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Formability Enhancement of Galvanized IF-Steel TWB by Modification of Forming Parameters

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Tailor-welded blanks (TWBs) have numerous advantages over traditional blanks used in manufacturing, such as energy conservation and environment protection. Low formability and weld line movement during forming operation are main limitations of these blanks. In this research, the effects of forming parameters including thickness ratio (TR), rolling direction with respect to the weld line and direction of major stress with respect to the weld line, on formability and weld line movement of TWBs made of galvanized Interstitial-Free (IF) steel were investigated experimentally. Also the effect of application of non-uniform blankholder force on weld line movement was studied by FEM simulation. By utilization of ABAQUS software, blankholders with different geometries, namely one-piece and two-pieces were modeled and forming process was simulated. The results revealed that formability maximized when the major stress and rolling direction were along the weld line. The results showed applying different blankholder forces, by application of the two-pieces blankholder, leads to more uniform strain distribution and correspondingly less weld line movement in TWBs with TR greater than 1. It was also concluded that the effect of geometric discontinuities on reducing formability was greater than the effect of the weld region.

Keywords formability, forming parameter, TWB, weld line movement

1. Introduction

Reduction in energy consumption and protection of the environment are now universal objectives. In an attempt to comply with increasing tougher regulations concerning these issues, the automobile industry has made every effort to produce lighter automobiles and application of Tailor-welded blanks (TWBs) is one of the best ideas (Ref 1). Tailor-welded blanks are multiple sheets of material which are welded together before the forming process (Ref 2). Materials within a TWB could be of different thicknesses, grades and/or coatings, e.g., galvanized versus ungalvanized (Ref 3). By consolidating parts, TWBs offer the auto industry an excellent opportunity to reduce cost, decrease vehicle weight, and improve the overall quality of sheet metal-stamping processes (Ref 4).

Despite their numerous benefits, the forming process of TWBs is a challenging task due to a significant reduction of formability associated with this type of blank and also movement of weld line during forming (Ref 5). Therefore, studying the effect of forming parameters on formability and stress-strain distribution is important to maximize the former and evenly distribute the latter as well as to decrease weld line movement. Nagasaka et al. (Ref 6) reported that deep drawability of high-strength steel TWBs is deteriorated with increasing carbon equivalent. Chan et al. (Ref 7) found Forming Limit Diagram (FLD) level and minimum major strain in FLD are generally decreased with an increase in TR. Miles et al. (Ref 8) studied the effect of welding method and parameters on formability. According to their results, the blanks tailored using friction stir welding method are more formable than those welded using gas tungsten arc welding method. One of the many influential parameters in the deep drawing of TWBs is the blankholder force. Low blankholder force leads to wrinkling, while an excessive blankholder force causes tearing (Ref 9). Hence, applying proper blankholder force not only increases draw depth value and decreases weld line movement but also minimizes wrinkling (Ref 10, 11).

In this research, in addition to experimental investigation of the effects of forming parameters on formability, effect of the blankholder force on formability (dome height, strain distribution, and weld line movement) was studied using FEM. Stress and strain distributions within TWBs are interesting issues to study because of the effect of localized phenomenon. Also contribution of two parameters, i.e., geometric discontinuities and existence of the weld region, on reduction of formability of the studied TWBs with respect to the monolithic sheet was determined.

2. Experimental Methods

Although TWBs consisted of steels can be joined using various welding processes (laser beam welding, mash seam welding, electron-beam welding, or induction welding), laser welding is the most common technique, which is used in major production facilities (Ref 12). The TWB material used in this study was CO_2 laser-welded Interstitial-Free (IF)-galvanized steel alloy. Optimum welding parameters were determined

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Table 1 Chemical composition of the IF steel

Element	C	Si	Mn	Ni	Al	Ti	Cu	P	S	V	Cr	Fe
wt.%	0.002	0.004	0.149	0.015	0.033	0.046	0.017	0.015	0.007	0.002	0.022	99.682

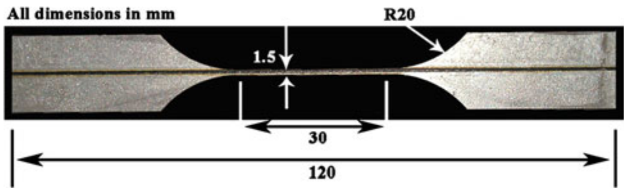

Fig. 1 Specially designed tensile specimen used in this study for obtaining mechanical properties of the weld

using Taguchi method that is explained in details in Ref 13. To assess the effect of thickness ratio on formability, three gage combinations utilizing butt-welded sheets were considered (1, 1.71, and 2.14 related respectively to combination: 0.7-0.7 mm, 1.2-0.7 mm, and 1.5-0.7 mm). All test materials were collected from a single material lot, though the lot for each thickness was different. Table 1 shows the chemical composition of the steel used in this study. Tensile tests were conducted using subsized tensile test specimens, based on ASTM-E8, and special miniature tensile specimens (Ref 14), to obtain the true stress-true strain data for monolithic sheets and the weld region of the TWBs with TR = 1.71, respectively. The miniature specimen used in this study only included the weld and the Heat Affected Zone (HAZ) in the gage area. The miniature specimen, shown in Fig. 1, was prepared using an electron discharge machine. The strain rate was 10^{-3} s^{-1} during the tensile tests. Subsized tensile test specimens in longitudinal and transverse weld orientations were also prepared to study the combined effect of the parent materials and the weld region on mechanical behavior. The hardness profile across the weldment, HAZs, and the thinner/thicker parent metals were established using Vickers microhardness.

Formability was assessed using the limiting dome height (LDH) test. The geometry of the specimens (125 × 200 mm) provided a plane strain or near plane strain state depending on the weld orientation. Plane strain condition is a critical condition during forming that formability is the least (Ref 15). Two weld orientations have been considered: transverse and longitudinal to the main loading direction. Two rolling directions were also considered: perpendicular and parallel to the weld. Schematic of the samples used in experiments is shown in Fig. 2.

Schematic and image of punch-die assembly for LDH tests are shown in Fig. 3. Clamping force on different segments of TWB was applied using bolts and adjusted by control of the torque on each individual bolt. Punch speed of 0.1 mm/s was used for the LDH experiments. No lubricant was used to reduce the friction. Specimens were tested to failure.

Simulation of the experimental forming process was done using ABAQUS software that is commonly used for solving dynamic, non-linear large scale deformation events and processes, including quasi-static sheet metal forming problems. Average element sizes of 4 mm in the base zones and 0.5 mm in the weld zone with one layer of through thickness elements were used in the simulations. The 1-mm-wide weld line was discretized by two in-plane elements.

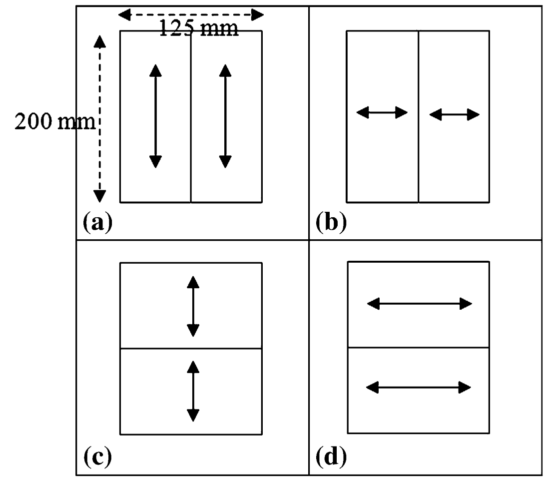

Fig. 2 Schematic representations of samples used in experiments (solid arrays indicate the rolling direction)

The forming tools consisting of punch, blankholder, and die were modeled as rigid bodies. The friction between different tool components and the TWB was modeled using Coulomb law. 0.15 was used as the coefficient of friction at the tool-blank contact. The TWBs were created simply by joining the nodes. The corresponding properties/thicknesses were also assigned to the two halves of the blank and the weld region. Figure 4 illustrates geometry of the weldment used in simulation. Weld region and HAZs were treated as identical during simulation, and they were represented wholly as one region in which the mechanical properties were different from those of the parent materials.

3. Results and Discussion

3.1 Microstructure and Mechanical Properties

Figure 5 illustrates the microstructure of the weld, HAZ, and parent thin sheet. The grain size of the weld material is significantly smaller than that observed in the monolithic sheet. In addition, in the center of the weld, grains are equiaxed while columnar grains are observable at the sides. HAZ consists of very large columnar grains. These can be justified based on cooling rate condition each region experiences during welding. Very high cooling rate in the weld region and steep temperature gradient in HAZ are responsible for very fine grains of the weld and columnar growth of HAZ grains, respectively.

Figure 6 shows the hardness variation across the weld region, HAZ, and parent metals. Hardness values are lower than 280 $HV_{0.8}$. As can be seen from Fig. 6, the hardness of the weld region is approximately three times the hardness of parent metals, and the hardness of HAZs varies in between the hardness of the weld and the hardness of parent metals. Very low values of carbon in composition as well as hardness values

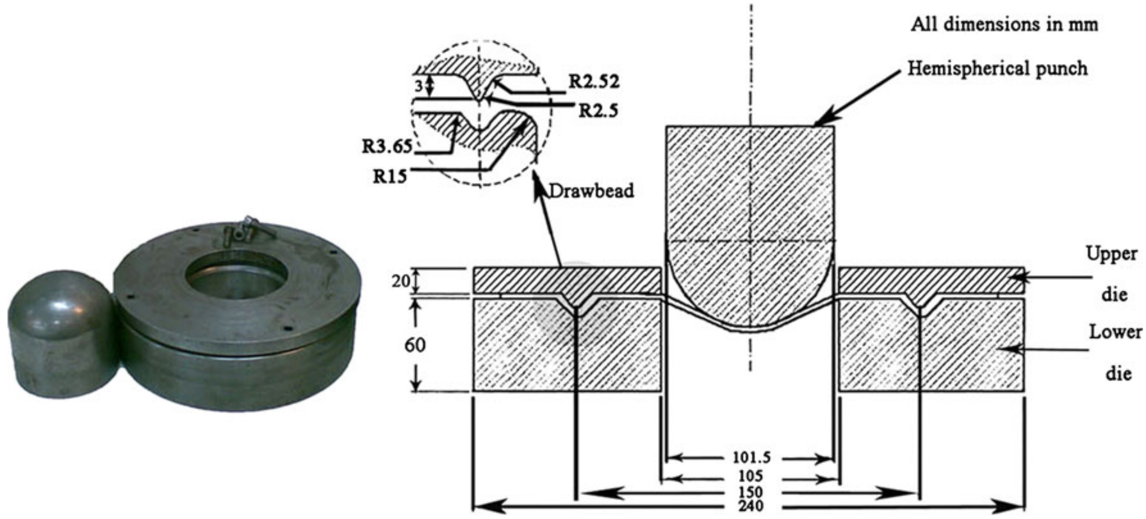

Fig. 3 Representation of instruments which were used in experiments as well as their geometry

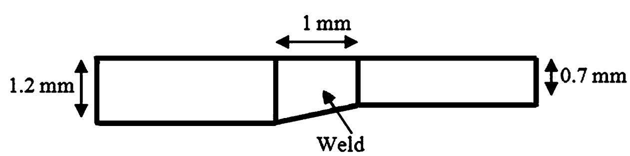

Fig. 4 Geometry of the weldment used in simulation

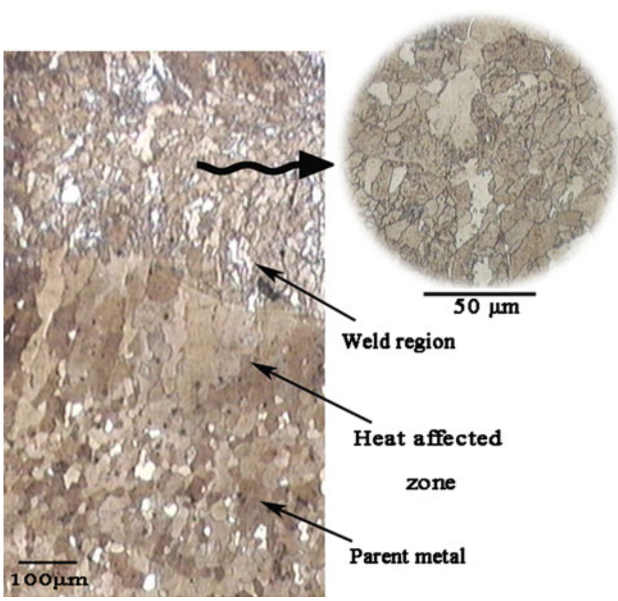

Fig. 5 Microstructure of the weld, HAZ, and parent thin sheet

lower than 300 $HV_{0.8}$ indicate the presence of ferrite in microstructure at different regions. Hardness values less than 300 $HV_{0.8}$ can be related to ferrite phase (Ref 16). Microhardness data indicated that the width of the weld and HAZs together can be taken to be about 1 mm.

In Fig. 7, true stress-strain curves of the weld region, thin (0.7-mm thickness) and thick (1.2-mm thickness) sheets are represented. As can be observed in this figure, the weld has

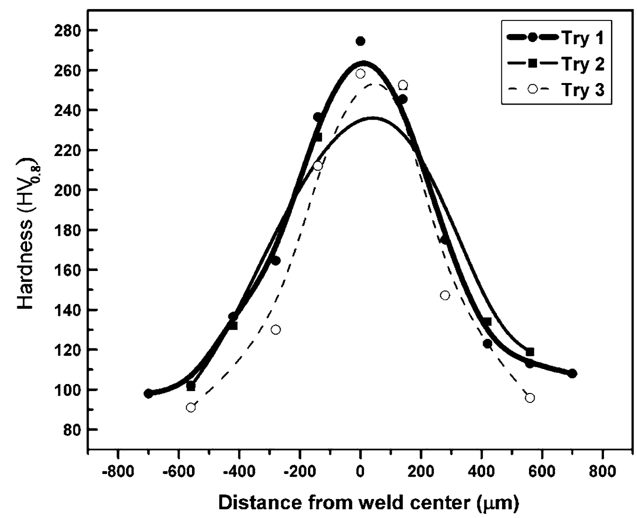

Fig. 6 Hardness variation across the weld region, HAZs, and parent sheets for three blanks with TR = 1.71

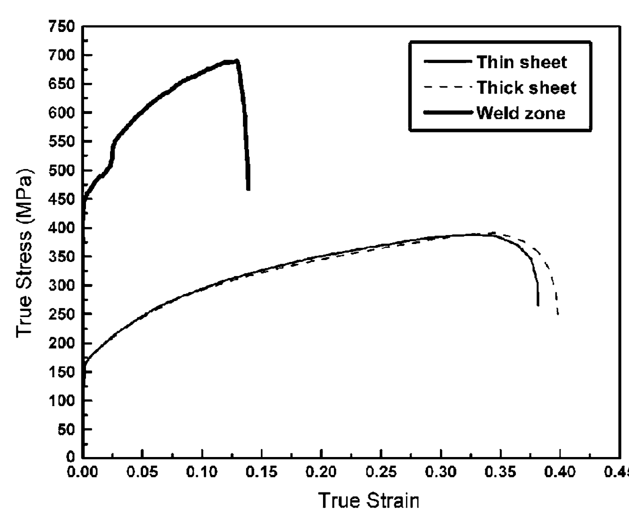

Fig. 7 True stress-true strain curves of weldment and monolithic sheets

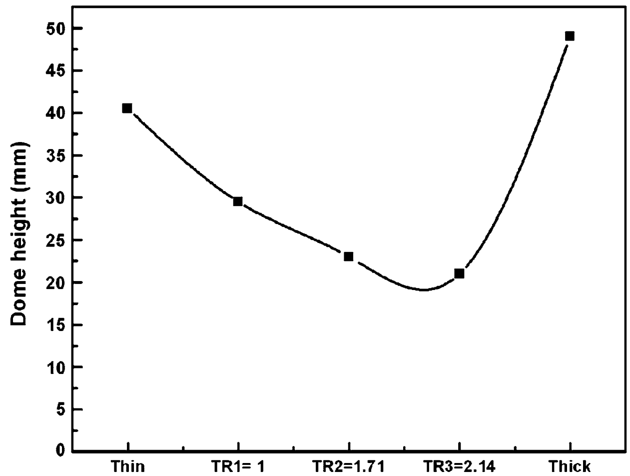

Fig. 8 Dome height values of the monolithic sheets and TWBs with different TRs. The thicknesses of thin and thick monolithic sheets were 0.7 and 1.2 mm, respectively

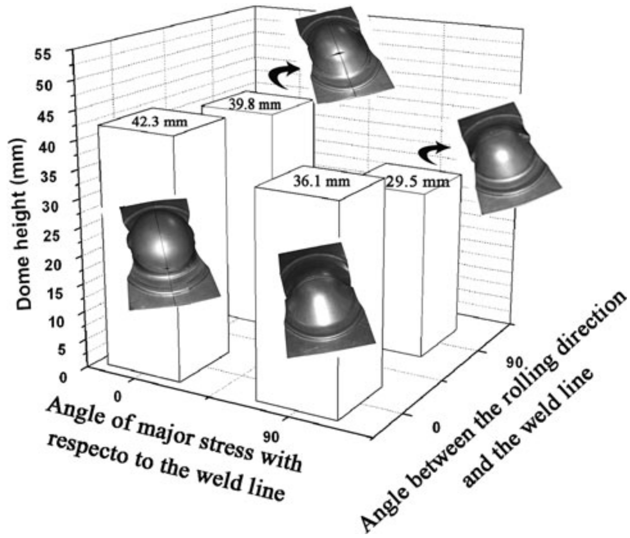

Fig. 9 Dome height values relating to blanks (TR = 1.71) with different angles of the weld line direction respect to the major stress and rolling directions

obtained higher ultimate tensile strength (UTS) and yield strength (YS) than those of the monolithic sheets. In addition, the miniature specimen has reached an elongation of 14%, while the elongation of parent sheets is about 45%.

Mechanical properties observed in Fig. 7 can be related to different morphologies of ferrite phase. Weld and parent sheet metals are composed of very fine and coarse equiaxed grains of ferrite phase, respectively. The former results in a high work hardening characteristic due to impediment of dislocations movement, while the latter facilitates easy movement of dislocations during the tensile test, and leads to a low strain hardening behavior and ductile specimen (Ref 17). Development of internal stresses in the joint should also be regarded as other reason of low ductility of the weld.

3.2 Forming Parameters

Effect of different TRs on limiting dome height is shown in Fig. 8. Values for the monolithic sheets (0.7- and 1.2-mm-thick sheets) are also included in this figure. For all the TWB specimens, the rolling direction and also the major stretching axis were perpendicular to the weld. For monolithic sheets, the rolling direction was parallel to the major stress direction. As can be seen in Fig. 8, the dome heights of parent sheets are higher than those of TWBs. As deformation in the monolithic sheets is relatively uniform and they have similar properties, their formability depends mainly on their thickness. As the thickness of a sheet increases, its formability often increases (Ref 18). The 1.2-mm-thick sheet has the highest dome height as shown in Fig. 8. The decrease in the dome heights of TWBs compared to the parent sheets arises mainly from non-uniform deformation in the blank because of the difference in thickness and also the presence of the weld bead. Any increase in TR increases non-uniformity of deformation, and as a result dome height decreases. For all the considered TWBs, strain localization occurred first on the thinner side of the TWB, and failure was always on the thinner side.

Figure 9 is a plot of the dome height value against the angle of major stress with respect to the weld line and also the angle between the rolling direction and the weld line at a constant thickness ratio of 1.71.

In Fig. 9 specimens in which the rolling direction was parallel to the axis of the major stress show higher dome height values than the others. It relates to development of grains during rolling. As a result of rolling, grains in the rolling direction become elongated and work hardened, and the correspondent anisotropy coefficient increases. Increment of anisotropy coefficient along the major stress expands the yield surface in the major stress direction and contracts it in the normal direction (Ref 18). Therefore, when rolling direction is normal to major stress as yielding occurs at a low punch force, plastic deformation initiates at small displacement of punch, and necking occurs sooner. The lowest dome height obtained in a sample in which the major stress and rolling direction were perpendicular to the weld line.

Figure 9 shows longitudinally welded specimens have higher dome height values and correspondingly formability with respect to transversely welded specimens; furthermore, Fig. 9 shows that fracture is initiated in the weld/HAZ areas in the former in return of thin sheet for the latter. When the angle between the major stress and the weld line is 0°, due to geometry of specimen, all three parts (parent 1, parent 2, and the weld) experience nearly the same major strain (Ref 19). This requires the same stress and correspondingly more force on thicker sheet. This leads to a nearly uniform strain distribution and minimal movement of the weld line. However, when the angle is 90°, both thinner and thicker sides and weld undergo the same level of applied force along the major loading direction. Therefore, stress on the thinner sheet will be more than that on the thicker sheet as well as the weld due to mainly its lower thickness. Therefore, strain distribution will be non-uniform and weld line will move (Fig. 9).

In a different experiment, a sample with a geometry resembling that of a TWB was made through machining. This sample included geometric discontinuity, but not actually weld region, i.e., a discontinuity line similar to the weld line which was perpendicular to both major stress and rolling directions. In Fig. 10(a), sample containing only the geometric discontinuity and the sample containing both weld region and geometric discontinuity (Fig. 10b) after being tested are shown.

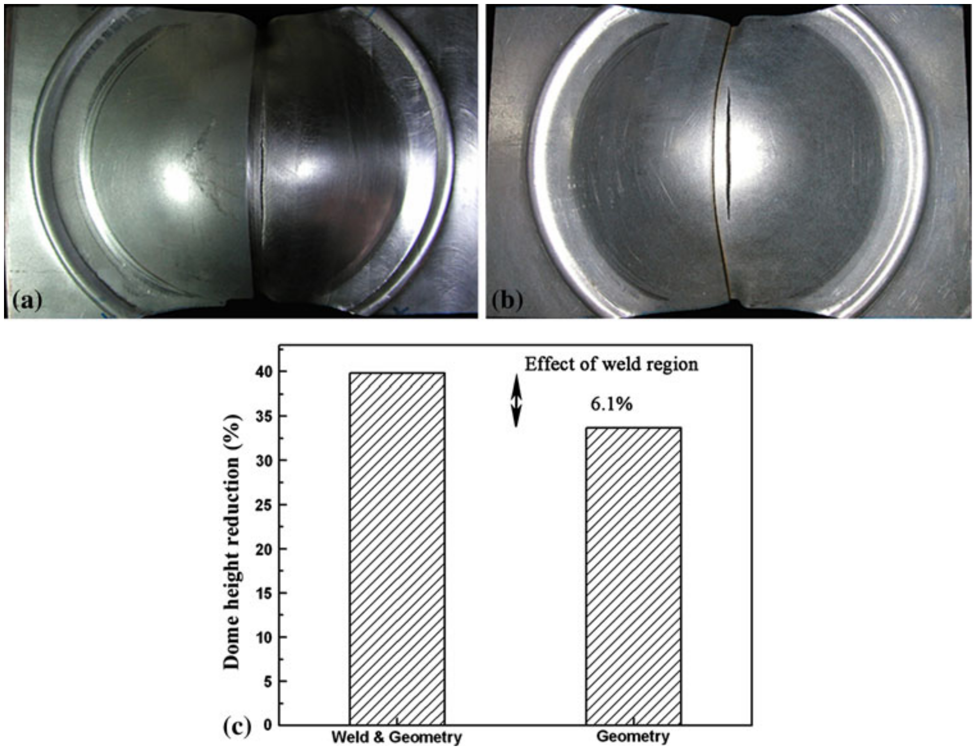

Fig. 10 Determining the contribution of the weld region and geometric discontinuity on reducing the formability of TWBs made of 1.2-0.7-mm sheets. (a) A blank containing thickness variation similar to a TWB without having an actual weld region, (b) a tailor-welded blank, and (c) reduction in dome height due to presence of considered variables

The former had a dome height value of about 32.5 mm, and the latter had a value of about 29.5 mm.

Effect of the presence of weld region and geometric discontinuity on reducing the dome height value of tailor welded blank (with TR = 1.7), compared to dome height value of 1.2-mm-thick sheet, is shown in Fig. 10(c). It is observed that the effect of the presence of weld region on reducing the formability due to its properties is rather small compared to the effect of the presence of the geometric discontinuity in a TWB. It can be concluded that minimizing the geometric discontinuity is an effective method in increasing formability of TWBs. In this regard, treatments such as machining on TWBs with TR more than 1 are recommended to decrease the slope of thickness variation across geometric discontinuity

3.3 Simulation

An increase in weld line movement by an increase in TR is illustrated in Fig. 11. Weld line movement and strain distribution in simulated samples are shown in Fig. 12 and 13.

During deep drawing of TWBs, the weld line shifts across the blank, depending upon the strength of the base materials (Ref 20). The weld line moves toward the thicker sheet due to higher amount of flow in the thinner sheet (Fig. 12).

Figure 13(a) and (b) show the strain distribution in TWBs with different TRs, at a punch displacement distance of 30 mm. It can be seen that in a sample with TR = 1, strain distribution is uniform and both halves of the blanks experience the same strain. However, in a sample with TR = 1.7, the thinner side experiences more deformation than the thicker side, as

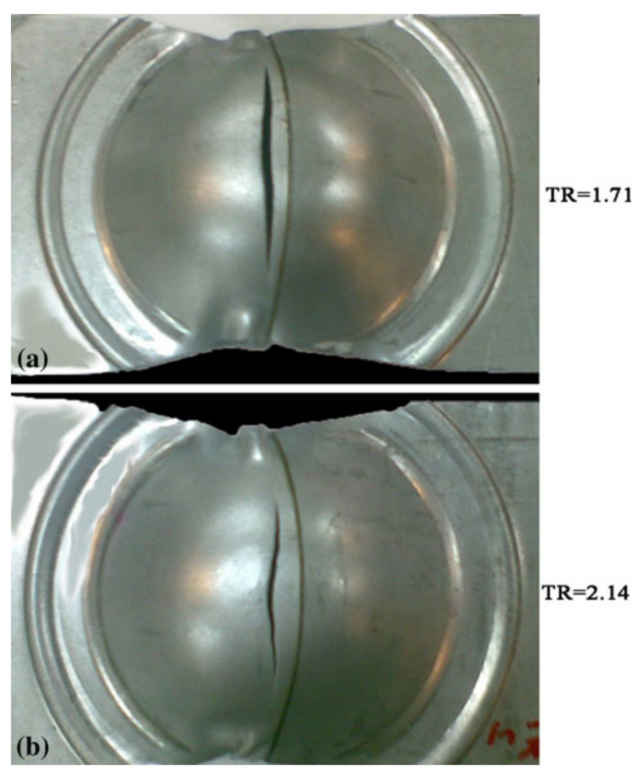

Fig. 11 Movement of the weld line: (a) specimen with TR = 1.7, and (b) specimen with TR = 2.14

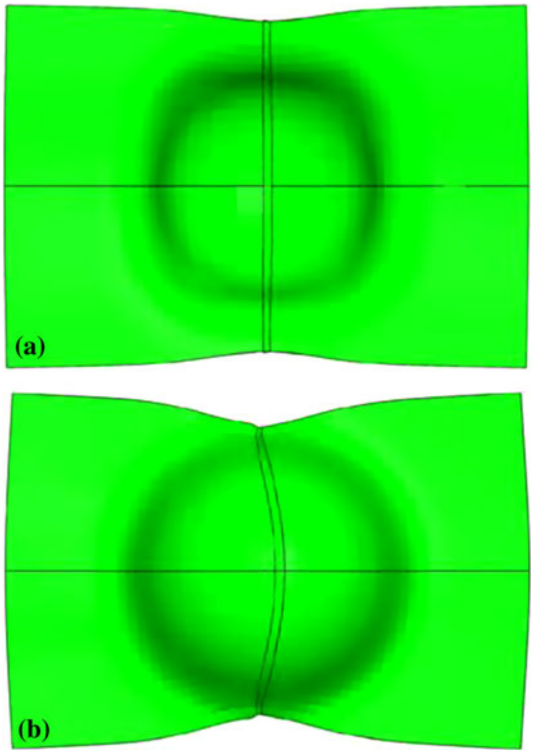

Fig. 12 Presentation of the weld line movement in TWBs with different TRs obtained through simulation: (a) TR = 1, and (b) TR = 1.7

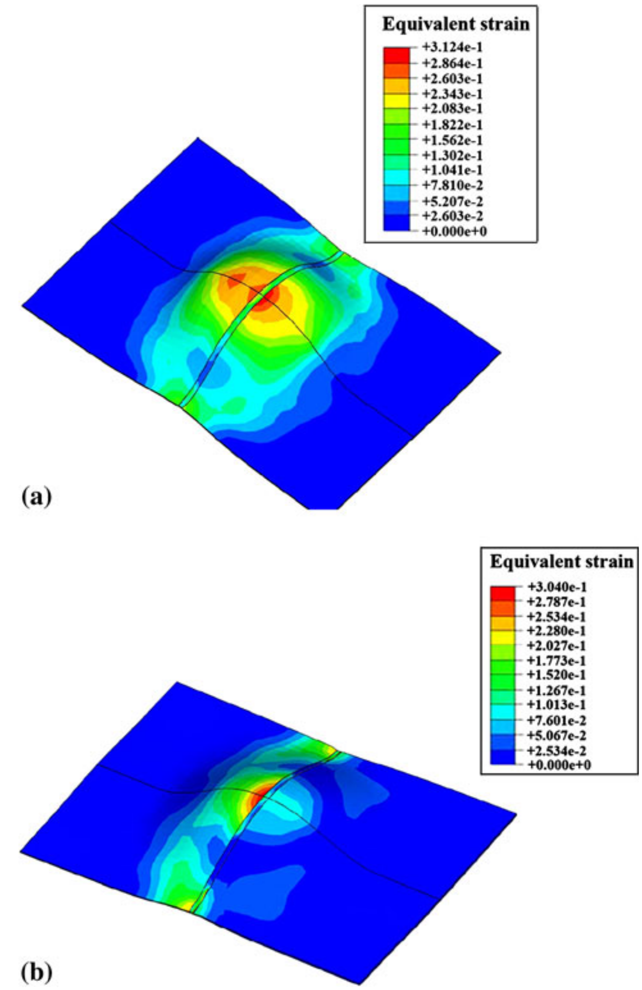

Fig. 13 Presentation of strain distribution in TWBs with different TRs obtained through simulation: (a) TR = 1, and (b) TR = 1.7

evidenced by higher strains. Apparently, the weld region experiences very little deformation in both samples, but this deformation for sample with TR = 1, is even lower. Once necking starts in the most severely deformed region, the major strain rapidly increases leading to failure with no significant further increase in the minor strain. In Fig. 12(a) and (b), weld line movements of TWBs corresponding, respectively, to Fig. 13(a) and (b) are shown. In sample with uniform strain distribution, no movement of the weld line is seen, but in the other part, weld line has moved.

During experimental investigation of formability of TWBs, a one-piece blankholder was used. In an attempt to control the weld line movement effectively, application of a split blankholder was also simulated. The blankholder was split into two halves to apply different forces on the thin and the thick segments of the TWB. Two paths were defined: one along the weld line (consisting of 10 points); and the second normal to the weld line (consisting of 21 points with the 11th being in the middle) (Fig. 14). In Fig. 15(a), the displacements of the points, related to the path "along the weld line," in the x direction for two simulation conditions as well as the experiment are compared. Despite good agreement between curves 1 and 3 in Fig. 15(a), results from the experiment are higher than those obtained in simulation (curve 1). This can be attributed mainly to the opening of the tearing line during the experiment, while in simulation, necking was used as the failure criterion. It can also be seen in Fig. 15(a) that by using a two-pieces blankholder and applying different forces (a force of 55 kN was applied on the thin sheet side, and a 35-kN force was applied on the thick side), the weld line movement (about 5.5 mm) is lower than the condition of applying the same force (35 kN) on two halves of blankholder (about 10.1 mm). The blankholder force was maintained constant throughout the simulations. In Fig. 15(b), the plots of strain distribution corresponding to the conditions cited above are shown, respectively. The strain values correspond to the points on the path "normal to the weld line" (Fig. 14) at punch travel distance of 30 mm. Figure 15(b) shows that if the same force is applied on blankholder for the same punch displacement, maximum value of strain is higher, and strain distribution is less uniform with respect to using the two-pieces blankholder.

Applying higher and lower blankholder forces on thin and thick parent sheets of a TWB, respectively, results in impediment of thin parent sheet deformation and easy deformation of the latter. Material flow is controlled based on the strength of the sheet and the thick sheet has more strength. Applying less blankholder force on the thick sheet causes it to flow more, and as a result, different segments of a TWB nearly deform uniformly and higher formability characteristic is obtained; additionally. weld line movement decreases. The weld line movement depends on distribution of strain. The more the uniform distribution of strain in the parent sheets and the weld, the less will be the movement of the weld line.

An important note to be made of in Fig. 15(b) is strain distribution in the weld. In Fig. 15(b), points 10, 11, and 12 correspond to the weld zone with point 11 being placed in the middle of weld between points 10 and 12 which are placed,

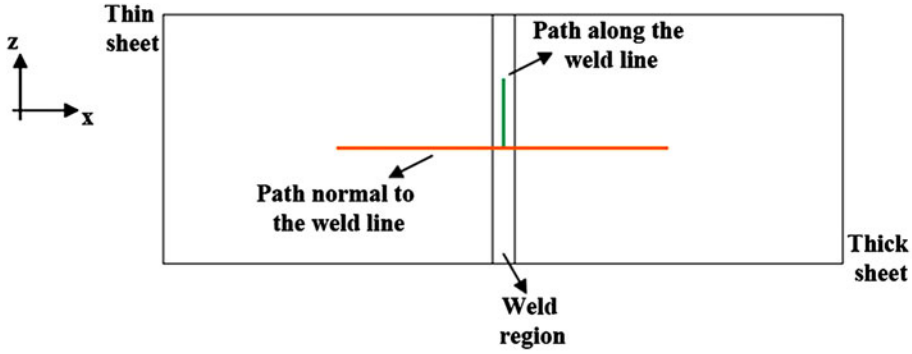

Fig. 14 Paths defined on a tailor-welded blank

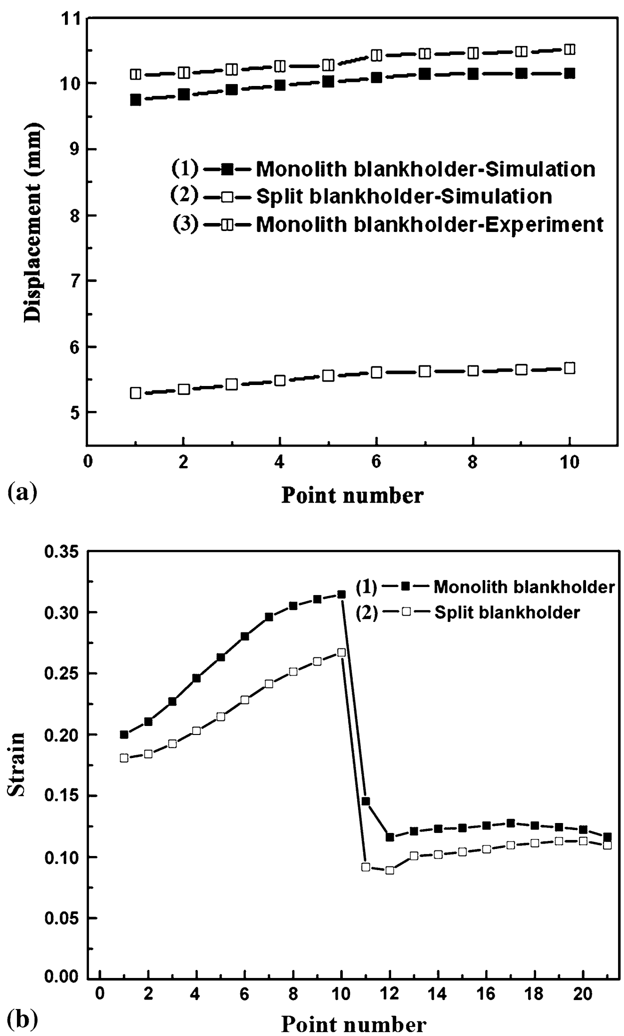

Fig. 15 (a) Movement of the weld line from middle of a TWB with TR = 1.7, and (b) strain distribution on a path normal to the weld line at the middle of a TWB with TR = 1.7

respectively, close to the thin and thick sheets. It can be seen in Fig. 15(b) that in condition of using a split blankholder, the weld shows a small amount of strain (about 0.07). As the weld region has relatively high strength and low ductility, less deformation in this region postpones fracture in the weld region or HAZ which almost increases formability characteristic of TWBs.

4. Conclusions

The effect of forming properties on formability as well as strain distribution and weld line movement of TWBs was investigated. The TWB material used in this study was CO_2 laser-welded IF-galvanized steel alloy. Using a two-piece blankholder, the effect of applying different blankholder force on formability of TWBs (TR > 1) was studied using simulation. The existence of the weld as well as the presence of the geometric discontinuity, resulting from welding two sheets of metal with different thicknesses, both decrease the dome height of TWBs and their contributions were determined. It was also concluded that

(1) The reducing effect of the weld region on formability of a TWB is mainly due to the presence of a geometric discontinuity rather than the weld itself. Therefore, reducing the steep gradient of thickness change in TWBs with TR greater than 1, as far as the part design permits, is highly recommended.
(2) Maximum formability of a TWB is obtained when the weld line is positioned parallel to the major stress and rolling direction of parent sheets.
(3) Simulation results showed that applying different blank-holder forces on different segments of a TWB consisting of monolithic sheets with different thicknesses via using a split blankholder decreases the weld line movement and increases uniformity of strain distribution and consequently improves formability.
(4) Weld line movement and the limiting dome height of the TWB specimens have been predicted successfully by considering the properties of the weld region for simulation. It is reasonable to expect improvement of the prediction through further optimizing simulation parameters, such as element kind, size, as well as assigning of proper mechanical behavior values to different segments of a TWB specimen.

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