Influences of thickness ratio of base sheets on formability of tailor welded blanks

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Abstract

The influences of thickness ratio of base sheets on formability of tailor welded blanks were examined based on Erichsen cupping tests. Three-dimensional finite element (FE) models, using Hill’48 yield criterion and iso-hardening rule, were built under the environment of the FE analysis software ABAQUS. The failure onset sites of tailor welded blanks were analysed and the quantitative relationships between the Erichsen index values and base thickness ratio were established. Based on these relationships, the formability of tailor welded blanks made from dissimilar base sheets are evaluated, provided that the Erichsen index values of tailor welded blanks made from identical ones are known and that the above two different types of tailor welded blanks undergo a similar stamping process. The experiments were then carried out to validate this method.

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1. Introduction

Tailor welded blanks are usually comprised of two or more sheets of metal with dissimilar strength and/or thickness that are welded into a single blank. The usage of tailor welded blanks meets the stringent requirements imposed by the automotive industry in terms of weight reduction and energy saving, etc. When using this
technology, the main challenge is the drop in formability due to the existence of welds. Therefore, it is necessary to investigate the influence factors of formability of tailor welded blanks. Up to now, many focus on the influences of stamping process parameters on the formability of tailor welded blanks. Choi et al. (2000) compared the effects of different geometries of tailor welded blanks on their formability. Heo et al. (2001) reports the effects of drawbead dimensions in the deep drawing of tailor welded blanks. Padmanabhan et al. (2008) investigated the effects of the binder types on the deep drawing behaviours of aluminum–steel tailor welded blanks. Leitao et al. (2011) discussed the affects of mismatch type between the weld and base metals on the formability of tailor welded blanks.

As for the influences of thickness ratio of base sheets, only several reports can be found. Shakeri et al. (2002) point out that the thickness ratio of base sheets is a significant factor affecting the failure types of tailor welded blanks. Davies et al. (2002) developed a forming limit diagram measurement method of describing the formability of tailor welded blanks. So far, the literature relevant to formability prediction of tailor welded blanks made from dissimilar base sheets, however, is still very limited. This issue will be addressed in this paper by conducting a series of simulations and experiments of Erichsen cupping tests for tailor welded blanks.

2. Simulations

A group of tailor welded blanks made from base sheets with different thickness ratio, \( \beta \), were chosen. If \( t_1, t_2 \) represent thicknesses of base sheet 1 and 2 respectively, then \( \beta = t_2 / t_1 \). In this case (hereinafter Case 1), \( t_1 \) was a constant of 0.75 mm, while \( t_2 \) increased from 0.75 mm to 1.75 mm at intervals of 0.25 mm. Thus, a series of \( \beta \), i.e., 1.00, 1.33, 1.67, 2.00, 2.33, were obtained. As can be seen from Fig. 1, the plastic deformation behaviours of the base and weld metals are assumed to follow the Hollomon-type power law, namely \( \sigma = K\varepsilon^n \). Here, \( \sigma \) and \( \varepsilon \) are the true stress and strain respectively; \( K \) and \( n \) are the strength coefficient and strain hardening exponent respectively. Note that \( K \) and \( n \) of weld metals were approximately computed using the empirical formulas, i.e.,

\[
K_w = 0.8 \times (K_1 + K_2), \quad n_w = 0.8 \times (n_1 + n_2)/2,
\]

based on our former research work (Song, 2012). Subscripts 1, 2 and \( w \) here refer to base sheet 1, base sheet 2 and the weld.

As for the simulations, three-dimensional FE models, using Hill’48 yield criterion and iso-hardening rule, were built under the environment of the FE analysis software ABAQUS 6.10 (Fig. 2a). The dimensions of tailor welded blanks were 90 mm × 90 mm and the laser weld width was assumed to be 1.2 mm. The blank was modelled with a total of 7680 reduced integration four-node shell elements (S4R) with a fine mesh near the weld region and a gradually coarser mesh further away, to achieve a balance between computational efficiency and accuracy (Fig. 2b). For example, the mesh sizes the weld and heat-affected zone were nearly 0.44×0.15 mm. Note that within weld and heat-affected zone homogeneous properties were assumed by applying 1.0 for all anisotropic coefficients in Hill’48 yield criterion. As for the failure criterion, forming limit curves of the base and weld metals were calculated separately on the basis of the diffuse instability and localized instability theories (Song and Hua, 2012). The stamping parameters used in this study are listed in Table 1.
Table 1. Stamping parameters in the Erichsen cupping tests.

| Punch velocity (mm/s) | Binder type | Blank holding force (kN) | Friction coefficients |
|-----------------------|-------------|--------------------------|-----------------------|
|                       |             |                          | Punch/Blank | Die/Blank | Binder/Blank |
| 30                    | Segmented blank holder | 50 (thicker side)/50 (thinner side) | 0.08 | 0.08 | 0.08 |

3. Results and discussion

Fig. 3 shows the FLDCRT contour of tailor welded blanks in the Erichsen cupping tests in Case 1. Here, FLDCRT stands for maximum value of the forming limit diagram damage initiation criterion, $\omega_{FLD}$, during the analysis. A higher value of $\omega_{FLD}$ indicates a higher risk of crack initiation and in case of $\omega_{FLD} = 1$, a crack occurs. It can be seen that cracks initiate in the heat-affected zones beside the thinner base sides and then propagates parallel to the welds for all the samples except for the one made from base sheets of identical gauge (i.e., $\beta = 1.0$).

Fig. 3. FLDCRT contour of tailor welded blanks made from base sheets of different thickness ratio $\beta$: (a) $\beta=1.00$, (b) $\beta=1.33$, (c) $\beta=1.67$, (d) $\beta=2.00$ and (e) $\beta=2.33$.

The influences of different base thickness ratio on the formability of tailor welded blanks are given in Fig. 4. Note that the first contact instant between the punch and each tailor welded blank was different because the cross sections of welds were dissimilar. Therefore, the punch stroke at the instant that the punch load sharply increased are different for each sample (Fig. 4a) and some amendments were adopted to ensure the accuracy of the Erichsen
index values. From Fig. 4b and c, it can be seen that increasing base thickness ratio causes a linear decrease in the Erichsen indexes and a curvilinear decrease in the maximum punch loads. The fitted curves are given as follows

\[
IE = 0.1834\beta^2 - 2.864\beta + 10.37, \quad (1)
\]

\[
F_{\text{max}} = -0.2798\beta^2 + 0.3065\beta^2 + 0.371\beta + 7.061, \quad (2)
\]

where \( IE \) and \( F_{\text{max}} \) stand for the Erichsen index values and the maximum punch loads respectively. According to Eqs. (1) and (2), the change rates of \( IE \) and \( F_{\text{max}} \), which are denoted by \( \chi_\beta \) and \( \gamma_\beta \) respectively, can be calculated as

\[
\chi_\beta = 0.024\beta^2 - 0.372\beta + 1.349, \quad (3)
\]

\[
\gamma_\beta = -0.038\beta^2 + 0.041\beta + 0.05\beta + 0.947. \quad (4)
\]

Therefore, provided that the Erichsen index value and the maximum punch load of a tailor welded blank made from base sheets of both identical strength and thickness are known as \( IE_0 \) and \( F_{\text{max}0} \) respectively, the forming performance of the tailor welded blank made from base sheets of identical strength but different thickness (i.e., the base thickness ratio being \( \beta \) ) can be evaluated as

\[
IE(IE_0, \chi_\beta) = \chi_\beta \cdot IE_0, \quad (5)
\]

\[
F_{\text{max}}(F_{\text{max}0}, \gamma_\beta) = \gamma_\beta \cdot F_{\text{max}0}. \quad (6)
\]

Fig. 4. Influences of thickness ratio \( \beta \) on forming performance of tailor welded blanks made from base sheets of identical strength (Case 1): (a) Erichsen index value and (b) maximum punch load.

4. Other case study

Further simulations were conducted to examine the application scopes of Eqs. (1)-(6) and the schemes were listed as follows (Case 1 has been addressed in Section 2).
(1) Case 2: The initial thickness of base sheet 1, \( t_1 \), was a constant of 1.0 mm and all the other conditions including the strength coefficient, \( K \) (i.e., \( K_1 \) or \( K_2 \)), remained unchanged, i.e., \( t_1=1.0\text{mm}, K=500\text{MPa} \).

(2) Case 3: The initial thickness of base sheet 1, \( t_1 \), is a constant of 1.0 mm, the strength coefficient, \( K \) (i.e., \( K_1 \) or \( K_2 \)), was a constant of 1000 MPa and all the other conditions remained unchanged, i.e., \( t_1=1.0\text{mm}, K=1000\text{MPa} \).

In Case 2 (and 3), increasing the base thickness ratio, the simulation results were obtained as shown in Fig. 5. It can be seen that only changing \( t_1 \) (from 0.75 mm to 1.0 mm) leads to inconspicuous changes in both \( IE \) and \( F_{\max} \) curves (Case 2), compared to the results in Case 1. However, when changing both \( t_1 \) (from 0.75 mm to 1.0 mm) and \( K \) (from 500 MPa to 1000 MPa), the fitted \( IE \) curve still change indistinctly, while the fitted \( F_{\max} \) curve increase greatly (Case 3), compared to the results in Case 1.

![Fig. 5. Influences of base thickness ratio \( \beta \) on formability of tailor welded blanks with different initial thickness and strength coefficient (Cases 2 and 3): (a) Erichsen index value and (b) maximum punch load.](image)

Therefore, assuming that the \( IE \) values of the tailor welded blanks made from base sheets of both identical strength and thickness are known and all tailor welded blanks undergo a similar stamping process, the \( IE \) values of tailor welded blanks made from base sheets of identical strength but different thickness can be evaluated base on Eqs. (3) and (5); On the other side, the forming forces, however, may not be accurately estimated by using Eqs. (4) and (6) in some cases. On this basis, the following assumption can be further made. For a tailor welded blank made from base metals satisfying \( 500\text{MPa} \leq K \leq 1000\text{MPa} \) and \( 0.75\text{mm} \leq t_1 \leq 1.0\text{mm} \) (\( t_1 \) is the thickness of the thinner base metal), its Erichsen index can be predicted by using the fitted \( IE \) curves in Fig. 5a.

5. Experimental verification

In this section, the Erichsen cupping tests were conducted on a number of DP600 steel tailor welded blanks experimentally to verify the above results. The mechanical properties of base and weld metals can be found in our former work without taking the gauge into consideration (Song and Hua, 2012). The stamping parameters adopted in the verification tests were in accordance with those listed in Table 1. Note that a rigid plate blank holder was adopted in the experiments with some auxiliary measures since the segmented blank holder was difficult to be used in the existing test machine. The experimental results and the aforementioned \( IE \) curves are compared in Fig. 6. As can be seen from this figure, when \( \beta=1 \), the crack is initiated in the weld and then propagates perpendicularly into the base metals; and when \( \beta>1 \), the crack is initiated in the heat-affected zone beside the thinner side and then propagates parallel to the weld. It reveals that the experimental results on the crack sites are in accordance with the simulated ones (Fig. 3). Provided that the base sheets meet the requirement of \( (500\text{MPa} \leq K \leq 1000\text{MPa} \) and \( 0.75\text{mm} \leq t_1 \leq 1.0\text{mm} \)), it can be further found that the experimental results agree to the fitted curves. These facts have confirmed the reliability of the proposed method in this work.
6. Conclusions

In this work, the crack onset sites of tailor welded blanks during the Erichsen cupping tests were analysed. The quantitative relationships between the forming performances and the base thickness ratio were established for tailor welded blanks made from base sheets of identical strength. Based on these relationships, the $IE$ values of tailor welded blanks made from base sheets of identical strength but different thickness can be evaluated and the forming forces, however, may not be accurately estimated in some cases, assuming that the $IE$ values of the tailor welded blanks made from base sheets of identical strength and thickness are known and the two different types of tailor welded blanks undergo a similar stamping process. The fact that the experimental results basically agree to the fitted curves has confirmed the reliability of the proposed method in this work.

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References

[1] Choi, Y., Heo, Y., Kim, H. Y., Seo, D. G., 2000. Investigations of weld-line movements for the deep drawing process of tailor welded blanks. Journal of Materials Processing Technology, 108(1), 1–7.
[2] Davies, R., Grant, G., Smith, M., Mccleary, S., 2002. Describing the Formability of Tailor Welded Blanks. International Body Engineering Conference & Exhibition and Automotive & Transportation Technology Congress, SAE Technical Paper Series, 2002–01–2085.
[3] Heo, Y. M., Wang, S. H., Kim, H. Y., Seoa, D. G., 2001. The effect of the drawbead dimensions on the weld-line movements in the deep drawing of tailor-welded blanks. Journal of Materials Processing Technology, 113(1–3), 686–691.
[4] Leitao, C., Zhang, B. K., Padmanabhan, R., Rodrigues, D. M., 2011. Influence of weld geometry and mismatch on formability of aluminium tailor welded blanks: numerical and experimental analysis. Science and Technology of Welding and Joining, 16 (8), 662–668.
[5] Padmanabhan, R., Oliveira, M. C., Menezes, L. F., 2008. Deep drawing of aluminum–steel tailor-welded blanks. Materials and Design, 29(1), 154–160.
[6] Shakeri, H. R., Buste, A., Worswick, M. J., Clarke, J. A., Feng, F., Jain, M., Finn, M., 2002. Study of damage initiation and fracture in aluminum tailor welded blanks made via different welding techniques. Journal of Light Metals, 2(2), 95–110.
[7] Song, Y. L., 2012. Fundamental study on weld bead modelling and forming behaviour for laser welded blanks. Doctoral Dissertation, Wuhan, Wuhan University of Technology ( In Chinese).
[8] Song, Y. L., Hua, L., 2012. Influence of inhomogeneous constitutive properties of weld materials on formability of tailor welded blanks. Materials Science and Engineering A, 552(8), 222–229.