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A Novel Approach for Formability Prediction of Tailor Welded Blank

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Abstract: Formability of Tailor Welded Blank (TWB) is an important parameter which limits this kind of blanks usage. A forming criterion for tailor welded blank is presented based on the analytical model in this research. This criterion suggests Limit Strength Ratio (LSR) and Limit Thickness Ratio (LTR) for forming limit of TWB. When thickness ratio or strength ratio in tailor welded blank is greater than LTR or LSR, formability will be limited and necking will happen sooner. The influence of thickness ratio on the formability of TWB has been investigated by experimental tests and Finite Element (FE) simulations, but strength ratio has just been studied by simulation. All the simulation and experiment results indicate that by the increase of thickness ratio and strength ratio, the formability will decrease and weld line movement will increase. The obtained results of the present study indicate that fracture happens in the thinner side of TWB and near to the weld line. Moreover, fracture line is parallel to weld line and the fracture position moves farther than weld line by thickness ratio decreasing. Simulation results have a good agreement with experimental results as well.

Keywords: Tailor Welded Blank (TWB), Limiting Thickness ratio (LTR), Limiting Strength Ratio (LSR), Weld line movement

1. Introduction

Weight decrease of automotive through using plastic, composite and light metallic parts is one of ways to decrease automotive fuel consumption. Automotive weight decrease which uses low strength parts will be incompatible with parts rigidity and hence the automotive safety in accidents will be decreased. Using TWB in automotive parts is a solution for this incompatibility [1]. TWBs consist of two or more sheet metals having different thicknesses or strengths, which is joined by one of the welding processes. TWBs use in forming process and form to final parts. Weld line movement is one of the important parameters which has an influence on the TWBs forming. Weld line movement is important from two aspects: First, its position in the final part is very important because TWB part will be assembled with other parts and weld line movement can influence assembling. Second, weld line movement which is often toward the stronger (thicker) metal causes necking and fracture in weaker (thinner) metal. Eisenmenger et al. [2] in their research concluded that weld line movement during the forming process causes erosion of die surface and also necking and fracture in the thinner blank. Forming height can be increased by some changes in forming process of TWBs. Ahmetoglu et al. [3] used different blank holder force to study formability of TWB by increasing the thicker (stronger) material flow and decreasing the thinner (weaker) material deformation. In their research, TWB consisted of two sheets with different thicknesses or strengths. Minor blank holder force was used for the thicker material. Cayssials [4] determined forming limit diagram of tailor welded blanks. Kinsey et al [5] used a hydraulic system for clamping of TWB's weld line during the forming process and tried to increase formability of TWB by this system. They [6] presented an analytical

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model to predict the weld line movement and forming height for a uniform binder force in TWB forming application. Forming height is the height of samples after forming. He et al. [7] used a two dimensional analysis to determine no uniform blank holder force ratio. Safdarian Korouyeh et al. [8] investigated performance of different numerical criteria for FLD prediction of TWB. Second Derivative of Thinning (SDT) was found as a good post-processing criterion for FLD prediction of TWB. SDT is a numerical model for forming limit prediction of TWB. Considering this model, thickness of all elements of Finite Element Method (FEM) was analyzed in order to determine minimal thickness for each stored time interval. Thinning values for all the elements with minimal thickness were stored and finally, second derivative of thinning was analyzed. Due to a fast local change of sheet thickness at the necking point, the thickness strain changes its value abruptly. They also studied the effect of thickness ratio on the level of FLD for St12 TWB with different thickness ratios in another research [9]. In their research, TWB consisted of two blanks with different thicknesses which thickness ratio is the ratio of the thickness of two part of TWB. Their results showed that FLD's level increase by thickness ratio decreasing of TWB.

As explained before, TWBs consist of two blanks with different thicknesses or strengths which were jointed together with one of the welding methods. In the present study, Nd:Yag laser welding is used to prepare TWBs. Moreover, thickness (strength) ratio is the ratio of thickness (strength) of two blanks which jointed together and made TWBs. Limit Strength Ratio (LSR) and Limit Thickness Ratio (LTR) were calculated by using force equilibrium and were introduced as a useful forming criterion. The thickness ratio or strength ratio, in which one material just reaches initial yield strength when the other material reaches its forming limit, is called the Limiting Thickness ratio (LTR) or Limiting Strength Ratio (LSR). Analytical results are compared with the experimental and FEM results. The Results indicate that forming of TWB is safe, when the thickness ratio (TR) and strength ratio (SR) of TWB is respectively less than LTR and LSR.

2. LTR and LSR calculation

When the thickness ratio or strength ratio of two materials exceeds a certain value, the material with greater thickness (higher strength) may be limited to elastic deformation or very little plastic deformation in the direction is perpendicular to the weld even though the material with less thickness (lower strength) exceeds its forming limit near the weld. The thickness ratio or strength ratio, in which one material just reaches initial yield strength when the other material reaches its forming limit, is called the Limiting Thickness ratio (LTR) or Limiting Strength Ratio (LSR). When the thickness ratio is less than the LTR and the strength ratio is less than LSR, plastic deformation would occur in both materials. When the thickness ratio (or strength ratio) are larger than the LTR (or LSR), the material with greater thickness or higher strength does not reach its yield point (no plastic deformation) in the direction perpendicular to the weld. This LTR or LSR can be determined using a simple mechanics analysis [10]. Figure 1 shows two welded materials of A and B when this welded sheet undergoes deformation, the equilibrium equation (without the presence of the friction) in the transverse direction can be expressed as

$$F_A = F_B \tag{1}$$

where F is force in unit width and subscripts A and B represent the materials A and B respectively.
Eq. (1) can be rewritten as

$$\sigma_A t_A = \sigma_B t_B \tag{2}$$

where σ is the true stress and t is the current material thickness. Using true thickness strain definition and incompressibility law (constant volume law), Eq. (2) becomes

$$\sigma_A t_{0A} e^{-(\varepsilon_1)_A-(\varepsilon_2)_A} = \sigma_B t_{0B} e^{-(\varepsilon_1)_B-(\varepsilon_2)_B} \tag{3}$$

where ε_1 and ε_2 are two true strains parallel and perpendicular to the weld in the sheet plane (Fig. 1). The strain component parallel to the weld must be the same $(\varepsilon_1)_A = (\varepsilon_1)_B$ and Eq. (3) becomes

$$\sigma_A t_{0A} e^{-(\varepsilon_2)_A} = \sigma_B t_{0B} e^{-(\varepsilon_2)_B} \quad \text{OR} \quad S_A t_{0A} = S_B t_{0B} \tag{4}$$

where S is the engineering stress. The above equation provides the relationship of the stress state in materials A and B for the given thickness ratio.

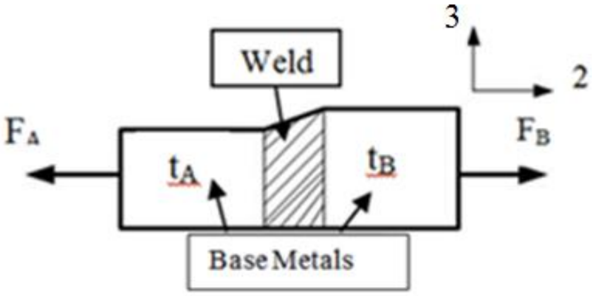

Fig. 1. Force balance element near the welded in the transverse direction [10].

2.1. Determination of the LTR and LSR

Let us assume that material B has greater thickness or higher strength than material A. It can be shown that S_B, reaches the maximum value when S_A, reaches the maximum value. The maximum value for S_A is the tensile strength of material A. Therefore, the LTR and LSR can be obtained when the flow stress S_B in material B reaches the yield strength of the material and S_A reaches the tensile strength of material A. Eq. (4) is then rewritten as

$$S_{TA} t_{0A} = S_{YB} t_{0B} \tag{5}$$

where S_{TA}, is the tensile strength for material A and S_{YB} is the initial yield strength for material B. Hence, the LTR and LSR can be obtained as

$$LTR = \left(\frac{t_{0B}}{t_{0A}}\right)_{\lim it} = \frac{S_{TA}}{S_{YB}} \quad \text{and} \quad LSR = \left(\frac{S_{YB}}{S_{TA}}\right)_{\lim it} = \frac{t_{0A}}{t_{0B}} \tag{6}$$

The LTR depends upon the tensile strength in the less thickness material and the yield strength in the greater thickness material while the LSR depends upon the thickness ratio of the two materials [10].

3. Experimental Work

In the experimental part of this research TWB with different thickness from St12 steel was prepared using Nd:YAG laser welding. As illustrated in Fig. 2, a Model IQL-10, the pulsed Nd:YAG laser with a maximum mean laser power of 400W was used as welding laser source for the experiments. Square shape pulses were the standard output of this laser. Laser parameters which were used for welding of specimens were presented in Table 1. Six specimens of 180mm×90mm with different thicknesses were welded together to produce TWB 180mm×180mm.

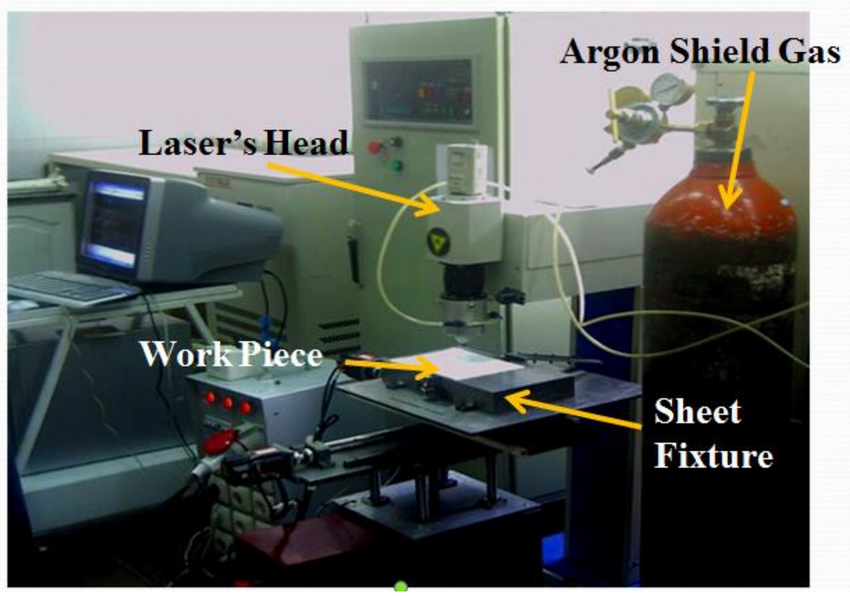

Fig. 2. Nd:YAG laser welding setup.

Table 1. Nd:YAG laser welding parameters

Average Power (Watt)	Welding Velocity(mm/s)	Pulse Duration (ms)	Frequency (HZ)	Laser's Head Distance with sheet surface (mm)
220	6.67	5.5	20	1.7

Mechanical properties and thickness of St12 steel blanks which were used in experiment tests was presented in Table. 2. The parameters – YS, UTS, Elongation, K, and n – were evaluated from tensile testing of ASTM standard E8M specification at 2mm/min cross-head speed [11].

Table 2. Mechanical and forming properties of St12 steel base metal from tensile tests

Sheet thickness (mm)	YS(N/mm^2)	UTS(N/mm^2)	Elongation (%)	n	K(N/mm^2)
0.47	277	305	35	0.26	563.4
0.8	236	370	40	0.29	705.8
1	239	370.3	33	0.25	653

The biaxial stretch forming tests or Limit Dom Height (LDH) were done according to the procedure suggested by [12] using a hemispherical punch of 101.6mm diameter on a 20 tones hydraulic press. The Limiting Dome Height (LDH) test is a formability test designed for the sheet metal industry. It tests the material in or near plane strain. Height of deformed samples is measured and reported as LDH.

The setup of the tool arrangement (punch, lower die and upper die) used in the experiments is shown in Fig. 3. A circular draw bead was provided on the die with 132mm diameter to restrict the flow of metal from the flange region into the die and to ensure that only the portion within the die opening was deformed by the punch. All the tests were conducted in dry condition at a punch speed of 20mm/min. An optimum blank holding force of 10 tones was applied on the upper die. The press was equipped to load and displacement sensors and experiments were stopped when forming load decrease suddenly.

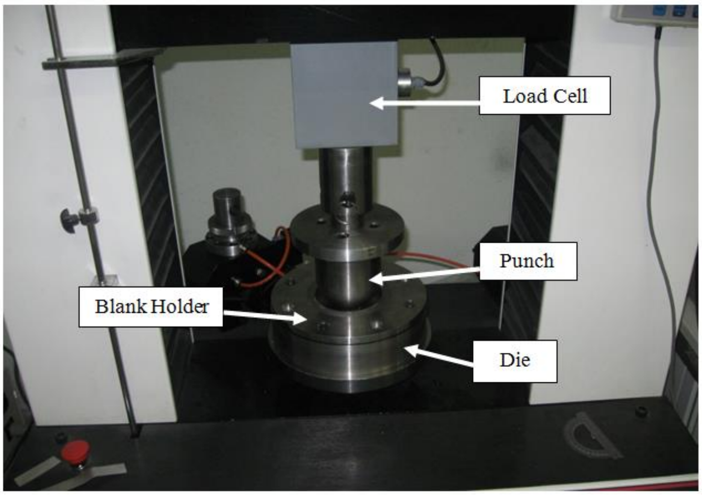

Fig. 3. Experiment setup for forming of TWB.

4. Modeling and simulation in ABAQUS

Abaqus 6.10 commercial software was used for TWB forming modeling. This model is shown in Fig. 4.

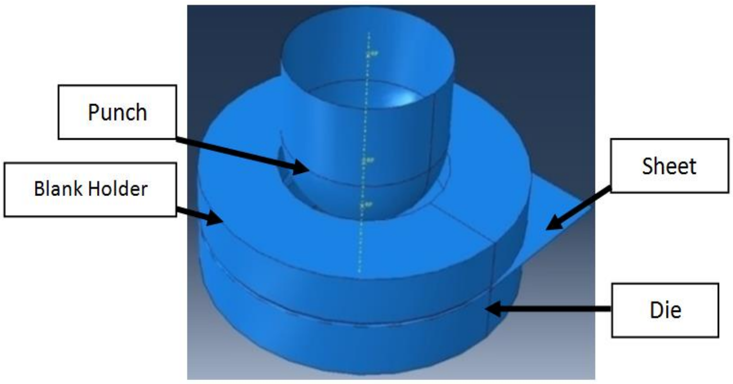

Fig. 4. Modeling in ABAQUS software.

Results of FEM for TWB with different thickness were verified by experimental tests which were done in the present research. After approving TWB modeling in ABAQUS based on the experiment, TWBs consist of blanks with different strengths were investigated by this model and the using material property of Panda et al. research [13]. This model was based on the Hecker forming limit diagram test [12]. Punch, die and blank holder were modeled as rigid parts, because they had negligible deformation. The Sheet was modeled as deformable part and considered as a shell with S4R elements. Frictions between sheet and punch, sheet and die, sheet and blank holder were considered as penalty with coefficient of 0.15. The die was a fixed entity and the punch was moved downward in Z-direction with a velocity of 1000mm/s. This speed for punch was selected based on the quasi static condition of process and this speed also was used in another study [8, 14, 15].

Steel sheets and their properties which were used for investigation of TWB with different strength are presented in Table 3.

Table 3. Mechanical properties of sheets which consist TWB [13]

Steel grade	YS[MPa]	UTS[MPa]	K[MPa]	n	Total Elon [%]	R_0	R_{45}	R_{90}
HSLA	413	463	756.8	0.18	23.97	0.75	1.26	1.11
DP450	298	491	835.1	0.2	31.43	1.03	0.87	1.51
DP800	544	885	1404.1	0.15	18.71	0.87	1.13	0.91
DP980	534	980	1510	0.14	15.20	0.8	0.93	0.85

Forming Limit Diagram (FLD) of thinner (weaker) sheet was used as forming limit of TWB in software. North American Dee Drawing Research Group (NADDRG) empirical equation was used for importing of FLD in Abaqus. FLD_0 was calculated as follow [14].

$$t \le 2.54mm, FLD_0 = \frac{0.01 \times n}{0.21}(23.3 + 14.13t) \tag{7}$$

where t is thickness of sheet and n is work hardening power. FLD_0 is a point on the major strain axes and is a minimum point of FLD which its minor strain is zero. According to this model, the FLD was composed of two lines through the point FLD_0 in the plane-strain state. The slopes of the lines located respectively on the left-side and right-side of the FLD were about 45° and 20°.

Hill's 1948 yield criterion was used to model sheet metal behavior in forming process [16].

$$f(\sigma) = \sqrt{F(\sigma_{22}-\sigma_{33})^2 + G(\sigma_{33}-\sigma_{11})^2 + H(\sigma_{11}-\sigma_{22})^2 + 2L\sigma_{23}^2 + 2M\sigma_{31}^2 + 2N\sigma_{12}^2} \tag{8}$$

$$F = \frac{1}{2}\left(\frac{1}{R_{22}^2} + \frac{1}{R_{33}^2} - \frac{1}{R_{11}^2}\right),\ G = \frac{1}{2}\left(\frac{1}{R_{33}^2} + \frac{1}{R_{11}^2} - \frac{1}{R_{22}^2}\right),\ H = \frac{1}{2}\left(\frac{1}{R_{11}^2} + \frac{1}{R_{22}^2} - \frac{1}{R_{33}^2}\right),$$

$$L = \frac{3}{2R_{23}^2},\ M = \frac{3}{2R_{31}^2},\ N = \frac{3}{2R_{12}^2} \tag{9}$$

F, G, H, L, M and N are the Hill's criterion coefficients. These coefficients can be imported into the software by 6 yield stress parameters of R_{11}, R_{22}, R_{33}, R_{12}, R_{13} and R_{23}. These parameters can be calculated using anisotropic parameters of r_0, r_{45} and r_{90} as fallow [17].

$$R_{11} = R_{13} = R_{23} = 1,\ R_{22} = \sqrt{\frac{r_{90}(r_0+1)}{r_0(r_{90}+1)}},\ R_{33} = \sqrt{\frac{r_{90}(r_0+1)}{r_{90}+r_0}},\ R_{12} = \sqrt{\frac{3r_{90}(r_0+1)}{(2r_{45}+1)(r_{90}+r_0)}} \tag{10}$$

Three types of tailor welded blanks with different strength ratios were investigated based on the data in Table 3. These TWBs were HSLA-DP450, HSLA-DP800 and HSLA-DP980 having equal thicknesses however different strengths were modeled and simulated in the software.

For investigating the thickness ratio effect on the forming behavior of TWB, three types of TWBs from ST12 with thickness ratio of 1.25, 1.7 and 2.13 (the absolute thicknesses are given in table 2) were simulated and their results were compared with the experimental ones. Von Mises yield criterion was also used for the numerical investigation of TWBs with different thickness ratio.

5. Results and Discussion

Figure 5 shows necking position of St12 TWB with TR=2.13 from FEM and experiment. Necking position for simulation and experimental results is near the weld line and in the thinner blank and parallel to the weld line. When the load is applied, the thinner side of TWB resists less and hence deforms to a more extent compared to the thicker side. This isolated deformation results in significant increase in the strain level in the material with less thickness and the maximum strain would occur in the area just adjacent to the weld.

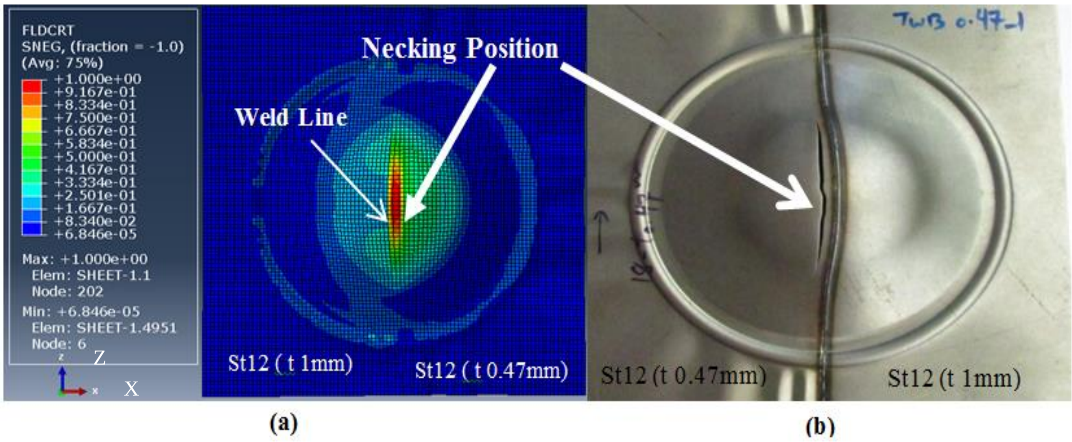

Fig. 5. Necking position for St12 TWB with thickness ratio 2.13 (a) from ABAQUS simulation (b) from experiment test.

Experimental results in Fig. 6 show that by TR decreasing, necking position will move far from the weld line. In Fig. 6, for samples (a) and (b) which their base metals have the most difference in thickness; necking is happened in the thinner part of TWB and near the weld line, but for TWB with TR=1.25 necking position is far from weld line and is similar to the necking position of unwelded blank.

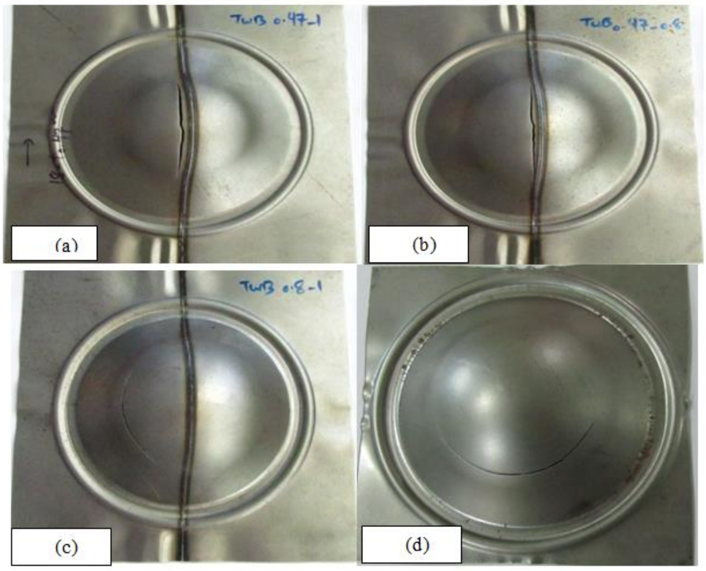

Fig. 6. TWB Necking Position for TR values (a) 2.13, (b) 1.7, (c) 1.25 and (d) Unwelded blank

1.1. TWB with different thickness ratio

Based on the analytical result (Eq. (6)) and the data in Table. 3, LTR for ST12 TWB with different TR is as follow.

$$LTR_{\mathrm{TWB(0.47\text{-}1)}} = \frac{(S_T)_{0.47}}{(S_Y)_1} = \frac{305}{239} = 1.28 \quad and \quad TR = \frac{1}{0.47} = 2.13 \tag{11}$$

$$LTR_{\mathrm{TWB(0.47\text{-}0.8)}} = \frac{(S_T)_{0.47}}{(S_Y)_{0.8}} = \frac{305}{236} = 1.3 \quad and \quad TR = \frac{0.8}{0.47} = 1.7 \tag{12}$$

$$LTR_{\mathrm{TWB(0.8\text{-}1)}} = \frac{(S_T)_{0.8}}{(S_Y)_1} = \frac{370}{239} = 1.55 \quad and \quad TR = \frac{1}{0.8} = 1.25 \tag{13}$$

Comparison of Eqs. (11-13) show that just in case of base metal thicknesses 1 and 0.8 mm (TWB 0.8-1), TR < LTR and for other TWBs this condition is not compatible. Based on this analytical result, it is expected that formability of this TWB be more than the two others. Future results for weld line movement and Limit Dome Height (LDH) of this kind of TWB (TWB with different thickness ratio) validate the analytical results.

LDH of TWB with different thickness ratio is presented in Fig. 7. LDH decreases by increasing the thickness ratio of the blanks which contained TWB. As mentioned analytically before, by TR increasing,formability will decrease which is agree with experimental results.

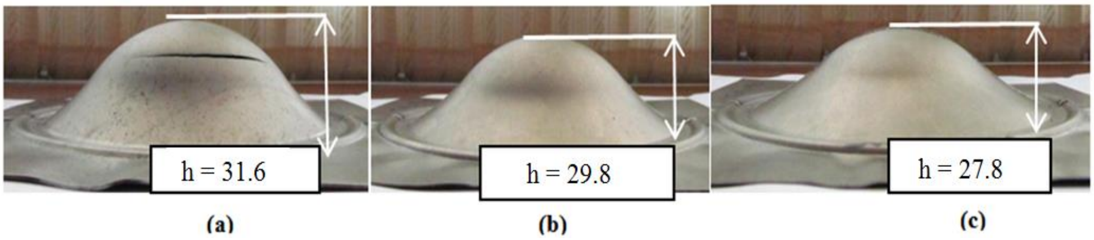

Fig. 7. LDH for St12 TWB with TR values (a) 1.25, (b) 1.7 and (c) 2.13.

Table 4 shows LDH comparison of FEM and the experimental tests for St12 TWB having different TR. The LDH of FEM is near to the experimental results, which shows that proper simulation conditions have been defined in ABAQUS.

Table 4. LDH comparison of experiment and FEM for TWB with different TR

Thickness ratio (TR)	1.25	1.7	2.13
LDH (mm) - Exp	31.6	29.8	27.8
LDH (mm) - FEM	35.8	27	23.34
Error (%)	11.7	9.3	16

Figure 8 shows experimental force-displacement for three types of St12 TWB. Load duration and also punch displacement are the maximum for TWB (0.8-1) which have the least TR and are minimum for TWB (0.47-1) having the most TR.

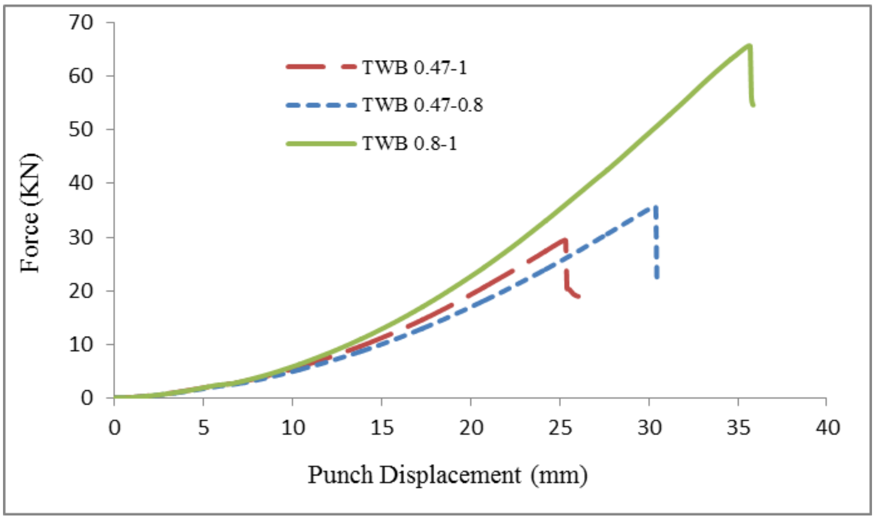

Fig. 8. Force-displacement of TWB with different thickness ratio

Weld line movement of TWB with different thickness ratios is shown in Fig. 9. Weld line movement is maximum in the pole of all samples and is minimum in the flange. Weld line movement is maximum for TWB 0.47-1 which has the most thickness difference in its base metals. It decreases by TR decrease in other samples.

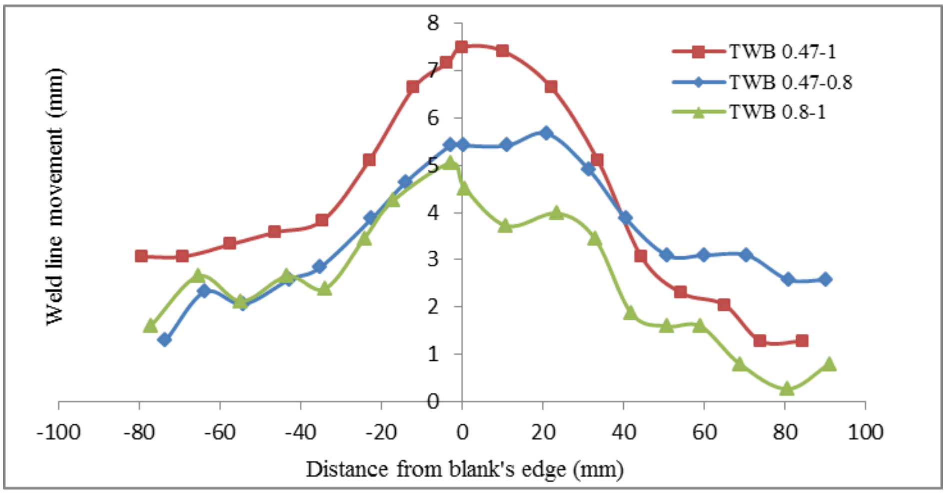

Fig. 9. Weld line movement of TWB with different thickness ratio

1.2. TWB with different strength ratio

Weld line movement and LDH of three types of TWB which their base metal has similar thicknesses but different strengths has been compared in Fig. 10 and Fig. 11, respectively.

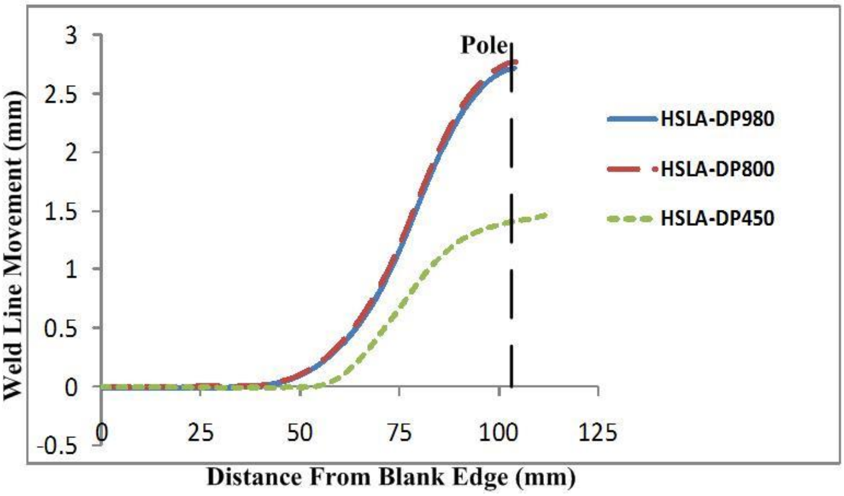

Fig. 10. Influence of strength ratio on the weld line movement for half of TWB

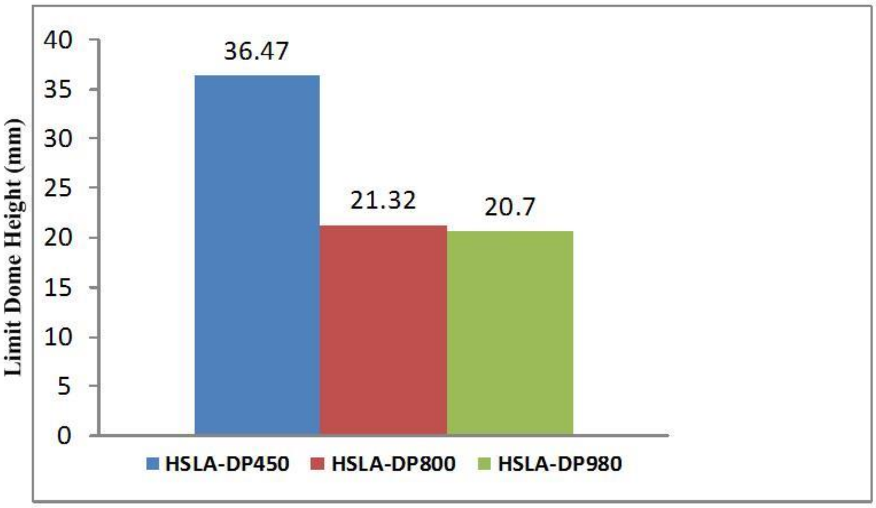

Fig. 11. Influence of strength ratio on the LDH of TWB

HSLA-DP800 has the most weld line movement and HSLA-DP450 has the least weld line movement. Based on the analytical result (Eq. (6)) and Table. 3, LSR for these TWB are as follow:

$$LSR_{\text{HSLA-DP450}} = LSR_{\text{HSLA-DP9800}} = LSR_{\text{HSLA-DP800}} = \frac{t_{\text{HSLA}}}{t_{\text{DP450}}} = 1 \tag{14}$$

But strength ratios (SR) are as follow:

$$SR_{\text{HSLA-DP450}} = \frac{S_{Y(\text{DP450})}}{S_{T(\text{HSLA})}} = \frac{298}{463} = 0.64, \quad SR_{\text{HSLA-DP9800}} = \frac{S_{Y(\text{DP980})}}{S_{T(\text{HSLA})}} = \frac{534}{463} = 1.153$$
$$SR_{\text{HSLA-DP800}} = \frac{S_{Y(\text{DP800})}}{S_{T(\text{HSLA})}} = \frac{544}{463} = 1.175 \tag{15}$$

For HSLA-DP450 TWB which SR<LSR, weld line movement is minimum and its LDH is maximum. For HSLA-DP800 and HSLA-DP980 which SR>LSR, weld line movement are maximum and their LDH are minimum. This indicates that by increasing the weld line movement, LDH decreases.

6. Conclusion

Limit Strain Ratio (LSR) and Limit Thickness Ratio (LTR) are two useful and practical ratios for TWB's forming limit specification. By increasing these ratios for TWB, weld line movement will be increased and Limit Dome Height (LDH) will be decreased. From the experimental result, it was found that fracture takes place in the thinner material and near the weld line, but by TR increasing fracture position will move far from the weld line.

As long as the base metals of TWB have less difference in thickness or strength, the formability of TWB will be increased. Results of this research indicate that when TR < LTR and SR < LSR, forming will occur without any defect and necking will happen posterior than samples when TR > LTR and SR > LSR. This result has been approved by LDH and weld line movement of experimental and numerical results. Moreover, Weld line movement can be a good criterion for formability of TWB and by weld line movement increasing, the formability of TWB will decrease and vice versa.

7. References

[1] P. Auto/Steel Partnership. Tailor welded blank design and manufacturing manual. Auto/Steel Partnership, [S.l.], (1995).

[2] M. Eisenmenger, K.K. Bhatt and M.F. Shi. I*nfluence of laser welding parameters on formability and robustness of blank manufacturing : an application to a body side frame*. Society of Automotive Engineers, New York, NY, ETATS-UNIS, (1995).

[3] M.A. Ahmetoglu, D. Brouwers, L. Shulkin, L. Taupin, G.L. Kinzel and T. Altan. Deep drawing of round cups from tailor-welded blanks. *Journal of Materials Processing Technology*. 53 (1995) 684-94.

[4] F. Cayssials, An industrial application of specific forming limit curves for tailor welded blanks. *Proceedings of the 2000 International Deep Drawing Research Group, North American Deep Drawing Research Group*, (2000) 17–22.

[5] B. Kinsey, Z. Liu and J. Cao. A novel forming technology for tailor-welded blanks. *Journal of Materials Processing Technology*. 99 (2000) 145-53.

[6] B.L. Kinsey and J. Cao. An analytical model for tailor welded blank forming. *Journal of Manufacturing Science and Engineering*. 125 (2003) 344-51.

[7] S. He, X. Wu and S.J. Hu. Formability enhancement for Tailor-welded blanks using blank holding force control. *Journal of Manufacturing Science and Engineering.* 125 (2003) 461-7.

[8] R. Safdarian Korouyeh, H. Moslemi Naeini and G. Liaghat. Forming limit diagram prediction of tailor-welded blank using experimental and numerical methods. *Journal of Materi Eng and Perform*. 21 (2012) 2053-61.

[9] R. Safdarian Korouyeh, H. Moslemi Naeini, M.J. Torkamany and G. Liaghat. Experimental and theoretical investigation of thickness ratio effect on the formability of tailor welded blank. *Optics & Laser Technology*. 51 (2013) 24-31.

[10] M.F. Shi, K.M. Pickett and K.K. Bhatt. *Formability issues in the application of Tailor welded blank sheets*. Society of Automotive Engineers, New York, NY, ETATS-UNIS, (1993).

[11] A.S.f.T.a.M. (ASTM), Metals test methods and analytical procedures. (1999) 78–98, 501–8.

[12] S.S. Hecker. A cup test for assessing stretchability. *Met. Eng.* . 14 (1974) 30–6.

[13] S.K. Panda, V.H. Baltazar Hernandez, M.L. Kuntz and Y. Zhou. Formability analysis of diode-laser-welded Tailored blanks of advanced high-strength steel sheet. Metallurgical and Materials Transactions A. 40A (2009) 1955-67.

[14] S.B. Levy, A comparison of empirical forming limit curves for low carbon steel with theoretical forming limit curves of ramaekers and bongaerts, IDDRG, (1996).

[15] S.K. Panda, D.R. Kumar, H. Kumar and A.K. Nath. Characterization of tensile properties of tailor welded IF steel sheets and their formability in stretch forming. *Journal of Materials Processing Technology*. 183 (2007) 321-32.

[16] R. Hill. A theory of the yielding and plastic flow of anisotropic metals. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*. 193 (1948) 281-97.

[17] Abaqus User Guide, ABAQUS Analysis User's Manual.

روشی جدید برای پیش بینی شکل پذیری ورق های ترکیبی

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چکیده: شکل پذیری ورق ترکیبی یکی از مهمترین پارامترهایی است که استفاده از این نوع ورقها را محدود کرده است. در این تحقیق یک معیار شکل دهی بر اساس یک مدل تئوری برای این نوع ورقها ارائه می شود. این معیار، نسبت حد استحکام[1] (LSR) و نسبت حد ضخامت[2] (LTR) را برای حد شکل دهی ورقهای ترکیبی پیشنهاد می کند. وقتیکه نسبت ضخامت یا نسبت استحکام در ورق ترکیبی بیشتر از LTR و LSR باشد، شکل پذیری محدود شده و ورق زودتر دچار پدیده گلویی می شود. تاثیر نسبت ضخامت بر روی شکل پذیری ورق ترکیبی با استفاده از آزمایشهای تجربی و شبیه سازی عددی و تاثیر نسبت استحکام تنها با استفاده از شبیه سازی های عددی بررسی شده اند.تمام نتایج شبیه سازی و آزمایشهای تجربی نشان می دهد که با افزایش نسبت ضخامت و نسبت استحکام، شکل پذیری ورق ترکیبی کاهش و جابجایی خط جوش افزایش خواهد یافت. نتایج تحقیق حاضر نشان می دهد که شکست در نیمه نازکتر ورق ترکیبی و نزدیک خط جوش اتفاق افتاده و خط شکست به موازات خط جوش است. نتایج نشان می دهد که موقعیت شکست در نمونه ها تجربی با افزایش نسبت ضخامت از خط جوش دور می شود. نتایج شبیه سازی از نزدیکی خوبی با نتایج تجربی برخوردار است.

کلمات کلیدی: ورق ترکیبی (TWB)، نسبت حد ضخامت (LTR)، نسبت حد استحکام (LSR)، جابجایی خط جوش

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[1] Limit Strength Ratio
[2] Limit Thickness Ratio