Determination of Forming Limit Diagrams of AA6013-T6 Aluminum Alloy Sheet using a Time and Position Dependent Localized Necking Criterion

S Dicecco1, C Butcher1, M Worswick1, E Boettcher2, E Chu3, C Shi4
1 Department of Mechanical and Mechatronics Engineering, University of Waterloo, Canada
2 Honda R&D Americas, Inc.
3 Alcoa Technical Centre
4 Promatek Research Centre

E-mail: sdicecco@uwaterloo.ca

Abstract. The forming limit behaviour of AA6013-T6 aluminium alloy sheet was characterized under isothermal conditions at room temperature (RT) and 250°C using limiting dome height (LDH) tests. Full field strain measurements were acquired throughout testing using in situ stereoscopic digital image correlation (DIC) techniques. Limit strain data was generated from the resulting full field strain measurements using two localized necking criteria: ISO12004-2:2008 and a time and position dependent criterion, termed the “Necking Zone” (NZ) approach in this paper, introduced by Martínez-Donaire et al. (2014). The limit strains resulting from the two localization detection schemes were compared. It was found that the ISO and NZ limit strains at RT are similar on the draw-side of the FLD, while the NZ approach yields a biaxial major limit strain 14.8% greater than the ISO generated major limit strain. At 250°C, the NZ generated major limit strains are 31-34% greater than the ISO generated major limit strains for near uniaxial, plane strain and biaxial loading conditions, respectively. The significant variance in limit strains between the two methodologies at 250°C highlights the need for a validation study regarding warm FLC determination.

1. Introduction
Current legislative requirements introduced by the Obama administration require Corporate Average Fuel Economy (CAFE) of 54.5 mpg (4.3 litre/100 km) by the year 2025 [1]. To achieve this goal, high strength aluminum alloys, such as the 6xxx and 7xxx series alloys, are being aggressively pursued for vehicle light-weighting applications. These alloys are heat-treatable and achieve peak strength through a multi-step aging process. In the peak aged condition, known as the T6 temper, these alloys have specific strengths comparable to ultra-high strength steels, however, their room temperature formability is limited, making the production of complex components difficult. To mitigate these formability issues, the warm forming processing route has been suggested [2].

Warm forming is a processing route in which the sheet material is deformed at temperatures above 150°C, but below the recrystallization temperature of the alloy. In this temperature range, the ductility of aluminum alloys is greatly improved, while flow resistance generally decreases, which has prompted studies [2, 3] on the benefits of the warm forming processing route on aluminum sheet formability.
While warm forming offers formability improvements in aluminum alloys, the exact quantification of the improvements in formability is less clear, since universally accepted standards for the warm formability characterization of aluminum sheet alloys have yet to be established. As a result, forming limit curves (FLC) of the same alloy and processing route may differ based on the adopted FLC methodology.

The concept of an experimentally determined FLC was first investigated by Keeler & Backhofen [4]. In their work, parts were incrementally formed under different loading conditions. Prior to localization, principal strain pairs at eventual localization points were recorded as ‘safe’ strain points. After many tests, various principal strain pairs were plotted as a function of the strain state, leading to the first experimentally derived FLC. If strain pairs on a formed part are found to lie above the FLC, the part is said to have exceeded the ‘safe’ strain limits of the sheet in that region. The FLD is useful for describing the formability of a sheet as a function of a processing route parameter, such as temperature. Decades after the work of Keeler & Backhofen [4], the FLC has seen wide acceptance within industry, although the methods for generating FLCs are not as widely accepted.

While the concept of an experimental FLC is useful, the testing procedures outlined by Keeler and Backhofen [4] were too resource intensive. Thus, practical standardized approaches have been developed over time for experimental FLC determination, such as ISO 12004-2:2008 [5]. The ISO approach was primarily developed for circle grid analysis of different limiting dome height (LDH) tests, where only the strain distribution of the dome post-failure is available. In the ISO approach, the post failure strain distribution of a dome specimen and an idealized assumption of the parabolic strain distribution about the dome pole prior to localization are utilized to calculate ‘safe’ principal strains for the dome. This assumption is valid for symmetric strain distributions with a single neck, however, in applications where multiple necks, or peaks in the major strain distribution, are present, the ISO approach is thought to be overly conservative [6, 7]. Additionally, the ISO standard was developed for room temperature (RT) applications and may not be applicable to warm forming. Consequently, alternative approaches for developing experimental FLCs are still actively pursued in the literature. Nevertheless, the ISO standard has been significant in standardizing FLC generation in an approach that is simple to implement and automate.

With the widespread adoption of commercial digital image correlation (DIC) techniques [6, 8] a surge in the number of alternative FLC methodologies has been observed. Digital image correlation allows for the tracking of the time-spatial evolution of dome strain distribution and dome topology over the duration of an LDH test. Thus, new FLC techniques have no longer been restricted to post-failure dome analysis. Some prominent DIC-based FLC techniques involve the work of Eberle et al. [9] and Li et al. [10], both of which are time-dependent methods that examine changes in the evolution of the major strain at the peak strain location over the duration of the dome test. Other FLC techniques include the work of Wang et al. [8] and Martinez-Donaire et al. [6], which are based on dome topology evolution and strain rate evolution, respectively, and are classified as both time and position dependent methodologies. The time and position dependent methodologies of Wang [8] and Martinez-Donaire [6] are developed based on the physical behaviour of sheet metals during the localization process. Therefore, these methodologies should be independent of temperature and strain rate effects and may potentially be applicable to warm forming FLC development.

In the current work, two different FLC methodologies are considered to generate an elevated temperature forming limit diagram for the sheet aluminum alloy AA6013-T6. The purpose of this work is twofold. First, the applicability of the ISO12004-2:2008 standard and the time-position dependent methodology of Martinez-Donaire et al. [6] are investigated with respect to warm formability characterization. Second, both methodologies are applied to the AA6013-T6 alloy to quantify the formability of the alloy in the warm forming processing route. Experimental procedures, DIC techniques, and FLC approaches are discussed in detail. Analysis between the two FLC methodologies is primarily comparative in nature, with validation work proposed for future study.
2. Necking Criteria

Necking criteria, or ‘safe’ limit strain criteria, encompass the various methodologies used for generating forming limit curves. Here, a brief discussion on the background, implementation, and automation of the two necking criteria that will be used to generate FLCs is presented: (a) ISO 12004-2:2008 and (b) the time-position method proposed by Martínez-Donaire et al. [6]. The ISO method was selected for its prominence in industry, while the time-position dependent approach was selected for its strong physical basis. As previously mentioned, both approaches have been automated for this study in an effort to reduce user subjectivity. To the knowledge of the authors, (b) has not been applied to warm forming applications. Other methods of FLC determination, such as those proposed by Eberle et al. [9] and Li et al. [10], are not considered in the current work but may also be suitable for warm FLC determination and are planned for implementation in a comprehensive future warm FLC determination study.

2.1. FLC Method 1 - ISO12004-2:2008 [5]

The FLC identification algorithm in ISO12004-2:2008 (hereafter, referred to as the ISO method) is well documented in the literature and within the standard so only a brief discussion of the method is presented here. Using the ISO method, the strain distribution perpendicular to the crack location of a failed dome specimen is extracted. This will be referred to as ‘line slice data’ for the remainder of this study. Line slice data can be extracted using DIC post-processing techniques or from circle grid analysis although only DIC measurements were used in this study. A DIC extracted line slice consists of a set number of points along the line where the major and minor strain data and deformation data are known at each location. For the ISO method, line slice data from multiple line slices are extracted from the DIC image before the onset of visible cracking, shown in Figure 1.

![Figure 1: Major strain distribution of an AA6013-T6 plane strain dome geometry one image before the onset of cracking (left) and the procedure used for extracting strain information (right) [5]](image-url)

With the extracted strain distribution, the peak major strain ($\epsilon_1$) location should be extracted. A fitting window is then established based on the peak strain location. This window typically omits $\pm 4\ mm$ from the failure location, and is meant to encompass the inflection points in the $\epsilon_1$ strain distribution. Strain data within the fitting window is then used to fit an inverse parabola, with the peak of the parabola generally coinciding with the location of the $\epsilon_1$ failure strain, as shown in Figure 2. The ‘safe’ strain limits for FLC generation are subsequently obtained from the inverse parabola fit.

The ISO method is frequently used in industry due to its ease of automation, and its ability to be used with both DIC and circle grid strain acquisition techniques. Furthermore, the method is relatively straightforward. Potential weaknesses of the method centre on the assumption of the inverse parabolic fit. If there is significant asymmetry in the $\epsilon_1$ distribution, for example, such as from multiple peaks, a poor or ill conditioned parabolic fit will result, which, in turn, can affect the calculated ‘safe’ strain values [6, 7].
Method 2 - Necking Zone Approach [6]

The so-called Necking Zone (NZ) approach was proposed by Martínez-Donaire et al. [6] where they discuss the $\epsilon_1$ (or $\epsilon_3$) strain rate evolution at different locations on the surface of the dome. The motivation for the NZ method is that the local strain rate at the centre of the localization zone should continually increase until fracture. Outside of the localization region, the strain rates should begin to decrease as the material begins to unload as deformation concentrates within the neck. An example of this behaviour is shown in Figure 3. In the NZ method, the detection of a decreasing strain rate at the boundary of the neck indicates that the forming limit has been reached and the strains at the centre of the neck are assumed to be the limit strains for the time at which a decreasing strain rate is detected.

The Necking Zone approach is attractive in that it is was developed from physical observations of localization and failure. Furthermore, the NZ approach requires no extra processing within the digital IDDRG2016 conference on "Challenges in Forming High-Strength sheets" IOP Publishing IOP Conf. Series: Materials Science and Engineering 159 (2016) 012009 doi:10.1088/1757-899X/159/1/012009
image correlation software relative to the ISO approach, since the same line slice data can be used for calculating strain rates (\(\varepsilon_1\) or \(\varepsilon_3\)). However, there are some challenges with the NZ method that introduce subjectivity and hinder its automation compared to the ISO method which has a well-documented implementation. First, smoothing of the DIC strain rate data is required. This smoothing is sensitive to the operator and smoothing algorithm. The second issue lies in the determination of the location for observing strain rates outside of the localization region, since there are many points where an ‘unloading’ in strain rate can occur (Figure 4), most of which can result in slightly different unloading times. This variation can also lead to differences in FLC curves based on user application. Finally, the NZ approach can be applied to each side of the crack location, which, in turn, results in the determination of two unloading times.

![Figure 4: \(\varepsilon_3\) strain rates for different locations along the length of a 250°C plane strain specimen](image)

For the NZ approach used in this work, \(\varepsilon_3\) strain rates were calculated for all spatial points ± 10 mm away from the location of the minimum \(\varepsilon_3\) strain in the image before visible cracking. In this work, the term ‘spatial point’ refers to a point taken along the previously described ‘line slice’. The ± 10 mm range corresponds to five times the thickness of the sheet material. The average spacing between points ranged from 0.05 mm to 0.10 mm. For each spatial point, the strain rate time history is searched for a point where the strain rate increases to a maximum value before decreasing some time before the final processed DIC image, herein referred to as an ‘unloading’ point. The first spatial point that contains unloading is marked as the spatial start point (S1 in Figure 4). From the spatial start point, spatial points up to 2 mm (one sheet thickness) away from the spatial start point are searched for unloading times in their strain rate histories (S8 in Figure 4). All unloading times are recorded and the median of all recorded times is considered to be the unloading time for ‘safe’ strain calculation (Figure 4). This process is completed for each side of the neck. The average of the two principal strain pairs is taken as the ‘safe’ strain set for the test.

The influence of the searching width on either side of the neck from first unloading, one sheet thickness (2 mm) in this instance, can have a large impact on the resulting safe strains and requires validation through future study. Although a fixed width is used in the current work, a more appropriate search width may also consider the stress state and hardening behaviour of the alloy.

3. Experimental Procedures

In this section, a brief description of the limiting dome height testing parameters is provided. This includes, but is not limited to, sheet material properties and geometries, lubrication conditions, and forming parameters. The image acquisition equipment and procedures are also described, as well as the corresponding DIC analysis parameters.
3.1. Limiting Dome Height Testing

The material used for testing in this work was 2.0 mm gauge sheet aluminium alloy AA6013 in the T6 temper provided by Alcoa. The T6 temper is considered to be fully age hardened by Alcoa [11]. The sheet is specified to have a nominal yield strength of 317 MPa, a nominal ultimate tensile strength of 379 MPa, and a total elongation of approximately 8% [11]. All specimens were machined lengthwise parallel to the rolling direction of the sheet.

Three geometries were machined from the sheet with approximate stress states of uniaxial tension, plane strain, and balanced biaxial loading. These geometries are discussed in the ISO12004-2:2008 standard for Nakazima LDH testing. The first two geometries are similar in shape to the specimen depicted in *Figure 1*, with reduced width sections of 25.4 mm and 76.2 mm, respectively. The balanced biaxial specimen is a 200 mm by 200 mm square blank.

Prior to testing, a random black and white speckle pattern was applied using aerosol based paint to the center regions of all blanks, on the side of the blanks not in contact with the punch. The speckle pattern was used to enable DIC analysis. *Figure 5* shows a typical speckle pattern with an artificially increased contrast to highlight the speckle pattern. It is important to note that the samples were cleaned with acetone and dried with compressed air before speckling, to promote good adhesion between the speckle paint and the samples.

![Figure 5: Random speckle pattern distribution](image)

Isothermal testing was completed at RT and 250°C. During testing, a flat die set was used with a clamping load ranging from 300 kN to 600 kN. The variation in loading served only to mitigate material draw-in. In warm forming, the blank was uniformly heated to the desired test temperature within tooling that had embedded cartridge heaters, ceramic insulation, and PID control, as shown in *Figure 6*. Given PID control associated with the heated tooling and insulation, the process is considered isothermal. To achieve a temperature within 2% of the target of 250°C, roughly 200 seconds of blank heating was required from the time the cool blank was clamped by the warm tooling. With the current setup, it was possible to heat the blank for a significantly longer period of time to achieve exactly the desired temperature, however, the T6 temper condition of the alloy is sensitive to time at temperature and the authors wished to minimize the over-aging of the alloy.

The punch geometry used for LDH testing was a 100 mm diameter hemispherical (Nakazima) punch. Lubrication between the tooling and the blank consisted of different layers of Polytetrafluoroethylene (PTFE) for 250°C testing, and a combination of PTFE and Vaseline for room temperature testing. Using this lubrication scheme, failure was almost always found to coincide with the maximum dome height location. The punch was operated at a speed of 0.25 mm·s⁻¹.

3.2. Image Acquisition and Post-Processing

Two cameras were operated at 5 to 15 frames per second for stereoscopic image acquisition, which corresponds to 20.0 images·mm⁻¹ to 6.67 images·mm⁻¹ of punch displacement for a punch speed of 0.25 mm·s⁻¹. A single LED light source was used to illuminate the blanks during testing.
Image processing was completed using the Correlated Solutions software program Vic-3D. Relevant analysis parameters in Vic-3D 7 consist of: (a) step size, (b) subset size, and (c) strain filter. The subset size represents how the area of interest on the dome is discretized for analysis. Each subset must contain a sufficiently random paint speckle distribution. The step size corresponds to the number of pixels within a subset that are to be analysed for correlation purposes. If a step size of three is selected, every third pixel within the subset will be analysed. Finally, the strain filter is a type of smoothing operation applied to the raw strain distributions. In this study, the DIC processing parameters consisted of a step size of 5, a subset size ranging from 25 to 35, and a strain filter of 11. The resolution of each DIC image was approximately 0.09 mm/pixel.

Following processing, line slice data was extracted for the last 100 images before observations of cracking. Five line slices were extracted perpendicular to the crack location for each dome test. Each line slice was processed using the FLC methodologies outlined in Section 2.

Smoothing of the DIC data is generally necessary, as is often the case when computing time derivatives from experimental datasets. In this study, a simple and general two-stage smoothing process was employed within the Matlab software environment for calculating $\epsilon_3$ strain rates. First, a LOESS filter with a span of five data points was applied to the datasets to be smoothed. Following this, a quintic $b$-form smoothing spline was generated from the LOESS filtered datasets [12]. While it is beyond the scope of this work to discuss the $b$-form smoothing spline, it should be noted that this type of spline can essentially be thought of as a weighting ($p$) between a least squares polynomial approximation ($p \sim 0$) and a piece-wise cubic spline ($p \sim 1$). In this work the weighting (or smoothing parameter) of the spline was 0.5. A smoothing parameter of 0.5 was utilized for time sensitive data because it is inherently noisier, notably at warm forming temperatures where heat waves can cause minor fluctuations in the measured strain. Nevertheless, smoothing of the time series data was still relatively minor, as illustrated in Figure 7, where an example of the level of smoothing of two $\epsilon_3$-time datasets for different spatial locations on a dome is presented.

![Figure 7: Fitting example of a raw partial $\epsilon_3$-time series dataset for an AA6013-T6 plane strain LDH specimen at 250°C](image)

4. Experimental Results and Discussion

In this section, forming limit curves generated using the ISO approach and the NZ approach for AA6013-T6 at RT and 250°C are presented. Both localized necking detection schemes are compared based on the observed differences in FLCs.

Average limit strains and standard deviations from the LDH testing of the AA6013-T6 alloy for the two localization detection methodologies discussed in this study are included in Table 1. Standard
deviations greater than or equal to 0.02 are bolded for easier identification. These results were generated from five LDH tests per specimen geometry and temperature combination for all conditions, except for the room temperature biaxial and 250°C uniaxial tension datasets which were generated from only three tests, respectively. Five line slices were extracted from the DIC data of each test. The average strains to failure and standard deviations of each geometry and temperature combination were also extracted from the line slice data, and have been included in Table 1. These failure strains do not necessarily represent the fracture behaviour of the alloy and have only been included to provide guidance on the potential variation of each dataset. Limit strains from Table 1 are plotted to generate forming limit curves based on the two localization methodologies in Figure 8 for both room temperature testing and 250°C testing. All strain data reported in this section and the remainder of the study will be strictly true strains.

| Temp. | Specimen | ϵ1 Failure Strain | ϵ2 Failure Strain | ϵ1 ISO Strain | ϵ2 ISO Strain | ϵ1 NZ Strain | ϵ2 NZ Strain |
|-------|----------|-------------------|-------------------|---------------|---------------|---------------|---------------|
|       |          | Avg | Std  | Avg  | Std  | Avg  | Std  | Avg  | Std  | Avg  | Std  | Avg  | Std  | Avg  | Std  | Avg  | Std  |
| RT    | 25.4 mm  | 0.34 | 0.04 | -0.08 | 0.01 | 0.22 | 0.02 | -0.06 | 0.01 | 0.21 | 0.02 | -0.05 | 0.01 | 0.22 | 0.01 | -0.06 | 0.01 |
|       | 76.2 mm  | 0.27 | 0.01 | 0.02  | 0.00 | 0.16 | 0.01 | 0.02  | 0.00 | 0.16 | 0.00 | 0.02  | 0.00 | 0.17 | 0.01 | 0.03  | 0.01 |
|       | 200 mm   | 0.37 | 0.00 | 0.26  | 0.01 | 0.27 | 0.01 | 0.26  | 0.01 | 0.31 | 0.01 | 0.24  | 0.01 | 0.31 | 0.01 | 0.24  | 0.01 |
| 250°C | 25.4 mm  | 0.55 | 0.01 | -0.12 | 0.00 | 0.28 | 0.01 | -0.06 | 0.01 | 0.36 | 0.03 | -0.09 | 0.01 | 0.36 | 0.03 | -0.09 | 0.01 |
|       | 76.2 mm  | 0.46 | 0.02 | 0.01  | 0.00 | 0.20 | 0.01 | 0.02  | 0.00 | 0.25 | 0.01 | 0.02  | 0.00 | 0.25 | 0.01 | 0.02  | 0.00 |
|       | 200 mm   | 0.49 | 0.03 | 0.28  | 0.03 | 0.28 | 0.02 | 0.25  | 0.02 | 0.37 | 0.03 | 0.25  | 0.03 | 0.37 | 0.03 | 0.25  | 0.03 |

Figure 8: FLD of AA6013-T6 generated from LDH testing using ISO method and NZ method

In Figure 8, it can be seen how the two localization methodologies compare at RT and 250°C. At room temperature, it can be seen that the ISO and NZ methods produce similar limit strains for the uniaxial geometry, with major strain limits of 0.22 and 0.21, respectively. A similar trend is also observed for the room temperature plane strain testing. Conversely, in the biaxial regime, the ISO method predicts a significantly lower major limit strain (0.27) relative to the NZ method (0.31), while both methods produce standard deviations about the major biaxial limit strains of only 0.01.

At 250°C, the differences between the ISO and NZ method FLCs are profound relative to that observed for the RT FLCs. The major limit strains at 250°C for uniaxial tension, plane strain, and biaxial
loading are 0.28, 0.2, and 0.28 for the ISO approach and 0.37, 0.26, and 0.37 for the NZ approach. For the three geometries in the same previously stated order, the ISO 250°C limit strains correspond to increases of 26.7%, 20.6%, and 2.35% relative to the ISO RT limits, while the NZ 250°C limit strains correspond to increases of 76.8%, 56.7%, and 21.2% relative to the NZ RT limits.

On the draw side (negative minor strain) of Figure 8, it can be seen that both the ISO and NZ methods capture increases in formability at 250°C in the 6013-T6 sheet, however, the NZ method shows significantly better formability than the ISO method. While the accuracy of the NZ method in detecting the onset of localization at temperature cannot be confirmed until a validation study is complete, some guidance on the lower ISO limit strains is offered in Figure 9.

![Figure 9: Sample ISO12004-2:2008 inverse parabolic fitting process using an asymmetric $\epsilon_1$ distribution acquired from DIC dataset of a 250°C uniaxial tension dome specimen](image)

In Figure 9, an example of a measured $\epsilon_1$ strain distribution for a 25.4 mm Nakazima dome specimen tested at 250°C is presented. Note the asymmetry in the distribution and its effect on the parabolic fit. This asymmetry was frequently observed in uniaxial and plane strain specimens, despite attempts to improve lubrication conditions and achieve a central failure location. As seen in Figure 9, and previously discussed in Section 2, asymmetry in the strain distribution can cause an ill conditioned parabolic fit, which can subsequently lead to overly-conservative limit strain predictions. To illustrate the effect of strain distribution shape on the parabolic fit, a second parabolic fit, generated by mirroring the left of the distribution, is also shown in Figure 9. The second parabolic fit results in an increase in the major limit strain of approximately 0.06 strain, and has a peak which corresponds to the peak of the experimental strain distribution. Note that no recommendation is being made to mirror strain distributions in this manner. Instead, this mirrored fit is merely shown here to illustrate the dependency of the fit to the shape of the strain distribution. Furthermore, it is recognized that the ISO standard anticipates this issue by specifying that “good tests” must fail at the centre of the specimen, thereby avoiding this skewing effect, however, a central failure requires low friction conditions between the sheet and punch which is not always possible, particularly for warm forming conditions.

On the stretch side of Figure 8, a negligible increase in biaxial formability at 250°C relative to RT conditions is observed, as determined using the ISO method. This result is uncharacteristic of warm forming and does not coincide with the observed increases on the draw-side of the FLD. The reason for this behaviour may be the result of a poor inverse parabolic fit caused by asymmetry in the $\epsilon_1$ strain distributions in the elevated temperature biaxial specimens, although further investigation is required.
**Figure 10** shows sample strain paths extracted from the failure region of test specimens at RT and 250°C, as well as the ISO and NZ limit strains. It can be seen that the NZ limit strains generally closely follow their corresponding strain paths, as is expected for the NZ method. For the ISO method, the same is also true, except for the biaxial limit strains, which deviate significantly from their respective sample strain paths, notably at 250°C.

The observations made herein demonstrate that the NZ method, as implemented in this study, generally results in higher FLC values than those obtained when applying the ISO method to the asymmetric strain distributions obtained for the plane strain and draw specimens tested herein. On the stretch side of the FLD, it was found that the limit strains calculated using the ISO method deviate from the experimental strain path whereas the NZ method does not. The deviation in the strain path for the limit strains in the ISO method is related to its reconstruction of the strain distribution and its determination of the minor strain from the $\epsilon_3$ (thickness) and $\epsilon_1$ strain distributions. The limit strains in the NZ method lie on the experimental strain path because the limit strains are extracted directly from the DIC measurements. Nonetheless, further experiments and validation are required to identify the appropriate FLD detection algorithm for warm forming conditions.

5. **Conclusions**

The ISO method and NZ method show almost identical limit strains at RT for AA6013-T6 on the draw-side of the forming limit curve. On the stretch side of the RT FLC, the major limit strain using the current NZ method is 14.8% above the value calculated by applying the ISO method. At 250°C, the NZ method FLC lies anywhere from 31% to 34% above the FLC calculated by applying the ISO method to the measured (asymmetric) strain distributions. While neither approach has been validated at this point in time for warm forming applications, the summarized results highlight that different localization detection methodologies can yield very different warm forming limit strains. Therefore, it is paramount that a validation study be completed prior to the application of either approach to generating warm FLCs for industrial applications. A future validation study using the NZ approach, the ISO approach, the approach of Eberle et al. [9], and a topology based approach is planned.

The NZ limit strains fall closely onto corresponding sample strain paths at 250°C. Similarly, the ISO draw and plane strain limit strains fall onto corresponding strain paths, however, in the biaxial loading
condition, the ISO limit strains deviate from the biaxial strain path. The deviation of the ISO limit strains from the experimental strain path is an artefact of the algorithm in that it reconstructs the strain distributions. The drift in the ISO limit strains from the experimental strain paths under warm forming conditions may be related to the formation of asymmetric strain distributions as multiple localization zones can occur at elevated temperatures, however, further study is needed.

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