

Strain Field Measurement in the Vicinity of Ductile Rupture from Digital Image Correlation

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ABSTRACT

A methodology that enables two-dimensional strain field measurement in the vicinity of ductile rupture is described. Fully martensitic steel coupons were strained to fracture using a miniature tensile stage with custom data and image acquisition systems. Rupture initiated near the center of each coupon and progressed slowly toward the gage section edges. A state-of-the-art digital image correlation technique was used to compute the true strain field before rupture initiation and ahead of the resulting propagating macroscopic crack before final fracture occurred. True strains of the order of 95% were measured ahead of the crack at later stages of deformation.

INTRODUCTION

Fully martensitic steels have been the focus of considerable research in recent years. They exhibit high strength and energy absorption characteristics, which make them ideal for automotive applications [1]. Martensitic steels are typically used in high impact areas of a vehicle such as bumper beams and roof rail reinforcements [2]. These steels have low carbon content and are formed in a process which consists of heating above the austenitizing temperature and quenching in the die. The resulting structure is very strong but exhibits limited ductility. To increase ductility, the material is typically tempered. The temperature of the heat treatment is the most influential factor on the resulting material properties. Typically the best balance between strength and hardness on one hand, and ductility and toughness on the other hand is achieved at temperatures between 300°C-500°C [3-4].

This paper presents results from recent studies of tensile behavior and fracture of a 900 grade fully martensitic steel. Tensile properties were determined with a miniature tensile testing stage for load application and a state-of-the-art digital image correlation technique (DIC) for strain measurement after each test. Two-dimensional strain fields in the vicinity of ductile rupture were measured by positioning digital grids at the appropriate location in the tensile coupon gage section. Deformation

behavior was quantified with strain maps computed with DIC.

EXPERIMENTAL DETAILS

MATERIAL DESCRIPTION AND COUPON GEOMETRY

Martensite steel from Mittal Steel USA [5] was tested in this study. The nominal chemical composition of the material is shown in Table 1. In addition to the alloying elements in Table 1, trace amounts of sulfur, niobium, nickel, molybdenum, vanadium, and phosphorus (all < 0.01%wt.) were detected by optical emission spectroscopy.

Table 1 Chemical composition

	C	Mn	Si	Al	Ti	Cu	Cr	Fe
%wt.	0.04	0.39	0.06	0.06	0.039	0.03	0.05	Bal.

The shape and dimensions of the tensile coupon geometry are shown in Figure 1. The coupon thickness was 1.3mm and the gage width was uniform at 5mm. A uniform coat of white spray paint was applied to the gage section of each tested coupon followed by the application of black paint droplets. This resulted in a suitable grayscale contrast pattern required by the DIC algorithm.

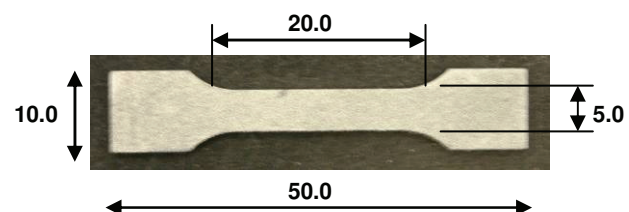


Figure 1 Tensile coupon geometry and dimensions (mm)

TENSILE TESTING AND DATA ACQUISITION

All tests were conducted at room temperature using a miniature tensile testing stage with suitable load and displacement electronics. The tests were conducted at a strain rate of 0.0006s^{-1} . During each test, the axial load and displacement were recorded at a sampling rate of 3Hz. Digital images of the gage section, or a portion of the gage section of interest, were captured every 2s by a 7 f/sec CCD camera with a 1280x960 pixel density. The DASyLab software package [6] was used to drive the camera and to record the axial load and displacement data corresponding to each digital image captured during a test.

STRAIN MAPPING BY DIGITAL IMAGE CORRELATION

Two-dimensional DIC is an efficient technique for measuring in-plane deformation and displacement fields of thin coupons or structural members. A set of digital images from one surface of the deforming material, recorded at fixed intervals during the test, is used by the correlation algorithm for displacement field computation. 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 successive image pairs are compared. Displacement and strain fields are computed from digital grids superimposed on each image and are displayed as strain contour maps. Each digital grid consists of a set of square pixel subsets, typically 10×10 , with each subset containing a grid point at its center. The correlation algorithm tracks the location of unique contrast features (e.g. in a spray paint pattern) corresponding to each grid point in each image, accounts for the rigid body motion of the system and 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 0.02 pixels, 0.02° and 100×10^{-6} , respectively [7]. More details on the DIC technique used herein can be found in [8-10]. Digital image correlation analysis of all test results was performed with the SDMAP3D software [11].

RESULTS AND DISCUSSION

MEASURED TENSILE PROPERTIES

The measured elastic modulus was 229GPa while the 0.2% yield strength was 831MPa. The ultimate tensile strength was measured to be 1017MPa with the corresponding elongation of 4.21%. Due to the ductile rupture process fracture stress and strain were not measured.

SELECTED STRAIN CONTOUR MAPS

Figure 2 shows selected cumulative strain maps for a representative test coupon. The strain localization shown in these maps is indicative of that observed in all tested coupons. Figure 2a shows contours of true axial strain

corresponding to a 6603N load. It is evident that diffuse necking has started to occur in the center of the coupon, as indicated by the red contours which show a peak strain level of 12%. By comparing contours in Figure 2a,c,e,g,i it can be seen that as the load decreases more and more from its peak value of 6716N, the diffuse neck region narrows down near the center of the coupon and the peak strains increase. The peak strain of 70% in Figure 2i corresponds to the last image correlation pair before rupture initiation. The strains are highly localized in the diffuse neck at the center of the coupon where rupture ultimately occurs. Contours of the peak strain are oval in shape and elongated perpendicular to the tensile axis which is along the horizontal of each map. Contours of the transverse strain field are shown in Figure 2b,d,f,h,j. The strains are compressive and are concentrated in the center of the coupon. Peak transverse strain values decrease from -10.5% to -26% just before rupture initiation.

STRAIN CONTOUR MAPS AFTER RUPTURE INITIATION

Rupture begins near the center of the gage section, as shown in Figure 3a. As stretching continues and the load decreases, (e.g. from 2650N in Figure 3a to 1512N in Figure 3b), the macroscopic crack in the center of the coupon propagates towards the edges of the gage section. Figure 3c shows the coupon after the crack has reached one of the edges. Note that at the other edge, the coupon was not completely separated and was still supporting the load of 781N. It was not uncommon to find that events between rupture initiation and final separation of the coupon required 12-15 additional digital images of the coupon gage section.

A significant advantage of the DIC technique is that the region of interest for strain field measurement is user-controlled. For example, to measure the two-dimensional surface strain field ahead of the lower end of the rupture tip shown in Figure 3, a digital grid (blue dots in Figure 4) was placed over the initial (undeformed) image in the location where rupture ultimately occurred. The digital grid follows the original pattern on the surface and deforms with the coupon as it is subjected to load increase. Figure 5 shows the same grid just before the final fracture. Note that the greatest distortion of the grid occurs at the rupture end that is propagating toward the lower edge of the coupon gage section. This is evident from the large separation between adjacent grid points.