Prediction of residual stresses in biaxial stretching of tailor welded blanks by finite element analysis

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Abstract. Residual stresses in sheet metal components play an important role in determining the life of parts especially in automotive industry. In this work, residual stresses have been predicted numerically in biaxial stretching of laser welded interstitial free (IF) steel blanks of different thickness combinations. The effective stress-effective strain curves of the parent sheets obtained from uniaxial tensile tests have been used as an input in finite element (FE) simulations to define the flow behavior of the materials. It has been found out that the residual stresses are tensile and similar on both sides of the weld zone in tailor welded blanks (TWB) of same thickness combination. In TWBs of different thickness combinations, the residual stresses on both sides are tensile and almost equal in the central region of the cup and they became compressive as the distance from the pole increases. The effect of thickness ratio on residual stresses has also been predicted in FE simulations of biaxial stretching of TWBs. It has been found out that with increase in the thickness ratio, the residual stress has slightly increased. Residual stresses have also been determined experimentally by using x-ray diffraction technique and it has been found out that the predicted values agreed well with the experimental results.

1. Introduction

Tailor welded blanks (TWBs) are being used in automotive industry for some sheet metal parts and they are generally prepared with the help of laser welding that generates residual stresses in the material due to the temperature gradient generated during joining process. Residual stresses also occur in the material due to non-homogeneous plastic deformation and structural changes [1]. Hariharan et al. [2] conducted stretch forming experiments using low carbon steel sheets of thickness 1 mm to determine residual stresses on the surface of the formed samples by using X-ray diffraction method. Residual stresses were also predicted by using Hill’s 48 and Barlat’s 89 yield criterion in commercially available LS-DYNA software. It was reported that the Barlat’s 89 yield criterion was able to predict more accurately as compared to the other criterion. Bedan et al. [3] performed experiments on AA1050 alloy sheets using single point incremental forming process and studied the effect of rotational speed, feed rate and depth size on residual stresses in the part. It was found out that high forming depth lead to higher residual stresses in the part. It was also reported that the higher rotational speed of the tool caused more uniform distribution of the residual stresses. Arshpreet et al. [4] determined and compared the residual stresses on AA6063-T6 aluminium alloy of thickness 1 mm by using nanoindentation method in conventional bending, incremental sheet metal bending and deformation machining (DM) bending. It
was reported that the residual stresses induced in DM bending mode were more uniform and comparable to the conventional bending. The residual stresses were reported to be higher in incremental bending process. Bruni et al. [5] determined springback and residual stresses by conducting experiments using double sheet hydroforming process under free expansion as well as under constrained expansion conditions at the die corners. The materials considered for the experiments are TRIP800 steel and FeP04 steel with 1.5 mm thickness. It was observed that high pressure, low corner radius and high friction allowed more equivalent plastic strain with a reduction in springback. Krux et al. [5] conducted deep drawing experiments using hydroforming process on low carbon steel (DC04) and austenitic high strength steel (X5 CrNi 1810) sheets of 1 mm thickness. The residual stresses were determined at the bottom of the cups and it was found out that high compressive stresses were present at the outer layer of bottom of the cup.

A few publications [7-10] have been found on determination of residual stresses in welded blanks. Clapham et al. [7] determined the residual stresses in same gauge and differential gauge laser welded TWBs by using neutron diffraction technique. The stresses were measured in as-welded condition and also after giving the uniaxial tensile strains of 0.5%, 3% and 7%. It was reported that residual stresses are lower on thinner side when compared to thicker side of the TWB. This was due to the less constraint applied by the thinner side of TWB during cooling of the molten pool. Peel et al. [8] studied the effect of welding speed on residual stresses present in the friction stir welded AA5083 sheets of 3 mm thickness. It was observed that with increase in the welding speed, the peak residual stress has been found closer to the weld line with higher magnitude. Staron et al. [9] used neutron diffraction technique to measure the residual stresses in two friction stir welded aluminium (AA2024-T31) sheets of thickness 6.3 mm or 3.2 mm. It was found out that the tensile residual stresses can be reduced by mechanical tensioning during welding. It was also reported that the maximum compressive stress in the weld zone was found to be -150 MPa in 3.2 mm thick sheet and -200 MPa in 6.3 mm thick sheet. Compressive residual stresses delay fracture in the material by increasing the required amount of stress to deform the material [10]. No literature has been found on prediction or determination of residual stresses due to forming of TWBs.

In this work, the residual stresses have been predicted in finite element (FE) simulations of biaxial stretching of TWBs of interstitial free (IF) steel sheets of same and different thickness combinations. The effect of thickness ratio on residual stresses in TWBs has been studied. Experiments were also conducted to determine residual stresses by using x-ray diffraction technique to validate the predictions.

2. Preparation of tailor welded blanks and properties

The thickness of the IF steel sheets (0.7 mm, 0.8 mm, 1.2 mm and 1.4 mm) have been chosen taking into consideration their usage in the automobile industry for manufacturing sheet metal parts. The tensile properties and anisotropic parameters of all the thicknesses were determined [11, 12] and they have been used in FE simulation of TWBs in the present research. Engineering stress-strain and true stress-strain curves of the parent sheets of thicknesses 0.7 mm and 1.4 mm are shown in Figures 1(a) and (b). TWBs of same as well as different thickness combinations (0.8 mm-0.8 mm, 0.8 mm-1.2 mm and 0.7 mm-1.4 mm) were made by laser welding the blanks in butt configuration. Initially the plain sheets were cut with the help of laser such that there was minimum burr on the edges of the sheets. After various trial runs, the sheets were welded in such a way that the alignment of the weld line was perpendicular to the rolling direction of both the parent sheets. Nd:YAG laser of power 4 kW was used to weld the blanks with a welding speed of 4 m/min. The weld zone properties of TWBs of thickness combinations 0.8 mm-0.8 mm and 0.8 mm-1.2 mm were already reported [11] earlier using miniaturised tensile specimens and the tensile properties of the weld zone of TWB 0.7 mm-1.4 mm were determined using the same geometry of the tensile specimen as shown in Figure 1(c). The uniaxial tensile tests were conducted on a universal testing machine (UTM) with a capacity of 100 kN at a constant crosshead speed of 2.5 mm/min. To make sure that the results are repeatable, 3 specimens were tested. The small pieces of steel (or thin strips) were placed on the thinner side of the tensile specimen of the weld zone to avoid the problem with the gripping. The flow curves of the weld zone of TWB 0.7 mm-1.4 mm are
shown in Figure 1(d). The tensile properties of the parent sheets and weld zone of TWB 0.7 mm-1.4 mm are given in Table 1. To represent the flow curves of the parent sheets and weld zone, Swift law of strain hardening \( \sigma = K(\varepsilon_0 + \varepsilon_p)^n \) (where \( \varepsilon_0 \) is the strain at the yield point and \( \varepsilon_p \) is the plastic strain) and power law of strain hardening \( \sigma = K\varepsilon^n \) (where \( n \) is the strain hardening exponent and \( K \) is the strength coefficient) were used as input to define the material model in FE simulations respectively.

**Figure 1.** Engineering stress-engineering strain and true stress-true strain curves of the parent sheets of thickness (a) 0.7 mm [11] and (b) 1.4 mm [11], (c) Dimensions of a tensile specimen for the weld zone used in uniaxial tensile tests [12] and (d) Engineering stress-engineering strain and true stress-true strain curves of the weld zone of TWB of thickness combination 0.7 mm-1.4 mm.

**Table 1.** Tensile properties of parent sheets and weld zone of TWB 0.7 mm-1.4 mm of IF steel.

| Thickness/Thickness combination (mm/mm-mm) | YS (MPa) | UTS (MPa) | Total elongation (%) | Strain hardening exponent (n) | Strength coefficient (K) (MPa) |
|------------------------------------------|----------|-----------|----------------------|-------------------------------|-------------------------------|
| 0.7 [11]                                 | 125      | 256       | 44.2                 | 0.29                          | 503                           |
| 1.4 [11]                                 | 140      | 270       | 48.3                 | 0.28                          | 520                           |
| 0.7-1.4                                  | 340      | 411       | 24.9                 | 0.18                          | 661                           |

3. Finite element (FE) simulation

3.1. Biaxial stretching of TWBs

The FE simulations of biaxial stretching of TWBs were carried to predict the dome height using a dynamic-explicit FE software, DYNAFORM with solver LSDYNA. The tools (die and blank holder) were modelled in the pre-processor such that the elastic deformation will not play any role during FE simulations and also the computational time will be reduced. The blank holder was modelled with a step to make sure that it makes contact with the TWB on both sides of the weld. A hemispherical bottom punch of diameter 50 mm was modelled. TWBs of dimensions 110 mm x 110 mm were modelled as surfaces followed by meshing with the triangular and rectangular Belytschko-Tsay thin shell elements of size 2 mm. Thickness of the thin shell elements was considered to be equal to the thickness of the blanks. The through thickness integration points were taken to be 9. Thickness of the weld zone was considered to be average of the thicknesses of the parent blanks. The nodes of the blanks and the weld zone were joined to make TWBs in such a way that one side of the TWB has a flat surface. The friction...
coefficient between the punch and the blank was assumed to be 0.04 [13]. The simulations have been performed up to a constant dome height of 12.50 mm in all the simulations. A constant clamping force to avoid material flow from the flange region was defined to be 100 kN. The yielding behavior of the material was defined by using Barlat’s 3-parameter material model [14] to incorporate the effect of anisotropy. Simulations were carried out by using the stress-strain curves obtained from the uniaxial tensile tests to define the flow behavior during the plastic deformation of the welded blanks.

3.2. Springback in biaxial stretching of TWBs

The springback simulations of formed TWBs were carried to predict the residual stresses in transverse direction (across the weld line) over the surface of the dome. The x-component and y-component of the residual stress was predicted at various points across the weld zone at different intervals. The output file of the forming simulation was imported into the springback simulation model. A FE model of the formed sample of TWB is shown in Figure 2(a). The material model was defined as in the case of forming simulations. The Barlat’s 3-parameter material model (Barlat’s 89) was used [14]. The nodal constraints of 8 were defined on the flange region. From the simulations, the residual stresses after springback were predicted.

4. Experimental work

4.1. Limiting dome height tests

The stretch forming experiments were carried out on TWBs of same as well as different thickness combinations. The experimental setup used for carrying out experiments consists of die, blank holder and a cylindrical punch of diameter 50 mm with hemispherical bottom. A thin shim was placed on the thinner side of the TWBs of different thickness combinations so that the blank holder makes uniform contact on both sides of the welded blanks. To reduce friction between the punch and the blank, teflon sheet of 0.5 mm thickness was used. In the experiments, a constant punch speed of 2 mm/sec was used. A schematic representation of biaxial stretching is given in Figure 2(b). After a few trial experiments, the tests on all the TWBs were stopped at the predetermined dome height and the dome height was measured using a vernier height gauge with a least count of 0.01 mm.

![Figure 2](image)

Figure 2. (a) A FE model of the formed sample of TWB and (b) Schematic representation of biaxial stretching with hemispherical punch of diameter 50 mm.

4.2. Residual stress measurement

The residual stress measurements were carried out after biaxial stretching of the TWBs to validate the predicted results. The residual stresses were also determined before forming of the TWBs. The experimental setup used for conducting the measurements consists of a sensor unit, power supply unit and a small adjustable table to keep the specimen as shown in Figure 3(a). A formed TWB sample are also shown in Figure 3(b) and the residual stresses were measured in the transverse direction. The sensor unit includes the x-ray tube (target material: chromium) that generates x-rays by using voltage and current of 30kV and 1 mA respectively. The beam wavelength was 2.29 Å and a collimator of 1 mm diameter size was used. The measurement time for each reading at a point was 90 seconds. In this work, costα technique was used for the residual stress measurement due to its ability to measure an entire Debye ring at once from the two-dimensional detector, thus not requiring multiple sample tilts [15].
The residual stress (in MPa) along the transverse direction was determined by using equation (1) [16].

\[
\sigma_x = -\left( \frac{E}{1+\nu} \right) \left( \frac{1}{\sin 2\eta \sin \psi_0} \right) \left( \frac{\partial \varepsilon_{\alpha 1}}{\partial \cos \alpha} \right)
\]

where \( E \) is the Young’s modulus, \( \nu \) is the Poisson’s ratio, \( 2\eta \) is the angle between the incident ray and the diffracted ray, \( \psi_0 \) is the angle between the incident x-ray and the surface normal to the specimen, \( \varepsilon_{\alpha 1} \) is the strain at azimuthal angle \( \alpha \) and \( \frac{\partial \varepsilon_{\alpha 1}}{\partial \cos \alpha} \) is the slope of the linear relation between \( \varepsilon_{\alpha 1} \) and \( \cos \alpha \).

5. Results and Discussion
5.1. Residual stress before forming
Residual stress patterns (before forming) in the welded blanks (are shown in Figure 4) as a function of distance from the weld zone on both sides of TWB for all the thickness combinations. The x-component of the residual stresses for all the thickness combinations is shown in Figure 4. The presence of tensile residual stresses are observed close to the weld zone because of the high rate of heating and cooling during laser welding of the two blanks of same and different thicknesses in butt configuration. During solidification, the material in the weld zone shrinks towards the center and the material away from the weld zone tries to pull the half solidified weld zone away from the center and hence higher tensile residual stresses are observed close to the weld zone [8]. The tensile residual stress has been found to decrease with increasing distance from the center and it became compressive away from the weld zone as shown in Figure 4(a)-(c). It has also been observed that the residual stresses on thicker side are higher as compared to the stresses on thinner side of the TWB with different thickness combinations. This is due to higher constraint applied from the thicker side of the TWB, towards the shrinkage of the molten pool during its solidification [7].
5.2. Effect of the thickness ratio on residual stress

It has been observed that the forming stresses before springback in transverse direction (across the weld line) are same for TWB 0.8 mm-0.8 mm due to which equal amount of deformation on either side of the weld zone has been observed (Figure 5(a) and (b)). In TWB with thickness combinations 0.8 mm-1.2 mm and 0.7 mm-1.4 mm, the forming stresses before springback are higher on thinner side due to which larger plastic deformation has been observed on thinner side when compared to the thicker side of both the TWBs (as shown in Figures 5(c)-(f)). During springback, the elastic energy gets relieved [2], leaving behind residual stresses in the weld zone as well as on both sides of the weld zone. The residual stresses are also induced in the formed TWB due to the inhomogeneous plastic deformation on either side of the weld zone [17]. In TWB 0.8 mm-0.8 mm, it has been observed that the two components (x and y) of the residual stresses are low, tensile and similar on both sides of the weld zone. In TWBs of different thickness combinations, the components of the residual stresses are tensile and almost equal in the central region of the cup on both sides of the weld zone and they became compressive as the distance from the pole increases. Even though the springback is expected to be higher on the thinner side of the TWB but as it is welded to the thicker sheet, due to the constraint at the weld zone from the thicker sheet on the thinner side the residual stresses are observed to be almost equal on both sides of the weld zone. The above effect increases with increase in the thickness ratio and due to which the residual stresses have been observed to be higher in the central region of the formed specimen, in case of TWB with higher thickness ratio. Even though in the TWB 0.7 mm-1.4 mm (with thickness ratio 2) the thicknesses are different, the residual stresses are still observed to be slightly higher when compared to the TWB 0.8 mm-1.2 mm in the central region of the formed TWB. The residual stresses are also observed to be non-uniform in nature on either side of the weld zone as shown in Figures 5(c)-(f).

**Figure 5.** Predicted stress patterns over the top surface of the dome before and after springback (at the dome height of 12.50 mm) of TWBs with thickness combinations (a) 0.8 mm-0.8 mm (x-component), (b) 0.8 mm-0.8 mm (y-component), (c) 0.8 mm-1.2 mm (x-component), (d) 0.8 mm-1.2 mm (y-component), (e) 0.7 mm-1.4 mm (x-component) and (f) 0.7 mm-1.4 mm (y-component).
Experimentally, it has been observed that in all the three thickness combinations, the residual stresses (after forming) at the weld zone have reduced. However, in the TWBs with different thickness combinations, the weld zone did not undergo much deformation rather it has moved towards the thicker side of the TWBs due to which the residual stresses (after forming) are not induced but they have reduced. It has been observed that the residual stresses on thinner and thicker sides of TWBs has slightly increased after forming as compared to the undeformed TWBs (as shown in Figure 6). This could be due to the plastic deformation occurred on both the sides of the weld zone [1]. Overall, it has been observed that experimental values agreed well with the predicted results.

![Residual stress patterns in transverse direction (only the x-component) over the top surface of the dome formed by biaxial stretching (at the dome height of 12.50 mm) with TWBs of thickness combination (a) 0.8 mm-0.8 mm, (b) 0.8 mm-1.2 mm and (c) 0.7 mm-1.4 mm.](image-url)

**Figure 6.** Residual stress patterns in transverse direction (only the x-component) over the top surface of the dome formed by biaxial stretching (at the dome height of 12.50 mm) with TWBs of thickness combination (a) 0.8 mm-0.8 mm, (b) 0.8 mm-1.2 mm and (c) 0.7 mm-1.4 mm.

**6. Conclusion**

It has been observed in FE simulations that the forming stresses are higher on thinner side of the biaxially stretch formed TWBs due to which larger plastic deformation occurred on the thinner side as compared to the thicker side of the TWBs. In TWB of same thickness combination, it has been observed that the two components (x and y) of the residual stresses are low, tensile and similar on both sides of the weld zone. However, in TWBs of different thickness combinations, the components of the residual stresses are tensile and almost equal in the central region of the cup and they became compressive as the distance from the pole increases. It is due to the constraint at the weld zone from the thicker side on the thinner side during the springback. It has been observed that with increase in the thickness ratio, the residual stresses slightly increased on both sides of the weld zone. Experimentally, it has been observed that the residual stresses on thinner and thicker sides of TWBs have slightly increased after forming as compared to the undeformed TWBs due to the plastic deformation occurred on both the sides of the weld zone. It has been observed that experimental values agreed well with the predicted results.

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