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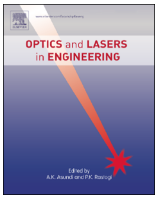

# In situ identification of elastic–plastic strain distribution in a microalloyed transformation induced plasticity steel using digital image correlation

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ABSTRACT

A non-contact strain measurement technique, based on an in-situ digital image correlation (DIC) method in association with magnetic martensite point measurement (Feritoscopy testing) was applied to study inhomogeneous deformation corresponding to martensitic transformation of a microalloyed low carbon transformation induced plasticity steel during tensile straining. The progress of inhomogeneous deformation is traced by the strain maps. The microstructural observation is used to validate the DIC results. The experimental steel shows continuous yielding with a high true fracture strength of 1410 ± 10 MPa at 25 °C along with the lack of tensile necking. The DIC results show that the yield point is controlled by stress-assisted martensite transformation, which in turn induces the strain inhomogeneity. The latter starts prior to the yield point after straining to 0.016. The microstructural evolution reveals the $\varepsilon$-martensite is obtained through stress-assisted martensite formation. After yielding, thanks to the strain-induced martensite transformation, the deformation inhomogeneity in strain maps is increased with strain, corresponding to increasing the volume fraction of martensite. The results suggest that the continuous yielding and initial strain hardening is controlled by stress-assisted martensite formation while the higher total elongation to fracture (80%) and the tensile necking behavior is mainly influenced by the strain-induced martensite transformation.

## 1. Introduction

As is well established, the TRansformation induced plasticity (TRIP) steel and TWinning induced plasticity steel (TWIP) are promising materials to meet excellence mechanical behavior composing of high strength and extended uniform elongation (Fig. 1). The latter is provided by martensitic transformation in TRIP steels. This transformation in fact is either assisted by stress [1] or strain [2] based on the martensite that forms before and after plastic yielding, respectively. The complex interrelationships between applied stress, plastic strain and the corresponding mechanical responses of TRIP steels, containing high C and Si, have been extensively studied [3–8]. They were able to define a temperature, $M_s^\sigma$, below which the yielding is controlled by transformation and above it the yielding is controlled by regular slip processes in the parent phase [3]. Indeed, this temperature is defined as the maximum temperature at which transformation is induced by a stress below the yield stress of the parent phase. The temperature dependency of the yield stress is reversed passing this temperature; it is negative above $M_s^\sigma$, but is positive below $M_s^\sigma$ (Fig. 2). Above $M_s^\sigma$, the applied stress should exceed $\sigma_Y$ in order to initiate the martensitic transformation. Accordingly, the stress and/or strain assisted martensite formation is distinguished by deformation temperature.

Even though TRIP steels have been the subject of different investigation, their deformation and fracture behavior in view of strain distribution analysis are still not well understood. As a matter of fact both types of martensitic transformation impose strain inhomogeneity, which affect elastic–plastic deformation behavior. The in situ monitoring of the deformation inhomogeneity characteristics, such as its magnitude (deviation from average of true strain across the specimen) and distribution frequency, has been remained unclear. A better understanding of strain distribution during deformation may assist clarifying any flow localization in TRIP steels. In addition, the necking-less behavior of some grade of TRIP steels during tensile deformation can be clarified.

The digital image correlation (DIC) is a state of the art technique that can be used to study in situ pre-yield and post-yield local strain distribution during deformation [9–11]. The simultaneous longitudinal

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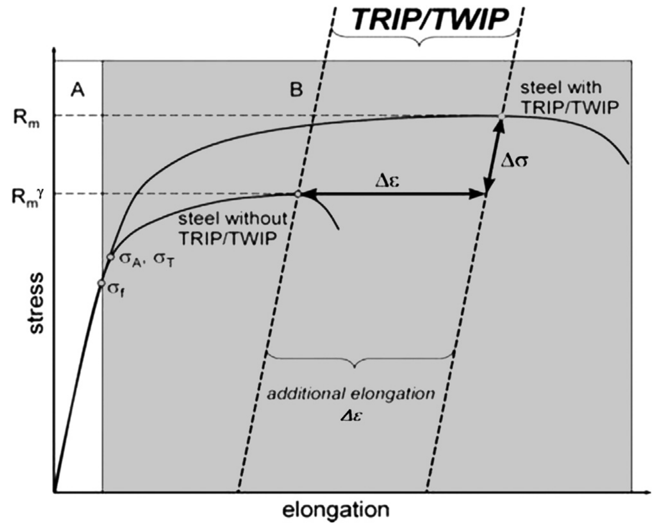

**Fig. 1.** The schematic representation of stress–strain curve of austenitic steels with and without TRIP or TWIP effects.

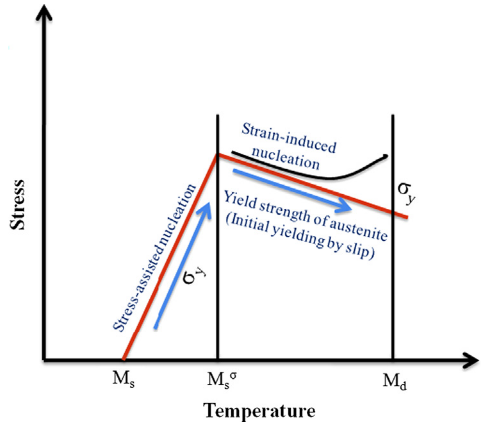

**Fig. 2.** The interrelationships between stress-assisted (below $M_s^\sigma$) and strain-induced martensite (above $M_s^\sigma$) in TRIP steels. Above $M_d$ temperature no martensite will be formed by strain.

and transversal strain field measurements can be well evaluated by DIC. The strain field measurements are particularly useful for understanding the heterogeneous deformations during straining, which would be difficult to explain using conventional extensometer measurements. The DIC possesses the advantages of fast data acquisition, full field, non-contact, and considerably high accuracy in displacement and strain measurements [12–13]. In this technique a series of images are recorded in real-time while the specimen is subject to elastic–plastic tensile loading. The images are then utilized for a full field analysis of surface deformation or strain evaluation through a dedicated DIC analysis software. In this way the exact strain level of transformation onset and its progress across the specimen depending on the true strain and true stress values can be examined. Additionally, strain fields maps will be evaluated for the selected moments of tensile deformation. Thus, DIC enables a better understanding of how deformation progresses and by using microstructural evolution what features may be responsible for flow localization. A general background on DIC is given in Ref. [14].

Some few valuable studies have been done on dynamic strain ageing and the propagation of Portevin–Le Chatelier (PLC) bands during tensile deformation of TRIP or TWIP steels by the DIC technique [15–19]. However, the characterization of local strain distribution, the mode of TRIP evaluation (stress and/or strain induced martensite formation) and the explanation of neckingless tensile behavior of new generation of TRIP steels through strain analysis using the DIC technique has not been dealt with yet.

The novelty of the present work is in-situ monitoring the elastic–plastic deformation behavior of a microalloyed low carbon TRIP steel using a combination of DIC and Feritoscopy methods, attempting to understand both the high toughness of the material and the relationship between inhomogeneous deformation and phase transformation. The microstructural evolution is served to validate the DIC results.

## 2. Experimental procedure

### 2.1. Material processing

The experimental material was received in as-cast condition with chemical composition of Fe–0.11C–21Mn–2.50Si–1.60Al–0.02Nb–0.02Ti–0.01V (in wt%). The as-cast material was first homogenized at 1180 °C for 8 h. Then it was heated to 1200 °C, held for 30 min, and hot-rolled. The hot-rolled microstructure was consisted of 99.5% austenite phase with grain size of $40 \pm 5$ μm.

The true stress–true strain behavior of the steel has been studied through tensile testing scheme at 25 °C under constant strain rate of 0.001 $s^{-1}$ using a Gotech AI-7000 universal testing machine. The tensile tests have been conducted according to ASTM E08 standard [20] with gage length of 34 mm. The microstructural analysis was performed by the SEM model Cam Scan, MV2300. Moreover, the actual martensite content was determined through the Feritoscope model MP30 using the following equation [21]:

$$\text{Vol\% martensite} = 1.75 \times \text{Feritoscope reading} \tag{1}$$

To perform the DIC analysis the specimens should be “speckle coated” to create a non-uniform surface pattern. This would be tracked by the ARAMIS software between digital images captured during the deformation test. The speckle patterns in this work were created using white and black aerosol paints. A solid white base coat was first applied and this was followed by a misted black paint. The latter resulted in the black speckles with the size of 2–5 pixels. A typical obtained speckle pattern is shown in Fig. 3. The pattern was applied as thin as possible. A reliable CCD camera with the resolution of 1280 × 1024 pixels (0.023 mm/pixel as pixel pitch) was utilized to acquire digital images at a sampling rate of either 0.5 or 1 frame $s^{-1}$ during tensile testing. In addition, In order to support the accuracy of the DIC results, electrical-resistance strain gage was used to measure the strains.

### 2.2. Principle of digital image correlation technique

Full-field optical techniques for displacement or strain measurements are widely used in experimental mechanics. The main techniques are photoelasticity, geometric moire, holographic technique, speckle interferometry, grid method and digital image correlation (DIC) [22,23]. It should be noted that some of these techniques can only measure in-plane displacements/strains on planar specimens and some of them can give both in-plane and out-of-plane displacement/strain fields on any kind of specimen (planar or not). Due to its simplicity and versatility, the DIC method is probably one of the most commonly used methods. For mesoscopic measurements, DIC can be used. Digital holographic technique is well suited for quantitative measurement of very small displacement maps on the microscopic scale [24,25]. The fact that digital holography directly provides the complex amplitude of the reconstructed object wave field.

The chief speculation of the DIC method is based on the gray scale intensity of a point in the reference image as well as in the