

A Study of Anisotropy and Post-Necking Local Fracture Strain of Advanced High Strength Steel with the Utilization of Digital Image Correlation

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ABSTRACT

The automotive industry has a strong need for lightweight materials capable of withstanding large mechanical loads. Advanced high-strength steels (AHSS), which have high tensile strength and formability, show great promise for automotive applications, yet if they are to be more widely used, it's important to understand their deformation behavior; this is particularly important for the development of forming limit diagrams (FLD) used in stamping processes. The goal of the present study was to determine the extent to which anisotropy introduced by the rolling direction affects the local fracture strain. Three grades of dual-phase AHSS and one high-strength low-alloy (HSL A) 50ksi grade steel were tested under plane strain conditions. Half of the samples were loaded along their rolling direction and the other half transverse to it. In order to achieve plane strain conditions, non-standard dogbone samples were loaded on a wide-grip MTS tensile test machine. Strain measurements were made using Digital Image Correlation (DIC). DIC is an optical method which delivers whole-field noncontact measurement of strain, providing the ability to accurately determine peak deformation as well as gradients over the entire area of interest. DIC uses gray scale intensities of light reflected from the surface area of interest as recorded by image detector(s)

to determine local strain. It was found that HSLA 50ksi steel exhibits, on average, a small but noticeable increase in post-necking local fracture strain values if loaded in the rolling direction, as opposed to the transverse. The dual-phase steel samples tested, i.e. DP600, DP780, and DP980, exhibit negligible post-necking strain variations along the rolling as opposed to the transverse directions.

KEYWORDS

Advanced High Strength Steel (AHSS), Digital Image Correlation (DIC), Anisotropy, Rolling Direction, Dual-Phase Steel

INTRODUCTION

The automotive and steel industries have a strong need for decreasing the weight and cost, while effectively increasing the safety, reliability and fuel efficiency of manufactured components. Constituting around 50% of the total weight of a vehicle, sheet metal has a significant effect on a vehicle's fuel efficiency. With emerging regulations on fuel economy and the need for decreasing carbon dioxide emissions, the ability to decrease weight while maintaining crashworthiness, material stiffness, and optimum safety is of utmost importance. According to a study by Baosteel, China, a 10%

reduction in vehicle mass would lead to an approximate 3-7% reduction in gasoline consumption [1].

The advent of AHSS and the need to push the mechanical limits of manufactured components necessitates an understanding of the impact of material anisotropy on plastic behavior. If there is in fact considerable anisotropic influence on necking behavior, the cutting of sheet metal blanks could possibly be optimized. Recent research by Eman et al. [2] has established a correlation for hardened 22MnB5 ultra-high strength steel between anisotropy and strain fields at necking. They observed a substantial increase in the sample's strain capacity near the necking region when samples were loaded along the rolling direction as opposed to the transverse. AHSS formability and strength could further be exploited once our macroscopic understanding can be extended to the microscopic level, i.e. to the crystallographic nature of the steel.

A material's plastic properties mark the basis for the development of the forming limit diagrams (FLD) used in stamping processes [2]. Although stamping processes are concerned mainly with high strain rate processes, a material's behavior in response to high static tensile forces can help shed light on the underlying mechanisms of failure. A material's yield strength marks the onset of plastic deformation (usually defined as a 0.2% strain offset); it is the minimum stress required to permanently deform the material. In addition, a material's ultimate strength marks the onset of strain localization, also known as necking, and is the maximum stress the material can withstand without introducing substantial stress concentrations to a localized area.

In various metal forming applications, steel is stamped, stretched, pulled, and bent. Springback of the steel to its original shape is undesirable; the material needs to plastically deform. It is important for the material to refrain from necking, as stress concentrations can leave significant residual mechanical stresses that can eventually lead to fracture after long term exposure to fatigue load cycling. Ideally, manufactured components are to be exposed to stresses that fall within the range of the material's yield and ultimate strengths in order to avoid the onset of necking. Unfortunately, this is not always the case and a thorough study of the behavior of AHSS materials around the onset of necking is necessary. In practical applications, necking is undesirable since the high strain rate around areas of increased stress will likely develop a crack, which can eventually propagate and lead to component failure [3].

The phenomenon known as necking is defined as the onset of plastic instability, in which large amounts of strain localize disproportionately in a small region of material. This is usually accompanied by a large decrease in thickness, which provides conditions for crack formation. A crack developing

poses a problem because under continued loading, it will propagate and ultimately lead to component failure/fracture. Traditional deformation measuring techniques, i.e. strain gauges and extensometers [4], are limited to strain readings averaged over an area. During a component's elastic deformation, strains are more or less uniform throughout the sample, so the use of a traditional gauge method can yield results to a tolerable degree of error. However, as the sample material is subject to stresses near its tensile strength, strain localization renders average strains impractical for determining peak values; peak values are necessary for predicting sections likely to fracture. Modern techniques include whole-field optical noncontact methods such as shearography, holography [5] and electronic speckle pattern interferometry. Holography and traditional electronic speckle pattern interferometry (ESPI) are too sensitive (in the nanometer range) for the required macroscopic strain range expected in this experiment and can be susceptible to environmental noise.

Digital Image Correlation (DIC), on the other hand, is an optical method that employs whole field, noncontact and noninvasive measurement of displacement which is relatively insensitive to environmental noise because it can measure rigid body motion and thus, it can eliminate the effect of such movements [6]. The technique uses gray scale intensity levels recorded by CCD cameras to correlate an area of $n \times n$ pixels before and after deformation. It can provide contours of displacement, and, thus, enable the accurate determination of strain data.

The goal of the present study was to investigate the effect that anisotropy, introduced in AHSS materials through rolling, has on the local fracture strain of these materials. Four typical AHSS materials were studied: high-strength low-alloy (HSLA) 50ksi, and dual-phase (DP) 600, DP780, and DP980. These materials have different microstructures. For instance, DP AHSSs owe their high tensile strength (UTS) to a hard martensite phase and their ductility to their characteristic soft ferritic (iron) matrix. HSLA steels on the other hand are made up of a carbon-reinforced iron matrix, with a few other alloying elements [3]. Mechanical testing was conducted using a wide-grip MTS tensile test machine. In order to precisely measure strain states on a given sample of high strength steel, the recently developed 3D-DIC system from Dantec-Dynamic GmbH was employed. In this paper, we report on the findings of these experiments, focusing in particular on comparing the post-necking local fracture strain values of the different materials when they are loaded in the rolling direction as opposed to transverse to it. Post-necking strain values are important in formulating forming limit diagrams and for optimizing the use of material depending on a component's mode of loading.

BRIEF DESCRIPTION OF DIC FUNDAMENTALS

Digital Image Correlation (DIC) is a modern optical strain measurement technique that measures displacement by tracking the gray value pattern in small neighborhoods called subsets (indicated in red in [Figure 1](#)) during movement/deformation. A DIC calculation provides a correlation coefficient, c , which presents the similarity of the gray value distribution of the subsets in different images. [Equation 1](#) shows the definition of the normalized correlation coefficient c :

$$c(\Delta x, \Delta y) = \frac{\sum_x \sum_y I_1(x, y) I_2(x + \Delta x, y + \Delta y)}{\sqrt{\sum_x \sum_y I_1^2(x, y) I_2^2(x + \Delta x, y + \Delta y)}} \quad (1)$$

where: $I_1(x, y)$ represents the pixel intensity at (x, y) of a reference image 1, and $I_2(x + \Delta x, y + \Delta y)$ represents the pixel intensity at $(x + \Delta x, y + \Delta y)$ of a second image, which varies from the first due to rigid body motion and/or deformations of the sample studied. The maximum value of this term shows the position $(x + \Delta x', y + \Delta y')$ matched to the best similar pattern in image 2, in reference to image 1. The corresponding value of $\Delta x'$ and $\Delta y'$ is the in-plane displacement u and v of the pixel subset. Theoretically, the maximum value that the correlation coefficient $c(\Delta x, \Delta y)$ can obtain is one. The condition $c(\Delta x, \Delta y) = 1$, indicates that the gray level distributions of the two subsets are identical. The closer to 1 the correlation coefficient is, the more similar the two subsets are. [Fig. 2](#) shows an example. The correlation coefficient $c(\Delta x, \Delta y)$ between two points is maximized when the most similar pattern around the points is obtained. The fundamental principle of digital image correlation is to track a point by finding the maximum correlation coefficient. By repeating this process for a large number of subsets, full-field deformation or displacement data can be obtained [7].

For a 3D-DIC system, two cameras are needed. This is done so that each camera captures the same image point at different angles, allowing one to track its relative motion to the rest of the image. Each camera takes images of the area of interest, then the normalized correlation coefficient between images taken by each camera is calculated. It is important to perform a calibration of the system prior to performing an experiment; such calibration is done to identify the corresponding distance between the two cameras and to determine the intrinsic and extrinsic parameters of the system [7]. With a 3D-DIC system, all three dimensional displacement components, u , v , and w , can be determined. Theoretically, a DIC method can achieve a measurement sensitivity of 1/100 pixels through interpolation and regression methods [9]. However, in practice, the measurement sensitivity is lower due to imperfect adjustments and environmental disruptions, and is usually

somewhere between 1/50 to 1/10 pixels, depending on the measurement conditions.

Since DIC is well suited for measuring large deformations and strains, the Lagrangian strain model, which is the most accurate mathematical model for large deformation, is used to determine the strain values when DIC is utilized. The engineering and true strains can be calculated from the Lagrangian strains as needed [9]. In this experiment, the main focus was on maximum principal engineering strains, as these will be crucial for setting limits on stress loads and for calculating their corresponding safety factors.

EXPERIMENT

Achieving plane strain and determining the extent to which the rolling direction influences strain distribution on a given sample requires the use of a non-standard wide dogbone sample with the dimension of 300mm × 300mm × 2mm (cf. [Fig. 3](#)). The dogbone's unusual width (300mm), with a 175mm gauge section, allows one to establish plane strain in approximately the middle third of the area in-between the notches (horizontal strain being close to zero). This is the reason why standard dogbones, with their very small width of about 12.5 mm, are not well suited for this study. The wide dogbone also helps minimize edge effects, such as those induced by residual mechanical stresses and stress concentrations near the notches caused by the cutting, heat treatment, machining, and preparation of the steel. Crack development is made to occur in the area of plane strain so that the rolling direction of the steel sample has a direct correlation to the localized strain in this area.

Digital Image Correlation operates on the principle of tracking an image point by calculating the gray intensity levels of the area in its immediate vicinity. The DIC grid space and the facet size employed are 6 and 21 pixels respectively. The setup uses an 8-bit system ($2^8 = 256$ levels) of gray intensity; 0 being the darkest (black) and 255 being the brightest (white). In light of this, the sample is first fully coated with white spray paint. Then, a random black speckle pattern is sprayed on the sample to maximize the difference in gray levels. One should be careful in making the speckle pattern as thin as possible (a few microns) so as to minimize foreign substance surface effects on the material properties of the steel sample. Although a 2D-DIC system using only one camera can be used for in-plane strain measurement, a 3D-DIC system using two cameras was instead used in our measurements. The purpose of using a 3D-DIC system was so that out-of-plane deformation could accurately be measured, values being especially important when large loads introduced in the necking area cause significant changes in width.

The non-standard wide dogbone sample was loaded on a wide-grip MTS machine (cf. [Fig. 4 left](#)) and two cameras,