ournal of University of Science and Technology Beijing
Vol.6(1999), No.3, p.201

Materials

Prediction and Control of both Wrinkle Limit and Fracture Limit on Cylindrical Cup Deep-drawing (II)

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(Received 1998-09-18)

Abstract: The prediction and control criterion of both the wrinkle limit and fracture limit on the cylindrical cup deep-drawing are given, and the prediction and control diagram of both the wrinkle limit and fracture limit are also given. The results show that it is suitable for no-flange cylindrical cup deep-drawing, narrow-flange cylindrical cup deep-drawing, wide-flange cylindrical cup deep-drawing/expanding compound forming and rigid punch expanding forming.

Key words: cylindrical cup; wrinkle limit; fracture limit; deep-drawing; expanding forming; compound forming

The cylindrical cup deep-drawing is not only the most common and representative technology in sheet forming but also the important test method evaluating sheet forming properties. It contains no-flange cylindrical cup deep-drawing, narrow-flange cylindrical cup deep-drawing and wide-flange cylindrical cup deep-drawing. This study aims to introduce the prediction and control criterion of both the wrinkle limit and fracture limit on no-flange cylindrical cup deep-drawing, narrow-flange cylindrical cup deep-drawing and wide-flange cylindrical cup deep-drawing.

1 Prediction and Control of Wrinkle Limit

The no-wrinkle limit on cylindrical cup deep-drawing in reference [1] is

$$Q^{\mathrm{W}} \geq \frac{\pi D_0 t_0 (\eta - m)}{2(f_{\mathrm{d}} + f_{\mathrm{b}})\sqrt{\eta}} \beta \bar{S} \times \left\{ 1 - \left[\frac{\frac{t_0}{D_0} \times 100}{22.71\sqrt{\eta}(\eta - m)\left(\sqrt{\frac{\bar{\varepsilon}}{n}} + \sqrt{\frac{\bar{S}}{E}}\right)} \right]^2 \right\} \tag{1}$$

where Q^{W} is the wrinkle critical blank-holder force, that is the wrinkle-proof minimum blank-holder force; D_0 the blank diameter; t_0 the blank thickness; $\frac{t_0}{D_0} \times 100$ the blank relative thickness; $\eta = \frac{D_{\mathrm{t}}}{D_0}$ the blank edge relative movement position, and D_{t} the flange outer-edge diameter; $m = \frac{d}{D_0}$ the deep-drawing coefficient, and d the cylindrical cup deep-drawing diameter; f_{d} and f_{b} are the friction factors between the blank and both the die and the blank-holder respectively; $\beta = 1.1$; $\bar{S} = B\bar{\varepsilon}^n$ the average flow stress in the flange deformation zone, and B the strength coefficient, n the strain-hardening exponent; $\bar{\varepsilon} = \left| \frac{1}{2} \ln \frac{\eta m}{\sqrt{1 - \eta^2 + m^2}} \right|$ the average logarithmic strain in the flange deformation zone ; E the modulus of elasticity. The equality sign expresses the critical condition of both the wrinkle and no-wrinkle.

Equation (1) is the no-wrinkle limit criterion determined by the wrinkle model. In accordance with it, the minimum blank-holder force—the wrinkle critical blank-holder force regarded as the prediction and control of the wrinkle limit can be calculated.

2 Prediction and Control of Fracture Limit

The no-fracture limit on cylindrical cup deep-drawing in reference [1] is

$$Q^{\mathrm{F}} \leq \frac{\pi D_0 t_0 m}{f_{\mathrm{d}} + f_{\mathrm{b}}} \times \left\{ \left[C_1 \mathrm{e}^n \left(\frac{1 + r}{\sqrt{1 + 2r}} \right)^{n-1} - \frac{t_0}{2r_{\mathrm{d}} + t_0} \right] \frac{\sigma_{\mathrm{b}}}{(1 + 1.6 f_{\mathrm{d}})} - \beta \bar{S} \ln \frac{\eta}{m} \right\} \tag{2}$$

where Q^{F} is the fracture critical blank-holder force, that is the maximum blank-holder force; $C_1 = 0.90$–0.94 the weakening coefficient, generally, taking $C_1 = 0.92$; r the plastic strain ratio (or thickness an-isotropic exponent); r_{d} the profile radial of die; σ_{b} the tensile strength. The equality sign shows the critical condition of both the fracture and no-fracture.

Equation (2) is the no-fracture limit criterion determined by the fracture model. By means of it, the maximum blank-holder force——the fracture critical blank-holder force regarded as the prediction and control of the fracture limit can be calculated.

3 Prediction and Control of both Wrinkle Limit and Fracture Limit

Combining the wrinkle limit (equation (1)) with the fracture limit (equation (2)), a prediction and control criterion of the wrinkle limit and fracture limit on the cylindrical cup deep-drawing is given:

$$Q^{W} \le Q \le Q^{F} \quad (3)$$

As soon as the blank-holder force Q meets the condition of equation (3), the two barriers—wrinkle and fracture in sheet forming can be removed, and the sheet forming is carried out successfully.

In order to express directly the prediction and control law of both the wrinkle limit and fracture limit on the cylindrical cup deep-drawing, austenitic stainless steel 1Cr18Ni9Ti is regarded as a calculation example. The changes of Q^{W} and Q^{F} in the deep-drawing process are shown in **figure 1**.

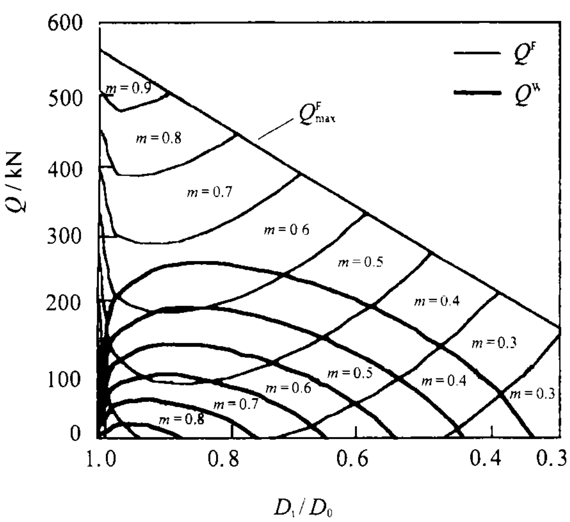

Figure 1 The changes of both the wrinkle critical blank-holder force Q^{W} and the fracture critical blank-holder force Q^{F} in the process of the deeping-drawing

It is obvious that Q^{W} has the maximum and Q^{F} the minimum. These two limit values appear in the same position. Moreover, it is the basic same with the blank relative thickness maximum position in reference [2]. When the deep-drawing coefficient m is greater (such as $m \ge 0.6$), Q^{W} curve and Q^{F} curve don't intersect each other. As soon as Q meets $Q \in [Q^{W}_{max}, Q^{F}_{min}]$, the sheet forming can be carried out successfully, that is the sheet forming of no-flange cylindrical cup deep-drawing and narrow-flange cylindrical cup deep-drawing. When m is smaller (such as $m \le 0.5$), Q^{W} curve intersects Q^{F} curve at two points (η_L is the left intersection point or the front intersection point, η_R the right intersection point or the back intersection point). The left intersection point is the flange minimum forming position, that is the sheet forming of wide-flange cylindrical cup deep-drawing. So long as Q meets $Q \in [Q^{W}, Q^{F}] \cap \eta \in [1, \eta_L]$, the sheet forming can be carried out successfully (or as $\eta < \eta_L$, the wide-flange cylindrical cup deep-drawing must be fractured).

The wrinkle-proof blank-holder force Q had better change with the law of Q^{W}, but realizing it is difficult in production. Thus, as soon as Q is greater than the maximum Q^{W}_{max} of Q^{W}, it can guarantee against the occurrence of wrinkle in the whole process of deep-drawing. However, Q is not greater than the minimum Q^{F}_{min} of Q^{F}, otherwise, the expanding forming up to the fracture (the tensile plasticity instability) would take place. In addition, Q is not even greater than the maximum Q^{F}_{max} of Q^{F}, or else fracture would take place. Consequently, the sheet forming (deep-drawing forming) of wide-flange cylindrical cup deep-drawing is the deep-drawing / the expanding compound forming. At present, the blank diameter D_t becomes smaller and smaller, and $\eta = \frac{D_t}{D_0}$ change is also small. The position η is not used to express the deep-drawing /the expanding compound forming process (η only expresses the deep-drawing forming process, when the sheet forming is expanding forming, D_t does not change, so does η). The drawing relative forming height h/d (h is the drawing forming height) is used to express the deep-drawing / the expanding compound forming process. Moreover, h/d must add the drawing relative expanding height h_e/d (h_e is the drawing expanding height). The sheet forming limit diagram of wide-flange cylindrical cup deep-drawing is shown in **figure 2**.

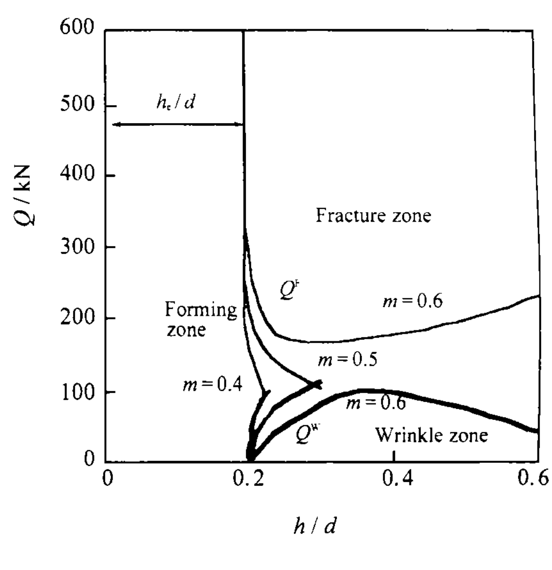

Figure 2 The sheet metal forming limit diagram on the wide-flange cylindrical cup deep-drawing

Figure 3 shows the prediction and control diagram of both the wrinkle limit and fracture limit on the cylindrical cup deep-drawing. It is drafted on basis of figure 1 or equation (1) and equation (2).

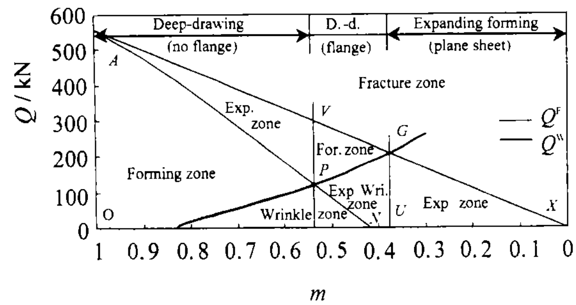

Figure 3 The prediction and control full diagram of the wrinkle and the fracture limits on cylindrical cup deep-drawing

In figure 3, the maximum Q^{W}_{max} curve of Q^{W} intersects the minimum Q^{F}_{min} curve of Q^{F} at point P, the responding deep-drawing coefficient m^{d}_{min} of point P is defined as the limit deep-drawing coefficient. The maximum Q^{W}_{max} curve of Q^{W} intersects the maximum Q^{F}_{max} curve of Q^{F} at point G, the responding deep-drawing coefficient m^{e}_{min} of point G is defined as the minimum deep-drawing coefficient. In addition, the minimum Q^{W}_{min} curve of Q^{W} intersects both the minimum Q^{F}_{min} curve and the maximum Q^{F}_{max} curve of Q^{F} at point N and X respectively. The responding deep-drawing coefficient m^{F}_{min} of point N is named as the limit deep-drawing coefficient determined by only fracture limit.

When $m\in[1, m^{d}_{min})$, the sheet forming is the deep-drawing forming of no-flange cylindrical cup deep-drawing. Moreover, the zone of $Q>Q^{F}_{max}$ is the fracture zone $(m\in[1, m^{d}_{min})\cap Q>Q^{F}_{max})$, the zone of $Q\in(Q^{F}_{min}, Q^{F}_{max})$ is the expanding zone $(m\in[1, m^{d}_{min})\cap Q\in(Q^{F}_{min}, Q^{F}_{max}))$, the zone of $Q\in(Q^{W}_{max}, Q^{F}_{min})$ is the deep-drawing forming zone $(m\in[1, m^{d}_{min})\cap Q\in(Q^{W}_{max}, Q^{F}_{min}))$, and the zone of $Q<Q^{W}_{max}$ is the wrinkle zone $(m\in[1, m^{d}_{min}]\cap Q<Q^{W}_{max})$. When $m\in[m^{d}_{min}, m^{e}_{min})$, the sheet forming is the deep-drawing forming of flange cylindrical cup deep-drawing (narrow-flange and wide-flange). In addition, the zone of $Q>Q^{F}_{max}$ is the fracture zone $(m\in[m^{d}_{min}, m^{e}_{min})\cap Q>Q^{F}_{max})$, the zone of $Q\in(Q^{W}_{max}, Q^{F}_{max})$ is the deep-drawing /the expanding compound forming zone $(m\in[m^{d}_{min}, m^{e}_{min})\cap Q\in(Q^{W}_{max}, Q^{F}_{max}))$, the zone of $Q\in(Q^{F}_{min}, Q^{W}_{max})$ is the wrinkle/expanding zone $(m\in[m^{d}_{min}, m^{e}_{min})\cap Q\in(Q^{F}_{min}, Q^{W}_{max}))$, and the zone of $Q<Q^{F}_{min}$ is the wrinkle zone $(m\in[m^{d}_{min}, m^{e}_{min})\cap Q<Q^{F}_{min})$. When $m\in[m^{e}_{min}, 0)$, the sheet forming is the rigid punch expanding zone. Moreover, the zone of $Q>Q^{F}_{max}$ is the fracture zone $(m\in[m^{e}_{min}, 0)\cap Q>Q^{F}_{max})$, the zone of $Q<Q^{F}_{max}$ is the expanding zone $(m\in[m^{e}_{min}, 0)\cap Q<Q^{F}_{max})$.

There are three forming zones in broad outline. OPA zone is the deep-drawing forming zone of no-flange cylindrical cup deep-drawing; PGV zone is the deep-drawing / the expanding compound forming zone of flange cylindrical cup deep-drawing; UXG zone is the expanding forming zone of plane sheet. Therefore, as long as Q is selected in respective forming zone, the two barriers——wrinkle and fracture in the sheet forming can be removed, and the sheet forming is carried out successfully. On basis of the energy consume, the wrinkle-proof blank-holder force Q had better be selected on the maximum Q^{W}_{max} of Q^{W}, or $Q\in[1, 1.2]Q^{W}_{max}$. The deep-drawing coefficient m is far from the limit deep-drawing coefficient point P or the minimum deep-drawing coefficient point G; otherwise, the narrower the forming zone determined by the wrinkle limit and fracture limit, the lower the forming stability.

The limit deep-drawing coefficients and the minimum deep-drawing coefficients on 1Cr18Ni9Ti and 08Al sheet are $m^{d}_{min}=m|_{Q^{W}_{max}=Q^{F}_{min}}=0.54$, $m^{d}_{min}=0.53$ and $m^{e}_{min}=m|_{Q^{W}_{max}=Q^{F}_{max}}=0.37$, $m^{e}_{min}=0.36$ respectively. The limit deep-drawing coefficient on 10F sheet is $m^{d}_{min}=0.56$, the minimum deep-drawing coefficient is $m^{e}_{min}=0.38$, *et al.* They are identical with **figure 4** [3–5]. Those show

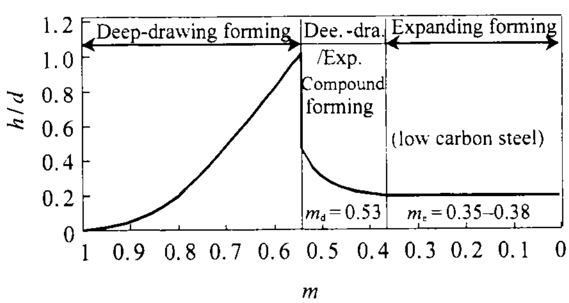

Figure 4 The relation between the deep-drawing forming and the expanding forming

that the prediction and control of both the wrinkle limit and fracture limit on the cylindrical cup deep-drawing is quite accurate, and is feasible in actual production.

4 Conclusions

(1) The prediction and control technology of both the wrinkle limit and fracture limit on the cylindrical cup deep-drawing is all suitable for no-flange cylindrical cup deep-drawing, narrow-flange cylindrical cup deep-drawing and wide-flange cylindrical cup deep-drawing. It not only enriched and developed the sheet forming theories, but also can be used to guide the sheet forming in actual production. Moreover, the results are quite accurate and reliable.

(2) The limit deep-drawing coefficient m^{d}_{min} and the minimum deep-drawing coefficient m^{e}_{min} should be determined by both the wrinkle limit and fracture limit. The limit deep-drawing coefficient m^{d}_{min} is the lowest bound of the deep-drawing forming, and the minimum deep-drawing coefficient m^{e}_{min} is the lowest bound of the deep-drawing / the expanding compound forming.

(3) The deep-drawing forming zone of the no-flange cylindrical cup deep-drawing determined by both the wrinkle limit and fracture limit is $m\in[1, m^{d}_{min}) \cap Q\in [Q^{W}_{max}, Q^{F}_{min})$; the deep-drawing forming zone of the flange cylindrical cup deep-drawing (narrow-flange and wide-flange)determined by both the wrinkle limit and fracture limit is $m\in[m^{d}_{min}, m^{e}_{min}) \cap Q\in[Q^{W}_{max}, Q^{F}_{max})$, generally $Q\in[1, 1.2]\ Q^{W}_{max}$ in the forming zones.

(4) The prediction and control technology of both the wrinkle limit and fracture limit on the cylindrical cup deep-drawing includes the deep-drawing forming, the expanding forming and the deep-drawing / the expanding compound forming.

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4 Conclusions

(1) CeO_2/Al_2O_3 thin film was easier to be reduced and re-oxidized than pure CeO_2 powder.

(2) The thermodynamics analysis indicated that if there were Al_2O_3 on the surface of the film and the partial oxygen pressure was low, CeO_2 would react with Al_2O_3 and to be reduced to Ce^{3+}.

(3) There was interaction between CeO_2 and Al_2O_3. Some Al^{3+} replaced Ce^{4+} and created oxygen vacancies, these vacancies moved to the surface and went out of the system, hence, the content of oxygen was decreased.

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