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이미지 프로세싱에 의한 금속 박판 인장실험에서의 변형도 분포

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Determination of Surface Strains in a Tensile Test by Digital Image Processing

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초 록

디입 드로잉용 냉간 압연 강판의 인장시험편에 디지탈 이미지 프로세싱 기술을 적용하여 표면에서의 변형 및 변형도 분포 구하는 방법을 제안한다. 이 방법은 시편표면상의 절점 위치를 이미지 프로세싱에 의해 결정하는 부분과 이들 위치점들을 이용하여 변형도를 계산하는 두 부분으로 구성되어 있다.

본 연구에서는 시편상의 각 절점 위치를 구하기 위해 검은 원형의 반점들로 배열된 사각 형상의 격자를 사용하였고, 이미지 프로세싱에 의해 구해진 절점 좌표를 이용하여 소재 표면에서의 변형 패턴, 주 변형도 분포, 유효 변형도 분포, 임계 변형도 등을 구하였다. 인장시험하는 동안 시편 표면상의 국부 네킹이 발생될때 까지 주변형도에 의한 변형 이력은 거의 직선적으로 변형되고 있기 때문에, 유효 변형도 값은 매 변형 단계마다 변형도 증분의 누적에 관계없이 거의 일정한 값을 보여주고 있었으며, 최대 유효 변형도는 시편의 중앙부에서 나타나고 있음을 알 수 있었다.

I. INTROCUCTON

Digital image processing is a technique which digitizes the actual image of an object and gives the desired data through a series of image processing tools. This technique which had mainy been applied to planetary science and biomecical examination has been improved with the development of computing technology[1].

Application of this technique to metal forming field has been made in a limited number of investigations [2-4]. Glibbery[2] has recently developed several softwares for image analysis and applied the method to simulation of bulk forming processes like upsetting, extrusion, forging and rotary forging, in order to investigate the 3-dimensional deformation characteristics such as strains and deformed configuration using model material of wax. For investigating strain distribution in sheet metal forming the nodal points of spots marked on the specimen are usually determined using a profile projector. This work is tedious and time-consuming and may furthermore cause some problems with the accuracy of measurement.

A few investigations of the image processing of sheet metal forming have been reported for determining the limit strains to draw the forming

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limit diagrams[3] or for examining the strains after deformation[4]. Schedin and Melander[3] carried out surface strain analysis of an automotive stamping using an automatic image analyzer. They found large differences depending on whether the strain path was determined linearly or incrementally. This automated system still has a drawback being only applicable to local strain measurement, not to the entire area of interest in the specimen.

Vogel and Lee[4] have developed an automated vision system for determining strain distributions in the deformed products. This analysis is performed by using two complete views of an object under the assumption of pure homogeneous deformation mode[5]. However, it is not possible to carry out a direct in-process analysis estimating the strain history of each material element in sheet metal testing.

In the present study a rectangular grid of solid circles(spots) for image analysis is applied to the tensile specimen of a deep drawing quality steel. The coordinates of the center of gravity of each deformed spot are determined in each step of image grabbing. These data are used as input data for calculating the strains. From a tensile test the accumulated effective strains, the principal strains, the strain path and the deformation pattern are presented and discussed.

2. IMAGE PROCESSING

The image is a visual representation of an object on a CRT(Cathode Ray Tube) after digitizing and it consists of a rectangular array of picture elements(pixels) having different level of brightness.

The camera used for the present experiments of sheet metal test is a Philips LDH-0600 CCD solid state video unit with a resolution of 604 (horizontal) x 576(vertical) pixels. The video signals produced by this camera is digitized by a frame grabber, Matrox PIP-512/1024A Video Digitizer Board[6]. The frame grabber has a spatial resolution of 512 x 512 pixels with an intensity resolution of 256 grey levels(0 representing black and 256 representing white) and comprises input-LUT(Look-Up Table) and output-LUT facilities. The digitized image is represented on the monitor screen of a 13" Mitsubishi C-3479 color display unit with the same resolution of 512 x 512 pixels.

The first operation on the digitized image is to determine the threshold value separating the circular black spots of the grid on the specimen surface from the background of the image. This information can be extracted from an image histogram. The histogram shows a frequency distribution of the intensity levels of all pixels on the monitor screen. It is computed by counting the number of pixels having the same grey level[7].

The threshold value determined is used to transform the original grey level of each pixel to a new one, which is accomplished by means of an input-LUT. After thresholding the initial image, the modified one of two grey levels is generated and represented with pseudo-color overlays on the monitor screen with the help of output-LUT Data extraction from this image is done by calculating the center of gravity of the spots after a series of image processing such as RLE-representation(Run Length Encoding) for image compression, shrinking and expanding for image enhancement and segmentation to find segment array[1].

Each pixel of an image in the computer vision system usually applied occupies an 8-bit byte which can store 256 grey intensity levels. In this case the computer needs a memory size of 262,144 bytes(512 x 512) for storing the entire image on the screen. This amount of data is too large to handle on a personal computer. It is therefore necessary to accomplish the image compression in order to save storage space and the enhancement eliminating noise or smoothing irregularities on the spot contours in advance.

Fig. 1 shows the initial image of the tensile test specimen when localized necking begins to appear in the central part of it and the result of image processing on this image is represented in Fig. 2 indicating the center of each spot with a cross. Consequently the coordinates of the sports are continuously stored in a data file which will be used to draw the deformed geometry and calculate the strains.

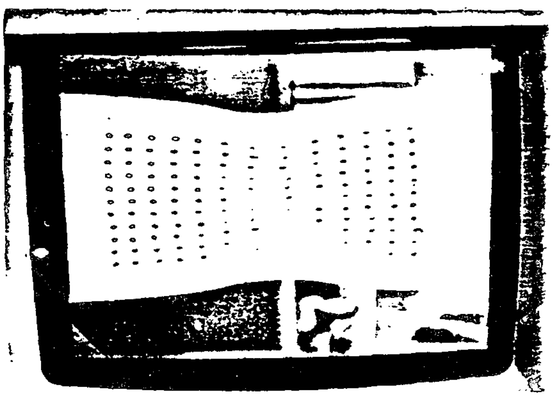

Fig. 1 The initial image of the tensile specimen as grabbed

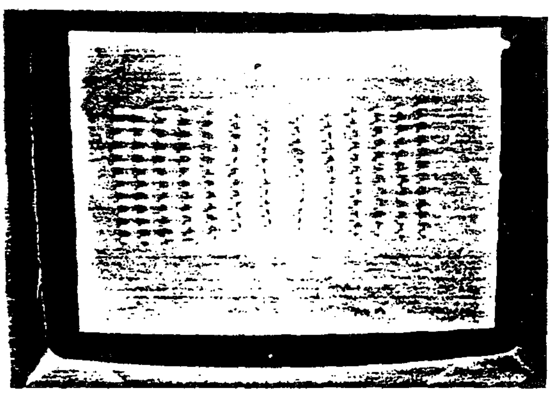

Fig. 2 The image representing the center of each spot with a cross after image processing

3. CALCULATION OF STRAINS

The circle grid method has been the most common one in the press shop because it is very easy to calculate strains by measuring the basic dimensions of a circle after being deformed (often to an ellipse) [8]. In this method the directions of the principal strains are determined by identifying the major and minor axes of the deformed ellipse and their magnitudes are calculated from the change in size of the major and minor axes relative to the original circle. However, in spite of the simplicity of this method it can not be employed to the determination of the directions of principal strains in cases where rigid body rotation of material elements occur during deformation.

One of the methods frequently used for large strain calculations is the coefficient method proposed by Bredendick[9], which utilizes the coordinates of a quadrilateral element in the analysis in order to eliminate the effect of rotation of the material elements. This method has proven to give better results than the circle grid method[10]. The strain calculation method is described in detail in appendix 1.

4. EXPERIMENT

A deep drawing quality steel (DIN St1403m, KS SCP3) was chosen as test material. In order to estimate the anisotropy of the sheet three kinds of specimens were cut 0°, 45° and 90° relative to the rolling direction of the sheet respectively. The strain ratio (R-value) which is defined as the ratio of width strain to thickness strain in a tensile test was measured at a level of effective strain of 0.2 and the average value of R=1.305 was obtained.

An array of 13×11 points were applied manually by painting ϕ 1.7 mm circular spots arranged in a square formed grid with 5×5 mm spacing. The tensile test was conducted using a 600 KN laboratory hydraulic press. Standard tools for a tensile test were employed to grip the specimens of dimension 300 × 80 mm. The video camera was placed in a removed position from the tools. The horizontal distance between the specimen and the camera was about 400 mm which produces an approximate image scale of 107 and 149 pixel spacings per 30 mm of surface length in the x- and y-directions respectively. This set-up enabled the monitor to cover the deformed image all the way through deformation. The specimen is placed carefully so that its longitudinal direction designates the x-direction on the monitor screen. This adjustment facilitated continuous observation of the deformation and plotting of the deformed configuration with respect to the reference coordinate system after image analysis. The press speed was kept below 5 mm/min. In most cases 6 to 8 images were captured in each test and then calculated the strains after determining the coordinates of the nodal points.

5. RESULTS AND DISCUSSION

Strain calculation is made by the coefficient method enabling a stepwise analysis of the deformation. This calculation can cover the whole area of the specimen which is of interest.

The deformation is considered to be uniform between each incremental step. The effective strain of each element is accumulated along the strain path from a zero strain, but the principal stains are independently calculated by using the coordinates of the undeformed and the deformed element regardless of the strain path. It would imply errors to add up the principal strain increments step by step in the analysis due to possible rotation of the principal strain directions during deformation.

A test specimen provided with grid is shown in Fig. 3 before and after deformation. In the tensile test deformation is finally localized in the central region of the specimen and the well-known bands of localized necking appear as seen in Fig. 1

The execution time calculating the coordinates of the nodal points by the image analysis is about 30 seconds for each step and the overall time to accomplish the whole image processing including thresholding, selecting image boundary, determining nodal points and storing these data is approximately 45 seconds. Considering the resolution of the image analyzer employed in this experiment (0.28 mm/pixel in the x-direction and 0.20 mm/pixel in the y-direction) and the spacing of spots (5 mm) the image processing equipment only gives an accuracy of strain $\varepsilon = 0.28/5 = 0.056$ per pixel at the initial stage of deformation. A higher resolution of the image analyzer can be obtained by decreasing the distance between camera and specimen, resulting in better accuracy of stain calcuation. Such a trial, however, may cause disappearance of the gridded area of the specimen on the monitor screen during a test.

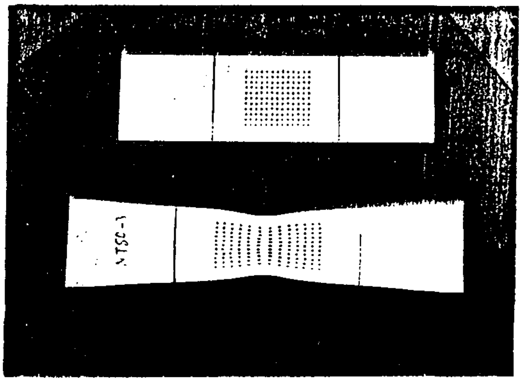

Fig. 3 Specimen before and after tensile test

A few steps showing the deformation pattern of 12×10 elements (13×11 points) during a tensile test are presented in Fig. 4 and the distribution of the effective strain is given for each deformed element. The inner frame surrounding the grid itself is to thought as a fixed reference frame like a window throught which the deformation is observed. As deformation proceeds, it can be seen that the specimen deforms uniformly until necking begins after which the deformation is concentrated in the central part of the specimen. The maximum effective strain is located in the center elements as can be seen in Fig. 4(c), which means localized necking or fracture starts in the center of a specimen and propagates outwards.

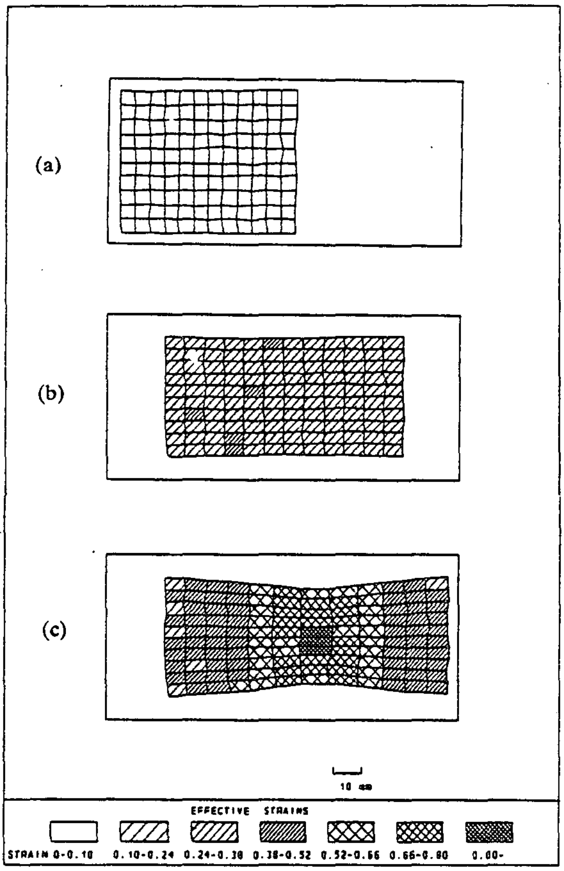

Fig. 4 Deformation pattern of 12 × 10 elements during tensile test. (a) step no. = 0 (undeformed), (b) step no. = 4 (intermediate), (c) step no. = 6 (final stage)

The left-hand part of Fig. 5 represents the strain path and the limit strain of an element having maximum effective strain at the final stage of deformation, showing the strain path to be almost linear. The right-hand part of Fig. 5 illustrates that the linearly calculated effective strain is always smaller than or equal to the incrementally calculated one and that the deviation between them increases gradually with further deformation. However, the difference is very small in this case where the material is deformed monotonically along a strain path in one direction.

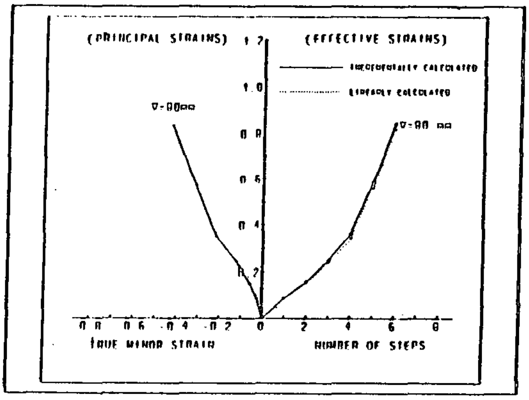

Fig. 5 Strain path and limit strain and comparison of effective strains calculated linearly or incrementally

6. CONCLUSION

A digital image processing technique was developed for the study of deformation pattern and strain distribution in tensile testing of sheet metal. A rectangular grid of circular spots was employed to get good accuracy of measurement in image analysis. The coordinates of the center of gravity of each spot were determined through a set of image processing algorithms and then used as the corner point of a quadrilateral element when calculating the surface strains.

In tensile tests the well-known deformed geometry of a specimen could be confirmed on the monitor screen and the maximum effective strain after necking was obtained in the central region of the specimen as to be expected. The magnitudes and directions of the principal strains for each element were calculated.

It is seen from this analysis that the image processing technique can be conveniently and systematically employed to analyze sheet metal forming for calculating the local surface strains and determining the deformed configurations.

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APPENDIX

1. Coefficient method

The coefficient method assumes a homogeneous and stationary strain field and it can be applied to 2-dimensional problems such as plane stress, plane strain and axisymmetric problems.

Fig. A. 1 shows a deformation field before and after deformation. The vectors 1 and 2 are deformed into vectors 1′ and 2′. The strains at a point P can be evaluated from the coordinates of the vectors, 1, 2 and 1′, 2′ passing through a point P. The coordinates of these vectors are given by computing the gravity centers of the spots using image processing techniques before and after deformation.

The coordinates of the vectors 1, 2, 1′ and 2′ are denoted as follows,

$$\mathbf{1} = (x_1, y_1) \qquad \mathbf{1'} = (x_1', y_1')$$

$$\mathbf{2} = (x_2, y_2) \qquad \mathbf{2'} = (x_2', y_2')$$

The true (logarithmic) strains at P after deformation are given by,

$$\varepsilon_x = \ln f + (C_{11} - C_{22})/2fq \qquad (1)$$

$$\varepsilon_y = \ln f - (C_{11} - C_{22})/2fq \qquad (2)$$

$$\varepsilon_{xy} = (\gamma_x + \gamma_y)/2 = (C_{12} + C_{21})/2fq \qquad (3)$$

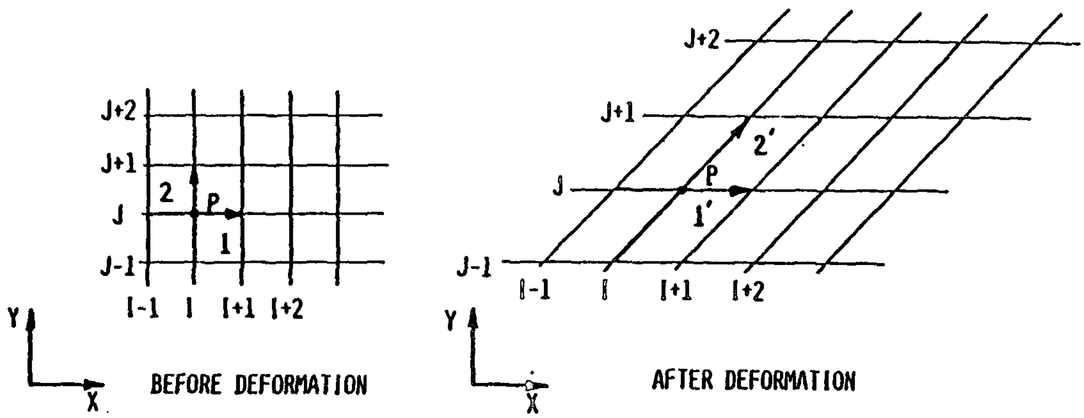

Fig. A. 1 Idealized grid pattern before and after deformation

where

$$C_{11} = (x_1' y_2 - x_2' y_1)/D$$
$$C_{21} = (y_1' y_2 - y_2' y_1)/D$$
$$C_{12} = (x_1 x_2' - x_2 x_1')/D$$
$$C_{22} = (x_1 y_2' - x_2 y_1')/D$$
$$D = x_1 y_2 - x_2 y_1$$
$$f = \sqrt{C_{11} C_{22} - C_{12} C_{21}}$$
$$q = \sqrt{B^2 - 1} \,/\, \mathrm{arccosh}\, B \quad \text{for } B > 1$$
$$= 1 \quad \text{for } B = 1$$
$$= \sqrt{1 - B^2} \,/\, \arccos B \quad \text{for } B < 1$$
$$B = (C_{11} + C_{22}) / 2f$$

From the above strain components, the magnitudes and directions of the principal strains are determined by,

$$\varepsilon_1 = (\varepsilon_x + \varepsilon_y)/2 + \sqrt{((\varepsilon_x - \varepsilon_y)/2)^2 + \varepsilon_{xy}^2} \tag{4}$$

$$\varepsilon_2 = (\varepsilon_x + \varepsilon_y)/2 - \sqrt{((\varepsilon_x - \varepsilon_y)/2)^2 + \varepsilon_{xy}^2} \tag{5}$$

and

$$\tan 2\theta = 2\varepsilon_{xy} / (\varepsilon_x - \varepsilon_y) \tag{6}$$

where θ is the angle between the x-axis and the major principal axis.

Assuming the material is characterized by normal anisotropy in the case of plane stress problem, the effective strain is calculated as follows.

$$\varepsilon_e = (1 + R) \sqrt{\varepsilon_1^2 + 2R\, \varepsilon_1 \varepsilon_2/(1 + R) + \varepsilon_2^2} \Big/ \sqrt{1 + 2R} \tag{7}$$

where R represents the normal anisotropy given as the ratio ($d\varepsilon_w/d\varepsilon_t$) between width strain and thickness strain of the sheet metal in uniaxial tension test.

Once the coordinates of the nodal points between two steps during deformation are determined, all informations necessary to calculate the grid deformation and the strains are given.