Application of self-consistent crystal plasticity framework as a constitutive description for commercial steel sheets

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Many of the empirical rules developed to predict properties and performance of single-phase steel products based on uniaxial mechanical test data fail to properly describe the constitutive behaviors of Advanced High-Strength Steels (AHSS). Multiaxial constitutive data is in high demand to account for differences between uniaxial and multiaxial deformation, which is required to accurately predict forming processes. The main objective of my thesis is to use advanced experimental techniques and develop crystal plasticity models to create accurate constitutive descriptions for commercial steel sheets.

Crystal plasticity provides a framework that incorporates details of the microstructural deformation into macroscopic response, as introduced in the first chapter of my thesis. The self-consistent crystal plasticity framework [1-3] was mainly focused in this thesis. This model is a hierarchical multi-scale framework that involves two types of “scale-jumps”: 1) from individual slip systems to an effective grain; and 2) from an aggregate of grains to the macroscopic material scale. Therefore, it can link the microscopic deformation behavior of each phase to the macroscopic deformation in AHSS. In addition, crystal plasticity models provide predictions for the aggregate grain deformation, which can be compared and validated by the experimental crystallographic texture evolution, which is typically not present in continuum level empirical constitutive models.

In Chapter II, a viscoplastic self-consistent (VPSC) model is applied to mechanical deformation an austenitic stainless steel. The multiaxial constitutive behaviors of the austenitic stainless steel were measured using 1) biaxial tests using cruciform specimens developed by [4]; and 2) hydraulic bulge test. The statistical representativeness in a sampled population of discrete grains was studied in terms of anisotropic parameters and yield stresses. To that end, a computational tool is presented that wraps the VPSC source code that is written in FORTRAN by Python scripts to use more advanced scientific libraries. Although the VPSC model used in this application lacked the description associated with the phase transformation kinetics, the predictions made by the VPSC model were in good agreement with experimental observations. This finding led to a conclusion that the anisotropic hardening behavior induced by crystallographic texture and its development might be a more dominant factor that determines the anisotropic hardening behavior of the material [5]. This application also explicitly demonstrated the appropriate procedures which should be performed by the end-user of the crystal plasticity model to enhance the predictive accuracy.

In Chapter III, an alternative method to measure multiaxial constitutive behaviors for the interstitial-free steel is presented. This method bases on a Marciniak tooling, that is augmented with a low-powered X-ray diffractometer as well as digital image correlation (DIC) technique [6]. With this method, the in-situ diffraction data together with ex-situ measurement for anisotropic diffraction elastic constants, were used to obtained biaxial flow stress [7]. The experimental data were compared with the hydraulic bulge test data, which resulted in reasonable agreement up to a Von Mises strain of 0.5 [7]. Additionally in this work, the elasto-viscoplastic self-consistent (EVPSC) crystal plasticity model developed by [8] was extended to calculate the diffraction strains based on the reflection method to compare with the corresponding experimental data.

Chapter IV follows-up on the work of Chapter II by incorporating the transformation kinetics from austenite to martensite in the EVPSC model. The following were added to the developed model: 1) the variant selection; 2) volume transfer between austenitic and martensitic phases; 3) calculate diffraction strains measured at various orientations to compare with neutron diffraction data; and 4) stress partitioning between phases. The model was validated through both in-situ neutron diffraction and X-ray diffraction in terms of diffraction strains and the evolution of the phase volume fraction [9].

Based on the results of the three applications, crystal plasticity can be used as a constitutive modeling framework.

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