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Compensation for process-dependent effects in the determination of localized necking limits

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ABSTRACT

This work describes a new procedure to remove the differences in measured forming limits obtained from Marciniak and Nakazima tests, which are the two most frequently used testing methods to obtain necking limits for forming limit diagrams (FLD) used in formability analysis of sheet metal stamping processes. The procedure compensates for the combined effects of curvature and nonlinear strain path that occur during these tests, using measurements recorded by digital image correlation (DIC) throughout the deformation history of the point on the test specimen that eventually necks. The severity of forming is then determined by presenting the critical forming conditions in a stress diagram in order to account for the effects of through-thickness pressure that influences the onset of localized necking in the Nakazima test. These stress-based forming limits are then transformed back to the familiar strain limits (or FLD), but now representing the limits under the restriction of in-plane perfectly linear stretching and plane-stress conditions. Accounting for the effects of nonlinear strain path is particularly sensitive to the detection of the actual onset of localized necking, so this work also recommends the use of realistic methods to detect the actual onset of localized necking. The method adopted in this work is based on a new method described by Min et al. [13,14], in which a change in the surface curvature is used to detect a geometric effect associated with the onset of localized necking. In addition to demonstrating that the standard Marciniak and Nakazima tests (punch diameter of 101.6 mm) produce essentially identical limit curves for a 980 MPa grade multi-phase high strength steel after correction for curvature, nonlinear strain path, and pressure, the method is also applied to the analysis of data from a non-standard Nakazima test with a smaller punch diameter of 50.8 mm, where the severity of these processing conditions are significantly enhanced. This additional test is further proof of the validity and comprehensive coverage of the corrections for the different processing conditions involved in measurement of forming limit curves.

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1. Introduction

The Forming Limit Diagram (FLD) is an important graphical aid in formability assessment used by the sheet metal forming industry in the analysis of both finite element (FE) simulations of sheet metal forming processes and in physical die tryout. The FLD describes the limit strains, represented by a Forming Limit Curve (FLC) that defines the upper boundary of deformation that sheet metals can endure before the onset of through-thickness or localized necking. This boundary is typically described in a plot of the major principal strain expressed as a function of the minor principal strain. There are two primary tests used to experimentally determine the FLC, developed independently and known as the Nakazima test and the Marciniak test. The Nakazima test [17] uses a hemispherical dome punch, while the Marciniak test [10] uses a cylindrical punch. Both tests involve using a set of several sheet specimen widths with the axisymmetric tool geometries in order to produce a range of straining conditions from uniaxial to equal-biaxial tension. The differences in these two tests, including other variants of test conditions developed from many different academic, government and industrial labs, particularly with respect to the details of the shapes of the specimen geometries, not only affect the resulting strain paths, but also the shape and characteristics of the FLC. These process-dependent differences in forming limits have until now not been adequately addressed in industrial application of the FLD.

Almost since the inception of the FLD, strain paths, sheet curvature, and contact pressure have been known to affect necking

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limits. While the effect of nonlinear strain paths (NLSP) on the necking limit measurement was first experimentally documented by Nakazima et al. [17], little attention was given to a solution to the strain path effect that was reported by Müschenborn and Sonne [16]. The reason for this was primarily because until the mid 1990's, most industrial engineers believed that strain paths were nearly linear in the first draw die, where most of the formability issues arose. Initially there was not much concern about NLSP effects, and few people were even aware of Müschenborn and Sonne's work, or if aware, did not appreciate its importance. Through-thickness pressure also has long been considered to play a significant role in necking. However, pressure effects have not been widely considered in industrial applications of sheet forming processes. The reason for their neglect is attributed to the wide use and acceptance of shell element elements in sheet forming simulations. The through-thickness stress components in shell elements are constrained to remain zero, even in areas of contact between the sheet metal and tool surfaces. The justification of ignoring pressure effects on necking in analysis using shell elements is based on consistency with the justification of using shell elements in the first place, which is that the through-thickness stress components are negligible.

The effect of sheet curvature was more obvious and solutions were adopted very early in industrial practice. The reason for this is that many automotive stampings involve bending sheet metal on sharp features with radii that approach the sheet thickness, so that the strain on the convex side of the sheet shows no sign of necking although it is often well above, sometimes by more than a factor of 2 higher than the FLC in the first draw die. Furthermore, when necks were observed in areas affected by this bending, they were often found in the area where the metal had moved away from the tool contact radius and had flattened out, essentially eliminating the high strain gradient through the thickness. Consequently, most industrial engineers adopted the idea of either restricting the assessment of formability to areas of small curvature, taking advantage of the fact that necking does not occur at sharp radii, or to be more consistent and provide a formability assessment in areas of smaller but nonzero curvature, adopted the intuitively popular idea of comparing the average strain on the mid-plane through the sheet thickness to the FLC. The latter idea became so popular, that when FEA analysis was introduced in the mid-to-late 1990's in commercial analysis codes, the developers adopted the practice of limiting their formability assessments to consider only the membrane values of elements that are subjected to out-of-plane deformation.

The conventional approach to how formability assessment was applied to the analysis of the first draw die process began to unravel as the use of metal forming simulation of stamping processes began to expand in the mid-1990's with the hope to effectively eliminate the high costs of physical die tryout. While consideration of the importance of accounting for NLSPs was essentially restricted to secondary forming processes for most of the following decade, Stoughton [22] emphasized that NLSPs are intrinsic to all forming processes, including the first draw die. Consequently, it was claimed that solutions to the NLSP problem were necessary for all metal forming processes in order to obtain reliable and robust manufacturing solutions. More recently, Leppin et al. [8] showed that a significant portion of the difference in measured forming limits between the Marciniak and Nakazima tests can be removed simply by accounting for NLSP effects in the analysis, which means that NLSP affects not only the use of forming limits, but how the forming limit is defined.

The ability to obtain reliable FLCs, as well as account for NLSP effects, is greatly improved with the use of digital image correlation (DIC) techniques. Several methods [11–14,30,6,9] have been developed to try to either detect the actual onset of localized necking, or define a suitable proxy for the limits based on an engineering approximation for the onset of localized necking in order to avoid the human detection methods from the early development of the FLD. Using DIC, the strain paths of all areas of interest on forming limit test specimens can be tracked precisely, which for the first time, makes it convenient to simultaneously account for effects on the forming process caused by NLSPs. While DIC strain measurements show that the strain paths of Marciniak specimens are nearly linear from zero strain up to the onset of localized necking, significant NLSPs are observed on Nakazima specimens [1,8].

It is important to note that while friction conditions can influence the location of the instability, as well as influence the degree of nonlinearity in the strain path in the area of localization, friction is not expected to have any effect on the necking limit. It can be advantageous to limit frictional influence using lubricants or viscoelastic materials and thus promote localization to occur near the pole of the specimen, but any localization that occurs can provide valid data for an FLD, provided compensation for nonlinear strain path is made. For example, high friction conditions in a Nakazima test might push the eventual instability to occur in the unsupported region of a specimen. In this case, it remains very important to apply the corrections for effects of NLSP and curvature, but not for the pressure effect since in this case there would be no punch contact where the neck occurred.

After compensating the FLC's for the effects of these forming process conditions, they are shown to converge to a single FLC for both tests, corresponding to the FLC for linear strain paths in the absence of through-thickness strain gradients, for in-plane stress conditions in the absence of through-thickness stress, i.e., under plane-stress conditions. The robustness of this experimental correction procedure is demonstrated in a third set of experiments using a 50.8 mm hemispherical dome, which effectively doubles the severity of curvature and pressure conditions that exist with the conventional Nakazima test using a 101.6 mm dome. It will be shown that with the correction procedure, the FLC using the 50.8 mm dome is consistent with the FLC for the 101.6 mm diameter Nakazima and 101.6 mm diameter Marciniak tooling.

2. Effect of processing conditions on localized necking limits

The next three sub-sections respectively review the challenge and solutions for handling effects of NLSP, curvature, and pressure in the use of the FLD. It is assumed that the strain limits for perfectly linear strain paths for in-plane stretching of a particular sheet metal in a process involving no through thickness normal or shear stress are known. The procedure for determining this FLC will be described in a later section. But here, with this FLC for linear in-plane deformation defined, the challenge is to describe the conditions for the onset of localized necking for cases when conditions are different from this simple mode of deformation.

2.1. Nonlinear strain path effects

The fact that NLSPs affect the forming limit strains has been noted by many scholars in the plasticity community, beginning with the seminal work of Nakazima [17]. Among the first to propose a solution to this challenge was Müschenborn and Sonne [16], who devised a method of accounting for the strain path effect based on the work-equivalent plastic strain. Later, Kleemola and Pelkkikangas [7] and Arrieux et al. [2] proposed using a stress-based FLD (or forming limit stress diagram, FLSD), defined with minor and major stresses on the abscissa and ordinate, which for isotropically hardening materials, is equivalent to the solution proposed by Müschenborn and Sonne [16]. However, all of these

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