

Tensile Deformation and Fracture of TRIP590 Steel from Digital Image Correlation

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ABSTRACT

Quasi-static tensile properties of TRIP590 steels from three different manufacturers were investigated using digital image correlation (DIC). The focus was on the post-uniform elongation behavior which can be very different for steels of the same grade owing to different manufacturing processes. Miniature tensile specimens, cut at 0°, 45°, and 90° relative to the rolling direction, were strained to failure in an instrumented tensile stage. True stress-true strain curves were computed from digital strain gages superimposed on digital images captured from one gage section surface during tensile deformation. Microstructural phases in undeformed and fracture specimens were identified with optical microscopy using the color tint etching process. Fracture surface analyses conducted with scanning electron microscopy and energy dispersive spectroscopy were used to investigate microvoids and inclusions in all materials.

INTRODUCTION

Increasing regulatory requirements in vehicle safety and improvements in fuel economy enabled by reduction in vehicle weight are currently the main factors driving innovations in automotive structural materials. Consequently, material strengths that exceed those of conventional steels will be required. Steels with high and ultra high tensile strengths often exhibit limited ductility at room temperature which imposes restrictions on part shapes that can be successfully formed. To address this difficulty, steel research proceeded along two directions. On the one hand, developments in forming techniques at high temperatures enabled applications of ultra high strength steels (UHSS) with relatively small elongations, such as boron steel [1] and fully martensitic steel [2], to vehicle structures. Current applications include high impact energy absorbing parts: front rails, door beams, bumper beams, roof rails, pillar

reinforcements, etc. [3-4]. On the other hand, significant effort was applied to the development of steels that exhibit high strength and high ductility at room temperature such as dual-phase (DP) [5-6], austenitic steel with twinning induced plasticity (TWIP) [7-8], and transformation induced plasticity (TRIP) steels [9].

Transformation Induced Plasticity (TRIP) steel, which is the focus of the present paper, has seen application in body-in-white manufacturing [10-11]. The microstructure of TRIP steel consists of “mixed phases”, namely a soft ferrite matrix containing bainite, which accounts for up to 90% of the structure, small amounts of martensite, and some retained austenite [12]. In addition, silicon (Si) and manganese (Mn) are added to inhibit carbide precipitation and stabilize the retained austenite [13] while niobium (Nb) is added to refine the grain size and increase strength [14]. The microstructure is the result of the combination of annealing and austempering (second annealing) processes [15]. An increase in the austempering temperature causes a corresponding increase in the yield strength (YS), work hardening exponent, and the total elongation, with a decrease in tensile strength [16].

Exceptional ductility of TRIP steels at room temperature is attributed to the transformation of the retained austenite into martensite. The amount of transformed austenite depends on the applied strain, dislocation density and temperature [17-18]. The transformation rate typically increases at lower temperatures [19] and decreases with an increase in strain rate [20]. The microstructure of TRIP steels influences macroscopic mechanical properties with the original percentage of retained austenite contributing the most to the increase in total elongation [21]. In addition to the microstructure, the final mechanical properties depend on the amount of pre-strain introduced during forming and the deformation rate. The YS and ultimate tensile strength (UTS)

increase significantly with an increase in strain rate while the total elongation slightly decreases [22]. The absorbed energy increases linearly with an increase in strain rate for all amounts of pre-strain, which is very favorable in crash events. Mechanical property measurements of several grades of TRIP steels derived from tensile tests may be found in [1, 23-24]. However, these studies do not compare the properties of the same grade of steel from different steel manufacturers.

In this paper, quasi-static, room temperature tensile deformation and fracture of TRIP590 steel from three different manufacturers are investigated. Yield strength, UTS, and the total elongation before fracture were determined from specimens that were deformed in tension until fracture. For each test, digital images were recorded from one surface of the specimen with a high speed, high resolution digital camera. Two-dimensional strain fields were computed in a post-processing step using a state-of-the-art digital image correlation (DIC) technique. Stress-strain curves were inferred from a simple uniaxial relation that has been shown to be valid beyond uniform elongation for thin sheet materials. Fracture surface analyses conducted with scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) revealed the geometries and chemistries of key microstructural features that contribute to fracture in tension.

EXPERIMENTAL DETAILS

TENSILE SPECIMEN PREPARATION AND GEOMETRY

The TRIP590 steel used in this study was obtained from three different steel manufacturers which are designated as Steels A, B, and C. The specimens from manufacturers A and B were uncoated while the specimens from the manufacturer C had a galvanized coating (GA). Tensile specimens were cut from sheet material with a nominal thickness of 1.5mm using water jet cutting. The numerical controller on the water jet cutter was programmed to slow the feed rate during cutting of the gage section of each specimen. This provided superior edge quality with no discernable machining defects. The specimens were cut along the rolling direction (0° orientation) and at 45° and 90° orientations with respect to the rolling direction (RD). A thin, uniform coat of white spray paint was applied to the gage section of each specimen followed by application of black paint droplets. This resulted in a suitable grayscale contrast pattern required by the DIC algorithm during post-processing of the strain fields that developed in the specimen during tensile deformation. The shape and dimensions of the specimen geometry are shown in Fig. 1.

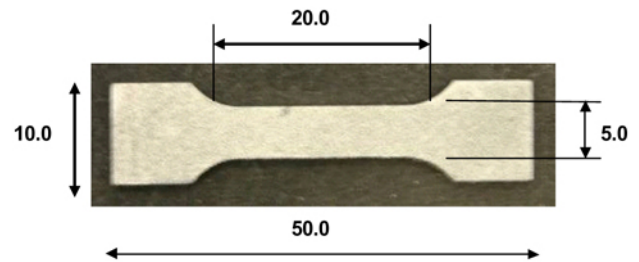


Fig. 1. Tensile specimen geometry and dimensions (in mm)

TENSILE TESTING AND DATA ACQUISITION

The tests were conducted at an average cross-head speed of 0.02mm/s which corresponds to a nominal strain rate of $0.001s^{-1}$. During each test, the axial load, measured with a 10kN load cell, and the displacement, measured with a 25mm displacement transducer, were recorded using a data acquisition system at a sampling rate of 40Hz. A fiber optic light source was positioned above each specimen to provide a suitable level of illumination.

Digital images of the gage section were captured with a high speed digital camera. The pixel density of each image was 1632×322 with a spatial resolution of 0.02mm/pixel. Variable framing rate image capture was enabled with a custom software algorithm written in the LabView Code [25]. The image capture algorithm monitors and records the force and displacement data from the tensile stage controller and sends trigger pulses to the camera based on load gradient thresholds defined by the user. When high load gradients were detected, e.g. during elastic loading, or during unloading prior to fracture, more images were captured in the 12GB camera buffer. This approach allowed capture of sufficient number of images in regions where the load changed significantly over small displacements. Captured image totals were in upwards of 550 for most of the tests. During the course of the present study, over 60,000 digital images were collected for DIC analysis. Further details on the variable framing rate image capture algorithm may be found in Ref. [26].

STRAIN MAPPING BY DIGITAL IMAGE CORRELATION

Two-dimensional digital DIC is a fast and precise method for measuring in-plane deformation and displacement fields of plastically deforming sheet materials. The input to the correlation algorithm requires a set of digital images that store the deformation history from one surface of the gage section, recorded at fixed intervals, up to fracture. Once a test is completed, the images can be compared in a cumulative fashion, in which an earlier image is compared with a later image, or in an incremental fashion, in which temporally

Table 1. Chemical composition of TRIP590 steel (wt. %)

Source	C	Mn	P	S	Si	Cr	Mo	Al	V	Nb	B
A	0.12	1.5	0.01	<.003	1.2	<.01	<.01	0.02	<.003	<.003	<.0003
B	0.15	1.5	0.01	<.003	0.35	<.01	<.01	0.95	<.003	<.003	<.0003
C	0.10	1.5	0.06	<.003	1.1	<.01	<.01	0.04	<.003	<.003	<.0003

successive image pairs can be compared to produce the deformation and displacement history of the material. Displacement and strain fields are computed from digital grids superimposed on each image and then displayed as contours of constant strain or strain maps. Each grid is divided into a set of square pixel subsets, typically 60×60, with a grid point at its center. An interpolation zone around each subset is then chosen along with a strain gage size, typically 5×5. The correlation algorithm then tracks the location of unique contrast features in the spray paint pattern corresponding to each grid point in each image, accounts for the rigid body motion of the system, and then computes an average displacement and true strain value at each grid point. The errors in local in-plane displacements, rigid body rotation, and strain measurements are estimated to be 0.02pixels, 0.020 and 100×10⁻⁶, respectively [27]. Digital image correlation analysis of all test results was performed with the SDMAP3D software [28]. For additional references on the DIC technique the reader is referred to Refs. [29-30].

EXTRACTION OF TRUE STRESS-TRUE STRAIN CURVES FROM STRAIN MAPS

Average axial true stress in a tensile specimen can be computed using the following expression

$$\overline{\sigma}_1 = \frac{F e \overline{\epsilon}_1}{WT} \quad (1)$$

where $\overline{\sigma}_1$ is the average true axial stress, F is the applied load, $\overline{\epsilon}_1$ is the average true strain computed from DIC, and W and T are the initial width and the thickness of the tensile specimen, respectively.

The contour maps computed in the DIC post-processing step provide a convenient means for visualizing the axial $\epsilon_1(X,Y)$, transverse, $\epsilon_2(X,Y)$ and shear strain fields, $\epsilon_{12}(X,Y)$ from one surface of a deforming tensile specimen. True uniaxial strain in tension was calculated according to the following expression:

$$\overline{\epsilon}_1 = \frac{1}{MN} \sum_{j=1}^N \sum_{i=1}^M \epsilon_1(i,j) \quad (2)$$

In Eq. (2), $\overline{\epsilon}_1$ is the axial strain averaged over the entire gage section of the specimen. The total number of digital grid points in axial and transverse directions are M and N, respectively, while $\epsilon_1(i,j)$ is the DIC-computed true strain at grid point (i,j). In Ref. [31] it was shown that the stress-strain state in the neck region in most thin metal sheets deviates only slightly from that of uniaxial tension despite increasingly heterogeneous strain distributions. Equation (2) is therefore a reasonable approximation of the uniaxial tensile stress-strain curve beyond the onset of diffuse necking and up to substantially larger plastic strains.

RESULTS AND DISCUSSION

CHEMICAL COMPOSITION AND MICROSTRUCTURE

TRIP590 steel from three different manufacturers, labeled A, B and C, were examined in this study. The chemical composition of each material, as determined by optical emission spectrometry, is listed in Table 1.

<table 1 here>

A color-tint etching technique [32] was performed on the microstructures in the as-received condition and after fracture. Material from each of the three steel manufacturers showed the presence of retained austenite (RA), martensite-austenite constituents (MA), and bainite (B) in a ferrite matrix. These phases are shown in the undeformed state in Figs. 2a, 3a, and 4a. The typical amount of retained austenite in TRIP590 steels varies between 5-10%. The microstructures shown in Figs. 2b, 3b, and 4b show the same TRIP590 specimens following fracture during tensile testing. The cross-sections were taken just beneath the fracture surfaces of the test specimens. It can be seen that in all cases the majority of the retained austenite has undergone transformation into martensite. Each specimen exhibited approximately 30% uniaxial engineering strain prior to fracture.

<figure 2 here>

<figure 3 here>

<figure 4 here>