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Elastic anisotropy of dual-phase steels with varying martensite content

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ABSTRACT

The elastic anisotropy of 5 cold-rolled steel sheets typical of automotive applications is probed experimentally and the results are represented using orthotropic elasticity. The steels have an increasing volume fraction of martensite, ranging from zero to over 90%. This leads to different strength and ductility for each of the 5 steels, with the strongest being 5.8 times so over the weakest, but only 0.11 times as ductile. The elastic properties measured are the Young's modulus and Poisson's ratio at 15° increments from the rolling direction of the sheets. These properties are measured by uniaxial tension and pure-bending experiments, respectively, instrumented with electrical-resistance strain-gages. The recorded responses are repeatable and, well within the limit of elastic deformations, linear. Both properties are found to have orientational dependence. The variation of the Young's modulus is the opposite of that of Poisson's ratio. In addition, the dual-phase (ferritic-martensitic) steels exhibit the opposite trends than the single-phase (purely ferritic) one. These experiments are then compared to the results of orthotropic elasticity. Under plane-stress, this material model depends on 4 material parameters. This simple model represents all of the experiments very well, indicating that the elastic anisotropy stems from the rolling-induced microstructure and, for the dual-phase steels, the presence of the second, reinforcing phase. Furthermore, the model allows the quantification of extension-shear coupling when these orthotropic materials are loaded off-axis to the material orientations. This coupling was found to be limited, so that the off-axis tension tests are indeed close to the uniaxial stress state. One of the material parameters needed is the in-plane shear modulus, which poses challenges in its determination for the present thin sheets. Despite the mild anisotropy found in these materials, assuming the isotropic value for the shear modulus deteriorates the predictions significantly. This work demonstrates that single- and dual-phase steels indeed behave elastically as orthotropic materials, as expected on theoretical grounds based on their pre-processing by rolling. The results of this work can be used to introduce elastic anisotropy in sheet metal forming simulations intending to predict springback, with only a limited number of experiments needed for calibrating the model for a given material.

1. Introduction

The plastic anisotropy of sheet metal has received extensive attention, due to its relevance to forming processes, and in particular the prediction of strain distributions and formability (Banabic, 2010). In addition, an ever-present concern in sheet metal forming is springback. This is accentuated by the modern alloys that are developed for the transportation industry for vehicle light-weighting purposes. In comparison to the conventional mild steels that these alloys are replacing, they exhibit either higher flow curves (e.g., the advanced- and ultra-high strength steels), or lower moduli (e.g., the aluminum and magnesium alloys), both of which accentuate the magnitude of springback. Springback is associated with the complex phenomena of unloading from a plastic state, e.g., (Lems, 1963; Yoshida et al., 2002; Luo and Ghosh, 2003; Sun and Wagoner, 2011; Korkolis et al., 2013), among many others. It is also directly dependent on the elastic properties of the material and, by extension, on the *elastic* anisotropy. Recently, Hayakawa et al. (2010) and Sumikawa et al. (2016) separately demonstrated that including the elastic anisotropy in springback simulations improves the agreement with experiments.

The origins of elastic anisotropy of polycrystalline metals lie in their crystallographic texture. Single crystals of metals are in general strongly anisotropic (Chawla and Meyers, 1999). Polycrystals with random textures will be isotropic at the macroscale. However, textured polycrystals are expected to exhibit anisotropy. Voigt and Reuss provided estimates (summarized in Chawla and Meyers (1999)) of the effective elastic properties of polycrystals, which are

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now understood as upper and lower bounds, respectively. These estimates were later improved by Hill (1952). Chung and Buessem (1967) measured the elastic properties by both resonance and ultrasonic methods, for a broad family of materials. They concluded that the Voigt–Reuss–Hill estimates are adequate for materials with low elastic anisotropy; however, they cast doubt on their validity when the anisotropy is more intense. Further comparisons of the Voigt–Reuss–Hill predictions to experiments were reported by Bunge et al. (1969) for cold-roller copper and by Bunge and Roberts (1969) for a low-carbon steel. The elastic properties were measured by the resonance method. These studies confirmed that Voigt and Reuss predictions are bounds, while the Hill one is a better approximation to experiments.

Numerous more elaborate and more physically consistent models have been developed, e.g., (Eshelby, 1957; Kröner, 1958; Hill, 1963; Hashin and Shtrikman, 1963; Kröner et al., 1966; Gairola and Kröner, 1981; Böhlke and Bertram, 2001), among many others. For this plethora of models, the question naturally arises: which offers the best approximation of reality with the minimum cost and complexity? For example, Ledbetter (1973) summarized 8 models for predicting the shear modulus; subsequently, Ledbetter (1984) and Ledbetter and Austin (1985) measured ultrasonically the elastic properties of a Fe-Cr-Ni alloy and compared the predictions of 9 models. They found discrepancies ranging from 2% for the Hershey–Kröner–Eshelby model to 49% for the Voigt–Reuss bounds. Luzin et al. (2005) measured the elastic anisotropy of a low-carbon steel using impulse excitation, 4-point bending and dynamic mechanical analysis methods, and examined the performance of texture-based models against these experiments. They found that agreement with experiments was strongly dependent on the calculation scheme adopted and on the texture information available to it.

Beyond the assumptions behind the models themselves, Bunge et al. (1969) identified other parameters, such as grain shape anisotropy and uncertainties in single-crystal elastic properties for the specific alloys at hand, as additional sources of discrepancy between experiments and predictions. More recently, Bunge et al. (2000) provided quantitative estimates of the stereology effects (i.e., grain shape, grain packing and grain misorientation) on the elastic property predictions and found that they could contribute up to 25% of the total texture influence – before the uncertainty in single-crystal constants is taken into account. A clear illustration of the effect of processing-induced texture and, by extension, stereology effects on elastic anisotropy is found in the work of Agnew and Weertman (1998). These authors measured ultrasonically the elastic anisotropy of Cu after severe plastic deformation, which produced highly-elongated grains. Subsequently, they recrystallized the sample (i.e., produced equiaxed grains) and found that the anisotropy had been erased, indicating that it was a direct consequence of the processing-induced texture and stereology. In the same spirit, Zeng and Ericsson (1996) measured the elastic anisotropy of various Al-Li alloys using a dynamic resonance method and found that, depending on the alloy composition, texture could have a strong effect on the elastic anisotropy.

One way of capturing the effects of the morphology and spatial distribution of the microstructure on the elastic properties is by the use of two-point (or higher, i.e., n-point) correlations. In that case, information beyond simply the volume-fraction can be used for determining the elastic properties. Beran et al. (1996) obtained the elastic stiffness and compliance of an orthotropic polycrystal from measurements of the statistical properties of the microstructure. They derived bounds for the elastic stiffness and compliance, and demonstrated their method on a copper alloy. Subsequently, Saheli et al. (2004) applied similar ideas, along with statistical continuum mechanics, to design the microstructure of dual-phase composites for desired elastic properties. Huang and Man (2003) considered polycrystalline aggregates of cubic crystals with arbitrary texture symmetry. They examined the effects of crystallographic texture on elastic response by keeping terms quadratic in the texture coefficients.

The purpose of this research is to measure the as-received elastic anisotropy of 5 automotive steels and to establish a modeling framework that can reproduce this behavior. The elastic anisotropy of dual-phase steels is reported, to the best of our knowledge, for the first time. These results are presented for steels with various levels of martensite volume fraction. The objective of the modeling is to allow the incorporation of elastic anisotropy in contemporary springback simulations by industry. In light of this, and given the multi-phase microstructures of the present steels, the challenges described above for analytical models and the cost of high-fidelity micromechanical computations, the modeling approach pursued here is the following: a few of the measured responses are selected as the reference ones; an orthotropic elasticity model is then used, which, depending on the way it is calibrated, predicts the remaining experiments very well. Having thus established that orthotropic elasticity is an accurate representation of material behavior, it can be easily incorporated in current industrial simulations, the only expense being the few experiments needed to calibrate it for the specific material and batch at hand. Based on the works of Hayakawa et al. (2010) and Sumikawa et al. (2016) it can be expected that this approach will improve the accuracy of springback simulations without adding any significant complexity to current practice.

This paper is structured as follows. First, the experimental setups used to probe the elastic anisotropy are described. Two properties, the Poisson's ratio and the Young's modulus and their orientational dependence are measured for each of the 5 steels of this study. The first is measured with a pure-bending test and the second with a uniaxial tension test. The results obtained for the 5 steels are then presented. All steels are found to be elastically anisotropic (more specifically, orthotropic), with the intensity of the anisotropy reducing, as the strength of the steel increases. These results are then represented using orthotropic, plane-stress elasticity. The assumptions of the theory vs. the actual measurements are delineated, and their effects on the model results are established.

2. Experiments

2.1. Materials

Five steels are investigated in this study: one purely ferritic (drawing-quality, specially-killed – DQSK), 3 dual-phase (ferritic-martensitic; DP 590, DP 980 and DP 1180, with the number indicating the UTS – ultimate tensile strength) and one almost purely martensitic (MS 1700). All are typical of auto-body and -structure applications. The DQSK sheet was received as 0.8 mm-thick, while the rest as 1 mm-thick sheets, all cold-rolled. The MS 1700 steel sheet exhibited some mild but visible waviness, which however has large enough wavelength (~1 m) to not affect the present work. The dual-phase steels consist of hard, martensite islands in a soft, ferritic matrix, as shown in Fig. 1. Hence, they behave essentially as metal-matrix composites, with the added complication that the 2nd phase, martensite islands are polycrystalline, too (Zecevic et al., 2016). These images were obtained in a TESCAN Lyra3 scanning electron microscope, using 10 kV for DQSK and 20 kV for all other steels.

The martensite volume fractions of these steels range from zero to over 90%. The volume fractions were measured per the ASTM E-562 standard (Anon, 2011a). For each material (except DQSK), 10 areas in the images of Fig. 1 were identified, and the intercepts of the martensite islands with a superimposed regular grid were

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