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

Youngung Jeong

GIFT, POSTECH

The main objective of the present thesis is to develop accurate constitutive descriptions for the commercial steel sheets on the basis of crystal plasticity framework. To that end, some of contemporary challenges in the community of sheet metal forming were selected for detailed investigations.

Many of the empirical rules used in the analysis of single-phase steel products often fail to properly describe the constitutive behaviors of Advanced High-Strength Steels (AHSS). Particularly, the retained austenite, which plays as an essential constituent in various AHSS grades, behaves quite differently from the ferritic phase thus complicating the macroscopic behaviors under multiaxial loading conditions. Although, multiaxial constitutive data have been highly demanded, the development of an accurate experimental method still remains as a challenging task. On the other hand, an accurate constitutive model that can model so-called the ‘dynamic’ anisotropy induced by large plastic capacity of AHSS is required.

In order to provide solutions of those challenges, a constitutive description that is more capable of implementing microstructural properties is required. To that end, the thesis explores potentials of crystal plasticity framework as constitutive modeling framework that is suitable for addressing the mentioned challenges. In particular, the self-consistent crystal plasticity framework [1-3] was primarily studied in this thesis. The self-consistent crystal plasticity model is a hierarchical multi-scale framework by itself in that it involves two types of “scale-jumps”: 1) from slip systems to an effective grain; and 2) from the aggregate of grains to the macroscopic material scale. Therefore, it can potentially link those microscopic phenomena occurring due to the presence of multiphase in the AHSS. Also, crystal plasticity models are capable of modeling the crystallographic texture evolution under arbitrary loading conditions, which often lacks in the empirical constitutive models constructed on the macro continuum-scale.

In the first Chapter of thesis is the Introduction to the crystal plasticity framework. In it, essential elements of physics employed therein are presented in detail. In Chapter II, an application of viscoplastic self-consistent model is made for an austenitic stainless steel. This application also explicitly demonstrates the appropriate procedures, which should be performed by the end-user of the crystal plasticity model to enhance the predictive accuracy. Particularly, the statistical representativeness in a sampled population of discrete grains is 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. 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. 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].

In Chapter III, an alternative method to measure multiaxial constitutive behaviors for the interstitial-free steel is presented. This method differs from the previously mentioned two multiaxial measurement methods using cruciform specimen and hydraulic actuator for bulge test. 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.

In Chapter IV, a follow-up work of Chapter II is which incorporates the transformation kinetics to the EVPSC model. The developed computer program can reasonably describe 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 diffractions and X-ray in terms of diffraction strains and the evolution of the phase volume fraction [9].

Based on the results of the three applications, it is concluded that crystal plasticity has potentials as a constitutive modeling framework and can provide more physical interpretations for the multiaxial constitutive behaviors of commercial sheet alloys studied in the current study.

References

1. Molinari A, Canova GR, Ahzi S (1987) A self consistent approach of the large deformation polycrystal viscoplasticity. Acta Metallurgica 35 (12):2983 - 2994

2. Hill R (1965) A self-consistent mechanics of composite materials. Journal of the Mechanics and Physics of Solids 13 (4):213 - 222

3. Lebensohn RA, Tomé CN (1993) A self-consistent anisotropic approach for the simulation of plastic deformation and texture development of polycrystals: Application to zirconium alloys. Acta Metallurgica Et Materialia 41 (9):2611-2624

4. Kuwabara T, Ikeda S, Kuroda K (1998) Measurement and analysis of differential work hardening in cold-rolled steel sheet under biaxial tension. Journal of Materials Processing Technology 80-81:517 - 523

5. Jeong Y (2010) Crystal plasticity application to 304 austenitic stainless steel. Pohang University of Science and Technology,

6. Foecke T, Iadicola MA, Lin A, Banovic SW (2007) A method for direct measurement of multiaxial stress-strain curves in sheet metal. Metallurgical and Materials Transactions A 38A (2):306-313

7. Jeong Y, Gnäupel-Herold T, Barlat F, Iadicola M, Creuziger A, Lee M-G (2015) Evaluation of biaxial flow stress based on Elasto-Viscoplastic Self-Consistent analysis of X-ray Diffraction Measurements. International Journal of Plasticity

8. Wang H, Wu PD, Tomé CN, Huang Y (2010) A finite strain elastic–viscoplastic self-consistent model for polycrystalline materials. Journal of the Mechanics and Physics of Solids 58 (4):594-612. doi:10.1016/j.jmps.2010.01.004

9. Wang H, Jeong Y, Clausen B, Liu Y, Maccabe RJ, Lee M-G, Barlat F, Tomé CN (Submitted) Effect of martensitic phase transformation on the behavior of 304 austenitic stainless steel under tension.