

Approximation of initial shape of the weld line in the stamping of tailor welded blanks

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Abstract. Tailor welded blanks consisting of interstitial free steel and high strength dual phase steel are laser welded with non-linear welds. The influence of parameters viz. non-linearity in the weld, strength of the parent materials and variable blank holder forces on the movement of weld line were studied. It was found that the effect of non linearity in weld dominated the other parameters in restricting the weld line movement. It was also noticed that the height of the formed cup obtained was comparatively more in non-linear weld than a straight weld.

1. Introduction

In the manufacturing of automobile components, it is mandatory to minimize the weight of the vehicle due to environmental issues and also to improve the economical conditions. In order to manufacture light weight vehicles, tailor welded blanks have come into existence. They satisfy all the structural aspects such as rigidity and crash worthiness [1].

Deep drawing and stamping are the most frequently used sheet metal forming operation in automobile industries. But, many challenges are being faced in the forming of tailor welded blanks due to the material heterogeneities, in which the weaker/thinner material deforms more than required thus leading to the movement of weld line. When the weld line movement exceeds a predefined value, forming problems such as fractures, wrinkles, and spring backs occur [2] which will hamper the quality of the stamped product. Weld line movement is significant whenever there are considerable variations in thickness ratio, strengths of the respective parent material and variable blank holder force [3].

Studies related to movement of the weld line in the forming of tailor welded blanks were carried out by Panda et al. [4] who investigated the deep drawing aspects of laser welded tailor welded blanks. They conducted limiting dome height tests to predict the failure locations. Li. et al. [5] adopted curvilinear weld shape in the laser welded tailor welded blanks and studied its dependence of formability with respect to the weld line position and geometry. They have considered different curvilinear weld profiles placed away from the centre of the blank. Hu et al. [6] studied the formability aspects of tailor welded blanks with curved weld line by applying variable blank holder force. Jeffery et al. [7] patented a device by adopting a non-linear weld at the structural inners formed from tailor welded blanks.

The movement of the weld line was studied by several researchers, but a clear scheme is yet to be carried especially for high strength and low cost materials. Understanding of the effect of various



parameters which are responsible for the weld line movement is possible only through detailed design of experiments based study.

2. Materials and methods

2.1. Experimental details

Uni-axial tensile testing as per ASTM E8 specifications was carried out at a crosshead speed of 2 mm/min. The mechanical properties of the parent materials are listed in Table 1.

Table1. Mechanical properties of the parent materials [8, 9]

Material	YS (MPa)	UTS (MPa)	% el	K (MPa)	n	Lankford Parameters			E (N/m ²)
						R_0	R_{45}	R_{90}	
DP(1mm)	517	819	24.67	1232	0.23	0.66	0.86	0.7	2.1e5
IF(0.7mm)	178	308	52.07	637	0.35	1.21	1.19	1.34	1.98e5

where UTS = ultimate tensile strength, YS= yield strength, % el = Percentage elongation, E = Young's Modulus, K = Strength co-efficient and n = Strain hardening exponent

2.2. Preparation of tailor welded blanks

Initially, two blanks consisting of Interstitial free high strength (IFHS 300) and Dual phase steel (DP 600) of size 150mm x 75mm were laser welded on a 3.5 kW CO₂ slab laser machine to obtain a butt weld configuration with the weld line oriented along the longitudinal direction as shown in the Figure 1. Laser welds involving IFHS steel (0.7 mm thick) and DP steel (1 mm thick) produced a weld bead of 1.22 mm width. Argon gas was used as the shrouding gas to protect the weldment from oxidation and contamination. The laser welding parameters employed in this work are enlisted in Table 2 based on the works conducted by of Hamidinejad et al. and Raihi et al. [9, 10]. Radiographic tests confirmed the quality of weld. The weld bead properties obtained by conducting tensile tests on longitudinal miniature size specimen are shown in Table 3.

Table 2. Parameters used in laser welding process

Parameter	Value
Flow	20 lit/mm
Power output	3 kW
Welding Speed	4 m/min
Spot size	360 microns (Donut beam)
Shielding Gas	Argon

Table 3. Mechanical properties of weld bead.

Material	YS	UTS	% el	K	n
Longitudinal Weld (1mm thick)	462	735	12.31	1155	0.18

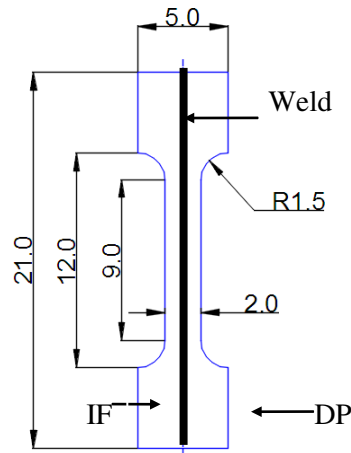


Figure1 Miniature tensile testing specimen.

3. Modelling and Simulation

3.1. Material model for parent materials and weld bead

The tailor welded blank was modeled using Barlat's three parameter yield criterion as an elastic-plastic strain hardening material. This criterion predicts the onset of plastic deformation of the anisotropic materials for studying the deformation characteristics during the forming of tailor welded blanks. This model takes into effect both planar and normal anisotropy in blank during deformation. The experimental values obtained for K , n , R_0 , R_{45} and R_{90} by conducting tensile tests were used to define the material parameters of tailor welded blank. The model is assumed to behave according to swift power hardening law, since it is difficult to determine strain hardening parameters and Lankford coefficients in the weld material due to its narrow size which makes it difficult to measure any anisotropy of properties, hence isotropic condition is considered.

3.2. Simulation of tailor welded blanks with boundary conditions

Finite element simulation of the stamping process was conducted by using LS-Dyna, a non-linear explicit finite element solver. The tooling surfaces were modeled using four-node shell elements. The sheet metal is meshed using four-node quadrilateral Belytschko-Tsay shell elements. Shell element with time scaling and adaptive meshing is used in building the finite element model. Initial element size for parent materials and weldment is taken as 2 mm. Die movement was arrested, however both blank holder and punch were allowed to move only in the vertical z -direction coinciding the punch axis. The punch was made to travel with a velocity of 5 mm/s. The binder force was varied between 3 kN to 7 kN to avoid formation of wrinkle during the drawing-in of the material into the die cavity. The parent materials are cut into 150 mm x 75 mm sheets and joined together to obtain a 150 mm x 150 mm single blank with a 1 mm weld bead in-between. The width of the weld bead obtained from laser welding was 1.22 mm. Square shaped punch with a size of 75 mm x 75 mm was considered to draw into a square cup with a clearance of 1.5 mm between the punch and the die. The draw die and punch radius was 3 mm with a punch stroke of 10 mm. During forming, the difference between the material properties of base materials and heat affected zone (HAZ) were neglected, since the size of the width weld bead width and HAZ are relatively small in comparison to the overall size of the blank. The finite element simulation setup is shown in figure 2. Coulomb law with a constant friction coefficient of 0.1 for each contact zone was used at the interface between different tool entities and the TWB.

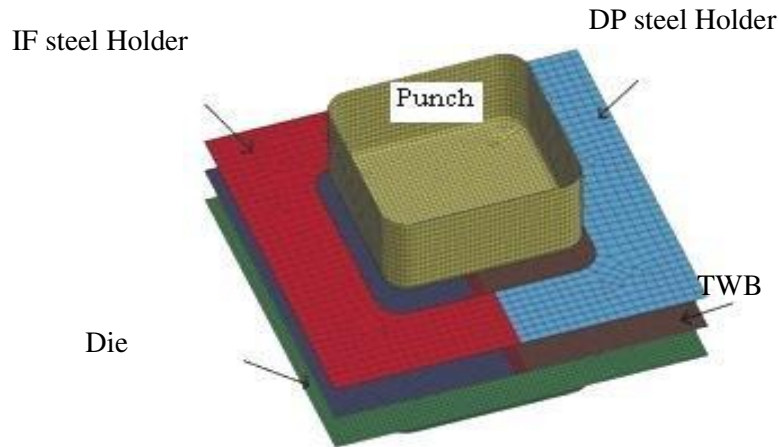


Figure 2 Finite element mesh of the TWB setup.

3.3. Preform weld design in tailor welded blanks

Due to the mismatch of properties, it is evident that the stronger material would resist deformation as compared to that of the weaker material during forming, leading to an unbalanced distribution of the stresses which directly causes the weld line to move towards the stronger side in the stamped part as shown in the Figure 3. The simulation experiments related to this phenomenon is experimentally validated on a cylindrical cup by Satya Suresh et al. [3]. To reduce the effect of this movement, non linearity in the weld is proposed in this work. Simulation studies were carried out on a square shaped blank by considering non-linearity of 3° and 6° with respect to the vertical axis.

Table 4. Initial parameters considered for simulating with a straight weld

Material side	Yield strength (MPa)	Blank holder force (kN)
IF	178	3
DP	517	3

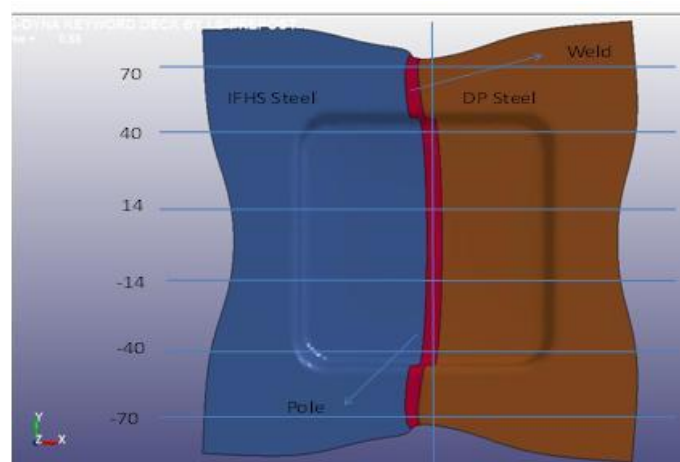


Figure 3 Weld line movement in the stamped TWB cup

It is observed from the Figure 3, that the weld line shifted towards the DP steel side in the cup bottom due to its higher strength. However, the shift is observed to take place towards the IF steel side in the flange region. So, a perform weld profile in the TWB blank with an inclination towards the DP steel side especially in the flange region is adopted in Figure 4(a) to control the movement of the weld line. Therefore, weld profiles of 0° , 3° and 6° as shown in the Figure 4(b) were chosen to study its effect on the weld line movement.

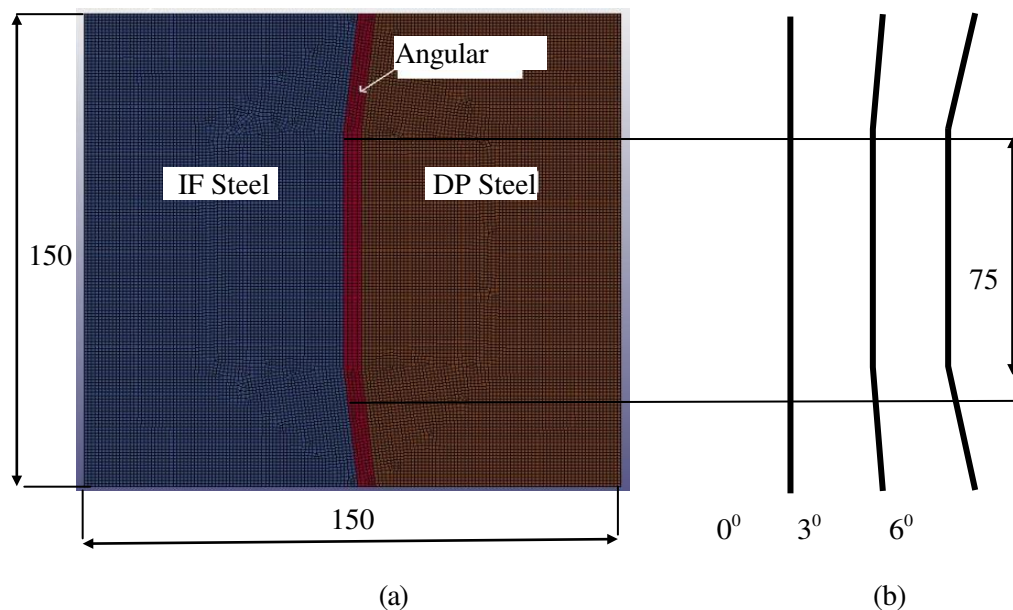


Figure 4. Preform design of weld line a) FE mesh b) Angles chosen in the flange

3.4. Process parameters used in design of experiments setup

Design of experiment study is an efficient and effective tool to optimize the parameters used in the manufacturing processes. It helps in minimizing the number of experiments to be conducted by understanding the effect of process parameters. Taguchi orthogonal arrays, Factorial designs, and response surface methodology are widely used DoE techniques to study the performance of various process parameters. In this work, Taguchi technique is used to reduce the number of experiments. The Taguchi Orthogonal array (L 18) with three levels and five factors were used to limit the number of simulation [11, 12].

4. Results and Discussion

The TWB blank was successfully formed into a square cup as shown in the figure 4 with the initial conditions listed in Table 4. The movement of the weld line was significant especially in the flange region. A section plane was taken perpendicular to the weld line at six symmetric locations viz. ± 14 , ± 40 and ± 70 mm respectively to assess the movement of weld line.

4.1. Weld line movement

The goal of this study is to obtain a straight weld after forming is conducted by properly combining the process parameters. Table 5 shows the parameters and their values required to conduct the design of experiments in this work. The responses R1 viz. weld line movement measured in mm are obtained from the DoE experiments are shown in Table 6. The maximum value of 5.9 mm is observed in the 3rd run and the minimum value of -4.23 mm is observed in the 1st run.

Table 5. Parameters used for Design of experiments study

Factors considered	Symbol	Levels
Strength on IF side	A	178 MPa & 250 MPa
Strength on DP side	B	375 MPa, 450 MPa &
Blank holder force on	C	3 kN, 4 kN & 5 kN
Blank holder force on	D	3 kN, 5 kN & 7kN
Weld bead Angles	E	0 ⁰ , 3 ⁰ & 6 ⁰

Table 6. Orthogonal array L-18 table

Runs	A	B	C	D	E	Response
1	1	1	1	1	1	-4.23
2	1	1	2	2	2	-1.425
3	1	1	3	3	3	5.900
4	1	2	1	1	2	-1.230
5	1	2	2	2	3	5.500
6	1	2	3	3	1	-2.915
7	1	3	1	2	1	-2.360
8	1	3	2	3	2	-0.820
9	1	3	3	1	3	5.255
10	2	1	1	3	3	5.300
11	2	1	2	1	1	-2.540
12	2	1	3	2	2	-0.815
13	2	2	1	2	3	4.870
14	2	2	2	3	1	-2.060
15	2	2	3	1	2	-0.555
16	2	3	1	3	2	-0.005
17	2	3	2	1	3	4.545
18	2	3	3	2	1	-1.953

4.2. Main effect of factors

Weld line movement in the case of 3⁰ angular weld is 0.005 mm obtained in the 16th run, where as for the 6⁰ angular weld, the least value obtained is 4.545 mm in the 17th run. For a straight weldment the least value obtained is 1.953 obtained in the 18th run. Thus, the weld line with an inclination of 3⁰ is resulting in less movement of the weld line.

The movement of the weld line is minimum in the case of 3⁰ inclination both in the cup region as well as the flange region. The 6⁰ inclination in the weldment has the greatest movement in the weld line as compared to 0⁰ and 3⁰ inclinations respectively as shown in the Figure 5.

The Model F-value is significant for each experiment which was conducted once. Values of "Prob > F" less than 0.0500 indicate model terms are significant. The "Pred R-Squared" of 0.897 is in reasonable agreement with the "Adj R-Squared" of 0.854; i.e. the difference is less than 0.05. The contribution of the parameter 'non linearity in the weld line' is nearly 89% as compared to the contribution from other parameters as per the Figure 6. The regression equation obtained from response surface methodology for the uncoded (actual) values using the minitab software is listed below:

$$R1 = + 711.7717 - 1.50578 (A) - 1.21754 (B) - 1.181 (C) + 0.86875 (D) - 206.03812 (E) \quad (1)$$

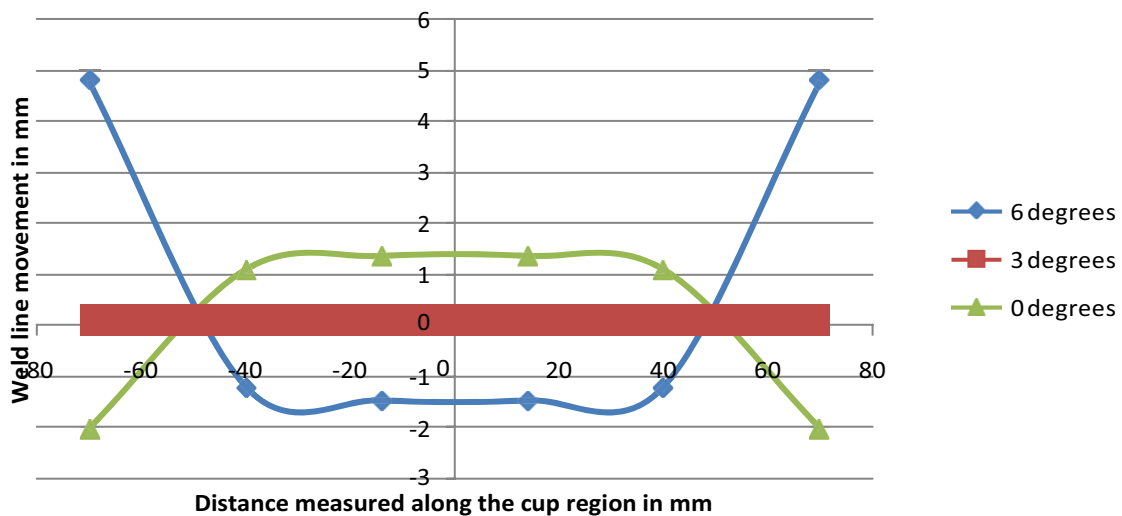


Figure 5 Movement of the weld line with respect to the centre line for various angles

Anova result: Design of experiments is conducted on Minitab software[4]

Predictor	Coef	SE Coef	T	P
Constant	-8.544	1.812	-4.71	0.001
A	0.2419	0.6216	0.39	0.704
B	0.1281	0.3806	0.34	0.742
C	0.1364	0.3806	0.36	0.726
D	0.2683	0.3806	0.70	0.494
E	3.8744	0.3806	10.18	0.000

S = 1.31857 R-Sq = 89.7% R-Sq(adj) = 85.4%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	5	181.681	36.336	20.90	0.000
Residual Error	12	20.863	1.739		
Total	17	202.544			

Contribution of factor 'Angle' is 89%

Figure 6 Anova results based on various parameters

As shown in the Figure 7, the cup height obtained in the case of 3^0 is greater than the other two angles when same process parameters under similar forming conditions were adopted.

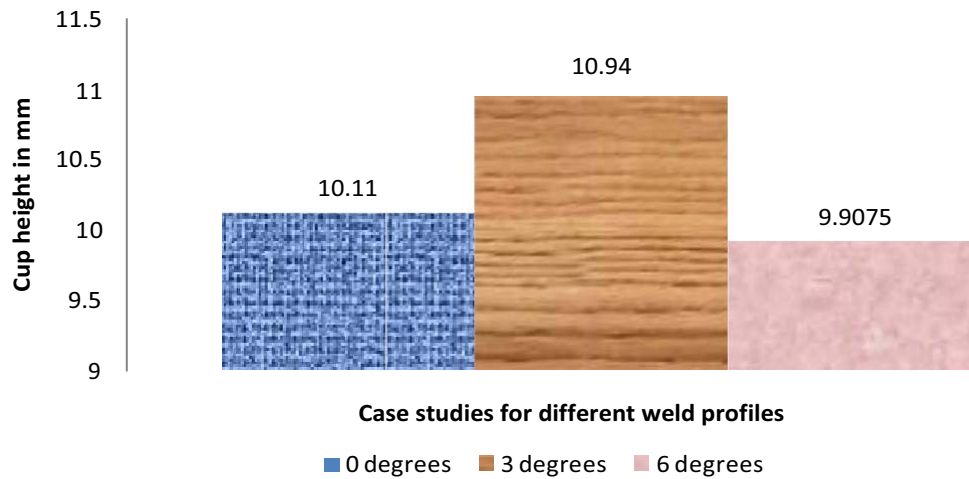


Figure 7 Comparison of cup height for different weld bead angles.

The contribution of the parameter 'E' (non linearity in the weld line) has the maximum slope as shown in the Figure 8, which indicates that it is the major contributor to the weld line movement as compared to the other parameters, hence it needs to be controlled.



Figure 8 Effect of various process parameters on weld line movement

5. Conclusions

The following conclusions have been drawn based on the results obtained.

1. The non linearity in the weld line approximation affected the TWB cup shape. It also resulted in minimizing weld line movement.
2. It is also observed that by applying non-linearity in the weld line, an improvement in cup height is achieved.
3. Non-linear regression models were effective in modeling the relationship between the process parameters viz. non-linearity of weld line, blank holder forces & strengths.

6. Further work

1. A mathematical relation can be established among the three parameters to minimize the weld line movement.
2. Weld profiles viz. spline, circular and elliptical shapes can be attempted for further investigations.

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