International Journal of Solids and Structures 51 (2014) 2840–2849

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

Suppression of necking in incremental sheet forming

D.Y. Seong [a,1], M.Z. Haque [a], J.B. Kim [b], T.B. Stoughton [c], J.W. Yoon [d,*]

[a] Faculty of Engineering and Industrial Sciences, Swinburne University of Technology, Melbourne, VIC 3122, Australia
[b] Dept. of Mechanical and Automotive Eng., Seoul National Univ. of Tech., Seoul 139-743, Republic of Korea
[c] General Motors Global Research and Development Center, MC 480-106-244, Warren, MI 48090-9055, USA
[d] School of Engineering & Institute for Frontier Materials, Deakin University, Geelong Waurn Ponds, VIC 3220, Australia

ARTICLE INFO

Article history:
Received 17 July 2013
Received in revised form 20 January 2014
Available online 13 April 2014

Keywords:
Incremental sheet forming (ISF)
Stress gradient
Stress-based forming limit
Necking

ABSTRACT

Incremental sheet forming enables sheet metal to deform above a conventional strain-based forming limit. The mechanics reason has not been clearly explained yet. In this work, the stress-based forming limit was utilized for through-thickness necking analysis to explain this uncovered question. Stress-based forming limit which has path-independency shows that the stress states in top, middle and bottom surfaces did not exceed the forming limit curve at the same time and each layer has different stress state in terms of their deformation history to suppress necking. It has been found that it is important to consider the gradient stress profile following the deformation history for the proper forming limit analysis of incremental sheet forming.

1. Introduction

Incremental sheet forming (ISF) is being popularly used to form a complicated shape beyond the formability of a sheet material as an innovative forming technology. However, it has been difficult to find a sound mechanics reason why incremental sheet forming can suppress (or delay) necking and how to stabilize the deformation of a sheet material.

In mechanics viewpoint, incremental sheet forming example in this manuscript is a clamped plate under dynamic point loading. Bending of a thick or thin clamped plate under elastic loading can be found in the pioneering works done by Hencky (1913), Galerkin (1915), Love (1927), Timoshenko and Krieger (1959). Footnote to page 197 of Timoshenko and Krieger (1959) gives a detailed explanation of history of plates under bending. Also, an analytical work by Love (1927) explains the tensile deformation of under bending with curvilinear & polar coordinate system which is similar to the mechanics of incremental sheet forming.

A review paper related to incremental sheet forming discussed six new mechanisms such as contact stress, bending under tension, shear effect, cyclic loading effect, geometrical inability, and hydrostatic pressure which lead to preventing unstable deformation from the viewpoint of a necking (Emmens and van den Boogaard, 2009).

Most of developments for incremental sheet forming have utilized a conventional forming limit in the strain space. Necking limit in the strain space is dependent on anisotropic yield functions and their material parameters (Dasappa et al., 2012). In addition, several theoretical studies showed that the strain-based forming limit using MK (Marciniak–Kuczynski) necking theory is also strongly dependent on the strain path (Stoughton, 2000; Stoughton and Yoon, 2005; Stoughton and Zhu, 2004). Although a deformation history mainly depends on tool path in ISF, the path-dependent forming limit has been being used to estimate necking.

The concept of path-independent forming limit such as stress-based forming limit was introduced for a valid necking assessment irrespective of a changing loading scenario. This stress-based limit curve in the plane-stress condition is extended to the forming limit in three-dimensional loading using equivalent stress and mean stress space (Simha et al., 2007). In addition, it was experimentally observed that any necking didn't occur during pure bending (Tharrett and Stoughton, 2003), because of the compressive stress in the concave part which made the stress state below the limit and prevented a through-thickness necking instability (Stoughton and Yoon, 2011). A recent ISF simulation found a stress combination of strong bending and membrane tension in some sheet elements (Guzmán et al., 2012).

In this work, the path-independent stress-based forming limit was utilized taking into account stress-gradient histories through the thickness direction in order to explain more scientific

* Corresponding author at: School of Engineering & Institute for Frontier Materials, Deakin University, Geelong Waurn Ponds, VIC 3220, Australia. Tel.: +61 3 5227 3425.

E-mail address: j.yoon@deakin.edu.au (J.W. Yoon).

[1] Current Address: LG Production Engineering Research Institute, LG Electronics, Cheongho-Ri, Pyungtak-City, Kyoungki-Do, Republic of Korea

http://dx.doi.org/10.1016/j.ijsolstr.2014.04.007
0020-7683/

explanation why the incremental sheet forming prevents a neck from initiating and activating.

2. Role of stress and strain gradient to necking

One of the primary factors that cause confusion in understanding forming limits is the role of the stress and strain gradients through the sheet thickness. These gradients are intrinsic to curved sheet and therefore critical to understanding and applying forming limit criterion based on stress or strain. For example, stretching a 1 mm thick sheet over a 2 mm radius will introduce a difference in the true strain between the top and bottom side of the sheet of up to $ln(1.5) = 0.405$, depending on the amount of in-plane tension that thins the metal. That strain difference is on the order of the FLDo value of most steels and twice the limit of aluminum. So this raises the question, "What layer do you use to define the stress (or strain) that will be compared the stress (or strain FLC) in the formability analysis?" When industry first started to implement the FLD in the 1960's, it was quickly discovered that strains measured most conveniently on the convex side of the sheet were commonly found to be well above the FLC with no sign of necking. Remarkably, without any experimental evidence to justify the decision, the metal forming industry adopted the approach of using the membrane strains in making comparison to the strain FLC. This assumption has continued unchecked in both physical tryout and analysis of numerical simulations for nearly two decades, and continues to be the dominant practice used in industry today, more than four decades later. Unfortunately, the assumption is wrong, and the truth has serious consequences in both the interpretation of forming limits and their application in analysis.

Tharrett at General Motors conducted a series of simple bending under tension tests on strips of different thickness of steel, aluminum, and brass and different punch tip radii with the objective to determine what strains through the thickness are the cause of necking. He discovered that necking initiated not when the membrane strains exceeded the strain FLC, as was previously thought, but much later in the forming process, when the strains on the concave side of the sheet rose to the level of the FLC. While the tests were limited to plane strain conditions, the results were confirmed in all materials and tooling geometry. The details of the experiments for steel were later published by Tharrett and Stoughton (2003), and the results for one test geometry are shown in Fig. 1. There are two necks observed in this specimen on either side of the center punch tip radius at the location where the strains on the concave side, shown by the enlarged circles, rose to the level of the FLC for this material.

Considering the importance of stress metrics, Stoughton and Yoon (2011) noted that Tharrett's results are also understood to apply to the stress conditions, so that this important factor can be applied to both linear and nonlinear deformation processes. In other words, for a neck to initiate, the stress on all layers through the thickness must exceed the stress FLC. To put this idea into practice in numerical simulation, the forming limit criterion must be applied to each integration point through the thickness of the element. In other words, necking is defined to initiate only when the formability index is larger than 1 at all integration points. This generalization has interesting consequences because often the stress field is more complex than the strain field, due for example, to a history of cycling bending/unbending. So the minimum or least critical layer may not be on the surface, but at an interior integration point. Furthermore, it is important to note that use of membrane values, which is the most widely accepted practice for formability assessment by industry, will result in overly conservative predictions of necking on curved sheet. This mistake will undermine correlation with experiment, but also, because the level of the conservative estimate is proportional to the strain gradient through the thickness, it will result in a proportional bias in the safety margin towards regions of higher curvature, while providing no additional margin of safety in regions of zero curvature or through-thickness stress gradient. Since failures most often occur away from curved areas of the product for this very reason, the bias of using membrane strains in formability assessment provides no real benefit to producing robust processes. Another interesting consequence of Tharrett's results is that it explains why necking is not often observed in hemming and never observed in pure

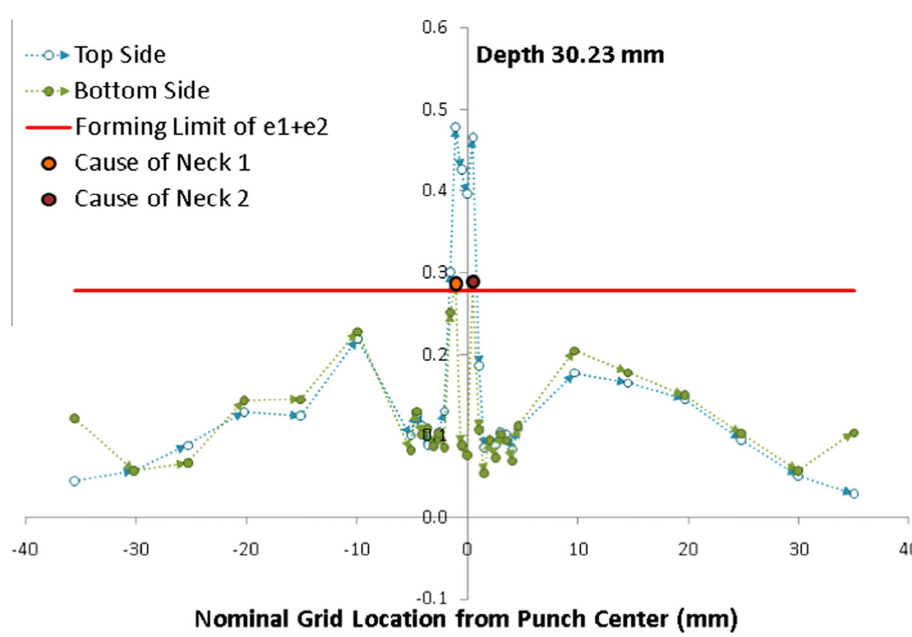

Fig. 1. Sum of the principal strains for a 50 wide strip of 1008 AK steel stretch-bent over a punch wedge with a ¼ inch radius to the depth at which onset of necking occurs, as reported (Tharrett and Stoughton, 2003). The forming limit is characterized as a simple limit on the sum of the principals because the minor strain was less than or equal to zero at all points along the strip in a region of the FLD characterized by a limit on thinning strain for this metal. The FLC and FLDo was obtained from standard FLD tests independent of the stretch-bend test.