Application of DIC techniques to detect onset of necking and fracture in uniaxial and bulge tests

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Abstract. This document provides information on and instructions for detecting the onset of necking in conventional uniaxial tension tests and biaxial bulge tests, using DIC technology and analysis methods developed at General Motors. The analysis enables reduction of the number and the costs of tests required in conventional FLD determinations using Marciniak and Nakajima tooling, while also avoiding the most serious process-dependent effects associated with the latter tests. It also provides a cost effective approach to develop forming limits for anisotropic sheet materials. In addition to providing this new experimental technique, the document will review the new procedures developed at General Motors for analysis of FLD tests and bulge tests to obtain reliable input for complete material card descriptions of advanced constitutive and forming limit models.

1. Introduction

Digital Imaging Technology (DIC) is increasingly being utilized for improving material characterization. In addition to providing a recording of the development of the inhomogeneous strain field of the visible regions of the test specimen throughout its deformation, it also provides a recording of the specimen shape. This technology both simplifies the testing procedure and greatly expands the ability to more fully analyze what is taking place in the test, which provides higher quality and more reliable data for calibration of constitutive and forming limit models.

For example, in the hydraulic bulge test, the ability to measure strains over the entire area avoids the need to attach strain gauges and related concerns about adhesion of the gauge at high strains, or accuracy limitations of the gauge. More importantly, it also enables measurement of non-uniform local strains over a wide area and thereby has the ability to record and account for the non-uniformity of the strain field. Furthermore, the ability to record the displacement of material points, which is what is actually employed to determine the strain field, enables the elimination of mechanical spherometers in the bulge test to measure curvature. Furthermore, DIC enables the experimentalist to measure the surface without making any assumptions about the surface shape such as being spherical or even elliptical. In fact, as described by Min et al. [1], it is now possible to employ much more realistic analysis of the bulge test using DIC to accurately calculate the thinning of the sheet using formulas that account for local non-equal-biaxial strain and non-spherical local curvatures. We can even account for elastic dilatancy, which can be important for metals with low modulus. Furthermore, Min et al. [1] did make any simplifying assumptions about the stress condition being equal-biaxial, but rather derived equilibrium equations from first principals to calculate the potentially non-equal-biaxial stress state based on improved access.
to critical information made available by DIC technology. The approach also simultaneously provides measurement of the so-called $r_b$ value, including the ability to account for changes with plastic deformation as well as the equivalent strain ratio in a non-equal-biaxial stress condition with a more general conclusion.

In another application of DIC technology, Min, et al. [2] provided a procedure to compensate for various test conditions in measurement of the onset of localized necking of forming limit curves (FLC) based on the particular test die geometry. Following this procedure, the FLC measured with a Marciniak test using a 100 mm diameter cylindrical punch, or with a Nakazima test using a hemispherical punch of any diameter can converge to a single FLC that can then be treated essentially as a material property. Differences between Marciniak and Nakazima test results were shown to be significant and caused by three factors, 1) difference in the degree of linearity of the strain path, 2) differences in the curvature of the sheet at the location of the neck, and 3) the presence or absence of tool-sheet contact pressure in the area where a necking instability arises. The authors used DIC measurements to take into account not just the surface strains, but also the strains (and stresses) on other layers through the sheet thickness, which is necessary because of the sheet curvature. Equations needed to calculate these strains require an accurate determination of the thickness, which requires accounting for the local strain and curvatures, both of which can be easily determined from the DIC data. A general method of converting these measured nonlinear strain histories to stress and then back to strain limits for linear strain paths was described, including an experimentally validated account of the curvature effect described by Tharrett and Stoughton [3]. Finally, a load equilibrium equation defined in terms of local thickness, principal curvatures, and the in-plane biaxial stress condition was used to define the tool contact pressure in the Nakajima tests and is taken into account in the necking limit based on a theoretical analysis of the effect of pressure on necking discussed by Stoughton and Yoon [4]. The procedure described in Min et al. [2] is shown to effectively remove the differences in the measurement of the forming limit curve obtained with three different tool geometries, resulting in a strain-based forming limit curve applicable to in-plane biaxial stretching under perfectly linear loading conditions in the absence of through-thickness pressure.

Another application of DIC technology, which is at the focus of this paper, is the precise determination of when localized necking initiates, i.e. to define what is referred to as the “onset of necking.”

2. Use of DIC Technology to Define the Onset of Necking

Many researchers have proposed DIC methods to define the onset of necking [5,6]. Most methods employ algorithms based on time and/or spacial variations of strain or strain-rate metrics. However, Martinez-Donaire [5] went a step further in arguing that their strain-rate-based space-time method was a good way to define the onset of necking by suggesting that the onset of necking occurs at a DIC frame image that is very close to but prior to the image when surface coordinate measurements begin to show clear evidence of the groove of a physical neck. While there is no question that many of these strain-rate-based space-time methods result in good estimates for the onset of necking for standard tests involving so-called “linear” strain paths, the reliability of these methods to obtain realistic measurement of limit strains for bilinear or more complex strain paths is questionable. Furthermore, since strains that occur in these experiments are a convolution of inhomogeneous straining induced by the geometry of the test (diffuse necking) and the inhomogeneous strain induced later in the process by localized through-thickness necking, it is possible that false signals of necking may be generated when using these strain metrics. A case in point is the fact that some metals stretched along strain paths close to equal biaxial conditions are observed to fracture without necking, yet generally involve significant inhomogeneous strain distributions caused by the tool geometry.

With the intention to avoid the challenge of de-convoluting the signal for the onset of localized necking from other causes of inhomogeneous strain using methods based on strain metrics, Min et al. [6] carried the direct observation of a visible neck further, setting aside strain data entirely and focusing on the geometry of surface coordinate measurements in search of a signal for onset of necking. However,
instead of looking for evidence of a groove in the section line that crosses the neck as reported by Martinez-Donaire, Min looked for evidence of necking in curvature fits to all the points along the line that would eventually be found at the bottom of the groove. In analysis of this data using a circle fit program, Min et al. reported observation of a distinct change in the curvature, which they interpreted to be the signal for the onset of necking. In the case of the Marciniak test, the signal appeared as a pulse in the nominally low curvature that was observed throughout most of the test. In the case of the Nakajima test, the signal appeared as a sudden drop in the high curvature that was observed throughout most of the test after the sheet came into contact with the punch. In both cases, the signal was interpreted to reflect how a neck initially forms and propagates into a well-defined groove. This causes a perturbation in the curvature calculation. It should be noted that the formation of this signal was not caused by an explicit change in the curvature, but rather was caused by a perturbation of a growing number of points used in the circle fit and their deviation from the curvature that existed prior to the start of the necking instability. In this case, because a large number of points were used to calculate the single value of curvature, the effect of measurement uncertainty of the individual surface coordinates was reduced. Dicecco et al. [7] also focused on the surface coordinate data using curvature analysis, but in this case performed a running curvature fit along a section perpendicular to the groove of the neck. In Nakajima tests, these fits result in a nominally uniform curvature across the section line prior to onset of necking with a radius of curvature equal to the sum of the punch radius and sheet thickness, and with a negative value representing the convexity of the surface of the sheet from the DIC camera perspective. As a neck forms, they observed the appearance and growth of a peak in the profile of the curvature fits such that local curvature increases to positive values in subsequent images up to the point of fracture of the specimen. These high local positive curvatures are caused by the concavity of the surface at the bottom of the groove of the neck. Their proposed method to define the onset of necking is the point in time when the curvature of this peak rises from its initial negative value and crosses to a positive value. While this appears to provide a robust solution, this signal clearly occurs at a specified time after the neck actually initiates, by an amount that depends on the magnitude of the negative curvature of the surrounding area, which in turn is nearly proportional to the punch radius.

While the method described by Min et al. [6] was found to be effective, further studies suggest it is challenging to ensure that all data points selected were located at the bottom of the groove. Variation in the selection of these points at varying offsets to the groove center was found to degrade the shape or magnitude of the curvature signal. While the method is currently undergoing further development to address this limitation, a simultaneous effort was inspired by Dicecco’s work to improve the signal detection for sections cut across the groove of the neck. The objective here was to minimize any test dependent artifacts in the neck detection algorithm. Consequently, a new algorithm has been developed and employed in the analysis of curvature fits along a section that crosses the neck. Furthermore, since this algorithm was developed to minimize dependency on the test method, it can be applied not only to traditional FLD tests using Nakajima and Marciniak tooling, but also to the analysis of hydraulic bulge tests, and more importantly, to uniaxial tension tests. The advantage of the latter application is that it opens the door to economical study and understanding of the anisotropy of onset of necking, which are prerequisites for developing and validating models to predict deformation limits of anisotropic metals.

3. Description of a New Curvature-Based Onset-of-Neck Detection Algorithm

The procedure used in the neck detection algorithm is first described schematically and then with greater detail in subsections 3.1 and 3.2. The first step is to identify the unique signature of the neck groove in the distribution of curvature of a section cut across the line of fracture in the DIC recorded image just before fracture. The signature of this groove is defined to be the observation of a peak in the curvature profile with a large positive value, which is interpreted to arise from the concavity of the section at the lowest point in the groove. On either side of this low point, there are peaks of negative curvature, smaller in magnitude, which are interpreted to arise from the convexity of the section on the two shoulders of the groove. The appearance of this signature is a necessary condition to establish the existence of the groove. However as noted by Min et al. [6], this is not always observed, for example in the equal biaxial
tension condition where fracture without necking occurs in some metals. However, detected the existence of a neck is only the first step in the determination of its onset.

Having established the existence of the neck, which defines both its location and provides a measure of the peak curvature of the neck in the last image before fracture, the neck detection algorithm then goes back in time, frame by frame, and analyzes the curvature distribution in each frame using a ratio of two metrics. The numerator of this ratio is equal to the magnitude of the curvature of the surface in the current frame at the material point of the peak curvature in the last frame. The denominator of this ratio is the root mean square (RMS) of the measured curvatures along the entire section in the current frame. The RMS is interpreted to be the noise level or measurement uncertainty of the curvature calculation. Ideally, the RMS should exclude all curvatures in the area identified to be on or between the shoulders of the groove in the last frame; but since the definition for the onset of necking is based on the disappearance of any evidence of this groove to the level of this “noise,” it does not matter if the area that later forms the groove is included in the calculation of the RMS.

![Figure 1](image.png)

Looking back in time from the last frame before fracture, the onset of necking is defined to occur in the first frame where the magnitude of curvature at the material point falls below the RMS of curvatures calculated in that frame, i.e., where the ratio falls below the value of 1. Note that if the calculated curvatures are distributed normally, there is a 32% chance that the curvature at the point necking could be higher than the RMS value. In other words, there is a 32% chance that even though the ratio is larger than 1, a neck need not have formed, or at least not detectable with more than a 68% confidence level. Since the definition of the onset of necking is equivalent to the interpretation that there is a 0% chance of exceeding the RMS value to qualify as part of the normal population, this definition has a bit of a built-in conservative assumption.
3.1. Reference Frame

Fig 1 shows the profile of the selected section along a uniaxial test specimen for a 1.3 mm thick DP 590 steel from the first image to the last image up to fracture. The selected points are chosen with a minimum spacing of 0.5 mm and span a distance of at least 10 mm on either side of the location where fracture occurs. The display of section for each subsequent frame in this figure cycles through a series of 6 colors resulting in what appears to be a series of rainbow-like patterns as the surface of the specimen moves away from the camera to a final displacement ranging from 100 to 200 microns, which is caused by thinning as the specimen stretches. The heavy black line shows the profile at the section of the surface at maximum load, which as expected, shows no sign of localization. The heavy red line shows the profile of the section at what will later be identified to be the onset of necking. While the red line shows a clear sign of localization, this is attributed entirely to the result of inhomogeneous thinning arising from the diffuse neck. What is interesting about the subsequent sections is that the surface profile in the last image before fracture shows the development of a very strong localization. While the data may at first lead one to view this as an additional localization that spans 10 mm, the correct interpretation is that what is seen in the images after localized necking initiates is a convolution of continuation of the effects of diffuse necking and the effects of localized necking, the latter of which spans a scale on the order of 2-3 times the sheet thickness.

![Figure 2. Surface displacement (mm) relative to surface at onset of diffuse necking (Frame 785) for test shown in Fig 1.](image)

Although it is not essential for this analysis to deconvolute the diffuse and localize necking signatures, it is helpful to remove contributions from paint thickness variation, camera alignment or surface rotation effects, as well as removing most of test geometry effects by measuring displacements of material points relative to a reference frame, and then plotting the displacement of these material points in the direction normal to the reference surface as a function of position along the length of the section in the reference image. This definition not only removes that contribution from the non-uniformity of the paint texture, but also removes most of the background curvature associated with the
test geometry, such as the large background curvature associated with the Nakajima test. The only requirement is that the selected reference frame must occur before onset of localized necking. In the case of the uniaxial tension test, this is most simply defined as the frame at maximum load. For that case, the relative surface displacements for the data shown in Fig 1 are shown in Fig 2.

3.2. Curvature Fitting and Detection of Onset of Localized Necking

The next step to define the onset of localized necking is to define the curvature along the sections for each frame shown in Fig 2. This is done by selecting a number of consecutive points from the left edge of the section covering a distance of 1.5 times the sheet thickness. These points are then used to fit a quadratic polynomial using the standard formula for curvature at the center of the selected group of points. This curvature fit is then repeated point by point, moving from left to right through the data shown in Fig 2, adding the next point on the right and removing the first point in the previous fit on the left, in order to obtain a distribution of local curvature across the section for the frame. These results for the last frame (Frame 1405) are shown by the black curve in Fig 3 and for previous frames at intervals of approximately 30 frame increments, shown in other colors, down to the frame at which the onset of localized necking is defined to occur (Frame 1287).

![Figure 3. Fitted curvature distribution (1/mm) for selected sections shown in Fig 2. See text for a description of how this information is used to define the onset of localized necking.](image)

While other frames between Frame 1287 and Frame 1405 are not shown in Fig 3 for clarity, they are consistent with the information provided in Fig 3. The magnitude of curvature at the material point located at the center of the section (where fracture occurs) in every frame after Frame 1287 is greater than the RMS of the calculated curvatures in that frame. Indeed, looking at the distribution of curvatures at Frame 1287 represented by the heavy red line, it is hard to argue that there is any evidence that this is the point when and where localized necking occurs. Yet 30 frames later, as seen in the blue line for
Frame 1317, there is evidence of the appearance of a curvature peak with a half width of about 2 mm, on the order of scale expected for the through thickness neck for 1.3 mm sheet.

4. Discussion
The method described here has been successfully applied to analysis of traditional FLD tests, bulge tests and uniaxial tension tests. Although the detection of a signal associated with the geometry of a physical groove is compelling evidence that the detection algorithm is an effective method for localized neck detection, the uniaxial tension test provides another piece of evidence that this onset of necking determination is realistic. It is well known that localized necking occurs at a point well past the maximum load of the engineering stress-strain relation.

![Figure 4. Engineering Stress vs Engineering Strain for DP 590 Steel shows the point at which the onset of necking occurs.](image)
As shown in Fig 4, the onset of necking is found to occur well down the load curve, but at a point consistent with expectations. It is also interesting to note that the DIC strain measurements show a linear strain path up to a much lower strain, which can be interpreted to occur with a change in stress condition from uniaxial stress, which is expected eventually to become significant.

Although further studies of the sensitivity of this determination of onset of necking are ongoing, it was found that no difference in detection of onset of necking (i.e. in the frame identified at which onset occurs) if the density of points (point spacing) was reduced from 0.5 mm to 0.25 mm, or reduced again to 0.125 mm, as long as the number of points in the local curvature fit was increased so that the span of the fit covered the same distance of 1.5 times the sheet thickness. Although small differences in identifying the frame at onset occurred if the number of points used in the curvature fit was held fixed while the density of points was increased these analyses resulted in an unrealistically higher frequency component in the curvature profiles that was very sensitive to measurement uncertainties, and in all cases only shifted the result by 1-3 frames.

Finally, the determination of onset of necking by this method is found to be independent of the selection of the reference frame as long as the reference frame is selected at a frame prior to the onset of necking. This obvious requirement is most conveniently guaranteed in uniaxial tension tests by selecting the frame at maximum load, but can be guaranteed in general based on selecting a frame where the strain level is at a value that is known to be below the localized necking limit. Alternatively, the reference frame can be determined empirically by successively moving the reference frame earlier and earlier until the defined frame on the onset of necking is found to be repeatable. Although there would be a higher influence of paint texture and test geometry effects that would require accounting in the signal for defining the onset of localized necking, another alternative is to not use a reference frame and calculate the surface curvature distributions from the raw data as shown in Fig 1. This choice would work well for uniaxial tension tests and Marciniak tests, but it could be difficult to define a physically meaningful RMS for Nakazima and bulge test without using a reference frame.

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