension–compression test. The test was performed at low cyclic deformations ($\pm 2\%$) due to the limitation of the test to achieve higher deformations during the compression without buckling. Therefore, this modelization is useful for low deformation processes such as the roll levelling process (Silvestre; 2013, Silvestre et al. *Steel Res Int*; 2012, 1295), in which the maximum deformations achieved are lower than 2%.

1. Introduction

In recent years, the development of new steel grades with high performance has been driven by new requirements in the automotive industry. Reducing the weight of a vehicle is a straightforward strategy to improve fuel economy, but it can potentially create safety problems. For that reason, efforts have been concentrated on the development of new steel grades with a competitive strength/weight ratio [1]. However, the development of these materials leads to the apparition of undesirable phenomena during forming process which affect the quality of the final product [2]. For example, new high strength steels (HSS) and advanced high strength steel (AHSS) grades satisfy the mechanical properties required for an adequate design, i.e. durability, strength, stiffness, good crash energy absorption, acoustic properties, low production costs compared with other materials and the possibility of recycling [3]. Nevertheless, there are limiting factors for the application of HSS grades: they usually show low formability with some difficulties like its low ductility, wrinkles and springback [4,5].

In view of this situation, industrial users focus on finding ways to obtain accurate predictions of the part geometrical features and post-forming characteristics. In addition, the prediction of possible defects and failures on the basis of the process parameters has also been studied [6]. In this context, numerical simulation by finite element method (FEM) is widely used as a tool for engineers to

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improve the part design taking into account the process limitations.

In forming operations, the metal sheets are normally subjected to bending–unbending and stretching processes, for example when a sheet is drawn over a die corner [7] or when it is subjected to a roll levelling process [8]. In these cases, the material is subjected to complex strain paths which make it difficult to accurately predict the final shape of the part after forming. For that reason, the accuracy and quality of the final product are highly dependent on the accuracy of the implemented material constitutive model amongst others.

Constitutive models can be defined by two different ways: by the physical theory (defined at microscopic level) and the phenomenological theory (defined at macroscopic level). Microstructural models for sheet metal forming simulations show a high accuracy level on the dislocation and phase transformation mechanics [9,10]. However they are currently limited in their use, especially in industry, due to the complex experimental techniques required for the identification of their material parameters [6] as well as the associated high computational cost.

On the other hand, the macroscopic models are widely used, since they provide good compromise between model accuracy and simulation computational time [11]. Complex models are introduced increasingly in FEM codes to provide accurate predictions of material behaviour and different phenomenon such as the Bauschinger Effect, the transient behaviour, the permanent softening and ratcheting. Predictions of all these phenomena which affect the final shape are linked to the hardening rule, which describes the evolution of the initial yield surface. In fact, various types of hardening models can be used, according to their ability to explain and predict the details of the plastic behaviour during a given deformation process. Eggertsen et al. [12] collected the cyclic phenomena that are captured by different hardening models. They determined that as the complexity of the model increased, the model was able to increase the accuracy of the predictions.

There are three types of hardening models: the isotropic models, the kinematic models and the combination of both. For simple applications, isotropic hardening models are used by expressing the proportional expansion of the initial yield surface [13]. These models have been widely used for industrial applications due to their simplicity and because they are able to predict hardening behaviour of a high range of different materials. Nevertheless, the simulation of new advanced materials, such as AHSS, introduces a challenge as the use of isotropic models overestimates the hardening in reversal loading under reverse strain paths [6]. This is due to the presence of different phenomena during reversal loading which occur commonly in these materials, such as: the Bauschinger Effect, the transient behaviour and the permanent softening [14].

Kinematic hardening laws provide more sophisticated models than isotropic, where yield surfaces preserve their shape and size but translate through the stress space. In recent years these models have received special attention due to their ability to predict some phenomena such as the Bauschinger Effect [12,15]. This phenomenon is a clear example of how the mechanical response of a metallic material depends not only on its current stress state but also on its deformation history. It describes the early re-yielding that occurs when reversing the load [16]. This is characterised by two stages which are presented in Fig. 1. Firstly, the transient Bauschinger deformation is composed of early re-yielding and smooth elastic–plastic transition with a rapid change of work hardening rate [17]. The second stage is the permanent softening defined by stress offset in a region after the transient period [18].

A combination of the isotropic and a non-linear kinematic hardening rule provides a uniform expansion and translation in shape of the yield surface. These types of mixed hardening models are proved to predict properly material behaviour of AHSS [19]. Kim et al. [10] found that the hardening behaviour including the Bauschinger and transient behaviour was well represented by a modified mixed Chaboche model for dual phase materials. Shi et al. [20] determined the constitutive parameters for a combined isotropic–kinematic hardening model based on the Yoshida Model for several AHSS, such as DP980 and DP780. The model was able to predict the stress and strain behaviours in various cycle tension and compression tests. Gil et al. [21] proved that a mixed hardening model was able to predict much more accurately the final geometry of a component of DP1000 than a standard isotropic hardening model. Currently, the Chaboche and Lemaitre mixed hardening model (1990) [22] is one of the most widely accepted in sheet metal forming simulations due to its simplicity and it is being implemented in most of Finite Element Codes. The model is the result of the combination of both the Voce isotropic hardening law [23] and the Armstrong–Frederick nonlinear hardening law [24].

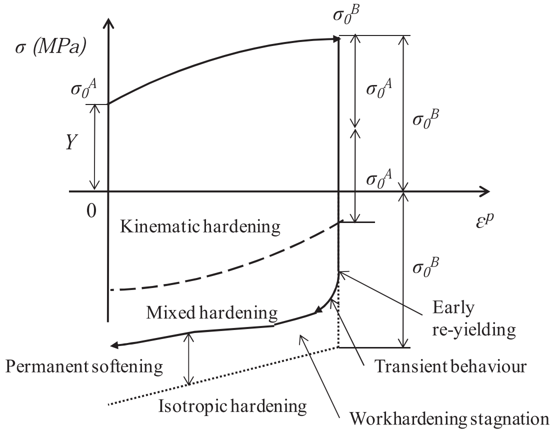

Fig. 1. Bauschinger Effect description.

The accuracy and complexity of models depend on the number of material parameters and history variables. Each model has its precise requirements in terms of experimental data and testing needed to identify its parameters. For example, isotropic hardening models are identified on the basis of experimental data obtained from monotonic test methods, e.g. Mendiguren et al. [25] obtained the Ludwik hardening model parameters from tensile tests of a Ti64Al4V alloy and for a MS1200 steel. However, in the characterisation of forming operations, cyclic loading experimental tests are usually used in order to analyse kinematic hardening [19]. Different authors have proposed several reverse loading tests. Experimental data using a tension–compression test were obtained for different dual phase materials by Grüber et al. [26], who used these parameters to simulate the roll levelling process. This is a low deformation process in which bending/unbending loading are involved. Brunet et al. [27] identified the hardening parameters by using bending test of a mild steel, however the results showed some limitations and uncertainties due to the fact that the strain state in the sample was not exactly a pure strain state of bending. The cyclic three point bending test was also used to determine various hardening laws of DP600 and 220IF steels by Eggertsen and Mattiasson [28]. This test required an inverse approach which involves considerable computing time.

Other authors compared different tests, such as Carbonnière et al. [29], who compared bending and simple shear test on a TRIP steel and an aluminium alloy and enabled to achieve higher deformations. Eggertsen and Mattiason [12] also compared hardening parameters determined from bending test and those determined from tensile/compression tests for DP600 steel. In both cases, each experiment yields a different set of hardening parameters; however numerical simulations from both tests seemed to