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Digital speckle based strain measurement system for forming limit diagram prediction

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ABSTRACT

A digital speckle based strain measurement system is developed to investigate the forming limit diagram (FLD) of sheet metal. A stochastic speckle pattern is sprayed on the surface of flat sheet metal before forming. A series of images are recorded by two cameras during the forming process. The strain field is then calculated for FLD determination, which involves the following key issues. First, to solve the problem of large deformation and strain measurement in sheet metal forming, a fractionized matching algorithm using deformation continuity of adjacent images is proposed. Second, an algorithm for three-dimensional (3-D) strain calculation is discussed, and a spline model is specially used to calculate the strain of the sheet metal in deep drawing. Third, a limit strain determination algorithm is proposed for forming limit curve (FLC) calculation by creating sections in the measured strain fields. Finally, a forming limit strain measurement system (also called Xi'an Jiaotong University Forming Limit Curve measurement system, XJTUFLC) is developed on the Visual Studio 2010 platform. With our self-developed image acquisition instrument and sheet metal bulging setup, FLD determination tests are conducted to validate the performance of the system. And the measured FLD is compared with the traditional experimental FLD as well as with that predicted by the empirical model. From the analysis of the experimental results, it can be concluded that the proposed system is feasible to measure the full-field strain during sheet metal forming processes and provides a better solution for forming limit diagram prediction.

1. Introduction

The estimation of material formability plays a principal role in the analysis and design of sheet metal forming processes. The forming limit diagram (FLD) developed by Keeler [1] and Goodwin [2], generally given in terms of the limiting principal strains under different loading conditions prior to the onset of localized necking, is a practical method for characterizing the formability of sheet metals. There are usually three possibilities to determine FLD: analytical, experimental, and numerical. Among those possibilities, the experimental technique is the most common one, which involves subjecting specimens of sheet metal to different in-plane strain states, e.g., by simple tensile testing or stretching over a hemispherical punch.

When using the experimental technique to determine the FLD, it is generally necessary to photographically print or electrochemically etch a grid pattern on the surface of an un-deformed specimen of sheet metal. The grid pattern could be defined as one or more lines, dots or other shapes. Quite often a circular grid pattern is employed and it is assumed that the circle is deformed into an ellipse. The major and minor strains are calculated from the deformed pattern by comparing its size (e.g., ellipse diameters) to the original size of the grid pattern. Traditionally, strains are often determined by using manual measurement methods. Types of tools used in the measurement include dividers, a ruler, and a graduated transparent (Mylar) tape or a microscope [3]. But the manual measurement methods are time-consuming. Therefore, there is still a need to develop an automated and efficient strain measurement system. There have been many published researches on better strain measurement. For example, Ayres et al. [4] presented a single grid element analysis system. A handheld digital camera was used to capture images and one grid element was processed at a time. Bednarski [5] used film-based stereo cameras to measure the deformation of a circular membrane. Vogel and Lee [6] introduced a well-known video camera-based system, which was capable of measuring several hundred elements in a single set-up. This system includes a camera, a positioning device, a rotary table and a computer. Orteu et al. [7] improved the stereo vision strain measurement system by adopting robust and sophisticated algorithms for camera calibration. Chan et al. [8] presented a high-accuracy laser digitizer-based sheet metal strain measurement system. Shi [9] developed a circular grid

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pattern based surface strain measurement system for sheet metal forming. However, these methods still have some drawbacks: (1) Making grid pattern on the specimen surface is often complex and time-consuming. (2) The measured limit strain may not be the real strain of the sheet at the time when localization occurs. Instead it is the strain of the sheet at the time when the crack has appeared. In addition, commercial strain measurement systems have been developed, such as the ARAMIS system (GOM Company, Braunschweig, Germany) and the VIC-3D system (Correlated Solutions, Columbia, South Carolina).

The digital image correlation method (DIC), originally developed by Sutton et al. [10] in the 1980s, has gradually become an important optical measurement means in experimental mechanics due to many researchers' contributions to it [11–16]. Based on the DIC method and the binocular stereo-vision technique [17], a digital speckle based strain measurement system (Xi'an Jiaotong University Forming Limit Curve measurement system, XJTUFLC) is proposed to measure the full-field strains during sheet metal forming processes. The applied key techniques are investigated, including large deformation measurement, speckle pattern matching, 3-D strain reconstruction and forming limit curve (FLC) calculation. The FLD measured by the proposed system are compared with the traditional experimental FLD as well as with that predicted by the empirical model [18] of the NADDRG (North American Deep Drawing Research Group). The experimental results show that the developed system can be more comprehensive and intuitive to measure the strains during the whole forming processes and provides a better solution for forming limit diagram prediction.

2. Methodologies

2.1. Digital speckle based strain measurement for FLD

2.1.1. Digital image correlation measurement

A digital speckle based strain measurement method, generally represented by the so-called DIC method, is adopted to investigate the FLD of sheet metal. Fig. 1 illustrates its basic principle. In the reference image, a square reference subset of $(2M+1)\times(2M+1)$ pixels centered at point (x_0, y_0) is picked. The matching procedure aims to find the corresponding subset centered at point (x'_0, y'_0) in the deformed image which has the maximum similarity with the reference subset. Assume that there are n pixels in the reference subset and the image pixels are corrupted by independent and identically distributed noise. The corresponding subset which has the maximum similarity with the reference subset can be obtained by minimizing the following function:

$$C_{SSD}(p) = \sum_{i=1}^{n} [f(x_i, y_i) - r_0 - r_1 \times g(x'_i, y'_i)]^2 \quad (1)$$

where $f(x_i,y_i)$ and $g(x'_i, y'_i)$ are the gray value of point (x_i,y_i) and (x'_i, y'_i), respectively, $e(x_i,y_i)$ indicates the noise component, r_0,r_1 are used to compensate the gray value difference caused by illumination diversity, and $p=[u,u_x,u_y,v,v_x,v_y,r_0,r_1]$ represents the vector of correlation parameters. As the relative relationship of the pattern in the reference image is almost unchanged in the deformed image, any point (x_i,y_i) in the reference subset can be mapped to a point (x'_i, y'_i) in the deformed image according to a first order mapping function [19]

$$x'_i = x_0 + \Delta x + u + u_x \Delta x + u_y \Delta y$$

$$y'_i = y_0 + \Delta y + v + v_x \Delta x + v_y \Delta y \quad (2)$$

where Δx and Δy mean the distances from the subset center to point (x_i,y_i), u and v are the displacement components of the reference subset center in x and y directions, and u_x,u_y,v_x,v_y are the first-order displacement gradients of the reference subset.

To get the minimum of C_{SSD} is a nonlinear minimization problem, which can be solved by using the iterative least-squares algorithm (ILS) [20]. It has to be noticed that an interpolation scheme is needed because the coordinates of points in the deformed image are not integer pixel. Therefore, a bicubic spline interpolation scheme [21] is adopted in the DIC calculation.

However, inaccurate initial values may decrease the ILS calculation speed or even lead to a wrong convergence result. To solve this problem, an algorithm based on seed point [22] is used. As shown in Fig. 2, after calculation area is specified and divided into subsets, one or more subsets are chosen as seed point(s) (red rectangle). Then the traditional method is used to match the selected seed point(s) coarsely and the ILS algorithm is subsequently adopted to match the seed point(s) precisely. Since the amount of the seed point(s) is small, the computational complexity could be negligible. Considering the continuity of deformation, the seed point is then used to calculate the initial value of the correlation parameters for its four neighbor points (left, right, up, down). Estimation of locations of these neighbor points in deformed image can be obtained according to Eq. (2), and they can be used to get the initial values of u and v directly. The initial values of the rest correlation parameters are set equal to the seed point and the ILS algorithm is used to refine the correlation parameters of the neighbor points. Once the four neighbor points are matched successfully, they can also act as seed points for their own neighbor points. The process repeats until all points are matched, as shown in Fig. 2. This method improves not only the precision of initial values but also the computing efficiency.

In addition, the surface speckle pattern is important for DIC practical applications [23–25]. First, the size of it must be adapted to the measuring volume, the camera resolution and the facet size. On one hand, the size of the speckle pattern should be small enough to allow a fine raster of calculation facets during evaluation. On the other hand, the pattern should be large enough to be completely resolved by the camera. Second, with a good gray level

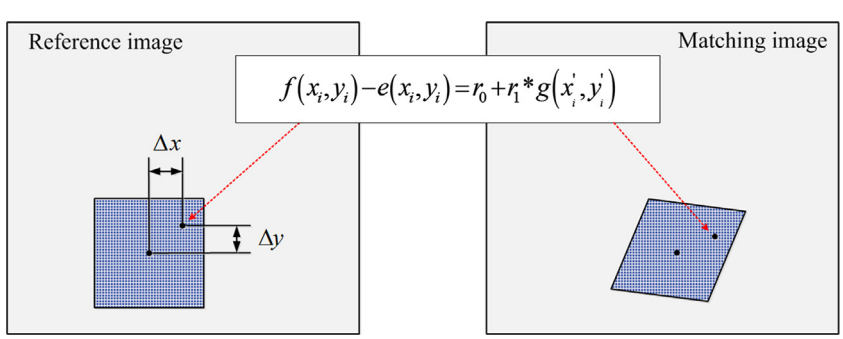

Fig. 1. Schematic diagram of image correlation.