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Determination of forming limit diagrams of sheet materials with a hybrid experimental–numerical approach

Q. Situ [a], M.K. Jain [b,*], D.R. Metzger [c]

[a] G.L. Tiley and Associates Limited, 46 Dundas East, Flamborough, Ontario, Canada L9H 7K6
[b] Department of Mechanical Engineering, McMaster University, 1280 Main Street West, Hamilton, Ontario, Canada L8S 4L7
[c] Atomic Energy of Canada Limited, 2251 Speakman Dr., Mississauga, Ontario, Canada L5K 1B2

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ABSTRACT

A new methodology is proposed to obtain the forming limit diagram (FLD) of sheet materials by utilizing routinely obtained experimental punch load versus displacement traces from hemispherical punch stretching experiments and by analyzing strain history of the test samples from finite element simulations of the experiments. The simulations based characteristic points of diffuse and localized necking are utilized to obtain the limit strains. The proposed method for FLD determination considers out-of-plane displacement, punch–sheet contact and friction, and avoids using experimental strain measurement in the vicinity of the neck on the dome specimens and the rather arbitrary inhomogeneity factor to trigger localization such as in the commonly used Marciniak–Kuczynski method. A criterion of maximum in the 'pseudo' major strain acceleration for the onset of localized necking, proposed earlier by the present authors, is utilized to determine the limit strain in FE simulations as well as in FLD verification experiments. The proposed overall approach for obtaining FLD is rapid and accurate and could be implemented for routine FLD generation in a laboratory setting with significant reduction in cost, effort and subjectivity.

1. Introduction

Industrial applications of forming limit diagrams such as in sheet stamping require a simple, accurate and rapid approach to evaluate them. Experimental methodology using grid measurement in the neck region to obtain limit strains and FLD tends to be laborious and time consuming. A procedure for FLD determination developed by Hecker in the 1970s [1] has remained largely unchanged over the years although a number of papers have attempted to quantitatively determine the strain gradient in the neck region to precisely establish the onset of necking [2–4]. The strains from selected grids on the deformed specimens can be analyzed in a position plot and interpolated with the Bragard criterion [2]. A quadratic curve fitting is often utilized to obtain the vertex in major strain and corresponding minor strain as the limit strain, as shown in Fig. 1 (ε_{Br} criterion). This criterion gives reasonable results when the maximum value of measured strain is at the very center of the specimen and a well-established strain gradient is present in the data. However, subjectivity exits since a different selection of measured points may produce errors in the shape and position of the resulting limit curves. More importantly, this so-called "maximum" value does not always physically exist (or is physically measurable). More recently, a speckle (stochastic) pattern has also been used with success [3]. Speckle pattern can be analyzed using automated strain measurement system and has less limitation on grid size since it can be produced at the micron level. On-line imaging with a speckle pattern has been employed in hemispherical punch stretching tests (hereafter called HPS tests) in conjunction with Bragard criterion to obtain the limit strains. The advantage of the on-line imaging and speckle-based strain analysis system is that the entire deformation process can be captured and calculated to obtain the history of a forming process. However, there is no commonly accepted criterion for the analysis of strain history to obtain the limit strains.

A method to compare the strain gradient of neighboring patterns at a given instance was proposed to obtain the limit strains [4]. The major strain distribution of a localized neck and its vicinity from a deformed specimen is obtained and plotted as a function of position and the first derivative of strain, i.e., strain gradient, is calculated. From a comparison of the gradient curves, the strain value corresponding to the gradient showing rapid increase is obtained as the limit strain ($(\varepsilon_1)_{cr}$ criterion). The question arises as to when a material point in its deformation history becomes the site of a neck. The selection of the instance after the failure requires a definite criterion but was not discussed. In other words, the strain history

* Corresponding author.
E-mail addresses: qsitu@tiley.on.ca (Q. Situ), jainmk@mcmaster.ca (M.K. Jain), metzgerd@aecl.ca (D.R. Metzger).

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