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Inhomogeneous deformation and residual stress in skin-pass axisymmetric drawing

*Heng-Sheng Lin**, *Yuan-Chuan Hsu*, *Chia-Chow Keh*

Department of Mechanical and Computer-Aided Engineering, National Formosa University, Hu-Wei, Yunlin 632, Taiwan

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ABSTRACT

Skin-pass drawing is usually conducted in the final stage of wire, rod or shaped-section drawing or shape rolling. It helps improve shape accuracy and reduce residual stress of the drawn or rolled workpieces. However, its characteristic low reduction induces large Δ-parameter, and causes significant inhomogeneous deformation in the workpiece. In this work, finite-element software DEFORM 2D was utilized to investigate the effect of Δ-parameter on inhomogeneous deformation and residual stress of mid-carbon steel through various combinations of area reduction and die semi-angle. The effect of the friction was also investigated. The results showed that the inhomogeneity factor of effective strain decreased with area reduction and increased with die semi-angle and friction. The level of inhomogeneous deformation could be reduced by drawing with small die semi-angle, and the influence of the friction was only substantial near the surface of the drawn workpiece. The axial and circumferential residual stresses would approach to compressive on the drawn surface in extreme light reductions.

1. Introduction

Skin-pass drawing is usually conducted in the final stage of wire, rod or shaped-section drawing or shape rolling. It helps improve shape accuracy and reduce residual stress of drawn or rolled workpieces. However, its characteristic low reduction induces large Δ-parameter, and causes significant inhomogeneous deformation in the workpiece. The Δ-parameter is defined as

$$\Delta = \frac{h}{L} \tag{1}$$

where h is the mean diameter of the workpiece and L is the contact length between the deforming workpiece and the die. The Δ-parameter, though not perfectly, is a measure of the influence of the deformation geometry upon the drawn workpiece (Hosford and Caddell, 1983). For axisymmetric drawing, Δ can be expressed as

$$\Delta = \frac{\sin\alpha}{r}\left(1+\sqrt{1-r}\right)^2 \tag{2}$$

where Δ is the die semi-angle, r is the reduction of the cross-sectional area. Eq. (2) indicates that Δ increases when α increases or r decreases. However, the small reduction used in skin-pass drawing intuitively bears a relatively large Δ value and impairs its goal of improving shape accuracy.

Backofen (1972) defines a hardness inhomogeneity factor to evaluate the level of inhomogeneous deformation as

$$\mathrm{IF} = \frac{H_s - H_c}{H_c} \tag{3}$$

where H_s and H_c are the Vickers hardness at the surface and center, respectively. This definition is suitable for experimental approach, whereas in the FE simulation the distribution

* *Corresponding author*. Tel.: +886 5631 5311; fax: +886 5 631 5310.
E-mail address: hslin@nfu.edu.tw (H.-S. Lin).

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of hardness is not available. Since hardness is caused by the straining of the material, and in order to facilitate the analysis of the data obtained from FE simulation, Backofen's definition of inhomogeneity factor is further modified as

$$IF_{\varepsilon} = \frac{\varepsilon_s - \varepsilon_c}{\varepsilon_s} \quad (4)$$

where ε_s and ε_c are the effective strain at the surface and center, respectively. The denominator is replaced by the effective strain at the surface because the magnitude of the effective strain might approach to very small value for skin-pass drawing and cause the inhomogeneity factor of strain to approach to a quite large value. A larger IF_{ε} represents a larger discrepancy between the effective strain of the surface and center, i.e., a drawing condition with more inhomogeneous deformation. Through the definition of Eq. (4), the level of inhomogeneous deformation incurred by the process parameters can be readily analyzed by extracting the effective strain of the surface and center out of the FE simulation, without consorting to the experimental measurement of hardness.

The definition of the inhomogeneity factor of hardness, Eq. (3), only takes into account the discrepancy of hardness between the surface and center of the drawn workpiece. It also assumes that the maximum hardness occurs on the surface and the minimum hardness occurs at the center. However, from the FE simulation of this work, it was observed that the effective strain does not necessarily increase monotonically from the center to the surface. The maximum effective strain might occur somewhere near the surface. Therefore a more objective definition, the mean variation of effective strain, was also applied to assess the level of inhomogeneous deformation which is defined as

$$\Delta\bar{\varepsilon} = \frac{\sum_{i=1}^{n} |\varepsilon_i - \bar{\varepsilon}| r_i^2 - r_{i-1}^2}{r_f^2} \quad (5)$$

where r_i is the radius of the ith point, and $i=0$ corresponds to the center and $i=n$ corresponds to the surface; r_f is the radius of the drawn workpiece. ε_i is the effective strain at point i, and $\bar{\varepsilon}$ is the mean effective strain of the cross-section which is defined as

$$\bar{\varepsilon} = \frac{\sum_{i=1}^{n} \varepsilon_i (r_i^2 - r_{i-1}^2)}{r_f^2} \quad (6)$$

Up to now, there has been abundant work reported for rod or wire drawing of medium reductions. However limited number of work was devoted to the drawing process of light reductions. This work focuses on investigating the relationship of the inhomogeneous deformation of effective strain as well as residual stress with the area reduction of the workpiece, the die semi-angle and workpiece/die friction condition by finite-element simulation.

2. Finite-element simulation

Finite-element software DEFORM was used in simulating the skin-pass drawing process. Since the process is axisymmetric in nature, the 2D Version 8.0 axisymmetric module was chosen. Mid-carbon steel AISI-1045 was used as the workpiece material, and the built-in stress–strain relationship of elasto-plasticity at 20 °C with yield strength 640 MPa was selected. Heat transfer effect was not considered. There were 5000 elements used in meshing the workpiece, and finer meshes were constructed close to the surface in order to better scope the "skin-pass" process. Billet length was 20 mm and the outlet diameter of the drawing die was 10 mm. Reduction of cross-section selected was from 2 to 10%. Converging die was used and assumed to be rigid. Values of the die semi-angle are from 2 to 20°. Die bearing length was 4 mm and the radius of the fillet joining the bearing and the converging zone was 0.2 mm. The drawing speed was fixed at 67 mm/s. The frictional law of constant shear strength was used and friction factors 0.1, 0.3 and 0.5 were selected. Usually drawing with a small friction factor corresponds to a forming condition of better lubrication at the workpiece/die interface and vice versa. Drawing with the billet is unsteady at the beginning and near the end of the process. Steady values appear at the middle of the billet and satisfactory data acquisition of the drawing load, cross-sectional distributions of the effective strain and the residual stress can be obtained.

3. Results and discussion

3.1. *Optimum die semi-angle*

Though minimizing drawing stress is not the primary consideration of skin-pass drawing, the evaluation of the optimum die semi-angle is still essential in understanding the characteristics of the process. Fig. 1 shows the variation of the normalized drawing stress with die semi-angle with area reductions ranging from 2 to 10%. The normalized drawing stress was obtained by dividing the drawing load with the outlet area of the drawn workpiece and normalized with the yield strength of workpiece. The friction factor was 0.1. For a selected reduction, the drawing stress first decreases and then increases with die semi-angle, as a consequence that the frictional work decreases and the redundant work increases with die semi-angle (Hosford and Caddell, 1983). The angle which yields the minimum drawing stress is the optimum die semi-angle of the respective reduction. The optimum angle gradually increases from 4 to 6° as the reduction increases from 2 to 10%. Same trends had been reported by Avitzur (1990)

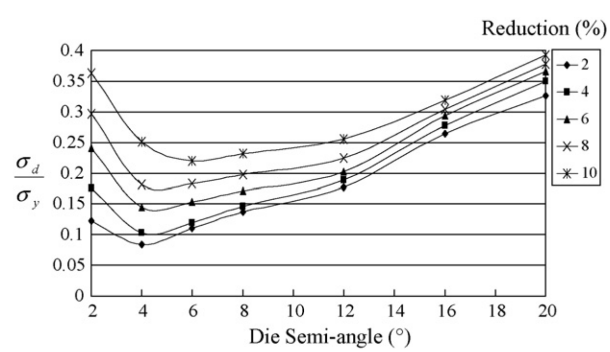

Fig. 1 – Variation of drawing stress with die semi-angle for various reductions.