

Loading Path Dependence of Forming Limit Diagram of a TRIP800 Steel

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ABSTRACT

In this paper, the microstructure-based finite element modeling method is used in investigating the loading path dependence of formability of transformation induced plasticity (TRIP) steels. For this purpose, the effects of different loading path on the forming limit diagrams (FLD) of TRIP steels are qualitatively examined using the representative volume element (RVE) of a commercial TRIP800 steel. First, the modeling method was introduced, where a combined isotropic/kinematic hardening rule is adopted for the constituent phases in order to correctly describe the cyclic deformation behaviors of TRIP steels during the forming process with combined loading paths which may include the unloading between the two consecutive loadings. Material parameters for the constituent phases remained the same as those in the authors' previous study [1] except for some adjustments for the martensite phase due to the introduction of the new combined hardening rule. Based on the new material parameters and new hardening rule, the predicted deformation behaviors of the TRIP800 steel show quite similar qualitative trends to those reported in other experimental works. Pseudo-forming limit strain diagrams (Pseudo-FLD) for the TRIP800 steel were then obtained for various loading paths. The computational results show that, similar to other single phase materials, the TRIP800 steel shows very sensitive loading path dependence in the strain-based forming limit diagrams (strain-FLD), but does not in the stress-based forming limit diagrams (stress-FLD). The results also show that the phase transformation does not have significant effects on the FLD for the TRIP800 steel. From the observations in this study, the current modeling methods can be used in examining the qualitative trends of FLD of TRIP steels under different loading paths/prestrains.

INTRODUCTION

Low-alloy multiphase transformation-induced plasticity (TRIP) steels can be considered as composite materials with a ferritic matrix containing bainite and metastable retained austenite, which gradually transforms into martensite during deformation. As a result of the deformation-induced martensitic phase transformation, a good compromise between ductility and strength is achieved in this class of materials. Consequently, TRIP steels are being increasingly used in the automotive industry because of their combined light weight and high energy absorption capabilities.

On the macroscopic and/or microscopic level, much effort has been spent on investigating the various aspects and deformation behaviors of TRIP steels by analytical, experimental and numerical methods [2, 3, 4, 5]. Recently, the authors [6, 7, 8, 9] developed a new microstructure-based modeling approach for multi-phase advanced high strength steels. In this modeling approach, the actual microstructures, recorded by scanning electron microscopy (SEM), are used for a representative volume element (RVE) to predict the overall deformation behaviors, including the failure mode and ultimate ductility, under different loading and boundary conditions. In these studies, the material properties of the constituent phases are determined by the in-situ synchrotron-based high-energy X-ray diffraction (HEXRD) technique and the ductile failure of the steels is predicted in the form of plastic strain localization resulting from the incompatible deformation between the constituent hard and soft phases. It is shown that the methodology described in these studies can be used as a powerful analytical tool in studying the separate effects of various factors on the deformation behaviors TRIP steels and dual phase steels.

Strain-based forming limit diagrams (strain-FLD) are commonly used in the sheet metal forming industry to

determine the development of local necking failure. However, this criterion is valid only for the proportional loading cases and shows very sensitive loading path dependence [10, 11, 12]. The loading paths in the sheet forming industry are often non-proportional and quite complicated. Therefore, the conventional use of strain-FLD for severe non-proportional forming process can lead to erroneous evaluation of the forming limits. It was recently reported that the stress-based forming limit diagrams (stress-FLD) seem to show no loading path dependence [10, 11, 12, 13, 14]. Subsequently, many researchers have investigated on the loading path dependence of stress-FLD in detail and found that the effects of loading path on stress-FLD can be increased as the prestrain in the initial loading increases [15, 16, 17, 18]. So far, most of the researches on loading path dependence of the FLD are focused on the single phase materials. The goal of this study is to examine the effects of loading path on the FLD of TRIP steels which exhibit the martensitic phase transformation during the deformation process.

In this paper, the microstructure-based modeling method that authors have developed is used in investigating the loading path dependence of formability of TRIP steels. For this purpose, the effects of different loading path on the FLD of TRIP steels are examined using the RVE of a commercial TRIP800 steel. The modeling method is first introduced with the material properties and hardening rule. The deformation behaviors of the TRIP800 steels are, then, investigated under different proportional loading conditions in order to validate the simulation results. FLD for the TRIP800 steel are finally obtained for different loading paths and discussed on qualitative trends based on the observations.

MICROSTRUCTURE-BASED MODELING OF TRIP STEEL

The microstructure-based finite element modeling method developed for TRIP800 steel [1,6,7] is used in this study. Figure 1(a) shows an actual microstructure recorded by SEM taken from the mid-plane along the rolling direction of a TRIP 800 sheet steel. After numerical image processing of Figure 1(a), the finite element model was obtained as shown in Figure 1(b), which is used as the RVE of the TRIP 800 sheet steel. Note here that even different RVEs based on the microstructures of different locations of the steel will predict similar results as long as they have similar volume fractions and grain morphologies of the constituent phases [8].

The commercial finite element code ABAQUS was used in this study, and two-dimensional plane stress CPS3 elements are adopted in the model to simulate the in-plane behavior of the TRIP800 sheet steel. It is noted here that the actual sheet deformation can be intrinsically three-dimensional in the sense that large local stresses may develop in the direction normal to the sheet thickness due to the large strength

differences of the constituent phases. From this perspective, the adopted two-dimensional plane stress model may overestimate the microstructure-level inhomogeneity and, therefore, predictions based on the two-dimensional model may be hazardous in investigating the three-dimensional deformation behaviors of multi-phase materials. However, due to the difficulties associated with creating a three-dimensional finite element model with actual three-dimensional microstructure and the availability of computational resources, the two-dimensional plane stress model is adopted here [7]. Our previous studies [7,8] have demonstrated that the simple two-dimensional model is able to well capture the essential overall features of the in-plane deformation behaviors of TRIP steels as observed in the experiments.

In this study, combined loading paths are applied to the RVE in order to examine the effect of different loading paths on the FLD of TRIP steel. The combined loading paths are assumed to consist of two (first and second) linear loading paths, including unloading between the first and second loadings. In order to correctly describe the deformation behaviors of TRIP steels during the forming process with combined loading paths, the constitutive behaviors of different phases under the cyclic loading/unloading are crucial. Note that there are no experimental data currently available on such information. Therefore, in this study, as a first step to examine the loading-path dependence of formability of TRIP steels, a simple combined isotropic/kinematic hardening rule as shown in Figure 2 is adopted for the constituent phases in order to account for the possible reverse plastic loading effects in some grains of those phases during the unloading process. More specifically, the combined hardening rule has nonlinear isotropic and linear kinematic hardening components.

The stress-strain curves for all the constituent phases during the initial loading process are shown in Figure 3. The plastic stresses σ_0 for the four phases during the initial loading process are assumed to satisfy the following laws.

$$\sigma_0 = \sigma_{y,i} + K_i \varepsilon_{ep}^{n_i} \quad (i = F, A, B, M) \quad (1)$$

Here, $\sigma_{y,i}$, K_i and n_i represent the initial yield strength, the hardening coefficient and the hardening exponent, respectively, for each phase. F , A , B and M represent the ferrite, retained austenite, bainite and martensite phases, respectively. These parameters and the linear kinematic hardening moduli for the ferrite, retained austenite, bainite and martensite phases are listed in Table 1, and the corresponding stress-strain curves for the constituent phases are also plotted in Figure 3. Note that the stress-strain curves in Figure 3 and the parameters in Table 1 are the resultants based on the combined isotropic/kinematic hardening rule. In

the simulations, the input stress-strain curves for the constituent phases are assumed to keep increasing up to very high levels of strain (i.e., 200% strain for ferrite and austenite phases, 100% strain for bainite phase and 50% for martensite phase). Here, the mechanical properties (i.e., initial stress-strain curves) of the ferrite, retained austenite and bainite phases were determined based on the in situ HEXRD tensile test [6,7] as well as the recently published self-consistent (SC) model [19]. However, since the mechanical properties of martensite phase are not available from the in situ HEXRD test, its properties were determined by fitting the macroscopic behavior of the RVE shown in Figure 1(b) with the uniaxial test results based on the assumption of the same linear hardening rate as in Choi et al. [1].

The following transformation yield function was used in this study in order to consider the martensitic transformation in TRIP steels [7]:

$$\Pi = R\sqrt{3J_2} \left[1 + k \frac{J_3}{J_2^{3/2}} \right] + \frac{\alpha I_1}{3} \quad (2)$$

where R corresponds to the maximum transformation strain obtained during a loading sequence, k describes the sensitivity of the transformation to the stress state and α represents the volume change during the martensitic phase transformation. In Eq. (2), I_1 , J_2 and J_3 are the stress invariants. A user-material subroutine based on the combined isotropic/kinematic hardening rule and the transformation yield function in Eq. (2) was developed and implemented into a commercial finite element code (ABAQUS). In the user-material subroutine, for each integration point, the current magnitude Π is compared with a critical value Π_c in order to determine whether the phase transformation has occurred. In this study, all the parameters shown in Eq. (2) remain the same as those in Choi et al. [1,7]: $k = 0.24$, $\alpha = 0.02$, $R = 0.025$, and the critical $\Pi_c = 29$ MPa.

Figure 4 compares the RVE prediction with test results under uniaxial tensile loading condition (without reverse unloading process process). With the above described modeling procedure and material properties, good agreements are obtained for both the engineering stress-strain curve and the retained austenite transformation kinetics for this steel. Figure 5 shows the predicted in-plane failure mode in the RVE under uniaxial tensile loading condition (without reverse unloading process). Here, the grey-colored failure band represents the region of plastic stain localization as proposed in this modeling method [7,8]. Overall vertical split failure mode is observed since the two vertical split bands originating from the top and bottom edges are connected together in the central region of the RVE during later stage of the deformation process. The details of failure band propagation for the TRIP 800 sheet steel are reported in Choi et al. [1,7]. Note that the predicted in-plane failure mode based on the new material

parameters and hardening rule for the constituent phases is also quite similar to that observed in the sheet sample failed from uniaxial tensile test [1,7]. The results in Figures 4 and 5 suggest that the current microstructure-based modeling approach can be used in predicting the overall behaviors of TRIP steels under tensile loading conditions.

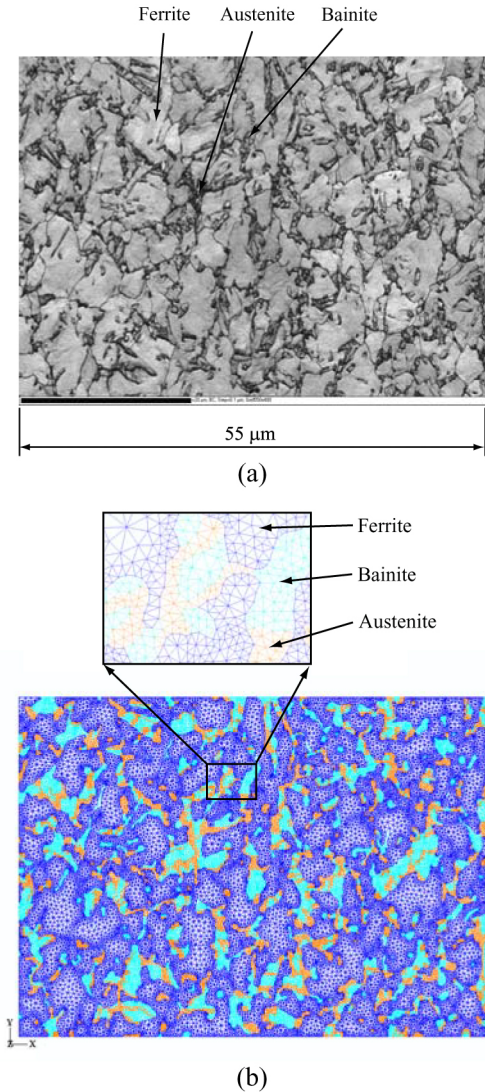


Figure 1. (a) An actual microstructure of TRIP 800 with $V_{f,A}^0 \approx 15\%$ and (b) the corresponding finite element model used for the RVE ($V_{f,F}^0 = 68.6\%$, $V_{f,B}^0 = 16.5\%$, $V_{f,A}^0 = 14.9\%$).