Effect of Curvilinear Weld Profile Shapes on Weld Line Movement in the Stamping of Tailor Welded Blanks

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1 Introduction

Nowadays, there is a growing concern of environmental pollution due to automotive emissions. To improve fuel efficiency, there is a greater need to optimize the weight of the automobile than before. Thus, TWBs have come into existence in automobile industries about two decades back to manufacture light weight vehicles which also lead to cost reduction; without compromising on structural integrity and crash worthiness.

Weld line movement is considered to be an important parameter in the stamping of TWBs because of two reasons: Firstly, when two automobile components are assembled, there would be a mismatch between them because the weld line shifts from its current location after forming. Secondly, WLM which is typically toward the stronger material causes necking and fracture in the weaker material. Such WLM contributes to tearing, distortion, wrinkling, die wear and parts with varying dimensions as compared to conventional single-sheet material.

WLM is significantly not high with soft steel combinations (<400 MPa tensile strength), but it becomes critical when high-strength steels such as dual phase/stainless steels are joined with soft forming steels viz. interstitial free steels/mild steels. Due to substantial difference in flow stress, based on thickness and strength ratio, the stronger material deforms much less compared to the softer material which leads to the movement of the weld line.

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S. K. Natarajan et al. (eds.), *Recent Advances in Manufacturing, Automation, Design and Energy Technologies*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-16-4222-7_18

2 Literature Review

In order to arrest the movement of weld line, researchers involved with TWBs identified several factors responsible for WLM occurring during forming viz. weld line location, thickness ratio, lubrication, parent materials strength, etc. They applied variable blank holder force (BHF) used draw beads of different sizes and also made changes in tooling. But, these techniques escalated manufacturing costs. Wherever thickness is one of the variable factors, newer designs are needed which increases the product cost.

Few authors suggested using preform design and made recommendations to use non-linear welded joint such as multiple welds in a TWB to overcome the problem of WLM. They have studied the effects of geometry and the position of weld line based on WLM and considered curvilinear welds as suitable alternative in their works. Hu et al. [1] and Panda et al. [2] studied the formability aspects involved in TWBs with respect to circular shaped weld line with variation in blank holder force (BHF). They observed an improvement in the dome height using the curved weld line. Li et al. [3] studied the dependence of formability parameters such as thickness ratio, strength ratio, etc., on the weld line shape by conducting experiments on laser welded TWBs. They have proposed a circular shaped weld profile and studied its effect on the formability of TWB by placing the weld at an offset distance with respect to the center of the blank. They could able to optimize the shape of the TWB component which led to manufacture a better component. Hossein et al. [4] also studied on the performance of TWBs with respect to formability under the influence of curved line using BHF strategy to achieve force equilibrium. Non-linear weld was prepared instead of a straight linear weld to overcome the movement of weld line. Kinsey [5] designed a special die setup in which adaptive controllers were used to maintain pressure on the TWB so that WLM could be reduced. Their work could be adopted in situations wherein there is no change in thickness ratio. Heo et al. [6] used different shapes and sizes of draw beads to control WLM. The shapes included are viz. square, triangle, semicircle, etc., to arrest the WLM. Riahi, et al. [7] conducted experiments by varying the location of weld line and thickness ratio. They concluded that the effect of thickness ratio on the WLM is far greater compared to the weld line location (WLL).

Tian et al. [8] worked on curved welds and studied its effect on the forming height. By increasing the curve radius, they found an increase in forming height especially at thickness ratios greater than 1.5. They also found that by increasing the radius, and a large variation in forming height took place during biaxial stretch forming thus concluded that the shape of the profile has an adverse effect on the formability. Very few authors [9–11] worked on multiple straight welds with inclinations. They concluded that greater the cup depth, minimum weld line movement could be achieved by considering optimum value in the inclination of weld. Since there is a gap in the literature with respect to the study of different curvilinear welds on the WLM, therefore, it is necessary to consider at least few of them.

Table 1 Material properties of the base materials and weld seam

Material	UTS (MPa)	YS (MPa)	E (GPa)	% elong	*K* (MPa)
ASS 304 (SS)	693	431	208	69.47	1483
IS 513 (MS)	337	202	210	44.02	677
Weld bead	479.4	293.6	209	15.6	1000

3 Numerical Simulation

Preparation of a comprehensive finite element simulation model for stamping of TWB of a combination of industrially relevant materials using finite element analysis (FEA) has been undertaken in LS-Dyna software. Validation of the FEA model was carried out by conducting experiments for certain parameters for which assumptions were made in the simulation model. The model has been redefined based on the experimental results. Later, studies related to the weld line movement using different weld profiles were undertaken.

Adaptive meshing which is an automatic meshing option given in LS-Dyna software was applied on the model to generate elements and nodes by considering four node quadrilateral elements developed by Belytschko-Tsay. At the interface between the parent material and the weld, nodes were merged thus producing a single-TWB sheet. Material properties as shown in Table 1 related to the parent materials and weld have been assigned to each material in the model. All the surfaces of the tools, viz., punch; die and blank holder were modeled using rigid shell elements. A coupled structural-dynamic analysis using fully integrated shell elements has been performed with a friction factor of 0.1.

The most common method, of rule of mixture as per Eq. (1), has been used to correlate the material properties of the weld seam given as

$$X_w = X_{ASS}(0.4) + X_{IS}(0.6) \tag{1}$$

where suffixes *ASS, w* and IS stand for austenitic stainless steel, weld and mild steel materials, respectively. Table 1 gives the properties of the respective materials from the tests conducted on a universal testing machine.

4 Experimental Work

Most of the TWB sheets are joined by welding processes. TIG welding has been carried out with the following parameters: Welding current of 80–100 amps, welding speed of 3.2 mm/s, rated output voltage as 25 V and heat input of 2.18 kJ/min. Argon gas with flow rate of 12 l/min was used to shield the material from oxidation. Radiographic tests have been performed to check the quality of weld in terms of

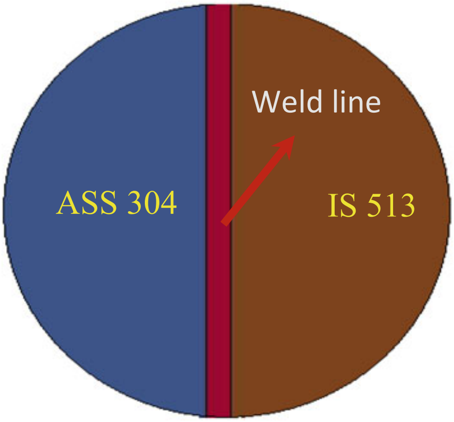

Fig. 1 Tailored weld blank

porosity and air gaps. TWB specimens were prepared by welding the two parent materials, and stamping operations were carried on an electronically operated 40 Ton hydraulic press for straight welds to validate the of simulation studies. Later, the simulation model was used with a change in profile shapes to study its effect on weld line movement.

As a case study, TWB preparation is made by considering semi-circular shaped blanks with base materials viz. IS 513 and ASS 304 each of 1-mm thickness as shown in Fig. 1. The materials were modeled for a diameter of 75 mm with a weld seam of 3-mm width in between them because the weld bead obtained from TIG welding was about 3-mm wide.

4.1 Weld Profile Shape

In this work, analytical curves viz. straight, circular, elliptical shapes and a synthetic curve, i.e., B-Spline as shown in Fig. 2 have been considered to model the weld seam with an offset distance of 2 mm placed toward the weaker material, since the maximum WLM obtained from experiments for a straight weld is 2 mm.

5 Results and Discussion

5.1 Weld Profile Shape

The effect of curvilinear welds on the weld line movement is a promising research work which has not been addressed so far. The requirement of curvilinear welds is

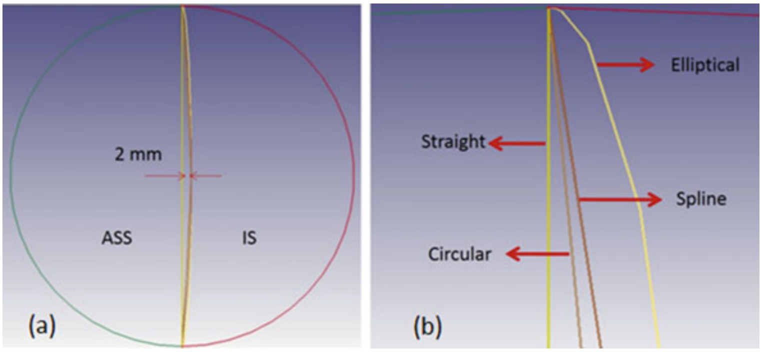

Fig. 2 **a** Curvilinear weld profiles in a TWB **b** enlarged view of the profile shape

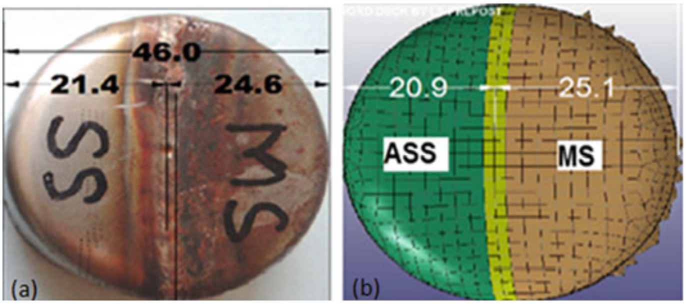

Fig. 3 The weld seam shape at the bottom of the cup **a** experimental **b** simulation

mostly in the design of car inner doors since it consists of multiple straight line welds which give rise to inflection points leading to fracture of weld during forming.

The weld seam in the cup bottom took the shape of a curvilinear which can be observed from both the simulation and laboratory experiments as shown in Fig. 3 [12]. Due to unequal plastic deformation, the stronger material among the two materials viz. ASS 304 pulled the weld toward itself.

The simulation model was further analyzed for other profile shapes viz. elliptical, spline and circular shapes. The finite element simulation carried out with these profiles gave contrasting results. The WLM in the case of spline curve gave better results as compared to the results obtained through analytical manner [13]. But, the reduction in sheet thickness was greater in the case of spline curve compared with the other curves. The deviation of WLM in the TWB cups with straight weld was 2.1 mm which reduced to nearly 1 mm in the case of circular and elliptical curves and about 0.7 mm in the case of spline curve as shown in Figs. 4 and 5, respectively. Thus, spline curve exhibited a reduction of 30% in WLM compared with the other two curves.

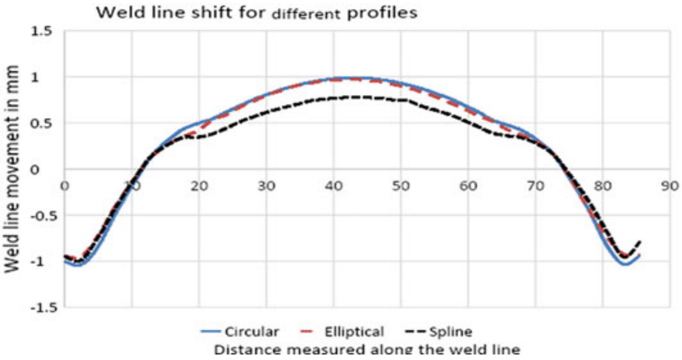

Fig. 4 Weld line shift for different profiles

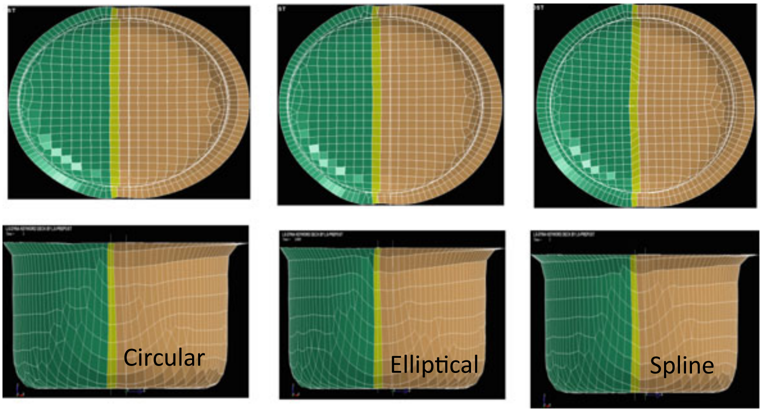

Fig. 5 Weld line movement of different profiles

5.2 Sheet Thickness Distribution Measured Across the Weld Section

Reduction in thickness after forming is an indication to predict for the fracture of the component. When the allowable thinning is less than 80% of the sheet thickness, failure/fracture is assumed to occur. In this study, it was noticed that all weld profiles have passed the test of fracture as shown in Fig. 6, since the thickness of sheet material after forming especially at the punch corner is above 80% with respect to the original dimension of 1 mm. The area under the elliptical curve is not evenly distributed, i.e., it is flat at the middle and bulged at the ends, which led to greater thinning at the punch corner as compared to the other curves.

The performance of B-spline in arresting the weld line movement is good due to its properties of localized control by using a special set of blending functions that provide local influence within the convex hull of the polygon. They also provide the

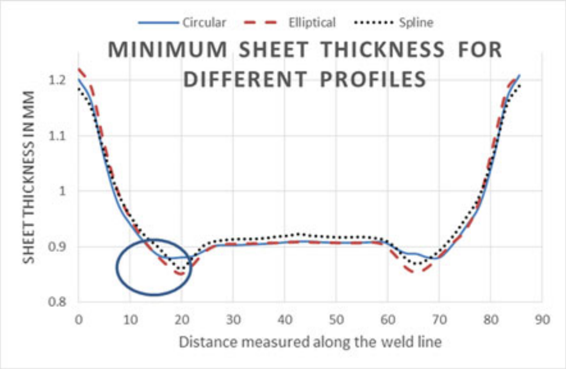

Fig. 6 Sheet thickness at punch corner

ability to add control points without increasing the degree of the curve. B-spline has C2 continuity which facilitates common tangent and center of curvature at the joints. In fact, the spline curve can be easily controlled with its parametric representation by shifting the control points. There is a possibility of greater control of spline curves in comparison with elliptical/ circular curves which are close bounded and come under the category of analytic curves, in which control is not possible. Moreover, the order of the curves in parametric form is only 1 in both circular and elliptical curves, whereas spline curve has higher order degree. Perhaps, this might be the reason for the spline curve to exhibit good formability.

6 Conclusions

1. In this work, the effect of different shapes of weld profiles viz. circular, elliptical and spline shapes on the weld line movement have been studied.
2. Simulation results showed that the shape of weld seam has a considerable effect on weld line movement as well as formability.
3. Weld line movement is less in case of spline profile at the cup bottom. It is more or less the same in case of circular and elliptical profiles.
4. In the cup wall, with respect to the pole, the weld line movement is maximum for the elliptical profile, followed by circular and spline profiles.
5. Maximum thinning occurred for the elliptical profile compared to the other profile shapes.

7 Future Work

A parametric representation of the weld profile (spline curve) can be established to minimize the weld line movement. Non-linear weld profiles viz. parabolic, hyperbolic, NURBS, etc., can also be attempted in future work to solve the problem of

WLM. A correlation between the WLM and the weld profile can be established. Further, a mathematical relation involving thickness ratio and strength ratio can also be derived.

Acknowledgements The authors express gratitude to JNTU Hyderabad, Telangana, India for arranging funds under collaborative research scheme to carry out this research work with Project No. JNTUH/TEQIP-III/CRS/2019/MECH/06 under TEQIP-III project in the year **2019**.

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