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ORIGINAL ARTICLE

Effect of different combinations of tailor-welded blank coupled with change in weld location on mechanical properties by laser welding

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Abstract Using tailor-welded blanks (TWB) in automotive industry is on the rise. This is done due to advantages such as reduction in weight leading to more effective operational cost and lower energy consumption of vehicles. The main objective of this investigation was to study the effect of location change of weld zone and differences in thickness combination of TWB sheets on their tensile characteristics and forming capabilities. Quality evaluations of weld zone metallographic and tensile as well as ball punch tests have been conducted. Tension characteristics of welded samples have been determined by conducting a uni-axial tensile test perpendicular on the weld line in those samples. Forming capability of TWB samples were also studied by using sphere head chisel test. By moving weld line toward thick sheets direction and increasing thin sheets share of the weld in TWB, an increase in relative elongation in tensile test and in chisel test increase in cups height was observed. This indicates that forming capability of TWB samples by moving weld line toward thick sheet increases and weld zone does not have much effect on forming capability of TWB. By using the derived recommended relation induced from this study, it is conceivable to obtain the amount of increase in relative length of TWB from its base sheets. Results of this relation are confirmed with obtained results from tensile test. Also by reduction in thickness difference of TWB sheets, their formability increases.

Keywords Tailor welded blanks · St14 steel · Laser welding · Formability · Tensile properties

1 Introduction

In recent years, automotive industries have persuaded policy of weight reduction in their products and lower energy consumption in the vehicles produced. One method of weight reduction is using TWB. TWB is comprised of two or more sheets in which their material, thickness, and/or their surface coding could be similar or different and become joined prior to forming [1]. Some advantages of TWB are reduction in material consumption and the weight, decreasing production cost at the same time improvement in local strength [2]. A common method of joining in TWB is laser welding. Some characteristics of laser welding method is low inlet heat, narrow weld zone, high speed of welding, and high quality of the weld [3, 4]. Despite points mentioned for TWB, a noticeable disadvantage is high reduction in formability of the sheets. Suggested reason is inhomogeneous shape change due to fluctuation in material and thicknesses of sheets forming TWB [5]. So far, many studies have been conducted to evaluate formability of TWB. In many of these studies, effect of weld zone characteristics on formability of TWB have been contemplated [6–8]. Results of these investigations indicate that weld zone has very little effect on formability of TWB. Moreover,

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Table 1 Chemical composition of St 14 steel

	C (wt%)	Si (wt%)	Mn (wt%)	P (wt%)	S (wt%)	Cu (wt%)	Al (wt%)
St14	0.035	0.004	0.223	0.006	0.004	0.027	0.057

it has been revealed that by increase in thickness ratio of sheets forming TWB, its formability decreases [9]. Some studies have also been conducted on the effect of angle change in weld line [10] as well as using fluctuating sheet grabber [11] on formability of TWB. In the present investigation, effect of change in thickness combination along with moving of weld line on tensile characteristics and formability of TWB made of St14 steel sheets. For this reason, mechanical and metallurgical tests have been conducted for determination of formability of TWB.

2 Methodology

2.1 Material used and its characteristics

In this investigation, St14 steel sheet with thicknesses of 0.8, 1, and 1.5 mm were used. St 14 is an alloy containing aluminum with deep drawing quality. This material has many applications in vehicles body based on its high formability. Chemical composition of this metal is presented in Table 1 and its mechanical characteristics for different thicknesses are presented in Table 2.

2.2 Laser welding and preparation of TWB

Prior to actual welding process samples in dimensions 8× 10 mm were cut from base metal sheet. Steel sheets St14 having thicknesses 0.8, 1, and 1.5 mm and two thickness combinations 0.8–1.5 and 1–1.5 mm were prepared for the experiment. Furthermore, three weld locations including weld zone at the center of the sample, 5 mm movement of weld zone toward thick sheet and 1.6 mm movement of weld zone toward thin sheet were welded by using a pulse Nd:YAG laser with maximum 400 W power following figure presents location of welds (Fig. 1).

To maintain samples from movement during welding process, a fixture was used. In order to make up for the thickness difference of weld samples with different thicknesses, a shim was used under thinner sheet. Also distance between two edges of sheet was almost zero. Laser beam was directed by a lens with focal point of 75 mm pure argan gas co-axial with laser beam with specific volume floret was used to protect the meld area. Figure 2 depicts welding process lay out with laser beam.

To obtain optimized parameters of the laser, initially a Seri of experiments were conducted on St14 steel sheets. In these experiments, laser parameters such as power peak, distance of head to surface, welding speed, pulse width, etc. were changed randomly. By repeating experiments on sheets with different thicknesses, suitable range of parameters for each thickness was determined. Considering standards ISO 13919-2 and ISO 15614-11 [12, 13], the weld's defects in light of weld surface condition and cross-section of profile of the weld was studied. General mechanical characteristics of weld zone were also measured by tensile test. Figure 3a rupture at weld zone under sphere head test of standard TWB because of imperfect weld and in Fig. 3b, cavity formation due to high inlet temperature is presented.

After completing several weld experiments, optimized parameters of laser for TWB welding with two thickness combinations of 0.8–1.5 and 1–1.5 mm were realized which are presented in Table 3. It is obvious that by increase in addition of thicknesses two parts of TWB, having a fixed power will yield a reduced weld speed to make up for required inlet heat.

In Fig. 4a and b, the cross-area of weld zone TWB with two thickness combinations of 0.8–1.5 and 1–1.5 mm, having been welded under optimized welding parameters, is depicted.

Table 2 Mechanical characteristics of St14 with different thicknesses

Thickness	Yield strength (MPa) 2/0 % (Ys)	Ultimate tensile strength (MPa)	Percent elongation (%El)	Strain hardness (*n*)	Strength coefficient (MPa) (K)
0.8	144.2	285.3	45.6	0.2515	516.7
1	181.3	311.7	44.82	0.2298	549.8
1.5	161.8	320.9	45.6	0.2392	577.1

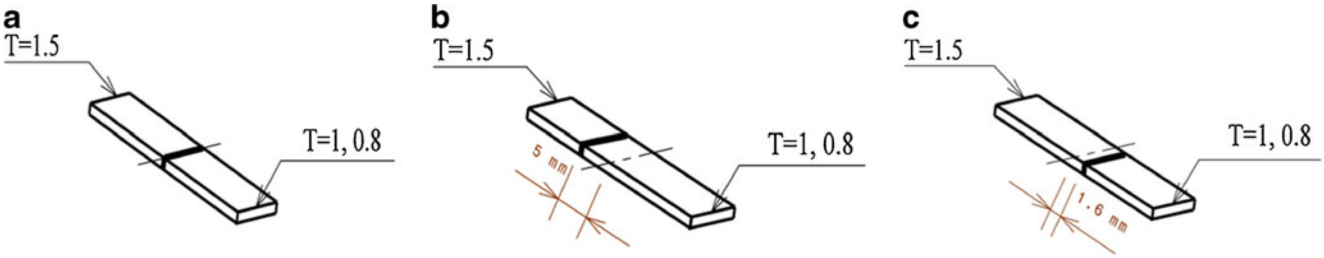


Fig. 1 Different locations of weld line; **a** weld line at the center of the sample, **b** 5 mm movement of weld zone toward thick sheet, and **c** 1.6 mm movement of weld zone toward thin sheet

2.3 Tensile test

Tensile test was done on base sheets without any weld as well as assortment of TWB with tension direction perpendicular on the weld line. Tensile samples were produced in accordance with ASTM E8M standard and were cut by a JSEDM wire cut machine from base sheets and welded samples [14]. In order to obtain precise tensile characteristics, an extensometer of 24 mm jaw length was installed at the center of tensile samples. As such, in TWB samples with different weld line locations, tensile characteristics were measured precisely along the 25 mm length. Figure 5 depicts installment procedure of extensometer for conducting tensile test.

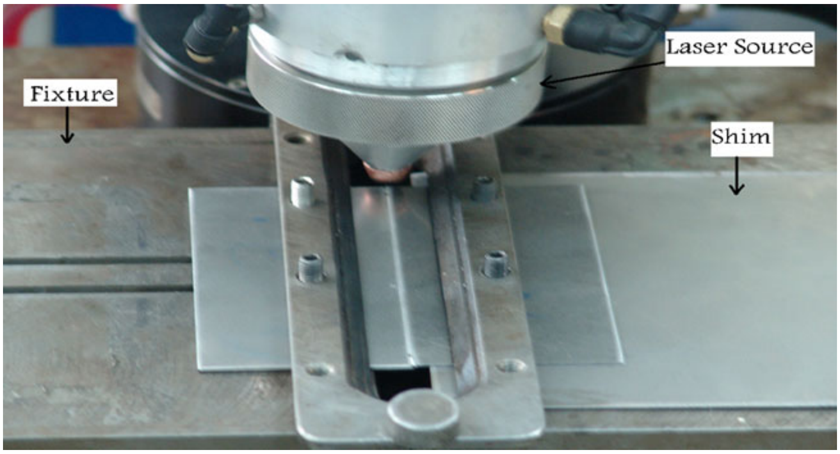
Standard tensile characteristics includes yield strength, ultimate tensile strength, percent over all elongation, strain hardness power (n), and coefficient of work hardening (K) in which from exerted force and measured displacement, were all obtained from tensile test. Tensile tests were conducted by using a 10 t Hounsfield machine and with strain rate of 2 mm per minute. In calculation of stress/strain diagram of samples of TWB, thickness of the thin sheet was considered as initial thickness. The reason for this was rupture occurrence in the thin sheet.

2.4 Standard ball punch testing

Standard ball punch testing was used to analyze formability of base sheets and TWB samples. For this purpose, a die and punch was designed and made in accordance with ASTM E643 standard [15]. In Fig. 6, dimensions of this die is shown. This test is used to evaluate and compare formability of medal sheets. The results obtained from this test is used for comparing materials formed bi-axial tension.

This die was placed on a 20 t Schenk Treble press. TWB samples and base sheets were cut in 90×90 mm dimensions and placed inside the die (Fig. 7). TWB samples were carefully adjusted such that weld line would be placed in designated location. Prior to conducting the test, surface samples and die was washed using acetone to remove any pollutants. Semisphere surface of the punch was lubricated by a thin layer of petroleum jelly. To make up for thickness difference in TWB samples, a shim was used under the thin sheet in order to distribute pressure exerted by the grip equally on all surfaces of the sample. Exerted gripper force was 2 t so that flange movement would be stopped while testing was conducted. Punches moving speed for all tests were set as 20 mm per minute. According to standard, the

Fig. 2 Laser lay out



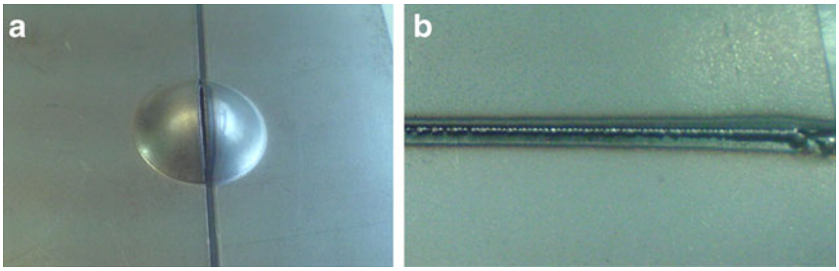


Fig. 3 **a** Rupture in weld zone TWB in sphere head standard test due to incomplete penetration of weld and **b** cavity formation and additional meld of weld zone in TWB because of high inlet temperature

approaching end of the test to increase measuring precision this speed was slightly reduced. Displacement amount of the ball punch at time of sudden reduction of force was recorded as index of formability.

3 Discussion

3.1 Tensile test

In Fig. 8, tensile samples of TWB are deformed upon conducting tensile test with perpendicular exertion of force on the weld line. As observed, rupture has occurred for all samples of TWB with different thickness combinations, away from weld zone and in thin sheet. As metallographic and micro hardness results indicated, weld zone was flawless without any fracture and with complete depth of penetration. Moreover, its strength was higher than that of base sheets. For these reasons, fracture occurred away from the weld zone.

As it is evident, strain values of all samples of TWB are less than that of the base sheets making them. This could be justified by the fact that in TWB samples, thin base sheet goes through highest shape change whereas thick sheet is less affected particularly at the plastic strain level. In TWB samples, by displacing weld line toward thick sheet, percentage of relative elongation increases. Moreover, thin sheets share in the tensile sample also increases. Since thin sheet goes through most shape change and thick sheet has less plastic strain, therefore a percentage of the overall increase of relative length goes higher.

By using limiting strength ratio (LSR) criteria, it could be predicted whether thick WB sheet goes through plastic shape change under test or not. The two sheets forming TWB reach LSR condition when strain in the thick sheet reaches yield strength (σ_y); on the other hand, strain in the thin sheet reaches ultimate strength (σ_T) hence Eq. 1 [16] would be as follows:

$$\sigma_{\mathrm{Tb}} t_b = \sigma_{\mathrm{ya}} t_a \Rightarrow \mathrm{LSR} = \left(\frac{\sigma_{\mathrm{yb}}}{\sigma_{\mathrm{Ta}}}\right) = \frac{\mathrm{t_b}}{\mathrm{t_a}} \tag{1}$$

In which a is indicative of thick sheet, b is the thin sheet, t is thickness of thin sheet and T is thickness of thick sheet. If strength ratio of two base metals would become grader than LSR, thick sheet shape changes perpendicular on the weld line remains as elastic whereas thin sheet has gone through maximum plastic strain. In Table 4, values of LSR and strength ratio for TWB with two thickness combinations of 0.8–1.5 and 1–1.5 mm is shown. In TWB with thickness combination of 0.8–1.5 mm, value of strength ratio exceeds LSR; as a result, TWB plastic strain perpendicular on weld line is only created in the thin sheet (0.8 mm) and no plastic deformation is observed in thick sheet (1.5 mm) for TWB with thickness combination of 1–1.5 mm value of strength ratio is less than LSR. This means both sheets go under plastic strain.

In TWB tension with different thickness combinations, values of plastic strain in thick sheet could be calculated in terms of strain in thin sheet. Considering Eq. 2, it is possible to calculate strain in the thick sheet in terms of strain in the thin sheet [17].

$$A_{a0} e^{-\varepsilon a} k_a \varepsilon_a^n = A_{b0} e^{-\varepsilon b} k_b \varepsilon_b^n \tag{2}$$

In this equation, a represents thick sheet and b is for thin sheet. If f is equal to the ratio of thin sheet to thick sheet,

Table 3 Optimized parameters of laser for TWB welding with different thicknesses combinations

Thickness combination (mm)	Welding speed (cm/min)	Pulse' width (ms)	Pulse' frequency (HZ)	Pulse' mean power (W)	Distance head to surface (mm)	Argon gas flow rate (l/min)
0.8–1.5	5.6	6	20	220	1.53	60
1–1.5	4.44	6	20	220	1.53	60

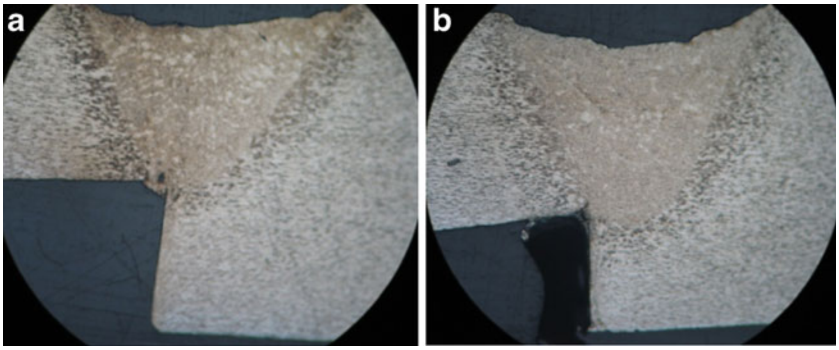


Fig. 4 **a** and **b** Cross-area of weld zone TWB of complete penetration with two thickness combinations 0.8–1.5 and 1–1.5 mm having been welded under optimized welding parameters (magnification, ×40)

meaning $f=\frac{t_b}{t_a}$ then for values of n and k, Eq. 2 could be solved with numerical solution to calculate strain of thick sheet as function of strain in thin sheet until it strain of thin sheet reaches n (this is where thin sheet reaches necking). In Fig. 13, diagram of plastic strain in thick sheet compared to plastic strain in thin sheet for thickness combination of 1–1.5 mm is depicted. These diagrams are drawn in terms of Eq. 2. Values n and k for two sheets, 1 and 1.5 mm, have entered Eq. 2 and with change in b from zero until n=0.23 (moment of necking 1 mm sheet); these diagrams are obtained for different values of f. As shown in the figure, in thickness combination 1–1.5 mm meaning f=0.667, plastic strain in thick sheet (1.5 mm) is equal to 0.018.

As it is evident, elongation of a tensile sample after necking will be limited to the narrowed area and other areas of the sample do not go through much shape change [17]. In tensile test of TWB having formed from sheets of different thickness, necking occurs in the thin sheet first; then in higher strains of necking, elongation is limited only in the narrowed area of the sheet and thick sheet after necking of TWB do not elongate plastically anymore. On these basis, in tensile test of TWB with different locations of weld line, increase in overall proportion of elongation could be found from the following:

$$\mathrm{El_T}=\frac{\mathrm{x_{thin}}}{\mathrm{L}}\times\mathrm{El_{thin}}+\frac{\mathrm{L}-\mathrm{x_{thin}}}{\mathrm{L}}\times\varepsilon_{\mathrm{thick}} \tag{3}$$

In which L is equal to the length of tensile area x_{thin} (millimeters) is equal to the length of thin sheet in tensile sample, $\mathrm{El_{thin}}$ is increase in relative length of base of thin sheet obtained from tensile test, El_T is increase in overall proportional length of TWB, and $\varepsilon_{\text{thick}}$ is obtained strain in the thick sheet on the basis of Eq. (2). By entering values of increase in proportional length of base sheets of 0.8 and 1 mm from Table 2, El_T for different types of TWB was calculated and have been compared with results obtained from tensile test (Fig. 9).

Difference between results is from 2.4 to 5.5 %. Since numerical results present a relatively good and acceptable value compared to experimental results, it can be induced that weld zone does not play a major role in elongation shape change of tensile samples of TWB. It is safe to state that base sheets particularly thin sheet plays a major role in elongation shape change of tensile TWB samples with different thicknesses.

In Fig. 10, ultimate tensile strength of different TWBs versus base sheets are compared. As evidenced, strength of ultimate tensile of TWB samples is comparable to that of sheets forming them or even better. Rupture in all TWB samples occurs in the thin sheet and thus its strength is indicative of strength of TWB. Consequently, it could be concluded that by using TWB of controlled thickness sheets, weight could be reduced enormously without sacrificing strength [9].

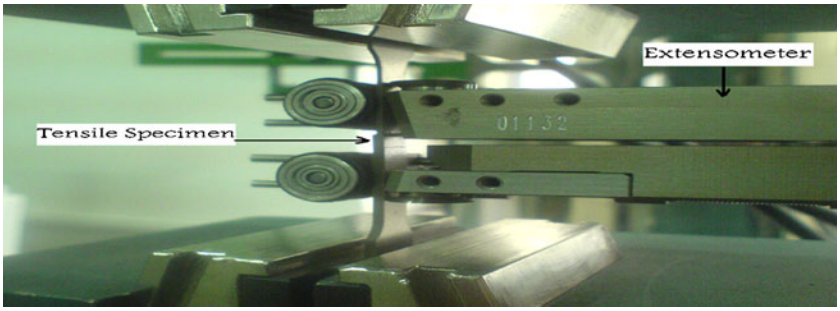


Fig. 5 Installing extensometer on tensile sample while test was conducted

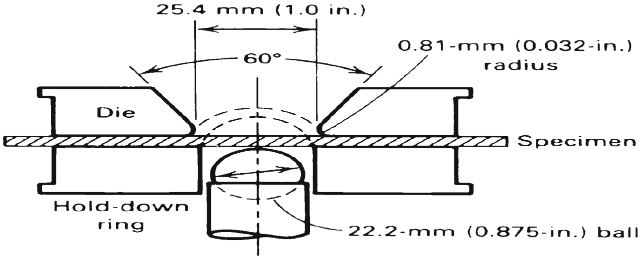


Fig. 6 Standard dimensions of die for ball punch test [18]

3.2 Standard ball punch test

In Fig. 11a, TWB samples with different thickness combinations are shown and in part (b) those samples are shown with different locations of weld line. As obvious from the figure, in all samples of TWB, rupture takes place in thin sheet and away from weld area. Similar to tensile test results, change in thickness causes unsteady generation of strain in thick and thin parts of TWB. Furthermore, plastic deformation would be concentrated on the thin part of TWB which leads to rupture in the thin sheet.

In Fig. 12, the height of formed cup by standard ball punch test on different samples of TWB and base sheets are presented for comparison. As evidenced from this figure, the height of formed cup of base sheets increases along with increase in their thickness. The main reason for this is that by increase in thickness, resistivity to local necking also increases [18]. Moreover, obtained cups height for all TWB samples is less than that of base sheets forming them. The height of cup indicative of overall plastic strain in both formed thick and thin parts of TWB until rupture point is less than sheets forming it. This is caused by unsteadiness of strain and having lesser plastic strain in the thick sheet. Also by reducing thickness, difference height of cup increases and shows that by reduction in thickness difference in TWB formability goes up. By reducing thickness difference, strain distribution in thick and thin parts of TWB becomes more homogenous. This means thicker sheet participates more in plastic strain. Also by reduction in thickness difference, average thickness of sheets forming TWB increases and as indicated by increase in thickness of base sheets height of cup also increases. Consequently, by increase in the average thickness of forming sheets of TWB, the height of cup has to increase.

By dislocating weld line toward thick sheet, the height of cup goes up. Therefore, it could be stated that by dislocating weld line toward thick sheet, formability of TWB increases. As observed in the results of tensile test, by dislocating weld line toward thick sheet, thin sheet's share in the TWB sample increases and since thinner sheet is capable of higher plastic deformity, therefore percentage of relative length increases. It could be safely stated that the height of cup which is indicative of plastic strain in both thin and thick parts of TWB increases proportional to any increase in the percentage share of thin sheet in TWB. Similarly, by increase in the share of thick sheet in TWB, it decreases.

3.3 Comparison between results of tensile test and ball punch test

In Fig. 13, relations between height of cup and percentage increase in proportional length of TWB samples with thickness combination 0.8–1.5 mm and with different locations of weld line is depicted. There is a straight relation between height of cup and percentage increase of proportional length in TWB samples with different locations of weld line. It is also evident that increase in length is a suitable criteria for analysis of formability.

4 Conclusion

A flawless, faultless weld with complete depth of penetration was obtained by using optimized parameters of laser in

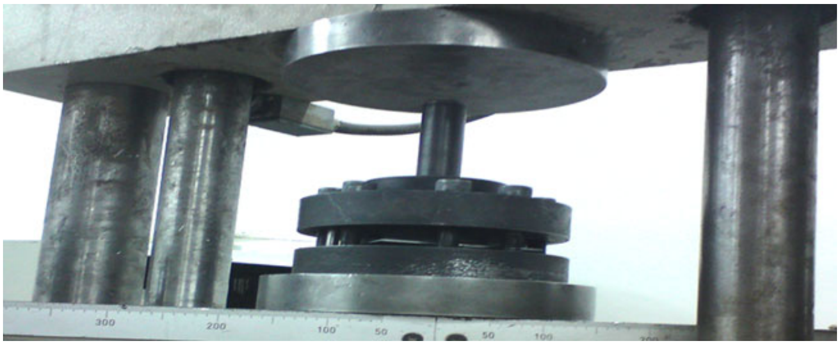


Fig. 7 Layout of standard ball punch test

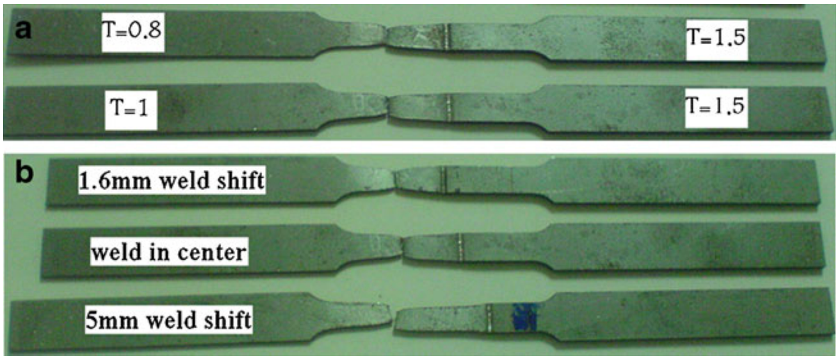


Fig. 8 Deformed samples of TWB after tensile test; **a** with different thickness combinations and **b** with different locations of weld line

Table 4 Values of LSR and strength ratio for TWB with different thickness combinations

Thickness combination	0.8–1.5 mm	1–1.5 mm
LSR	0.533	0.663
σ_{yB}/σ_{UA}	0.563	0.519

laser welding TWB made of St14 sheets. By conducting metallurgical and mechanical microstructure as well as tensile characteristics and formability of TWB was analyzed. The following are direct results of this process:

1. By using suggested relation, the increase in proportional length of TWB samples could be calculated via sheets forming it and results obtained from this relation is in conformance with results obtained from tensile test. Thus, it is concluded that weld area does not play a major role in tensile forming of TWB.
2. Tensile strength of TWB is about that of sheets forming it and it is equal to that of thin sheet. Furthermore, it was also revealed that by using TWB weight could be reduced without any decrease in strength.
3. In light of results of tensile test and standard ball punch test, it could be deduced that by dislocating weld line toward thick sheet, formability of TWB samples increases.
4. The results of standard ball punch test indicated that by reduction in difference of thickness of sheets forming TWB, their formability increases. The rea-

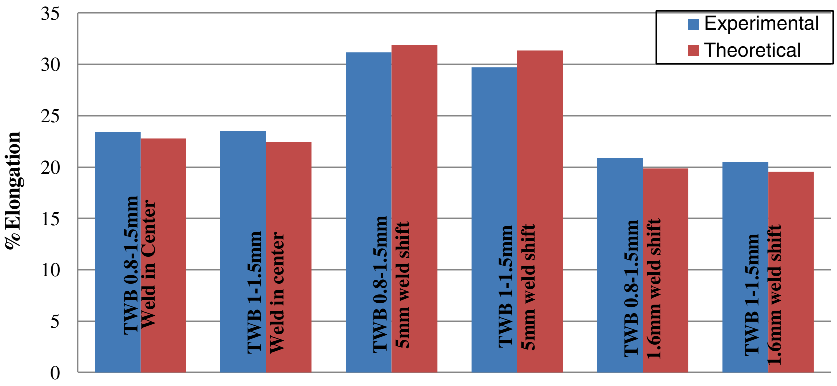


Fig. 9 Comparison of percentage increase of relative length obtained from experimental results with results calculated from Eq. 3 for different kinds of TWB

Fig. 10 Comparison between ultimate tensile strength of all kinds of TWB with their base sheets

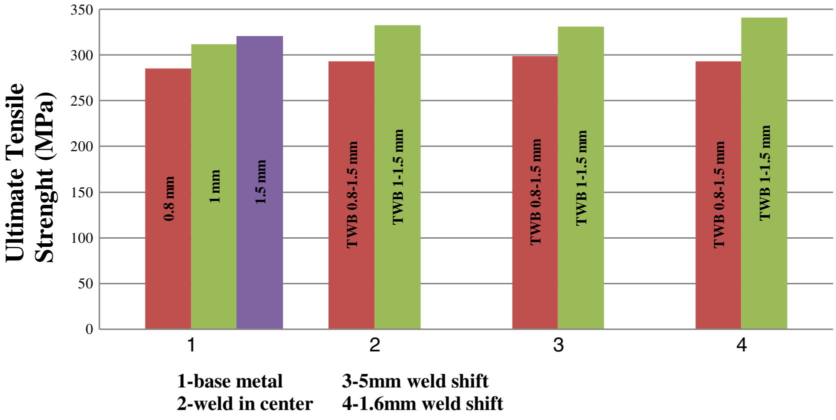


Fig. 11 Tested samples of TWB—**a** with different thickness combinations and weld line in the center and **b** different weld line and locations and thickness combination of 0.8–1.5 mm

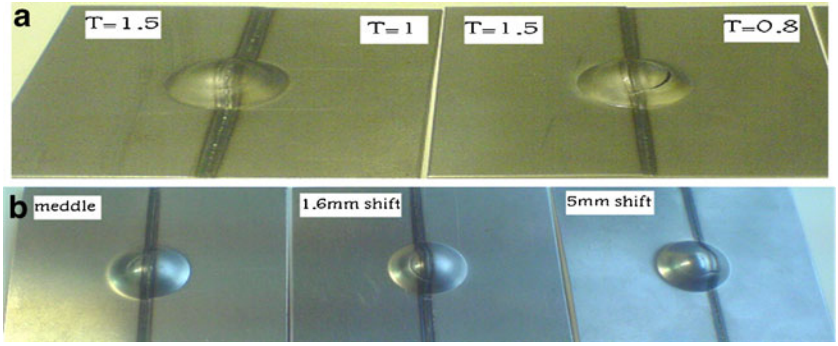
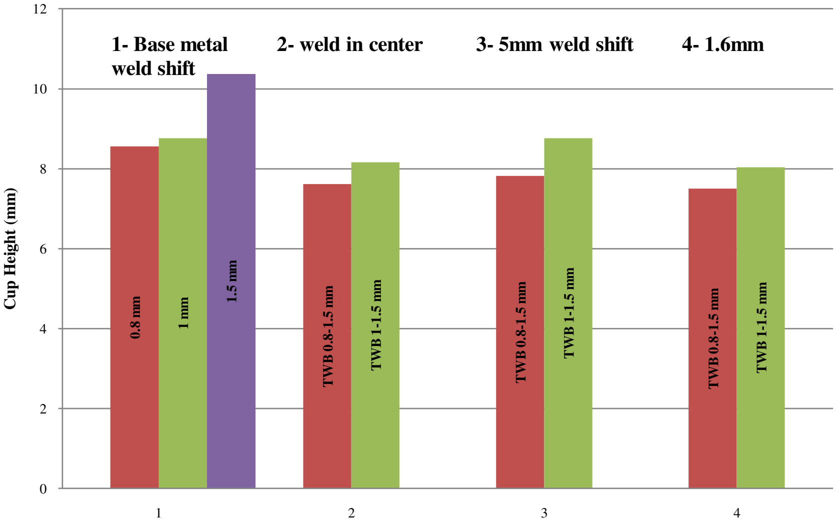


Fig. 12 Height of cup at ball punch test for TWB samples and base sheets



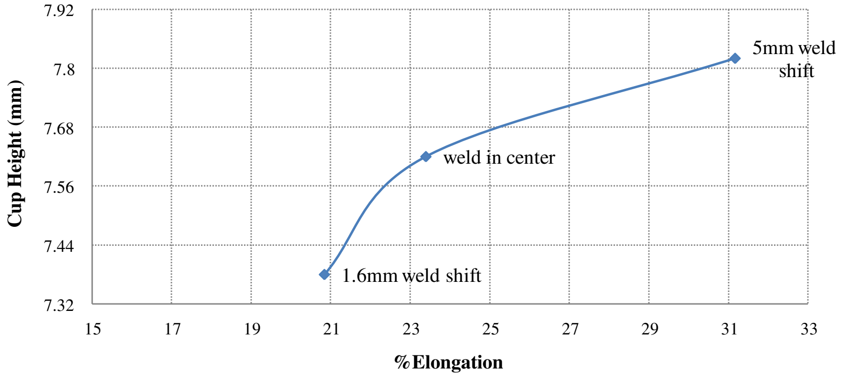


Fig. 13 Relation between height of cup and percentage increase of proportional length in TWB samples with thickness combination 0.08–1.5 mm and with different locations of weld line

son for that is increase in the average thickness of sheets forming TWB in addition to less thickness difference as well as generating more homogeneous plastic strain in both thick and thin TWBs.

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