Determining a threshold Strain Nonuniformity Index (SNI) to predict failure in sheet metal components

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Abstract. The Strain Nonuniformity Index (SNI) was introduced as a strain distribution based failure criterion about 10 years ago and its application to prediction of failure in industrial sheet metal components was demonstrated in the previous Conferences. Quantitatively, the SNI represents the rate of change of spatial strain gradient. This means that higher the SNI, sharper the neck, and hence greater is the likelihood of failure. It is immaterial as to how the neck / strain gradient came into existence, and failure is linked with the threshold value of this quantity, beyond which failure could be expected. Since phenomenological parameters are not linked with the process of establishing a threshold SNI, it does not seriously matter whether it was aluminium that was formed or whether it was steel, it does not very much matter if it was hot forming or cold forming. The present paper describes the methodology of estimating the threshold SNI for each of the numerous critical planes in the deforming sheet metal component. Interestingly, the relationship between SNI of major strain and SNI of the thickness strain was found to lie in a narrow band for a diverse set of materials. This therefore helps in finding the critical planes on which the SNI at a given punch travel has crossed the threshold value and failure locations so determined have correlated well with the shopfloor predictions as presented earlier.

1. Introduction

Forming Limit Diagrams (FLDs) suffer from several drawbacks including their sensitivity to strain path. It is often seen that along one strain path failure is observed below the FLD and along another strain path the part is safe despite the strains exceeding the limit strains indicated by the FLDs. As a result, FLSDs were developed to overcome this limitation. Earlier efforts to overcome this limitation involved strain distribution based quantities being defined to predict imminent failure [1,2]. Process signatures [1] were found to be stable unless there was a significant change in forming conditions like change in tool setting, tool wear etc. Melander et al [2] used the strain distributions from various materials to draw inferences from the strain distribution.

A recent development, namely, the strain non-uniformity index (SNI) is a quantitative measure of the degree of non-uniformity of spatial strain distribution [3]. The major advantage of this method is that a user can define his/her own SNI as a failure criterion. In other words, SNI at necking or failure alone need not constitute a failure criterion. SNI at which the non-uniformity of strain in the product crosses the criterion for acceptance of the part can be the failure criterion. Hence, with SNI, a user...
defined failure criterion is easily possible and practicable. However, the present paper is about determining a threshold (or limiting) value of SNI beyond which failure may be indicated.

Here the degree of non-uniformity of the strain distribution on a number of planes of interest passing through (a) major strain peak (b) least deformed region, i.e., the one with minimum value of major strain (called ‘pole’) and (c) the direction of forming, is quantified as the SNI for each of the planes. It is possible to have a multiplicity of major strain peaks, and multiple poles, thereby generating a number of planes of interest, called ‘critical planes’. A strain peak is identified as the one having the maximum major strain in the component and several of those with similar major strain (within the limits of a set tolerance value on either side of the peak strain) are identified as strain peaks. Similar is the case with the identification of the ‘poles’, wherein multiple poles are identified within set limits of tolerance on either side of the minimum major strain. Average strain is the hypothetical value of the strain if the spatial strain distribution in that plane were absolutely uniform.

The strain nonuniformity index (SNI) then is simply the difference between the peak strain and the average strain [1]. The terminology has been illustrated in Figure 1. Mathematically, the SNI for a plane defines the rate of change of strain gradient in that plane, and hence the curvature of the strain peak in that plane. This may be inferred by representing the spatial strain distribution as a Fourier series,

\[ \varepsilon = \sum_{n=1}^{m} \left[ a_n \cos(n\pi x/L) + b_n \sin(n\pi x/L) \right] \tag{1} \]

where \( \varepsilon \) could be \( \varepsilon_1 \) or \( \varepsilon_3 \); ‘x’ refers to a position in the critical plane from one end of the section to the other along the deformed sheet. L refers to the end to end span of the deformed sheet along the section of the part taken by a ‘critical plane’.

Greater the SNI, sharper is the strain peak. Sharper the peak, greater is its curvature. What threshold SNI seeks is to obtain the curvature of the strain peak at failure. Curvature of the strain peak exceeding this threshold would indicate failure. It is noteworthy that the SNI based methodology is a means of interpreting the strain distribution over the entire component. Therefore, how the strain distribution was produced (by cold forming, hot forming, stretching, drawing, hydroforming etc) is immaterial.

Processes leading to small extent of non-uniformity in spatial strain distribution(lower curvature of strain peaks) and hence a small SNI can deform the same sheet metal to much greater strains. For instance, the SNI for a part deformed by hydroforming would be much smaller than that deformed by conventional die-punch methods on account of a more uniform strain distribution obtained in hydroforming. The SNI will stay well below the limiting curvature of the strain distribution permitting greater deformation.

Whether the part will fail depends upon whether the SNI associated with any of the critical planes has crossed the ‘threshold SNI’. This means that failure may occur only when the degree of non-uniformity of strain distribution exceeds a threshold value. Each critical plane has a threshold SNI of its own. This is why, in the SNI based procedure of predicting failure, strain path effects need not be explicitly taken into account as the given state of the part (safe or failed), the state of strain and the given strain distribution is the final outcome of the effect of strain history and hence the strain path.

One does not have a single threshold SNI for the entire component since every point on the surface of the sheet experiences a different strain path. It is therefore natural for the threshold SNI for a given plane to change during the forming process. The continuous evolution of the non-uniformity in strain distribution is not captured by any of the other prevailing measures of formability. Studies on the SNI behaviour for different geometries are available in the literature [4,5] and the application of SNI in process design involving multistage drawing operations is illustrated in [6].

Application of this concept in the Automotive industry towards identifying the occurrence and location of failure in sheet metal parts has been demonstrated earlier for complex industrial parts and the prediction using the SNI was found to correlate very well with the shopfloor experience [7-9].
The present work describes the procedure to establish a threshold SNI, which is used as a yardstick to say if failure is likely or not. This is based on an extensive experimental programme wherein Nakazima tests were performed on different grades and thicknesses of ferrous and non-ferrous materials.

It is important to use a consistent method of measuring the strains. For instance, SNI threshold established using a DIC technique or automated systems like the GOM and the VIALUX cannot be used with the strain distribution obtained using, say, the circle grid analysis technique. This is because of different levels of accuracy of measurement obtainable by different techniques, and different capabilities of capturing the strain gradient.

**Figure 1.** Terminology for determining the SNI [3].

**Figure 2.** The concept of numerous critical planes. Each plane will have the strain distribution with features shown in Figure 1 [4].
FEM simulation results may be used, wherein the nodal coordinates and the nodal strain components for all the nodes in the component can be exported for further analysis. In the present work AUTOFORM software was used for all simulations, since it is possible to obtain the strain data for all the elements in one go.

2. Experimental procedures

Sheets of various grades (steel grades, as well as aluminium alloy) were tested for formability using a standard Nakazima test. The experimental data was based on the strain distribution taken along the longitudinal meridian of the blank. Twenty one different materials (one material-sheet thickness combination is treated as a separate material) were tested and two sets of Nakazima tests were performed on each of the materials.

Further, square cup tests were performed on each of the materials, and the strain distributions along two diagonals (of the square bottom) from one end of the flange to the other, were measured. Further, strain distributions from tensile samples at 0, 45 and 90 degrees to the rolling direction (3 samples per direction, for 21 materials) were used to determine the SNI in each of the tensile samples. AUTOFORM simulations were also used to generate the strain distributions for about 40 industrial parts and the Nakazima samples. The SNI was determined for each set of the strain distribution obtained experimentally as well as those obtained analytically. For this study, the samples were deformed to visible localised necking.

The complete set of tested samples on which strain distribution was taken, are shown in Figure 2. In order to analyse the strain distribution from the AUTOFORM simulations, a computer code was developed so as to identify critical planes, determine the SNI on each of the critical planes (see Figure 1), and check if failure could be anticipated on the critical plane, and then show on the deformed geometry of the part where the failure could be expected. The latter part was possible only after comparing the SNI of a given critical plane with its threshold SNI, the topic of the present work.

In order to obtain the threshold SNI at failure, the relationship between the SNI of the major strain with that of the thickness strain at failure by visible localized necking was established for all test samples.

![Nakazima Test](image)

Figure 3. Nakazima samples tested from the 21 materials.
3. Results and Discussion

For each material, a relation between the SNI of major strain and the SNI of thickness strain was established based on observations of strain distributions from different samples. Further, it was found that the correlation was much better if the SNI of a strain distribution in a critical plane was normalised by the peak strain in that plane. Such curves for single materials are shown in Figure 4(a) and Figure 4(b). The outcome of the strain measurements, therefore, was in the form of a plot between the normalised SNI of major strain with the normalised SNI of the thickness strain. While one is interested in curbing the non-uniformity in the thickness strain distribution, it is the non-uniformity in the major strain that serves as a ‘driving force’ to create the nonuniformity in the thickness strain distribution.

Interestingly, it was possible to generalise this relationship for diverse kinds of materials and diverse testing conditions into a single trend represented by a single equation relating normalised SNI of the thickness strain with that of the major strain.

One can therefore use the SNI relation at failure, for a single material if the material is known (as in Fig. 4(a)) or the single equation as given below [4]:

\[
\text{SNI of Thickness strain} = 0.8371 \times (\text{SNI of Major Strain})^2 + 0.1232 \times (\text{SNI of Major Strain}) + 0.1679, \tag{2}
\]

for a material for which the relationship at failure under uniaxial and biaxial conditions is not established as yet.

This way, one can establish the threshold SNI of thickness strain once the SNI for the major strain is determined for that critical plane. Likewise each critical plane thus has its own degree of strain non-uniformity in the major strain distribution which would lead to a given magnitude of strain non-uniformity in the thickness strain.

A given strain non-uniformity in the major strain on different planes can therefore lead to different magnitudes of SNI of thickness strain depending on the minor strain variation along that plane. Minor strain on a plane is strongly influenced by the contact constraints (due to sheet-tool contact geometry) and those due to processing variables like blank holding force and frictional conditions. It is therefore logical that the SNI of the thickness strain would be much higher for a given value of the SNI of the major strain if plane strain has been reached, i.e., there has been negligible change in the minor strain. In contrast, when the minor strain is relatively large, a given SNI of the major strain might lead to a small SNI of the thickness strain. Such a situation may be visualised in the flange of the deep drawn cup wherein development of the minor strain suppresses enhancement in the SNI of the thickness strain, for a given SNI of the major strain.
Figure 4. Normalised SNI of the Major strain correlates well with that of the thickness strain for diverse materials, strain paths, part geometries and forming methods (a) Correlation for one sheet (b) Correlation for another material (c) correlation based on all 21 materials.

3.1. Effect of grid size
Since the sharpness of the strain peak is being discussed, it is important to consider the effect of grid size (closeness of the spacing of grid circles and grid circle diameter). Since both the SNI values (those of the major strain and the thickness strain) would be similarly influenced by the grid size, the relation between the two will remain unaffected by the grid spacing. It is known that the formability of sheet metal components is influenced by component size. That is, given a constant draw ratio, an increasing component size (and correspondingly increasing blank size) leads to different degrees of formability. Hence an empirical relation is obtained to compensate for effects of size and sheet thickness.

The effect of grid size was studied using square cups of different sizes drawn from sheets of different thicknesses, and different materials. Strains were measured using a grid of circles of 2mm diameter laser marked on the surface of each sheet. An equivalent grid size parameter, $GS_{eq}$, was formulated as

$$GS_{eq} = \frac{(\text{grid size})^2}{(\text{thickness} \times (\text{projected area})^{0.5})}$$  \hspace{1cm} (3)
This is because, the capability of an element to capture localized necking (where the width of the localized neck is nearly equal to the sheet thickness) would be influenced by the sheet thickness. Hence if one wanted to have a constant equivalent grid size, one could determine the actual size of the circle one might need to mark on the sheet using the equation 2.

![Graph](image_url)

**Figure 5.** SNI variation with equivalent grid size (a) TL1550Z (b) DC04 [5]

The correlation of the SNI so obtained, with this parameter, is shown in Figure 5 (a,b) in the context of two materials. Here the projected area is the area of the ‘bounding box’ of the part. Size effects (variation in formability depending on the size) of the formed part are known to influence...
strain gradients. Simply put, the strain distribution in a full sized sample would be different from that in a subsize sample of a given material and a given thickness [5].

It may be seen that the effect of equivalent grid size shows some variation for relatively small sizes, but diminishes for relatively larger effective grid sizes.

4. Conclusions
From the foregoing, it may be concluded that

a. The relation between the SNI of major strain and the SNI of thickness strain lies in a narrow band, for the 21 materials (material and sheet thickness combinations) studied.

b. The SNI for thickness strain increases with an increase in the SNI of the major strain. This depends upon the distribution of the minor strain. For instance, hypothetically, if major strain were to be uniform, the minor strain distribution will induce non-uniformities in the distribution of the thickness strain.

c. It is thus possible to estimate the threshold SNI and use it to predict occurrence and the location of failure, by comparing the actual SNI on a critical plane with the threshold value for that plane at any point in time during the deformation of the sheet.

d. The relation between the two SNIs would remain unaffected by grid size because both the quantities would get similarly influenced by the grid size. However, in general, it might be useful to select the right size of the circle to minimise errors of measurement.

The application of the method to identifying potential locations of failure in laboratory as well as industrial sheet metal parts have already been published in the references listed.

References
[1] Schedin E and Melander A, 1987 On the strain distribution during the stretch forming of low and high-strength sheet steels. J. of Mech. Working Tech., 15 pp 181–202.

[2] Karima, Chandrasekaran N, and Tse W, 1989 Process signatures in metal stamping: basic concepts. J. Mater. Shaping Technol. 7 pp 169–183

[3] Desai S G and Date P P 2006 On the quantification of strain distribution in drawn sheet metal products J Mater Processing Technol 177 439

[4] Jadhav S, Tekale, R R and Date, P P 2016 Analysis of Strain Non-Uniformity Index (SNI) for different geometries of drawn sheet metal parts, Proc. Int. Conf. Numerical Modelling Sheet Forming Processes (NUMISHEET2016) September 4-9 2016 Bristol UK

[5] Date P P 2014 Effect of mesh size on the calculation of the strain nonuniformity index in drawn sheet metal parts Proc Int Conf Tech of Plasticity (ICTP2014) October 19-24 2014 Nagoya Congress Centre Nagoya Japan

[6] Marathe, P., Date, P. P., 2013. On the design of a multistage process in drawn sheet metal products using strain distribution based parameters, Proc. IDDRG 2013, ETH Zurich, 2nd to 5th June 2013, Zurich, Switzerland

[7] Date P P 2016 Strain distribution based failure prediction and intelligent materials specification, Final Report (including software), Project no. DRD/ME/PPD-8/2012-13, Volkswagen AG, Wolfsburg, Germany, June 2016

[8] Date P P and Jamadar K D 2016 A strain distribution based approach to predict failure in sheet metal Proc Int Conf IDDRG 2016 June 12-15 Linz

[9] Date P P and Jamadar K D 2016 Application of Strain non-uniformity index (SNI) based approach to predict failure in sheet metal components, Proc. Int. Conf. Numerical Modelling Sheet Forming Processes (NUMISHEET2016) September 4-9 2016 Bristol UK