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Investigation on the plastic deformation during the stamping of ellipsoidal heads for pressure vessels

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ABSTRACT

Ellipsoidal heads are widely used for constructing thin-walled pressure vessels. Stamping is an efficient way to manufacture massive amount of them, providing fine surface quality and accurately controlled shape. To accurately predict the plastic deformation of the head during the stamping is a vital aspect of controlling head quality. Yet, no satisfactory solution to this has been provided by current industrial standards, including GB/T 150.4–2011, GB/T 25198–2010, GB/T 18442.4–2011, ASME BPVC VIII 2–2017, EN13445-4:2014 and AS4458-1997. Thus, in this paper, equivalent plastic deformation (PEEQ) is proposed to be used for characterizing the plastic deformation. An FEM model was built and was experimentally verified. Then, the detailed perspective to the plastic deformation behavior of the head material during the stamping was provided with assistance of the FEM simulation. An empirical equation to predict the maximum plastic deformation was proposed based on extensive FEM simulations.

1. Introduction

Head is an important part of pressure vessels that are widely used in petroleum, chemical, nuclear power, and many other industrial applications [1]. Among various types of heads, ellipsoidal head is commonly used due to its ease of forming and economy. For a nominal diameter up to 3200 mm, the ellipsoidal heads are primarily produced by stamping which provides fine surface quality, accurately controlled shape, and massive production rate with high efficiency.

However, the blank material experiences a significant plastic deformation during the stamping process, that reduces the mechanical properties of the material. Although the plastic deformation induces strain hardening generally increasing the hardness and the yield strength, the excessive strain results great reduction in plasticity and toughness [2–5] which are more concerned in many applications, such as cryogenic pressure vessels. Furthermore, for the commonly used meta-stable austenitic stainless steel (mASS), strain-induced martensitic transformation occurs during the stamping resulting in a large amount of martensitic content in the high-strain region [6]. Those martensites degrade in the mechanical properties of the steel, and also cause pitting, surface cracking, and stress corrosion crack propagation [7,8]. Thus, there have been many vessel failure cases due to the cracks on the heads [9,10] that may be very much related to the material degradation due to the large plastic deformation during the stamping manufacturing. Heat treatment is subsequently desired at certain conditions to restore the mechanical properties of the head material after the forming. According to current industrial standards, including GB/T 150.4–2011 [11], GB/T 25198–2010 [12], GB/T 18442.4–2011 [13], ASME BPVC VIII 2–2017 [14], EN13445-4:2014 [15] and AS4458-1997 [16], the forming strain is an essential criterion for deciding whether the post-heat-treatment is required. Therefore, an accurate prediction of the head plastic deformation during the stamping process is a vital aspect of controlling head quality.

Two calculation methods for the maximum forming deformation for pressure vessel heads are provided by the current industrial standards. The equation given by Chinese standards, i.e. GB/T 150.4–2011, GB/T 25198–2010 and GB/T 18442.4–2011,

$$\epsilon_{\max} = \frac{0.75\delta_n}{\rho_{\min}} \times 100\% \tag{1}$$

presents the maximum engineering strain of the metal fiber in the longitudinal direction. Whereas, ASME BPVC VIII 2–2017, EN13445-4:2014 and AS4458-1997 recommend:

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Nomenclature

Latin letters

a	Semi major axis of the ellipse [mm]
D_b	Diameter of the blank [mm]
D_n	Nominal diameter of the head [mm]
h	Height of the skirt section [mm]
t	Time [s]
X	Longitudinal coordinates on the formed head [mm]
X_0	Radial coordinates on the blank [mm]
ΔX	Longitudinal stretching of the formed head [mm]
Y_{punch}	Punch stamping position [mm]

Greek letters

ϵ	Forming strain [−]
ϵ_X	Engineering strain in the longitudinal direction [−]
ϵ_δ	Engineering strain in the thickness direction [−]
ϵ_θ	Engineering strain in the latitudinal direction [−]
$\bar{\epsilon}^{pl}$	Equivalent plastic strain [−]
$\dot{\epsilon}^{pl}$	Equivalent plastic strain rate [s^{-1}]
δ_n	Nominal thickness of the head [−]
ρ	Curvature radius [mm]

Abbreviations

ARD	Absolute value of the relative deviation
FEM	Finite-element method
mASS	Meta-stable austenitic stainless steel
PEEQ	Equivalent plastic strain
RMSD	Root-mean-square deviation

$$\epsilon_{max} = ln\left(\frac{D_b}{D_n}\right) \times 100\% \tag{2}$$

which calculates the maximum true strain of head material in the latitudinal direction. These two methods analytically describe the strain in one direction, however, they are not sufficient for presenting the realistic complex deformation during the stamping process [6,17]. The complex strain includes not just normal strains in longitudinal, latitudinal and thickness directions, but also the shear strains that represent the slip motion between the inner layers and outer layers of the blank material. Therefore, in this paper, we propose using equivalent plastic strain (PEEQ, $\bar{\epsilon}^{pl}$) to characterize the plastic deformation. PEEQ is defined by [18],

$$\text{PEEQ} = \bar{\epsilon}^{pl} = \bar{\epsilon}^{pl}|_0 - \int_0^t \sqrt{\frac{2}{3}\dot{\epsilon}^{pl}:\dot{\epsilon}^{pl}}\,dt \tag{3}$$

where $\bar{\epsilon}^{pl}|_0$ is the initial equivalent plastic strain and $\dot{\epsilon}^{pl}$ is the equivalent plastic strain rate. PEEQ basically presents an accumulation of the plastic deformation during the process. By using PEEQ, the complex strain during the stamping process can be described more comprehensively, and evaluated and compared more easily by using a scalar rather than a strain tensor. Moreover, the strain-induced degradation in the mechanical performance of the material is related to PEEQ more closely rather than strain in a single direction.

In this paper, the stamping process was simulated by FEM method, that was experimentally verified by comparing simulation to the real longitudinal elongation on stamped heads. With the assistance of FEM simulation, the plastic deformation and the stress condition during the stamping process are analyzed. Stamping processes of various sizes of the ellipsoidal heads have been simulated, and the resultant maximum PEEQ is fitted by an empirical equation correlating with the diameter and thickness of the heads.

2. Head stamping and FEM model

2.1. Definition of the coordinates and sections

In order to identify the large plastic deformation distribution on an ellipsoidal head during the stamping process, a reference coordinate is defined on the formed head as shown in Fig. 1(a). The X-axis represents the longitudinal direction on the outer surface of the head, the θ-axis is the latitudinal direction and the δ -axis shows the thickness direction. Y-axis stands for the symmetric axis of the head, which shows the stamping direction as well. Solo X-coordinate is sufficient enough to locate any infinitesimal element of interest because of the well defined axial-symmetry shape of the formed head. Moreover, similar coordinate denoted with an additional subscript of "0" is also constructed on the blank before stamping, as shown in Fig. 1(b).

In this paper, standard ellipsoidal heads with a major/minor axis ratio of 2 are discussed as they are most widely used in the real application. As a matter of convenience for the discussion, the ellipsoidal head has been divided into three sections based on the curvature radius of the ellipse. As shown in Fig. 2, the blue line represents the ratio of the curvature radius to the semi major axis (ρ/a), which varies from 2 to 0.25 as its position moves outwards from the center. A "Crown section" is identified as $\rho/a \geq 1$, whereas the rest part of the ellipse is denoted as the "Knuckle section". The "Skirt section" is the straight part at the edge of a head. Because the projection of the inner surface on the cross-section is a pre-defined ellipse with an eccentricity of $\sqrt{3}/2$, by neglecting the offset due to the thickness, such division on the X coordinate (which is set on the outer surface of the head) is approximately given by,

$$\begin{cases} \text{Crown section:} & 0 \leq X < 0.362D_n \\ \text{Knuckle section:} & 0.362D_n \leq X < 0.606D_n \\ \text{Skirt section:} & 0.606D_n \leq X < 0.606D_n + h \end{cases} \tag{4}$$

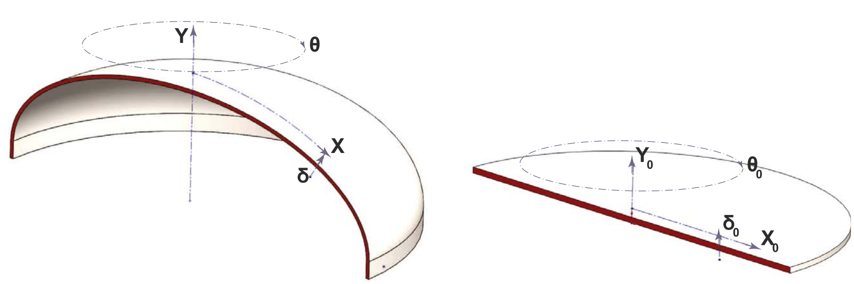

Fig. 1. Coordinates definitions for the ellipsodial head stamping: (a) coordinates on the stamped head; (b) coordinates on the blank.