Advances in characterization of sheet metal forming limits

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Abstract. This paper accounts for nonlinear strain path, sheet curvature, and sheet-tool contact pressure to explain the differences in measured forming limit curves (FLCs) obtained by Marciniak and Nakajima Tests. While many engineers working in the sheet metal forming industry use the raw data from one or the other of these tests without consideration that they reflect the convolution of material properties with the complex processing conditions involved in these two tests, the method described in this paper has the objective to obtain a single FLC for onset of necking for perfectly linear strain paths in the absence of through-thickness pressure and restricted to purely in-plane stretching conditions, which is proposed to reflect a true material property. The validity of the result is checked using a more severe test in which the magnitude of the nonlinearity, curvature, and pressure are doubled those involved in the Nakajima Test.

1. Introduction

Although the limitations of the forming limit diagram (FLD) concerning the role of nonlinear strain paths on the onset of necking have been known nearly since its inception, and solutions to handle these limitations had been formulated in terms of limits on the effective plastic strain and equivalently by limits on the true stress, limited recognition of the importance of these limitations was acknowledged by industry until stress-based solutions were rediscovered and more recently promoted. While there exists many equivalent representations of the stress-based solution, supported by bifurcation theory and MK Analysis, a wide-spread misunderstanding of forming limits persists as is evident in the continued ineffective use of the conventional strain-based FLD. This presentation will review the fundamental inadequacy of the strain-based FLD, in particular focusing on the inability to assess the severity of forming, i.e., the likelihood of exceeding the necking limits of the sheet material, which applies even in the forming conditions where the strain path is almost perfectly linear.

The primary contribution of this paper is to combine knowledge of the effects of 1) nonlinear strain paths, 2) sheet curvature, and 3) tool contact pressure, to explain the differences in measured forming limits obtained by Marciniak and Nakajima Tests, and define the forming limit for the onset of necking under conditions of perfectly linear in-plane stretching in the absence of a through-thickness pressure. The validity of the interpretation of the resulting FLC as a material property is demonstrated by applying the same corrections to data obtained from a 50 mm diameter punch, which doubles the magnitude of the nonlinearity, curvature, and pressure that is involved in the conventional Nakajima Test.

2. FLC Correction Procedure

In order to employ this procedure it is assumed that the history of both the strain and surface coordinates at the location of neck is recorded using Digital Image Correlation (DIC) methods. It is also assumed

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that the frame rate if the DIC camera system is sufficient to capture an image within a negligible strain difference from those at which onset of necking occurs. And finally, it is assumed that a method is employed to detect the true onset of necking from analysis of the strain and/or geometry data. The method adopted for this study is based on detecting a curvature change in the area of the neck, obtained by fits to the surface coordinates [1].

While the corrections employed here depend on the material model, this often-cited criticism of the stress-based approach to dealing with strain path nonlinearity is a red herring since the primary application of the FLC is in the analysis of FEM simulations, which necessarily is based on a specific material model to simulate the deformation of the metal. So the least of all concerns is the use of the material model to account for experimental processing effects on the measurement of the FLC. However, there should be no question that in both the use of the FLC and in its experimental determination, one should always use the most reliable available material model for the material in question, and that means using an advanced material model that is calibrated to uniaxial and bulge test data, even including tension-compression tests to account for kinematic effects, when these are important to the forming processes that require analysis. More details of this method can be found in the literature [2].

2.1. Correction for Nonlinear Strain Path Effect

The procedure for correcting the FLC for nonlinear strain path is most easily described and implemented in a general way in terms of the same UMAT function that is used in the FEM code. But here, instead of applying to UMAT to calculate the increments of the stress tensor and effective plastic strain for a given increment of the total strain tensor *defined by the simulation*, we use the experimental strain tensor history from the DIC strain measurements up to the onset of necking to calculate the experimental increments to the total strain tensor as input to the same calibrated UMAT. It is important to note that this procedure requires care to correctly translate these experimental DIC strain tensors into the material coordinate system in which the material model parameters are defined, to correctly utilize the features of this UMAT solution. This procedure is represented by the following two simple equations,

$$\left(\delta\vec{\sigma}(t), \delta\bar{\epsilon}_p(t)\right) = UMAT\left(\vec{\sigma}(t), \bar{\epsilon}_p(t), \delta\vec{\varepsilon}(t), MP\right) \tag{1}$$

$$\left(\vec{\sigma}(t+\delta t), \bar{\epsilon}_p(t+\delta t)\right) = \left(\vec{\sigma}(t), \bar{\epsilon}_p(t)\right) + \left(\delta\vec{\sigma}(t), \delta\bar{\epsilon}_p(t)\right), \tag{2}$$

where $\vec{\sigma}(t)$ and $\bar{\epsilon}_p(t)$ are the stress tensor and effective plastic strain at time t in the DIC record, both initialized to zero, $\vec{\sigma}(0) = 0$, and $\bar{\epsilon}_p(0) = 0$, the δ in front of these two variables represents their calculated increments obtained from the UMAT function in Eq. 1 and integrated in Eq. 2, $\delta\vec{\varepsilon}(t)$ represents the increment of the total strain at time t obtained the DIC record, and MP represents the set of Model Parameters for the selected material model. If a kinematic hardening model is used, the required back stress tensor values will also be input to the UMAT and their increments returned and integrated along with the stress tensor components and effective plastic strain. The final result of the integration for a given strain path up to the onset of necking is the stress tensor and effective plastic strain given by $\left(\vec{\sigma}, \bar{\epsilon}_p\right)_{onset}$.

2.2. Correction for the Sheet Curvature Effect

Sheet curvatures induce geometrically necessary strain gradients through the sheet thickness. Based on previous studies, onset of necking is suppressed until the conditions on every layer through the sheet thickness are able to participate in the formation of the neck geometry. This means that in the analysis of the conditions for onset of necking, the stress and strain conditions on every layer must be considered, so that the conditions on the least critical layer may be used to correctly define the FLC for in-plane stretching. Although the curvature of the sheet in the area of the neck in the Marciniak Test is small, the bending resistance of metals causes a slight crown on the surface, so that in principle, correction for the sheet curvature should be done for the Marciniak Test. However, in the case of the Nakajima Test, the curvature is dictated by the punch radius, so the strain differences between the top and bottom surface

for 1 mm sheet are on the order of 2% strain, which is more than 10% of the available ductility of some metals. These gradients are even higher for thicker gauges.

Fortunately, the DIC measurement system provides surface coordinates as well as the strains, which allow measurement of the principal curvatures (κ_1, κ_2) on the convex (Outer) surface along the directions of the principal strains, which then allows calculation of the sheet thickness and computation of the principal strains on any layer through the sheet thickness by geometric constraint. These calculations are done for the Middle and Inner surfaces and the strain paths on these layers are processed through the same procedure as applied for the Outer layer using Eqs. 1-2, after transforming these calculated principal strains back to the material coordinate system. Except for the consideration of the pressure effect, to be discussed next, one can then identify the critical layer for the determination of the onset of necking under conditions of purely in-plane deformation, by determination of the layer with the lowest value of effective plastic strain, i.e., the layer with the least amount of plastic work.

2.3. Correction for the Contact Pressure Effect

From the theoretical argument that hydrostatic pressure has no effect on the plasticity of pressure-insensitive metals, it is argued that through-thickness pressure delays onset of necking by increasing both components of the biaxial stress condition above those that apply in the absence of pressure. From equilibrium conditions, the pressure P on the contacting side of a doubly curved sheet characterized by principal curvatures (κ_1, κ_2) in balance with the stress in the plane of the sheet (σ_1, σ_2), is given by

$$P = \left(1 + \tfrac{1}{2}h\kappa_2\right)h\kappa_1\sigma_1 + \left(1 + \tfrac{1}{2}h\kappa_1\right)h\kappa_2\sigma_2, \tag{3}$$

Using this calculated pressure at the onset of necking, the biaxial stress components on the Inner layer is obtained by subtracting P from both stress components. This leads to a lower stress condition at the onset of necking for this layer and also a lower value of the effective plastic strain, which can be obtained by inverting the hardening law after computing the yield function at this lower stress state. The same correction is made for the Middle layer, but in this case $P/2$ is subtracted from the integrated stress conditions on the Middle layer, resulting in a smaller reduction of the effective plastic strain. Then, the critical condition for onset of necking is determined by the layer with the smallest value of the pressure-corrected effective plastic strain.

3. Strain-based FLC

While the described procedure results in the correct definition of the general conditions for the onset of necking, $\left(\vec{\sigma}, \bar{\epsilon}_p\right)_{onset}$, it is critical that this limit criterion be restricted to use in applications with the same material model specifically defined and calibrated in the UMAT used in the processing of the FLD experiments. However, depending on the application, the engineer may prefer to use a different material model, and it would be a serious mistake to use these stress limits or effective plastic strain limits with a different material model. In order to mitigate the consequences of using a different material model, it is recommended to convert these stress and effective plastic strain limits into a limit on the plastic strain $\vec{\epsilon}_{\text{onset}}$ defined for linear stress path. The equation for this calculation is the plastic flow rule, whose explicit equations can be extracted directly from the UMAT code. If $\bar{\sigma}_p(\vec{\sigma}, MP)$ is the plastic potential function, then the plastic strain for a linear stress path ending at the critical stress $\vec{\sigma}_{onset}$ and critical effective plastic strain $\bar{\epsilon}_{p,onset}$ is given symbolically by the following simple formula,

$$\vec{\epsilon}_{onset} = \bar{\epsilon}_{p,onset} \frac{\partial \bar{\sigma}_p(\vec{\sigma}_{onset}, MP)}{\partial \vec{\sigma}}. \tag{4}$$

The net strain limits at the detected onset of necking involved in Marciniak (M), conventional Nakajima (N-4), and 50 mm Nakajima punch (N-2) tests on MP 980 steel without consideration of process effects are shown in Fig 1. It is obvious that these forming limits are test-dependent, and therefore do not represent a material property. The movement of the minimum of the FLC to positive minor strain that is observed in the conventional Nakajima Test (N-4), is significantly amplified in the N-2 test result, which shows that the forming limit is both translating to the right and moving upwards.

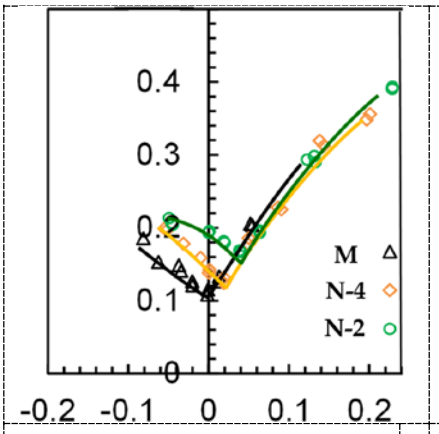


Fig 1. Onset of necking limits for MP 980 steel.

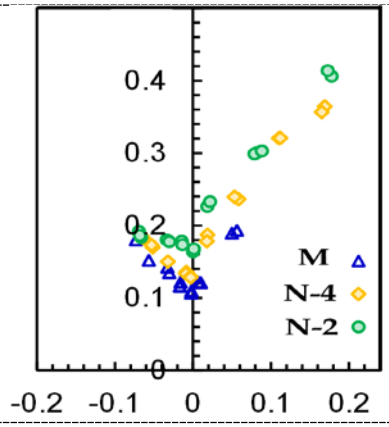


Fig 2. Correction of limits for curvature and nonlinear path.

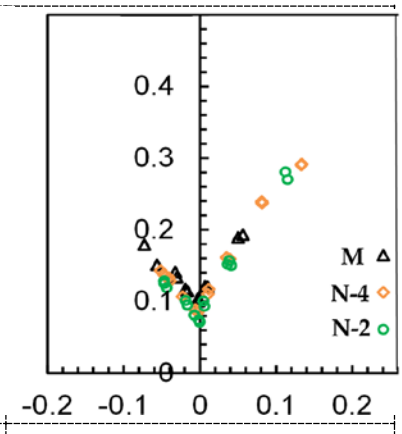


Fig 3. Additional correction for contact pressure effects.

Fig 2 shows the result of correcting for curvature and nonlinear strain path using a simple in-plane isotropic version of Hill 1948 yield function. While the result of the corrections for the N-4 test are similar to the M test, they are still systematically higher than the M test results. The non-convergence is even clearer in comparison with the same corrections for the N-2 test, which are higher still. Fig 3 shows the results of correcting for the contact pressure effects on the Inner and Middle layers of the N-2 and N-4 tests, based on an isotropic hardening law that is obtained by fitting to the experimental data. With these corrections, the forming limits obtained from the M, N-4, and N-2 tests are very close and show the same characteristic slopes on both sides of the FLD.

4. Discussion and Conclusions

Closer inspection of Fig 3 shows that the Nakajima tests are slightly but systematically below the FLC obtained from the Marciniak Test on the left hand side of the FLD. This bias can be attributed to the use of the isotropic hardening model, which leads to an over estimation of the stress and therefore the pressure corrections, particularly on the left hand side of the FLD where the strain path change is largest and the kinematic hardening effects would be expected to be largest. While such an explanation should be investigated and validated using more realistic hardening models, a key conclusion of this study is documenting the importance and role of contact pressure in the Nakajima test. This also leads to the conclusion that unless one has a fully calibrated kinematic hardening model, one should not expect to remove all the process-dependent effects in FLC data obtained from the Nakajima test. That leads to the conclusion that FLC's from the Marciniak Test are more realistic. The final conclusion is based on the observation that the very small differences in the deformation conditions involved in these tests lead to significant variations in limit strains as shown in Fig 1, which emphasizes the importance of accounting for these processes effects in the application of the FLD. As impressive as the fact that one can correct for these differences in measurement of the FLC by applying science to determine a process independent forming limit as shown in Fig 3, the benefits of utilizing this knowledge to determine formability in applications, where the complexity of strain path, the magnitude of curvature, and the contact pressure effects are orders of magnitude larger than these tests, are comparatively orders of magnitude higher.

References

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