

Measurement of r-values of High Strength Steels Using Digital Image Correlation

2011-01-0234

Published
04/12/2011

Gang Huang and Benda Yan
ArcelorMITTAL

Z. Xia
Ford Motor Co

Copyright © 2011 SAE International

doi:[10.4271/2011-01-0234](https://doi.org/10.4271/2011-01-0234)

ABSTRACT

The r-value is a very important parameter in the forming simulations of high strength steels, especially for steels with prominent anisotropy. R-values for sheet steels conventionally measured by extensometers were found neither consistent nor accurate due to difficulties in measuring the width strain. In this study, the Digital Image Correlation (DIC) technique was applied to determine r-values in Longitudinal (L), Transverse (T) and Diagonal (D) directions for cold rolled DP980 GI, DP780 GI, DP600 GI and BH250 GI sheet steels. The r-values measured from DIC were validated by finite element analysis (FEA) of a uniaxial tensile test for BH250. The simulation results of the load-displacement for two plasticity models were compared to experimental data, with one being the isotropic yield (von-Mises) and the other being an anisotropic model (Hill-48) using the r-value measured from DIC. The comparison showed that the simulation using anisotropic model yielded much better accuracy than isotropic model. It served as a strong indication of the advantages of using DIC to generate accurate r-values along different orientations for simulating the deformation behavior of anisotropic steels.

INTRODUCTION

The r-value (or the Lankford coefficient) is a very important parameter as an input in Finite Element Analysis (FEA) of forming processes for AHSS that exhibits anisotropy and the simulation results could be very sensitive. It reveals the relative strengthening between the width and the thickness direction. In order to improve simulation accuracy for AHSS when anisotropy is not negligible such as failure prediction in

hydroforming or springback prediction in stamping, it is critical to characterize steel sheets with accurate measurement of r-values. While extensometers have been conventionally utilized to measure r-values for sheet steels, it was found that the results were neither consistent nor accurate due to difficulties in measuring the width strain [1]. Digital image correlation is a tool for measuring surface displacement and strain of materials under deformation [2,3,4]. It has become an effective and popular measurement technique since it can provide full-field strain distributions on material surfaces through accurate, fast and non-contact measurement during the deformation process.

In this paper, the measurement of r-value in L, T and D direction using DIC is presented for four different steel grades: cold rolled DP980 bare, DP780 GI, DP600 GI and BH250 bare. The r-values determined using DIC are compared with those from conventional measurement using extensometers. For validation of the r-value measured from DIC, the uniaxial tensile test on BH250 was simulated using finite element analysis (FEA). In addition, full stress-strain measured using DIC and two plasticity models, isotropic plastic model (von-Mises) and anisotropic model (Hill' 48), using the r-value measured from DIC were applied. The simulation results of the load-displacement were compared to experimental data.

EXPERIMENT

The tensile properties of the four steels are shown in [Table 1](#). All properties are averages over longitudinal (L), transverse (T) and diagonal (D) directions.

Table 1. Tensile properties of four materials

Material	Thickness(mm)	YS (MPa)	UTS (MPa)	UE	TE
DP980 CR	1.45	665	996	0.098	0.14
DP780 GI	1.2	467	843	0.124	0.209
DP600 GI	1.2	380	668	0.173	0.234
BH250 GI	0.74	250	350	0.255	0.330

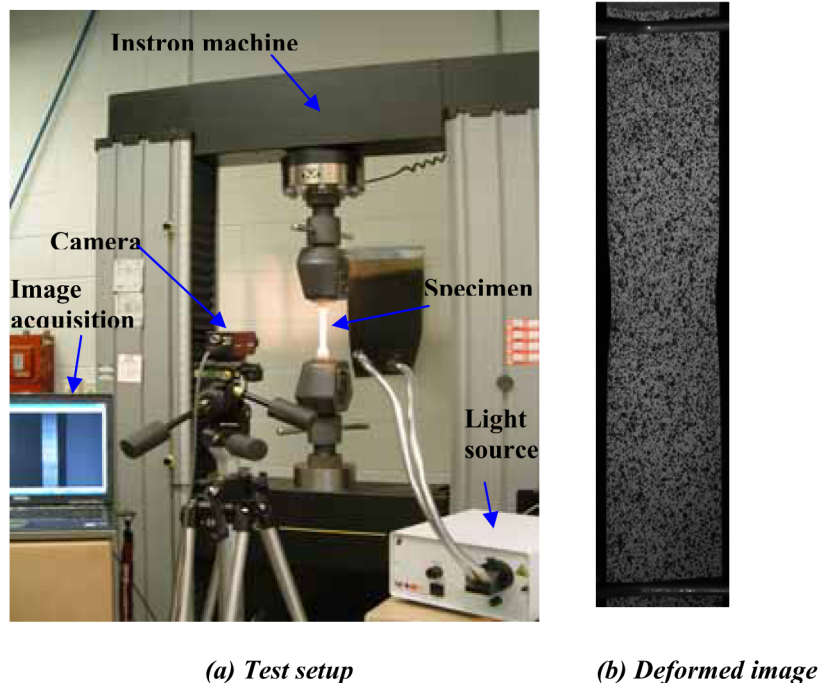


Figure 1. Tensile test setup with DIC system and typical image for DIC

Digital Image Correlation (DIC) system was applied to measure r -values as a function of tensile strain. The specimen geometry is based on ASTM E08. The test setup is shown in Figure 1. Before testing, the specimens were prepared with random paint speckles. Monochrome images of specimens were taken at a speed of 15 frame/second during tests. After testing, the acquired images were analyzed using DIC software to calculate major and minor strains to determine r -values. Conventional method was also used to generate r -values for comparison, where longitudinal and transverse extensometers were used in uniaxial tensile tests to measure strains in length and width directions. R -value was measured as a function of tensile strain up to uniform elongation. The testing procedure and specimens for conventional method were according to ASTM E08. All tensile tests were performed on an Instron testing system (model 4485 15).

RESULTS AND DISCUSSIONS

Results of r -values for the four steel grades using DIC and conventional measurements are presented in the section. In the meanwhile, the r -values measured using these two methods are compared. Furthermore, the r -values of BH250 measured using DIC are validated through finite element analysis on the ASTM tensile tests.

The r -value, sometimes also referred as the Lankford coefficient, is usually defined as the ratio of total true width strain to true thickness strain from tensile tests up to uniform elongation [5], or denoted as accumulative r -value in Equation (1).

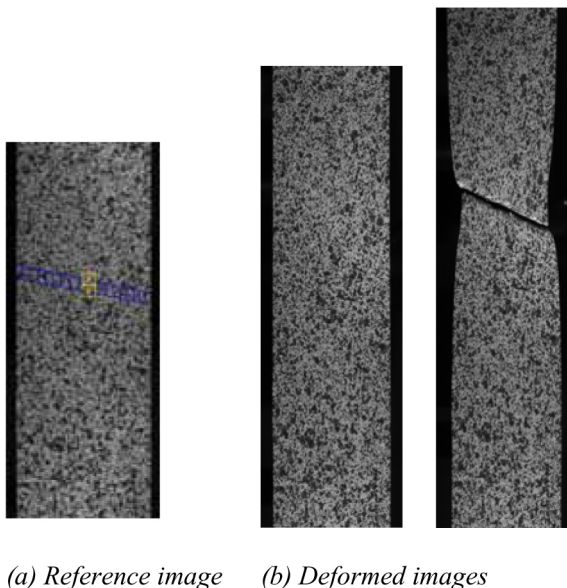
$$R_a = \frac{\varepsilon_w}{\varepsilon_t} = \frac{\ln(w/w_0)}{\ln(t/t_0)} \quad (1)$$

However, if the relationship between width strain and thickness strain is not linear, the accumulative r-value is the average up to the strains of measurement, and might not well represent the continuous behavior of anisotropy. In this case the instantaneous r-value should be used instead, which is defined as the ratio of the plastic strain increment in the width direction to the plastic strain increment in the thickness direction as expressed in Equation (2). In fact, when the slope is constant the accumulative r-value and instantaneous r-value are the same.

$$R_i = \frac{d\varepsilon_w^{pl}}{d\varepsilon_t^{pl}} \quad (2)$$

R-VALUE MEASURED USING DIC

After tensile tests, images of specimens up to uniform elongation (or maximum load) were processed with DIC software (made by Correlated Solutions). Figure 2 illustrates changes of images from stages of undeformed, uniform elongation to fracture. The area close to the center of the specimen in axial direction was focused on for strain measurement. A gauge length of 2 mm was used for axial and width directions in calculations of true major and minor strains. As an example, the imaginary gauge length in the axial direction was shown in Figure 2a.



(a) Reference image (b) Deformed images

Figure 2. An example of deformation stages with reference and deformed images (BH250)

The accumulative r-values according to Equation (1) are illustrated as function of tensile strain in Figures 3, 5, 7 and 9 for DP980, DP780, DP600 and BH250, respectively, where the r-values for L, T and D directions are included. To calculate the instantaneous r-value using Equation (2), transverse strain (in width direction) was plotted with respect to thinning strain (thickness direction); linear curve fitting was attempted on the raw strain data up to uniform elongation, as shown in Figures 4, 6, 8, 10. Meanwhile, Equation (2) was applied to determine the instantaneous r-value as a function of tensile strain. Due to the measurement noise especially at the initial deformation stage, direct differentiation can lead to much higher noise. Smoothing of raw data was thus conducted prior to differentiation. The results of instantaneous r-values are shown in Figures 11,12,13,14.

The plots of accumulative r-value reveal that different steel grades behave differently in the evolving of r-value with respect to tensile strain. For DP980, the r-value increases all along through uniform elongation (Figure 3). For DP780, r-value shows only slight change after 4% of tensile strain (Figure 5). In contrast, for DP590 and BH250, the r-value reaches a steady state, i.e. no more change after tensile strain of 6% (Figure 7). It suggests that the accumulative r-value of steel grades of higher strength might be more sensitive to the initial stage where the relation between transverse strain and thinning strain either exhibits more nonlinearity or are has more noise in its measurement.

The linear curve fitting on Figures 4, 6, 8 and 10 exhibits very good correlation of linearity between transverse strain and thinning strain throughout the uniform deformation of tensile specimens, except that DP980 shows some slight deviation from linearity. The slopes from curve-fitting shown in Figures 4, 6, 8, 10 denote the average slope up to uniform elongation, or the average r-value for the individual materials in different directions. To reveal the history of instantaneous r-value, however, Equation (2) is needed to calculate the derivative at each data point of transverse and axial strains. In the data processing, a noise filtering algorithm called Loess fitting was used to remove most scattering. Loess fitting is based on fitting localized subsets of raw data and no global function is needed. In Loess fitting for the data of width strain versus thinning strain, smoothing level of 10% was used. After fitting, the instantaneous r-value was calculated as function of tensile strain. The instantaneous r-value histories as illustrated in Figures 11,12,13,14 indicate that except for DP980, overall the r-value is maintained close-to constant after tensile strain of about 2%, though local data variation is observed, which should be attributed to numerical error from differentiation.

Comparisons of accumulative and instantaneous r-values measured using DIC are illustrated in Figures 15 and 16 for DP600 and BH250. Although clear difference between

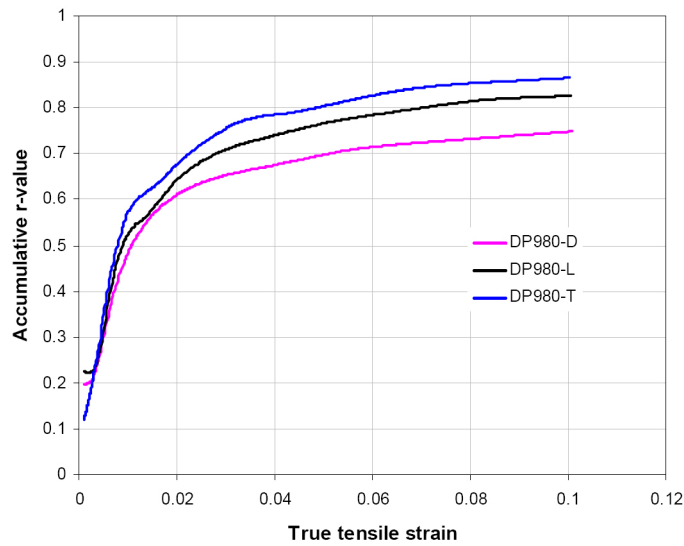


Figure 3. Accumulative r-value of DP980 CR using DIC

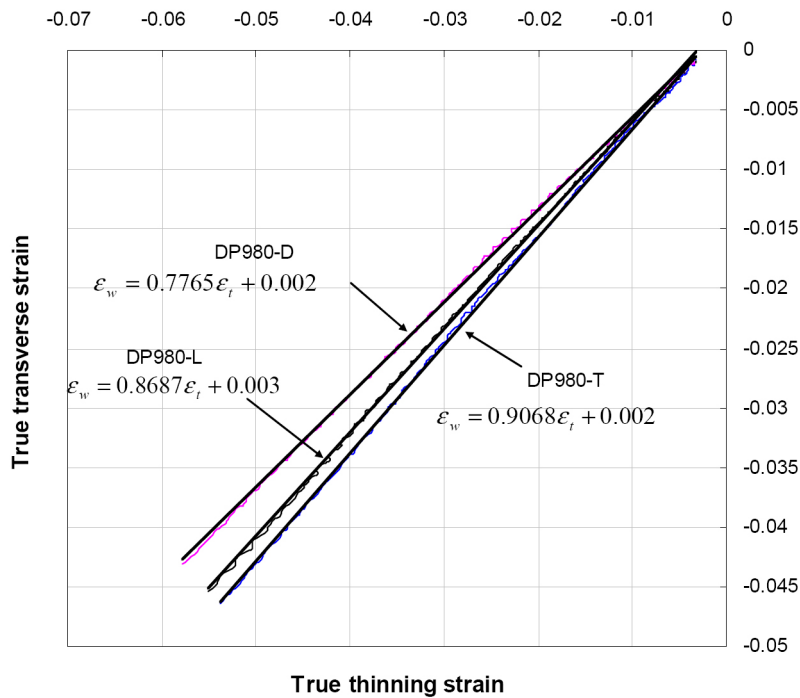


Figure 4. Transverse strain (width direction) as function of thinning strain (DP980) using DIC

accumulative and instantaneous r-values can be observed, they approach the same value when close to uniform elongation. The similarity of accumulative and instantaneous r-values at steady state indicates that when reaching steady state the initial nonlinearity has little effect on the ratio of the transverse strain to the thinning strain.

The general linearity shown in [Figures 4, 6, 8 and 10](#) can easily lead to the inference that the instantaneous r-value is constant for AHSS. While a constant r-value can be used for forming simulation on AHSS with large plastic deformation,

the initial variance of r-value (as illustrated in [Figure 11,12,13,14](#)) should be taken into account when the initial plastic deformation is important.