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# Thermomechanical response of a TWIP steel during monotonic and non-monotonic uniaxial loading

Omid Majidi [a,*], B.C. De Cooman [a], Frederic Barlat [a], Myoung-Gyu Lee [b,**], Yannis P. Korkolis [c]

[a] Graduate Institute of Ferrous Technology, Pohang University of Science and Technology, Pohang, Gyeongbuk 790-784, South Korea
[b] Department of Materials Science and Engineering, Korea University, 145 Anam, Seongbuk-gu, Seoul 136-701, South Korea
[c] Department of Mechanical Engineering, University of New Hampshire, 33 Academic Way, Durham, NH 03824, USA

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ABSTRACT

The tensile properties of a Fe-18%Mn-0.6%C-1.5%Al Twinning-Induced Plasticity (TWIP) steel were investigated at different strain rates in three loading modes, i.e. uniaxial monotonic loading, stress relaxation and loading-unloading-reloading. Infrared thermography was used to investigate the effect of the dynamic strain aging, the strain rate and the temperature on the flow stress. In addition to the standard, i.e., non-isothermal tensile tests, isothermal uniaxial tensile tests were performed at 25 °C, 45 °C and 65 °C. While the non-monotonic loading modes resulted in an increase of the total elongation at a low strain rate of $10^{-3}$ $s^{-1}$, no increase was observed for strain rates higher than $6 \times 10^{-3}$ $s^{-1}$. The temperature gradients observed during non-isothermal tests were reduced when non-monotonic loading conditions were used. Temperature changes were found to influence the hardening behavior, and consequently the ductility, of the TWIP steel. Deformation twinning also had a significant influence on the results as its kinetics in TWIP steel are determined by the temperature dependence of the stacking fault energy.



## 1. Introduction

There is an increasing interest in the automotive sector toward the substitution of conventional automotive sheet steel grades with advanced high strength steel (AHSS) with a higher specific strength. Twinning induced plasticity (TWIP) steel is an AHSS which can provide both the required specific strength and the superior elongation [1,2]. Microstructural studies have demonstrated that the gradual segmentation of the grains by deformation-induced nano-sized twins during straining, a process usually referred to as the “dynamic Hall-Petch effect”, results in a higher rate of work hardening as compared to the work hardening rate of other AHSS grades [2].

It has been reported that mechanical properties of TWIP steels, e.g., yield stress, work hardening rate, ultimate strength and ductility, depend on the composition, the thermo-mechanical processing of the material and the deformation conditions, in particular the strain rate and the temperature [3–6]. It has, for example, been shown that the strength of TWIP steel decreases with increasing temperature due to changes in the stacking fault energy (SFE) [4]. Another important characteristic of TWIP steel are the serrations which are observed on the flow curve of carbon-added TWIP steel. The serrations, which are related to strain localization effects, are due to dynamic strain aging (DSA) [7–9]. The physical process resulting in DSA is most likely the interaction between mobile dislocations and C-Mn point defect complexes [7]. According to a model proposed by Lee et al., DSA is initiated when the interaction time between a dislocation and a C-Mn point defect complex is equal to the time it takes for the C-Mn defect complexes to oriented into a low energy position which enables them to pin the dislocation [7]. In addition to serrated flow curves, the DSA in TWIP steel is associated with two important characteristics: (a) a negative strain rate sensitivity, and (b) strain localization, i.e. the occurrence of localized deformation bands commonly referred to as Portevin-Le Châtelier (PLC) bands [8]. The PLC bands are classified in three groups, i.e., type A, B and C, depending on their nucleation frequency and the distance the PLC bands move along the specimen gauge [10]. Type A bands, which have often been reported to be formed during the DSA of TWIP steel, are individual bands which propagate along the full sample length. The nucleation and propagation properties of PLC bands in

* Corresponding author. Present address: Department of Mechanical Engineering, École de Technologie Supérieure, 1100 rue Notre-Dame Ouest, Montréal, Canada H3C 1K3.
** Corresponding author.
*E-mail addresses:* omid.majidi.1@ens.etsmtl.ca (O. Majidi), myounglee@korea.ac.kr (M.-G. Lee).

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TWIP steel have been measured using strain field measurements and by IR-thermography [8,9,11]. Type A bands are usually nucleated either in the center of the sample gauge or at the end of the test sample near the grips [9]. It has also been shown that, a stress relaxation following a temporary interruption of a tensile test without unloading, triggers the nucleation of type A PLC bands in a V-microalloyed TWIP steel at a strain which is smaller than the critical strain for the appearance of serrations as measured in an uninterrupted tensile test [12].

It has been reported that for different metallic alloys including dual phase (DP) steel, transformation-induced plasticity (TRIP) steel [13], austenitic stainless steels [14] and pure titanium [15], the ductility increases by applying a non-monotonic loading. Recently, the authors of the present contribution addressed the role of temperature distribution in enhancing the ductility of a DP780 steel [16]. A more uniform temperature distribution was observed when the tension tests were temporarily interrupted during both stress relaxation tests and in the loading-unloading-reloading (LUR) deformation mode.

Deformation-induced heating results in a temperature rise which increases the stacking fault energy of TWIP steel. This temperature increase will impact the twinning behavior and therefore the strain hardening of TWIP steel, as deformation twinning is suppressed when the stacking fault energy increases. In this study, the impact of the temperature gradients developed during uniaxial tension tests was studied in order to evaluate their impact on the ductility TWIP steel. IR-thermography was used to obtain a detailed and continuous view of the temperature distribution evolution across the entire sample surface, making it possible to visualize clearly the thermal effects of the deformation bands formed as a result of the dynamic strain aging of the TWIP steel during deformation in standard, non-isothermal tests and in controlled iso-thermal tests.

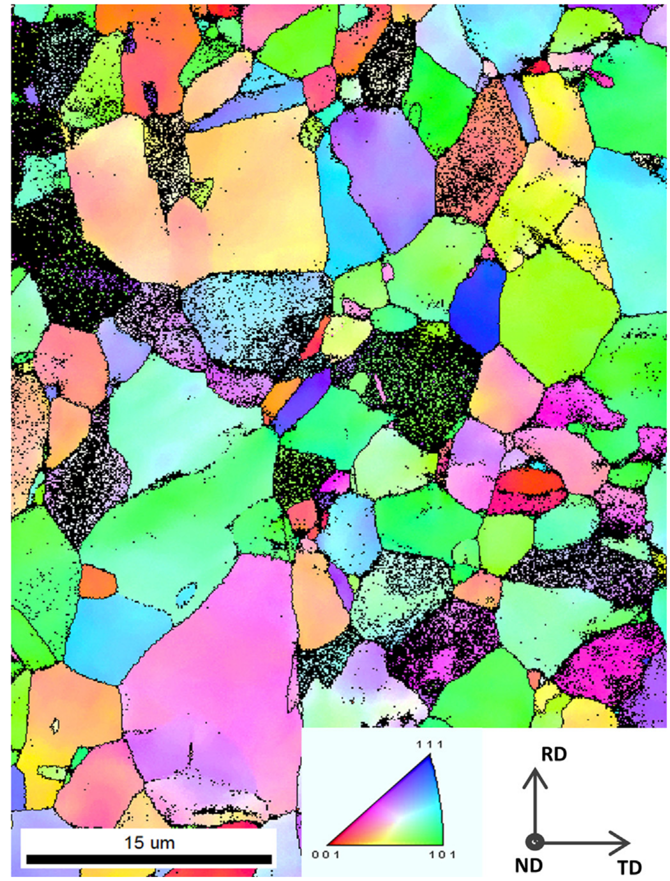


**Fig. 1.** Inverse pole figure (IPF) map of the studied material projected in the normal direction (ND).

## 2. Experimental procedure

The material used in the present study was an industrially-produced fully austenitic TWIP steel with the chemical composition given in Table 1. The sheet material was 1.25 mm thick and the average grain size was ~7 μm as measured from the electron backscatter diffraction (EBSD) analysis (see Fig. 1).

Three different loading modes were used in the study: monotonic uniaxial tensile tests, stress relaxation tests and loading-unloading-reloading (LUR) tests. Table 2 reviews all the test conditions and lists the key parameter values used in each case. For the stress relaxation tests and the LUR tests, four successive interruptions were applied at predefined tensile strains. The experiments consisted of two types of uniaxial tensile tests: standard, non-isothermal tensile tests carried out at ambient temperature, and isothermal tensile tests in controlled temperature conditions. The standard, non-isothermal, tests were carried out at the ambient room temperature using a strain rate in the range of $10^{-4}\,s^{-1}$ to $10^{-2}\,s^{-1}$.

The samples were prepared according to the ASTM E8 standard with the tensile direction along the sheet rolling direction. The experiments were carried in a 250kN MTS universal servo-hydraulic testing machine. The Correlated Solutions® digital image correlation (DIC) system, VIC-2D, was used in all experiments. The images were acquired with a 2 Mega pixel camera (Point Grey Research GRAS-20S4M-C). The measured full-field displacements were used to calculate the logarithmic strains [17]. A FLIR® SC-645 infrared (IR) camera with temperature resolution of 0.05 °C and range of −20 to +150 °C was used to capture the full sample surface temperature distribution.

A flat copper heat exchanger was clamped at the stationary end of the test sample and attached to the back of the sample for the isothermal tests. The details of the experimental set-up are presented elsewhere [14,16]. The isothermal tests were carried out at 25 °C, 45 °C and 65 °C. The isothermal tests were carried out at a low strain rate $10^{-3}\,s^{-3}$, to achieve the required heat exchange rate between the sample and the heat exchanger plate.

**Table 1**
Chemical composition of the material in weight percentage.

| Elements | C | Mn | Si | Al | P | S | Fe |
|---|---|---|---|---|---|---|---|
| Contents | 0.62 | 18.2 | 0.12 | 1.42 | 0.016 | 0.003 | balance |

## 3. Results and discussion

### 3.1. Monotonic loading

It is well-known that the uniform elongation $\varepsilon_u$ achieved in a uniaxial tensile test is determined by the strain hardening (Considère's criterion):

$$\sigma_u = \frac{\partial \sigma}{\partial \varepsilon}_{\varepsilon=\varepsilon_u} \tag{1}$$

Here σ and ε are true flow stress and the true strain, respectively. $\sigma_u$ and $\varepsilon_u$ are the flow stress and the strain at maximum uniform elongation, respectively. Fig. 2 illustrates the effect of the strain rate and the temperature on the strain hardening behavior of the TWIP steel. The strain hardening exponent n was defined as