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Effect of material scatter on the plastic behavior and stretchability in sheet metal forming

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ABSTRACT

Robust design of forming processes is gaining attention throughout the industry. To analyze the robustness of a sheet metal forming process using finite element (FE) simulations, an accurate input in terms of parameter scatter is required. This paper presents a pragmatic, accurate and economic approach for measuring and modeling one of the main inputs, i.e. material properties and its associated scattering.

For the purpose of this research, samples of 41 coils of a forming steel DX54D+Z (EN 10327:2004) from multiple casts have been collected. Fully determining the stochastic material behavior to the required accuracy for modeling in FE simulations would require many mechanical experiments. Instead, the present work combines mechanical testing and texture analysis to limit the required effort. Moreover, use is made of the correlations between the material parameters to efficiently model the material property scatter for use in the numerical robustness analysis. The proposed approach is validated by the forming of a series of cup products using the collected material. The observed experimental scatter can be reproduced efficiently using FE simulations, demonstrating the potential of the modeling approach and robustness analysis in general.

1. Introduction

In the design of sheet metal forming processes, a general goal is to achieve a lightweight and efficient design by making optimal use of the process and material capabilities. The design phase of a forming process is currently done virtually using FE simulations, i.e. optimization can be done mathematically. However, deterministically optimized processes may become critical with respect to unavoidable sources of scatter in practice leading to product failures.

One of the inevitable sources of scatter that comes with the usage of material is scatter of its properties. To account for scatter and to judge the safety of the forming process, a common approach is the use of safety margins, usually 10% strain below the forming limit curve (FLC). It is shown is this work that the usage of such safety margins can result in overly conservative designs, not making optimal use of the material and process. Moreover, the choice for such a margin is arbitrary and application of it to different forming processes implicitly assumes that all processes are equally sensitive to scatter. Furthermore, the increasing use of advanced high strength steels with lower formability created the need to tighten safety margins making the processes more critical.

Instead of ensuring safety via an arbitrary safety margin, robustness techniques can be employed to incorporate input scatter and to quantify the resulting output scatter. Beyer and Sendhoff (2007) present an overview on robust optimization techniques, providing an extensive basis for choosing the most appropriate mathematical solving technique. Analysis of the robustness of the process in an early stage of the design process enables the engineer to recognize and anticipate on possible problems that can occur in the production environment due to the influence of scatter. Especially for critical processes where large safety margins are unacceptable, employing robust optimization techniques in a subsequent step can be the key to success.

Nowadays, scattering material properties are already being considered in robustness analyses of forming processes. Sigvant (2006) presents a process performance analysis of a front side member inner car part. The significant effect of among others material thickness and strength variation on product failure is demonstrated. de Souza and Rolfe (2008) discuss a multivariate modeling approach and conclude that the effect of material property scatter on springback behavior in a stamping process is significant. A similar study on the effect of scattering material properties on springback and

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thinning of a deep drawing part is presented by Maretta and Di Lorenzo (2010). It is concluded that the influence of the material variability differs for changing process conditions. Finally, the deteriorating effect of scattering material properties on the dimensional quality of a roll formed part is demonstrated by Wiebenga et al. (2013). Scattering of material thickness and strength is considered where a linear correlation between the yield stress and the ultimate tensile stress is adopted. However, these works include the scattering of material properties in a rather simplified manner in the form of independent scaling of parameters without accounting for possible parameter correlations or assuming a full correlation between parameters. This is far from realistic as will be demonstrated in this work. Moreover, Abspoel et al. (2011) discuss the characterization and modeling of the stochastic behavior of deep drawing steels demonstrating that due to lack of information and the use of computationally expensive non-linear FE simulations, the engineer is often forced to choose rather simple material models and work with a limited number of scattering material parameters. Finally, because of availability, research on scattering material properties is often only performed using a very limited number of samples as described by Gödel et al. (2011). All these aspects subsequently limit the accuracy with which the real material behavior and its associated scattering can be described and consequently limits the robustness of formed parts.

The ultimate goal of robustness analysis is prediction and reduction of the scrap rate of a process. This requires an accurate numerical prediction of both the mean of the response and the magnitude of response scatter. It is demonstrated in earlier work of Atzema et al. (2009) that for quantifying scrap rate, it is of no use to quantify the scatter accurately if the mean is off. Moreover, it is demonstrated in several works by Aspenberg et al. (2012), Gödel and Merklein (2011) and Moreira and Ferron (2004) that in order to accurately simulate the effect of material property scatter, the variations and correlations in input parameters must be represented as close to the physically observed values as possible. Aspenberg et al. (2012) presents an evaluation of the statistics of steel material model parameters based on extensive material testing of a DP600 material. Strong correlations between the many material parameters are measured. A variation study considering the effect of deep drawing steel grades properties on a cross die product is presented by Gödel and Merklein (2011). It is emphasized in this work that the effect of variation differs per stress state occurring in the product and therefore material testing under different loading conditions is required. Finally, Moreira and Ferron (2004) consider a hemispherical cup geometry and demonstrate that a flexible plasticity model should be adopted to accurately describe the yielding behavior. In this case, a good agreement between numerical simulations and experimental results can be obtained. As a consequence, flexible but complex material relations with an increased number of parameters must be used. Therefore an economic and accurate description of material properties and its associated scattering is required.

This work covers an extensive analysis demonstrating the effect of material property scatter on the plastic behavior and stretchability of sheet metal forming processes. An approach is presented to efficiently measure and accurately model material property scatter for use in non-linear FE simulations combining mechanical testing and texture analysis. Moreover, its effect on an example forming process is demonstrated numerically and validated experimentally, where comparable work in literature is often either confined to experiments or modeling only.

The paper is organized as follows: Section 2 describes a hybrid approach for obtaining a stochastic set of material data. The procedure combines mechanical testing and texture analysis to limit the required effort. In addition, the applied Vegter yield locus model and Bergström–van Liempt hardening model are briefly introduced. Section 3 describes the data set establishment, combining a Principal Component Analysis (PCA) with a sensitivity study to manipulate the material data for efficient implementation in FE simulations. The approach and its resulting effect are subsequently demonstrated numerically and validated experimentally in Sections 4 and 5 on an example forming process, i.e. the stretching of a hemispherical cup. Finally, points of discussion and the conclusions are provided in Section 6 and 7, respectively.

2. Determination of material scatter

In this work, the scatter in material behavior is determined with a hybrid approach, combining mechanical testing and texture analysis. Fully determining the stochastic material behavior to the required accuracy by mechanical testing only, requires many expensive tests to obtain the material parameters for both the yield locus description (see Section 2.2) and hardening model (see Section 2.3). These required tests are discussed in more detail in Vegter et al. (1999), Vegter and van den Boogaard (2006) and will be addressed in Section 2.1.1. Whereas this effort is acceptable in characterizing the (typical) behavior of a steel grade, it is prohibitively expensive for obtaining a statistical basis for robustness analysis. The required effort is therefore minimized by replacing part of the mechanical testing by texture analysis as described next.

2.1. Material collection

For the purpose of this research, samples of 41 coils of a forming steel DX54D+Z (EN 10327:2004) from multiple casts have been collected to study coil-to-coil variation. The nominal thickness of the studied sheets is 0.79 mm, and measured thicknesses of the individual sheets are in the range of 0.75–0.83 mm. Moreover, from a single coil, 6 sheets have been collected to study in-coil variation. The DX54D+Z material, a low carbon continuously annealed hot dipped galvanized steel with EDT surface finish, is chosen because of its wide application in cold forming processes in automotive industry.

2.1.1. Mechanical testing

For the full construction of the yield locus model used in this work (see Section 2.2), four types of mechanical tests are generally required: a uniaxial, an equi-biaxial, a plane strain tensile test and a shear test. Because of planar anisotropy, the tensile and plane strain tests are performed in three different directions 0°, 45° and 90° with respect to the Rolling Direction (RD). The latter direction is also referred to as Transverse direction (TD). The shear tests are performed in the 0° and 45° direction only due to symmetry and the equi-biaxial test is direction independent and needs to be performed once. For the entire material collective, tensile tests in three directions have been performed which is feasible because the tensile test is highly standardized and efficient. The same holds for thickness measurements for all coils. However, the plane strain, shear and equi-biaxial tests are less common and require much more effort, hence these are not performed on the full material collective.

2.1.2. Texture analysis

The stochastic material data for the yield locus construction is obtained by texture measurements onto the full material collective of coils. Using efficient Electron BackScatter Diffraction measurements in combination with polycrystal plasticity, a yield locus is constructed. The model used is proposed in the work of An et al. (2011) and is based on two yield loci derived from the Taylor full constraint model and the relaxed Pancake model, also referred to as Combined Taylor Full constraint and Pancake model or CTFP.

To validate the accuracy of the yield loci based on texture measurements, a comparison has been made using mechanical testing