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MODELING TAILOR WELDED BLANKS (TWB) – A CRITICAL ISSUE

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ABSTRACT

The critical issue during finite element analysis of Tailor Welded Blank (TWB) is the handling of the weld region - either the weld may be treated just as a weld line (without imposing mechanical properties) or as a weld zone (by imposing separate mechanical properties to the weld zone). Weld line assumption may not be accurate for all the weld conditions and this should depend on the relative mechanical properties of the weld zone and the base metal also. The above effects will be discussed by considering the Limiting Dome Height (LDH) test of the TWB. Samples deforming near plane strain and balanced biaxial stretching will be simulated by finite element analysis. Load-progression behavior will be monitored. Also, the effect of weld conditions on the limit strains will be studied by simulating the near tensile strain path in LDH test. It is found from the analysis that modeling weld region as weld line is not accurate for all the weld conditions. Also, the domain of weld conditions wherein weld line assumption breaks down depends on the deformation mode. The effect of weld conditions on the limit strains depends on the weld orientation and weld location.

Keywords: Tailor Welded Blanks, Forming, Simulation, Weld conditions

1. INTRODUCTION

Tailor Welded Blanks (TWB) are blanks composed of sheets of dissimilar or similar thicknesses, strength or coatings etc. welded in a single plane before forming. Applications of TWB include door inner panel, center pillar, bumper, side frame rails, deck lids etc. in the automotive sector[1,2]. Finite Element (FE) analysis is extensively used for simulating various sheet metal forming processes[3,4]. FE analysis of forming of TWB is performed by two methods, i.e., either by considering the weld region as a weld line (wherein no mechanical properties of weld zone is required and weld line is just a boundary between the two sheets welded) or by considering a separate weld zone (wherein mechanical properties of the weld region are required). Most of the analysis available in the literature considers weld just as a weld line to predict the forming behavior of TWB. The possible reasons for weld line assumption being popular are (a) difficulty in measuring weld mechanical properties and (b) weld line modeling predicts the forming behavior of TWB with acceptable accuracy in many cases. But in principle, weld zone is a separate zone where the mechanical properties will be different from that of base metal. Hence, modeling weld zone as a line may not predict the forming behavior accurately in all the cases.

Buste et al.[5] modeled TWB with different gauge combinations by rigid link modeling technique, where rigid links are used to join thinner blank to thicker blank. Strain distribution was predicted and it was comparable with the experiments except near the weld region. This model could not predict the failure locations accurately because of the sudden transition in gauge[5].

Instead of weld line modeling, if weld zone modeling was followed then one can possibly expect the model to predict the failure location accurately. It is indicated by Saunders and Wagoner[6] that the weld line movement predictions performed by assuming weld line and weld zone has negligible difference and hence they concluded that the entire formability simulations can be performed by weld line assumption. Bhagwan et al.[7] modeled the weld region as a separate zone (incorporating the weld properties) by varying the weld geometry and profile. It was indicated that weld geometry/profile is possibly more important than considering the mechanical properties of weld zone during the TWB forming analysis. But this conclusion was based on a particular combination of base-weld property, which may not hold good for other property combinations.

Most of the reported work assumed weld region as weld line. Also in some of the studies, it is simply stated that weld line modeling is sufficient to predict the forming behavior[6] without critically exploring the importance of assuming weld region as a separate weld zone. Also in the literature, there is no systematic study to clearly show the validity of weld line assumption under varied weld conditions. The effect of thickness ratio, weld orientation etc. on the forming behavior of TWB is explained to some extent in the referred literature. Also the forming behavior was studied by strain distribution, FLC, weld line movement etc. But there is no study, which details the effect of weld conditions on the limit strains developed during TWB forming. Different mechanical properties of the weld zone in comparison with the base metal affect the strain distribution on the sheet. Limit strains are nothing but peak strains developed in the sheet and hence the weld conditions should affect the same. Also, weld can change the strain path during forming of TWB. But some situations where limit strains are unaffected by weld conditions may also exist. The validity of weld line assumption needs to be tested with limit strains also.

In this study, it is proposed that weld line assumption will breakdown under certain weld conditions. In such situation it is essential to treat the weld region as a zone. The domain of weld conditions wherein weld line assumption breaks down will be identified by simulating Limit Dome Height (LDH) test. Load-progression behavior, progression till failure and maximum load attained will be monitored. The effect of weld conditions on the limit strains developed during TWB forming will also be studied by LDH test. In order to avoid the effect of other parameters in the forming behavior, similar thickness and base material are considered in the present analysis.

2. METHODOLOGY

The first part deals with the methodology involved in obtaining the domain of weld conditions wherein weld line assumption breaks down during TWB modeling. The effect of weld conditions on the limit strains in TWB forming is dealt with in the second part.

2.1. Representation of weld region in FE simulation

The weld conditions considered for this study includes weld width, combination of mechanical properties of weld and base material and weld orientation. Combination of mechanical properties of weld and base material is quantified by (a) Ratio of strain hardening coefficient of the weld (n_w) to base material (n_b) i.e., $n_r = n_w / n_b$ (b) Ratio of yield strength of the weld (YS_w) to base material (YS_b) i.e., $YS_r = YS_w / YS_b$ and weld orientation refers to the angle between the weld and major straining direction during deformation. Longitudinal and transverse weld orientations are considered in the present analysis. In order to obtain the domain of weld conditions wherein weld line assumption breaks down, forming behavior of TWB is studied by Limit Dome Height (LDH) testing. The load – progression behavior is monitored through out the study. All the analyses are performed by FE simulations.

2.1.1. Simulation of LDH testing of TWB

The standard LDH tool geometry[7], where the sheet is deformed by a hemispherical punch (diameter: 101.6 mm) inside a die opening (diameter: 105.7 mm) is considered for the analysis. Simulations are performed for near plane strain (Sheet sample dimension: 203 x 101 mm) and bi-axial stretching conditions (Sheet sample dimension: 203 x 203 mm). Both longitudinal and transverse weld orientations are considered for analysis in the near plane strain condition. Friction coefficient 'μ' is assumed to be 0.12 and is assumed to be constant through out the study. Blank Holder Force (BHF) was chosen such that the blank neither draws in nor tears near drawbeads during forming.

The base material properties assumed for the analysis are given in Table 1.
Assuming flow equation, $\sigma = K\,\varepsilon^{n}$
Here n_b and K_b values are obtained from the literature[8]. The base material having same thickness and mechanical properties are considered for the study so that the effect of just the weld on the forming behavior of TWB can be established, without the compounding effects of other parameters. A material database is constructed such that the 'n' ratio ($n_r = n_w / n_b$) and 'YS' ratio ($YS_r = YS_w / YS_b$) can be varied systematically at regular intervals. The following are the values considered for n_r, YS_r in this study. n_r: 0.5, 1.0, 1.7; YS_r: 0.5, 3, 7. This is achieved by assuming the 'n' and 'YS' values of the weld (n_w, YS_w) as appropriate multiples of the 'n' and 'YS' values of the base material (n_b, YS_b). It should be noted that the 'n' and 'YS' values of the weld zone are the only variables changed from the base metal and all other properties of the weld are same as that of the base material property. The weld widths considered are 2, 5, and 10 mm. For each weld orientation and weld width, simulations are performed for 9 'n_r' and 'YS_r' combinations. The same procedure is followed for all the weld orientations and weld width combinations and the load-progression behavior is monitored. The simulations are performed for both the weld orientations by considering weld line assumption also.

2.1.2. Criteria for breaking down of weld line assumption

The domain of weld conditions wherein weld line assumption breaks down is obtained by comparing the load-stroke behavior, maximum load at failure and progression till failure from simulations with weld line assumption and weld zone assumption. If the difference is beyond 10-15%, then for that particular weld condition line assumption is considered to break down. Since a difference of the order 15% exists between the experimental results and the TWB modeled with weld line as observed from the literature[5], and therefore it is decided to consider an acceptable limit of 10-15% difference between the load-stroke behavior predicted by weld line approach and weld zone approach.

2.2. Effect of weld conditions on the limit strains during TWB forming

The standard LDH tool geometry[7], where the sheet is deformed by a hemispherical punch (diameter: 101.6 mm) inside a die opening (diameter: 105.7 mm) is considered for the analysis. Limit strains are obtained for six strain paths so that Forming Limit Curve (FLC) of un-welded blank can be obtained. In the case of welded blanks, near tensile strain path is simulated to obtain the forming limit strains. Limit strain is obtained using a novel thickness based necking criterion[9,10]. Friction coefficient 'μ' is assumed to be 0.12 and is kept constant through out the study. Blank Holder Force (BHF) was chosen such that the blank neither draws in nor tears near drawbeads during forming.

The properties of base metal considered for this analysis are shown in table 1. The effect of weld conditions – weld orientation (longitudinal, transverse), combination of mechanical properties of weld and base metal are considered for studying the effect on limit strains developed during TWB forming. The properties of weld considered for the analysis are strain hardening coefficient (n_w) and yield strength (YS_w). The values of these properties are chosen such that the failure should not occur in the weld zone. The 'n' and 'YS' values considered for the weld are: n_w = 0.1, 0.15, 0.2, 0.25, 0.3 and YS_w = 564, 752, 940 MPa. All other properties of the weld are same as that of base metal. The mechanical properties of base metal in TWB are same as that of un-welded blank. Weld region is placed at centre of the blank and the width is kept constant as 5 mm throughout this analysis. Only near tensile strain path is simulated in this case. The limit strains are obtained by the novel thickness gradient based necking criterion as mentioned earlier. This is compared with the FLC of un-welded sheet.

A novel thickness gradient based necking criterion is used to obtain limit strain[9]. It is found from the earlier experiments that necking occurs in the sheet metal when the thickness gradient (ratio of thickness of neighboring circles) falls below 0.92[9,10]. Hence in the present FE simulations performed, element pairs where the thickness ratio equals or falls below 0.92, are considered as necked elements. The major strains in all the thicker elements are noted down. The peak major strain and the corresponding minor strain are treated as the forming limit strain. This procedure of obtaining the limit strain is followed for both un-welded and welded Blanks.

3. RESULTS AND DISCUSSION

3.1. Representation of weld region in FE simulation

3.1.1. LDH testing with transverse weld (Near plane strain condition)

The maximum load, progression till failure data for LDH test geometry in plane strain condition for transverse weld orientation is shown in Table 2. As expected, TWB modeled with weld line and TWB with n_r = 1, YS_r = 1, have same behavior. When $YS_r > 1$ (n_r = 1.7;YS_r = 7, n_r = 0.5;YS_r = 3.0) for a weld width of 2 mm, since the weld has higher YS than the base metal, deformation is concentrated only on the base material and the weld has negligible effect on the load-progression behavior. Since the variation in maximum load and progression is less than 10-15%, weld line assumption is acceptable to model TWB.

When $YS_r < 1$ (n_r = 1.1;YS_r = 0.9, n_r = 1.3;YS_r = 0.8, n_r = 1.7;YS_r = 0.5, n_r = 1.3;YS_r = 0.5, n_r = 1.0;YS_r = 0.5, n_r = 0.5;YS_r = 0.5), the weld behaves like a soft zone and therefore significant deformation occurs only on the weld region. Hence it is expected that the difference in load-progression behavior should be significant. But this difference depends on the YS_r value. It is observed from table 2 that when YS_r = 0.9 and 0.8, the difference is less than 10%. When YS_r reaches 0.5, the difference in load-progression behavior is more than 15%. It is expected that the difference in the load-progression behavior will increase as YS_r decreases below 0.5. It should be noted from the discussion that the conditions which exhibits higher difference in the load-progression behavior is independent of n_r values but YS_r value ($YS_r \leq 0.5$) decides the behavior. Even if the weld width is 5mm, this condition is expected to be unchanged because if $YS_r < 1$ then also the deformation will be concentrated in the weld region. The effect of strain hardening coefficient ratio (n_r) on load-progression behavior can be seen from table 2. As the 'n_r' value increases, because of the uniform distribution of strain in the weld region, the forming behavior of TWB approaches the base metal behavior. Hence when LDH testing (near plane strain) is considered, weld width ≥ 2mm, $YS_r \leq 0.5$ (for any value of n_r considered in this work) are the conditions where weld zone assumption should be followed.

Fig. 1 shows the representation of weld domain wherein weld line assumption breaks down and weld zone assumption should be followed for modeling TWB in LDH testing (plane strain stretching) of transverse weld. Here the domain obtained is independent of n_r and weld width, should be noted from the figure.

3.1.2. LDH testing of TWB in bi-axial stretching

Fig. 2 shows the load-progression behavior for LDH test geometry in bi-axial stretching condition. Since the weld occupies just 10% of the total width of the sample (with respect to the database created in this work), this has been analyzed separately and also this reflects the industrial sheet metal parts. TWB with weld line assumption and TWB with n_r =1, YS_r = 1 condition, exhibits similar load-progression behavior like LDH testing under near plane strain condition. Other than this condition i.e., n_r = 1, YS_r = 1 (or when $n_r \neq 1$, $YS_r \neq 1$), the load-progression behavior varies throughout the curve in comparison with that of TWB with weld line assumption. But from formability point of view i.e, when the progression attained till failure is considered as the criterion, there is only 15% difference in load-progression curve, compared with that of TWB with weld line assumption. This may be due to lesser weld width when compared with that of entire blank width. In this case weld line assumption is sufficient. When forming load is the reference, then a minimum difference of 20% exists and is dependent on the weld width (increase in weld width, increases or decreases the forming load depending on the weld mechanical properties). In this case weld line assumption breaks down completely and weld zone should be modeled separately.

3.2. Effect of weld conditions on the limit strains in TWB forming

Figure 3 shows the Forming Limit Curve (FLC) of un-welded sheet constructed using the thickness gradient based criterion. Six different strain paths are considered for constructing FLC of un-welded sheet. Also the limit strains of TWB with near tensile strain path (25 x 200 mm) having transverse and longitudinal weld are shown. In the case of transverse weld orientation, the weld is placed at the centre.

The limit strains of TWB shown in the Figure 3 are for near tensile strain path. The limit strains are grouped as ellipses within which limit strains vary with the mechanical properties (n_w, YS_w) of weld. It is clear from Figure 3 that in the case of transverse weld orientation, weld has insignificant effect on the limit strains developed in TWB. The welded blank has relatively same limit strains as that of un-welded sheet. The reasons behind the transverse weld having insignificant influence on the limit strains of TWB are (1) The effect of combination of mechanical properties of the weld and base metal is less, (2) Weld width being less and (3) Weld location is in non-critical region. Since weld exhibits higher yield strength in comparison with the base metal (more than 3 times that of the base metal), there are possibilities that the weld is not contributing to the deformation. Also failure occurs in the base metal, weld being at centre of the sheet, and the location is near punch nose region as in LDH testing of un-welded sheet. Since weld is placed at the non-critical location in TWB, the effect is very less. In this case, weld region can be modeled simply as a line instead of a separate zone in FE simulations. Suppose if the weld is softer than the base metal (i.e.) yield strength of the weld region lesser than the base metal and if the weld is placed at the critical location of the blank, one can expect a drastic change in the limit strains of TWB.

In the case of longitudinal weld orientation, as shown in Figure 3, limit strains are considerably different when compared to that of un-welded sheet. In this case, failure occurred at the interface of weld and base metal and propagated to the base metal. Hence the weld region affects the limit strains developed in the forming of TWB significantly. In this case, the strain hardening coefficient and yield strength of the weld (n_w, YS_w) play a vital role in the limit strains developed during TWB forming. It is found that with increase in 'YS_w', the limit strains decrease and with increase in 'n_w', the limit strains of TWB approach the limit strain of un-welded sheet. In this case, weld region should be modeled as a separate zone and not as a weld line.

4. CONCLUSIONS

The most critical issue in the FE modeling of TWB is representing the weld region – either as a weld line or as a zone. Also, the effect of weld conditions on the limit strains developed during the forming of TWB is dealt with. The following are the conclusions from the present work:

- Treating weld region as weld line is not accurate for all the weld conditions and it depends on the mode of deformation, weld-base metal property combination, orientation etc.

Domains of weld conditions wherein weld line breaks down and weld zone assumption should be followed are given below:

  - In the case of near plane strain condition of LDH test (transverse weld), weld width ≥ 2mm, $YS_r \leq 0.5$ (for any value of n_r considered in this paper) are the conditions where weld zone assumption should be followed.
  - When bi-axial stretching condition is considered, if the maximum load attained during forming is the criterion, then weld width ≥ 2mm, $n_r \neq 1$ and $YS_r \neq 1$ are the conditions at which weld line assumption breaks down. If pole height attained is the criterion, then weld region can be modeled simply as weld line for any weld conditions analyzed in this work.

- Transverse weld located at the centre of the blank has no effect on the limit strains developed in the forming of TWB. The limit strains are same as that of un-welded blank.
- Longitudinal weld has significant effect on the limit strains developed during the forming of TWB. The limit strains are lower than that of un-welded blank. There is an increase in limit strain in the case of tensile strain path depending on the weld properties.

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TABLES

Table 1 Base material properties assumed from simulations

n_b	K_b (MPa)	YS_b* (MPa)	R_0	R_{45}	R_{90}	Young's Modulus (GPa)	Poisson's Ratio	Thickness (mm)
0.18	561	188	1.2	1.3	1.5	206	0.33	1.2

Table 2 Maximum load and progression till failure for LDH testing with transverse weld

Weld conditions			Maximum Load (kN)	Progression till failure (mm)	% difference in maximum load	% difference in progression
n_r	YS_r	Width (mm)				
TWB with weld line			54.9	32	zero (Reference)	zero (Reference)
1.0	1.0	2	54.6	31.8	0.5	0.6
1.7	7.0	2	49.4	30.45	10.1	4.8
0.5	3.0	2	49.3	30.9	10.2	3.4
1.1	0.9	2	50.5	30.9	8	3.43
1.3	0.8	2	50.03	30.7	8.9	4.06
1.7	0.5	2	38.9	25.4	29	20.6
1.3	0.5	2	17.6	22	68	31.25
1.0	0.5	2	15.14	30.7	72	4.06
0.5	0.5	2	3.4	7	94	78
1.7	7.0	5	52.9	34	3.6	6
0.5	3.0	5	53.2	31	3	3.1
1.7	0.5	5	44.3	28	19	0.4

FIGURES

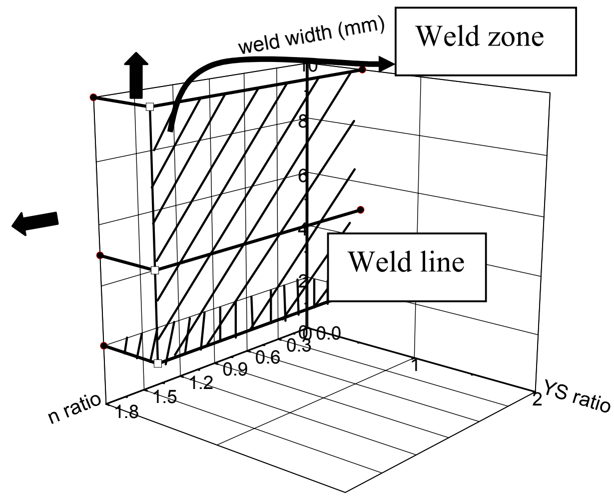

Fig. 1 Domain of weld conditions for representing weld zone in modeling
(LDH test-Plane strain, Transverse weld)

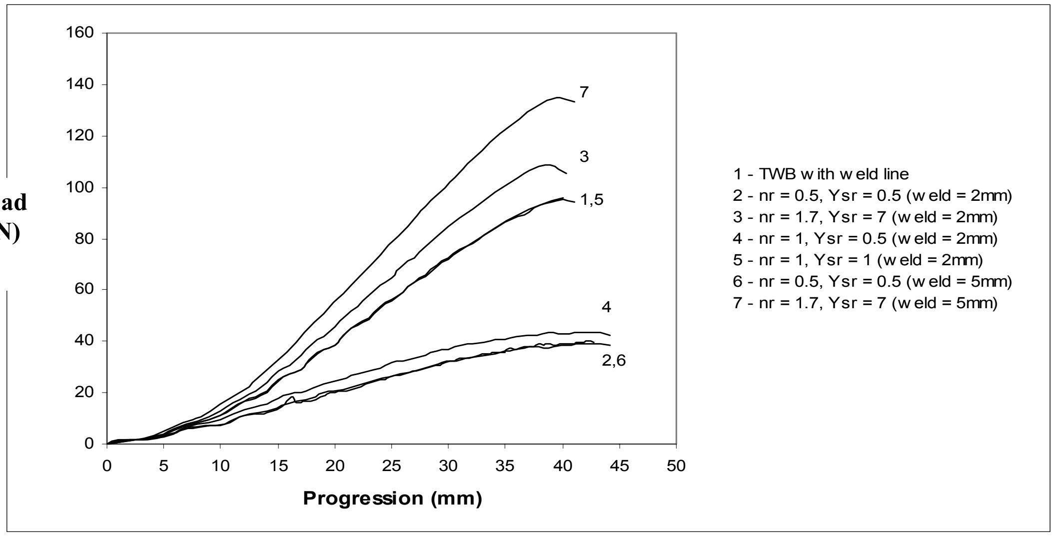

Fig. 2 Load – Progression behavior for LDH test in bi-axial stretching condition

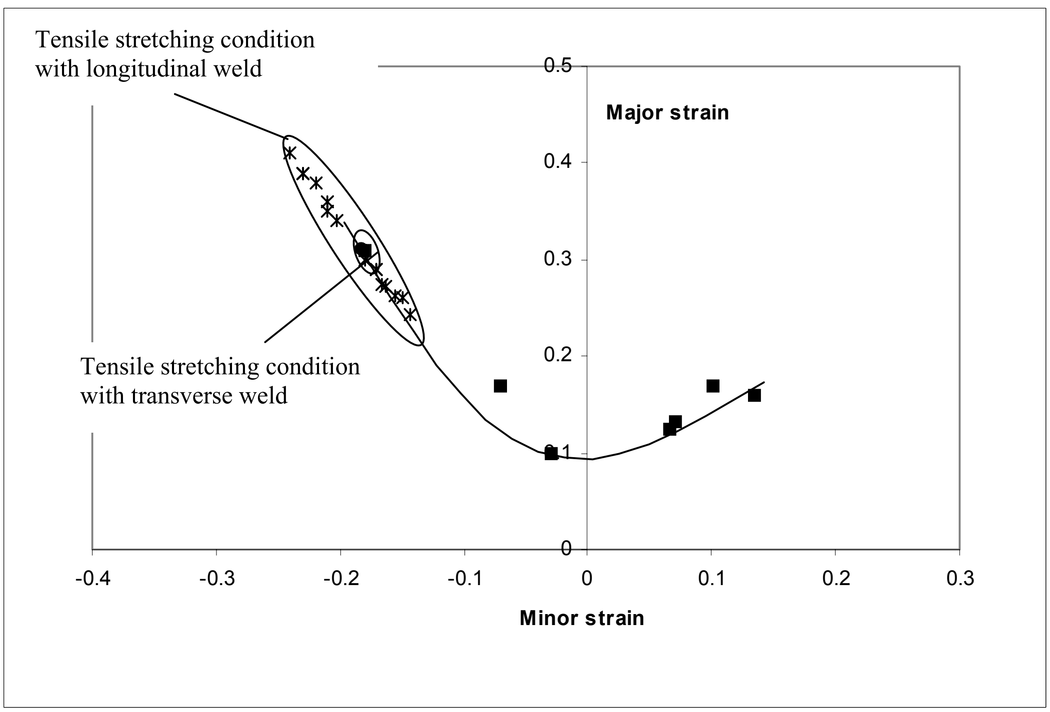

Fig. 3 Comparison of limit strains for un-welded blank and TWB