# Optimum tailor-welded blank design using deformation path length of boundary nodes

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**Abstract**

In this paper, the optimum shape of Tailor-Welded Blanks (TWB) is investigated. The optimization is performed for two different case studies. The first example is deep drawing of a TWB with dissimilar materials and uniform thicknesses and the next example is deep drawing of a TWB with similar materials and non-uniform thicknesses. The effect of blank optimization on the weld line movement is investigated. Also the effect of weld line location on the blank optimization and weld line movement is examined.

***Keywords:*** *Deep drawing; Blank shape optimization; Tailor-welded blanks; Weld line location; Weld line movement*

## 1. INTRODUCTION

A Tailor-Welded Blank (TWB) consists of sheet metals with similar/dissimilar and uniform/non-uniform thicknesses welded together to produce a single blank prior to the forming process. In order to reduce vehicle weight and manufacturing costs, application of the TWBs in the automotive industries have increased recently. However, it is important to understand and predict the parameters influencing the deep drawing of TWBs.

Some of the characteristics of the deep drawing of TWBs have been studied and reported in the literature. Heo et al. [1] investigated the weld line movement in deep drawing of laser welded blanks. They also studied the effects of the drawbead dimension on the weld line movement in the deep drawing process [2]. He et al. [3] proposed a strategy to control the weld line movement, using the control of the blankholder force. Bravar et al. [4] predicted the initial weld line placement using an analytical model and compared the results with the numerical simulations. Padmanabhan et al. [5] studied the effect of the anisotropy of the blank sheets in deep drawing of TWBs. Tang et al. [6] developed a one-step finite element code InverStamp which can be used to design TWBs, predict the movement of the weld line and optimize the position of the weld line. Rojek et al. [7] presented some experimental and experimental-numerical methods which can be used to determine mechanical properties of the weld zone in tailor-welded blanks. Padmanabhan et al. used the numerical simulations to determine the stress states and their influence on the springback behavior of deep-drawn tailor-welded blanks [8]. Valente et al. [9] investigates the influence of different finite element formulations in the performance and quality of solution obtained by numerical simulation in the analysis of tailor-welded hydroformed tubular parts. Abbasi et al. [10] analyzed the wall wrinkling tendency of a TWB, analytically, numerically and experimentally.

Among all the process parameters in deep drawing of TWBs, its optimum shape is one of the important factors, because it minimizes the forming defects, improves the formability of the sheet metal, the quality and thickness distribution of the drawn cup and also reduces the material cost. Therefore the design of the optimum TWB is a vital desire of the industries.

Several methods have been developed for the optimum blank design. Kuwabara and Si [11] designed the optimum blank using the slip-line field theory. The method is capable of predicting an optimal blank shape within few seconds but assumes the blank material as isotropic, rigid perfectly plastic. The change of the blank thichness during deep drawing process is neglected. Kim and Kobayashi [12] designed the blank shape of rectangular cups by proposing a velocity field with some assumed parameters in the deformation domain. The values of the assumed parameters are determined using experiments. Zaky et al. [13] used the stress and strain

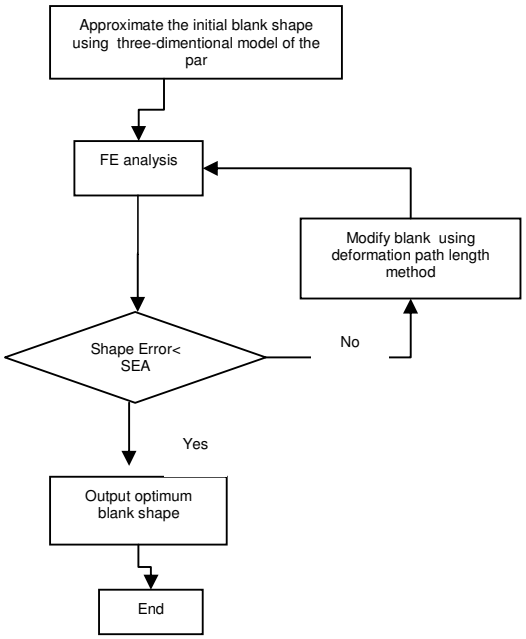


**Fig1.** Blank optimization procedure presented by Fazli and Arezoo [23]

Relationship according to the Hill's theory to calculate the optimum blank shape of cylindrical cups in the deep drawing of anisotropic sheet metals. Batoz et al. [14] proposed an inverse finite element method (IFEM) to obtain the initial blank shape and the thickness strain distribution by assuming membrane stress and total deformation theory of plasticity. Guo et al. [15] derived a nonlinear formulation for the field problems as an inverse method to obtain the initial blank shape and the strain distribution in a deformed part. Parsa and Pournia [16] developed the optimum blank with IFEM and compared it with conventional forward incremental. Azizi and Assempour [17] developed a linear IFEM to design the optimum blank. Kim et al. [18] proposed a roll-back method to predict the optimum initial blank shape in the sheet metal forming processes and applied it to design the weld line in a tailor-welded blank. Shim and Son [19] proposed the sensitivity method where an initial blank is supplied and the position of the point on the initial contour is modified iteratively by measuring the shape error with the known final cup shape. Son and Shim [20] proposed a method that iteratively designs the optimum blank shape using the initial nodal velocity of the boundary nodes. Vafaeesefat used the iteration of FE simulation to optimize the initial blank shape [21]. His blank modification algorithm is based on the projection of the target contour on the deformed blank and modifying the blank shape accordingly. Hammami et al. [22] developed the push/pull optimization technique to design the optimum blank. Fazli and Arezoo [23] approximated an initial blank geometry using the three-dimentional geometry of the given part and optimized this blank iteratively based on the shape error and the deformation path length of the boundary nodes. They also compared their algorithm with some other iteration based algorithms and found their algorithm to be more efficient [24]. De-Carvalho et al. [25] presented an optimization procedure to define the initial geometry of a sheet metal blank to produce a uniform thickness final part. Ku et al. [26] applied the backward tracing scheme for the rigid-plastic finite element method to design the initial tailor-welded blank for net-shape production and verified it by a rectangular example.

Although the optimum blank shape design for traditional blanks are reported in the literature, according to the knowledge of the author, except the work of Ku et al. [26], no rigorous attempt was made to predict the optimum shape of the tailor-welded blanks.

In this study, the approach developed by Fazli and Arezoo [23] for optimum blank design is applied to the TWBs and the results are investigated. Primarily an initial blank is designed using the three-dimensional geometry of the given product. The forming process is numerically simulated using this initial blank. The blank is iteratively optimized based on the shape error and the deformation path length of the boundary nodes of the previous deformed blank. The effect of some process parameters on the optimum blank shape is examined. During simulation, the difference between the material properties of Heat-Affected Zone (HAZ) and the base materials is neglected, since the width of the weld line and HAZ is relatively small in comparison to the overall size of the blank [26].

## 2. The blank optimization procedure

The flow chart of the blank optimization presented by Fazli and Arezoo [23] is shown in Figure 1. Primarily, the initial blank is approximated using the three-dimentional geometry of given product. The forming process is simulated using this initial blank. The deformed edge contour of the blank is compared with the target edge contour of the product geometry. If the shape error (which is the distance of the boundary nodes to the target edge contour in direction of the deformation path) is larger than the predefined value of Shape Error Allowance (SEA), the blank is modified using the developed algorithm and the forming process is simulated again. This process is repeated until the shape error is less than the predefined value of SEA at every boundary node. The initial blank approximation and the blank optimization algorithm are described in [23].

## 2. Examples

In order to examine the optimization method on the tailor-welded blanks, the optimization is performed for two different case studies. The first case study is deep drawing of a TWB made of dissimilar materials and uniform thicknesses and the next example is deep drawing of a TWB made of similar materials and non-uniform thicknesses. The deformation process is simulated using the finite element software ABAQUS/Explicit. The blank is modeled with a four-node linear shell element (S4R) and the tools are created using the rigid elements (R3D4).

### 3.1. Deep drawing of TWBs with dissimilar materials

The first case study is a deep drawn cup with a square cross section, made of two dissimilar materials DP600 and DC06 and uniform thicknesses. The drawing depth is 40mm and the geometry of drawing tools and desired part shape are shown in Figure 2 the properties of materials are given in Table 1. The left side of the TWB is considered from the weaker material DC06 and the right side of the TWB is considered from the stronger material DP600. The optimum blank shapes are obtained for five different Weld Line Location (WLL) of the sheet metals, which it is considered to be located at 0, 12, 24, -12 and -24mm from the centerline of the drawing dies.

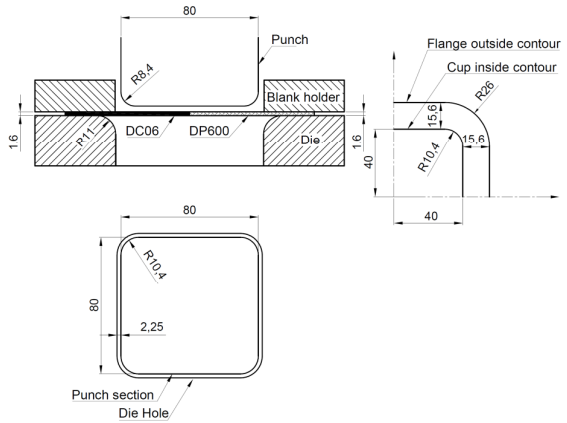


**Fig2.** Forming tool geometry for square cup drawing with dissimilar materials and the desired part shape

**Table:** Materials properties for FE simulation of square cup drawing with dissimilar material

| Material | | DC06 | DP600 |
|---|---|---|---|
| Young modulus E(GPa) | | 210 | 210 |
| Poisson's ratio, $\nu$ | | 0.3 | 0.3 |
| Anisotropy ratios | $r_0$ | 2.53 | 1.01 |
| | $r_{90}$ | 2.72 | 0.98 |
| | $r_{45}$ | 1.84 | 0.76 |
| Yield Stress, $\sigma_y$ (MPa) | | 123.6 | 330.3 |
| Stress Constant, K(MPa) | | 529.5 | 1093 |
| strain hardening exponent, $n$ | | 0.268 | 0.187 |
| Coefficient of frictions, $\mu$ | | 0.1 | 0.1 |
| Sheet metal thickness, mm | | 1.6 | 1.6 |

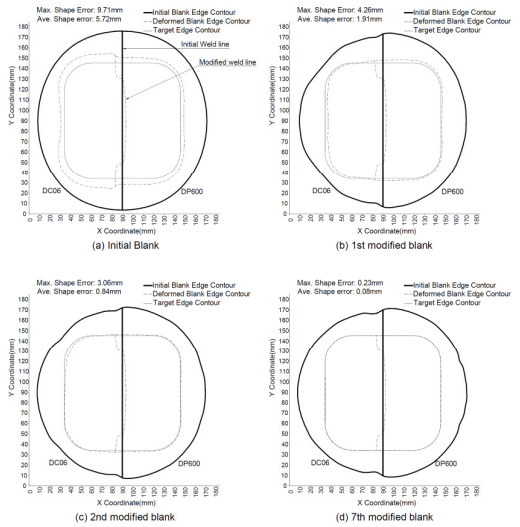


**Fig3.** Evaluation of flange edge and weld line contour after deformation for tailor-welded square cup with two different materials a) initial blank b)1st modified blank c) 2nd modified blank d) 7th modified blank

Figure 3 shows the blank edge contour, the drawn cup edge contour and the target edge contour for the initial blank, first , second and seventh modified blanks respectively for the condition where the weld line is located at the centerline of the drawing die (WLL=0mm). Also the maximum shape error and average shape error for each drawn blanks are represented in this figure. It can be seen that the shape error decreases in each modification compared to previous blank and it is reduced from 9.71mm in initial blank to 0.23mm in 7th modified blank. So the path length method is successful in prediction of optimum blank shape for tailor-welded blanks. The

deformed shape of the initial and optimum blanks for WLL=0mm are shown in Figure 4.

Figure 5.Shows the weld line movement for the initial and optimum blanks for the condition where WLL is 0mm. It can be seen that for both initial and optimum blanks, in the bottom of drawn cup, the weld line moves from the weaker material (DC06) toward the stronger material (DP600), while in the flange of the drawn cup, the weld line moves from the stronger material toward the weaker material. Also it can be seen that the weld line movement in the optimum blank is slightly less than in the initial blank, both in the bottom and the flange of the drawn cup. So the blank optimization decreases the weld line movement.

The blank optimization is performed for various WLL and the maximum shape errors for all iterations of optimization are shown in Figure 6 As it is shown, the convergence of the blank optimization is related to the position of the weld line. It can be seen that the maximum shape error converges when WLL is 0mm, 12mm and -12mm, while it does not converges when WLL is -24mm and 24mm. When WLL is 0mm, the maximum shape error converges to smaller values and it oscillates about the value 0.4mm, while when it is 12mm and -12mm, the maximum shape error oscillates about the values of 0.8mm and 1.2mm, respectively. So the convergence of the maximum shape error is completely related to the WLL and it may not converge when the WLL is far from the centerline of the drawing tools.

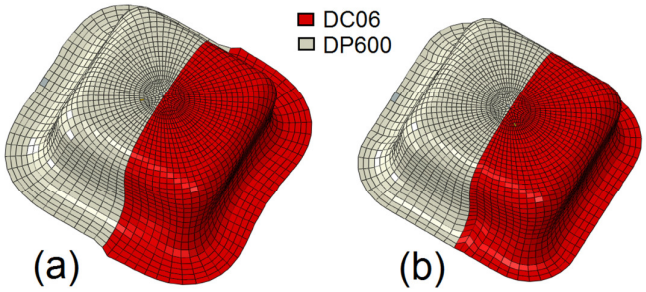


**Fig4.** The deformed shape of the TWBs for WLL=0mm. a) initial blank. b) optimum blank.

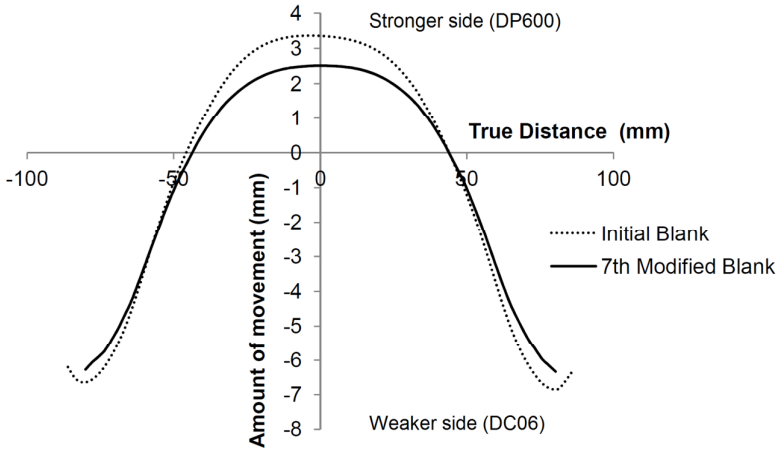


**Fig5.** Weld line movement in the initial and optimum blank for WLL=0mm

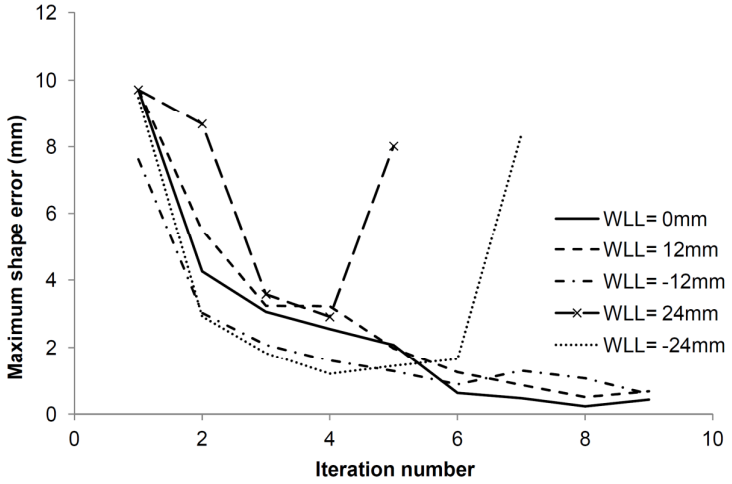


**Fig6.** Comparison of maximum shape error obtained in all iterations of various WLL.

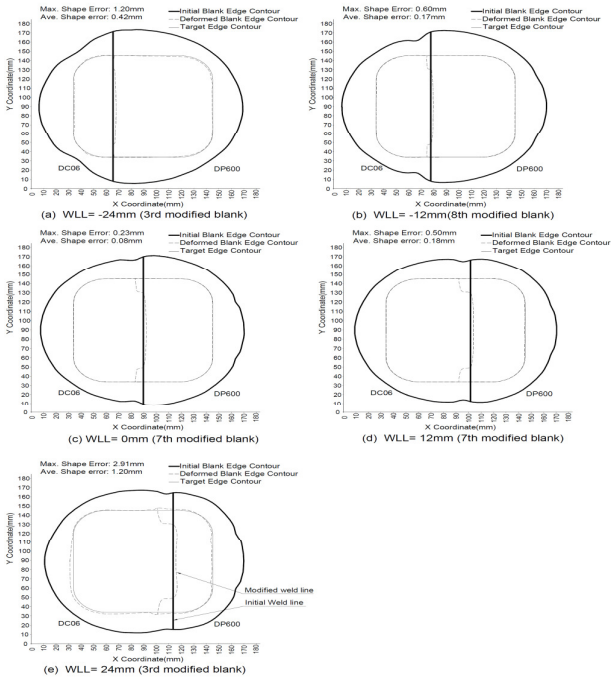


**Fig7.** Comparison of optimum blanks shape for various WLL. a) WLL=-24mm b)WLL=-12mm c)WLL=0mm d)WLL=12mm e)WLL=24mm

The optimum blank shape for various WLL is shown in Figure 7 It can be seen that optimum blank shapes for various WLL are not the same and it is affected by the position of the weld line.

The weld line movement for each WLL is shown in Figure 8 As shown in this figure, for all WLL, in the bottom of drawn cup, the weld line moves from the weaker material (DC06) toward the stronger material (DP600), while in the flange of the drawn

cup, the weld line moves from the stronger material toward the weaker material. However, it can be seen that the weld line movement at the bottom of the cups are almost the same for all WLL, while the weld line movement at the flange of the drawn cup is considerably related to WLL. The maximum weld line movement in the flange is for WLL=24mm where most of the blank is made from the weaker material and its minimum movement is for WLL=-24mm where most of the blank is made from the stronger material. This effect can also be seen in Figure 7.

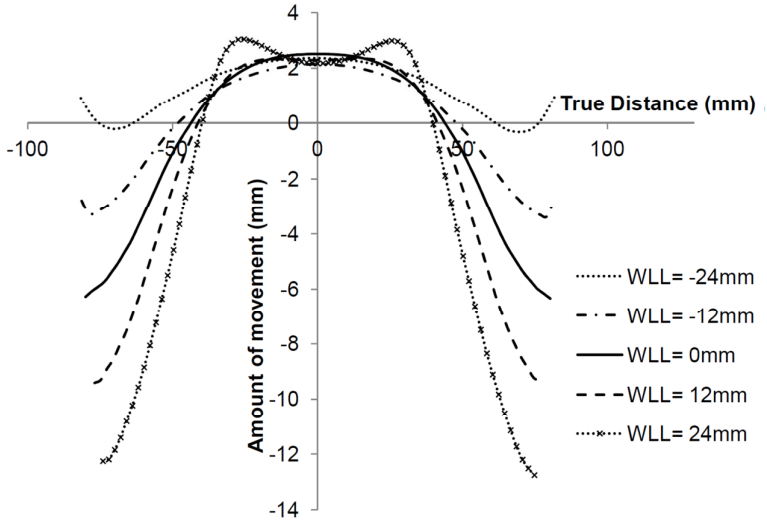


**Fig8.** Comparison of the weld line movement of the optimum blanks in various WLL.

**Table 2-** Materials properties for FE simulation of square cup drawing with similar materials and non-uniform thickness

| | | |
|---|---|---|
| Young modulus E(GPa) | | 210 |
| Poisson's ratio, $\nu$ | | 0.3 |
| Anisotropy ratios | $r_0$ | 1.0 |
| | $r_{90}$ | 1.0 |
| | $r_{45}$ | 1.0 |
| Yield Stress, $\sigma_y$ (MPa) | | 137 |
| Stress Constant, K(MPa) | | 498 |
| strain hardening exponent, $n$ | | 0.21 |
| Coefficient of frictions, $\mu$ | | 0.1 |

### 3.2. Deep drawing of TWBs with non-uniform thickness

The second case study is the same as the previous square cup, but it is made of sheet metals with non-uniform thicknesses of 1.6mm and 0.8mm and similar material SPC1. The material properties of drawn cup are given in Table 2. The drawing depth is 40mm and

the geometry of the drawing tools are shown in Figure 9 The left side of the TWB has a thickness of 1.6mm, while the right side of the TWB has a thickness of 0.8mm. The same as previous case study, the optimum blank shapes are obtained for five different WLL, where it is considered to be located at 0, 12, 24, -12 and -24mm from the centerline of the drawing dies. The punch, the die and the blank holder have modeled to have a step to consider the thickness difference of the two sides. However, since during the deep drawing of the TWB, the weld line moves, so the die should be made such that the thicker side never contacts the step. Therefore, as shown in Figure 9, the tools step is offset 5mm from the weld line toward the thinner side. When the weld line movement is more than 5mm, the offset is increased.

The blank optimization of TWBs with similar materials and non-uniform thicknesses is performed for various WLL and the maximum shape error for all iterations of optimization, is shown in Figure 10. As it can be seen, the convergence of the blank optimization is related to the position of the weld line. It can be seen that the maximum shape error converges when WLL is 0mm, 12mm and -12mm and -24mm, while it does not converges when WLL is 24mm. It can be seen that, when the weld line location is closer to the centerline of the drawing die, the blank optimization converges to a smaller values of shape error and when the WLL is far from the centerline of the drawing tools, the blank optimization may not converge.

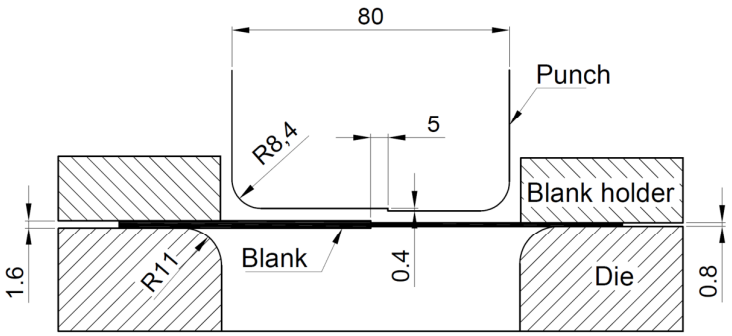


**Fig9.** Forming tool geometry for drawing TWB with similar materials and non-uniform thickness.

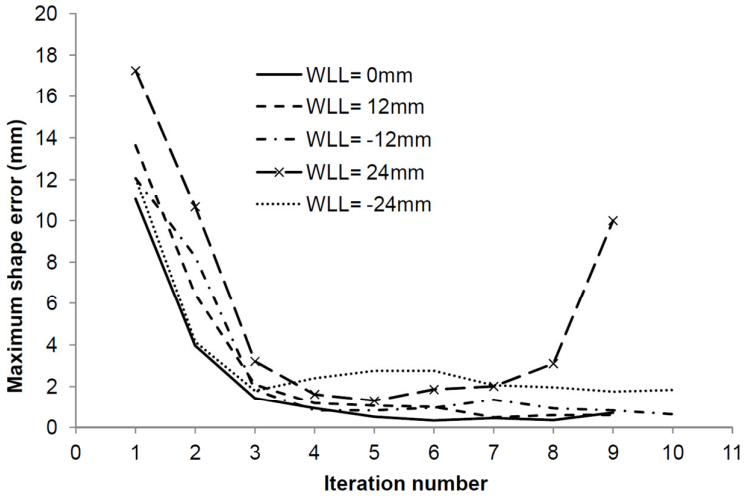


**Fig10.** Comparison of maximum shape error obtained in all iterations of various WLL.

The optimum blank shape is shown in Figure 11 for various WLL. It can be seen that optimum blank shape for various WLL are not the same and it is affected by the position of the weld line.

The weld line movement of TWBs with non-uniform thickness is shown in Figure 12 for each WLL. As it can be seen, for all WLL, in the bottom of the drawn cup, the weld line moves from the thinner side (THK=0.8mm) toward the thicker side (THK=0.8mm). In the flange of the drawn cup, for all cases except WLL=24mm, the weld line moves from the thicker side toward the thinner side. The maximum weld line movement in the bottom and flange of the drawn cup is when WLL= -24mm i.e. when most of the blank is made of the thinner sheet metal, while minimum weld line movement in the bottom and flange of the drawn cup is when WLL= 24mm i.e. when most of the blank is made of the thicker sheet metal. This effect can also be seen in Figure 11.

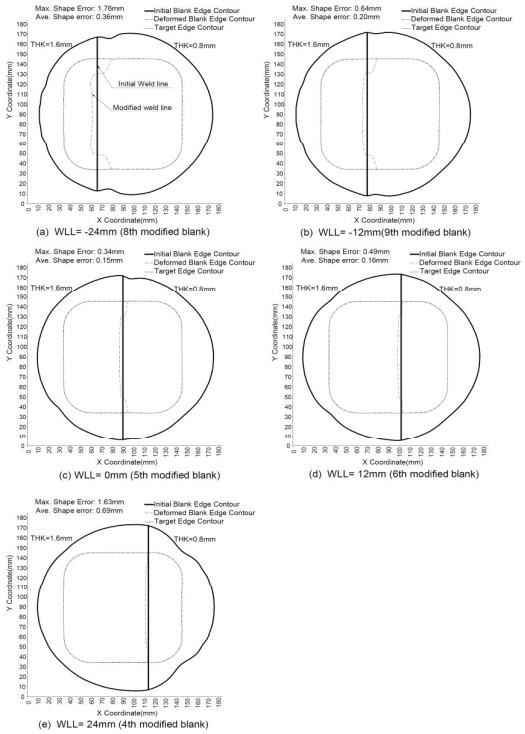


**Fig11.** Comparison of optimum blanks shape for various WLL. a) WLL=-24mm b)WLL=-12mm c)WLL=0m d)WLL=12mm e)WLL=24mm

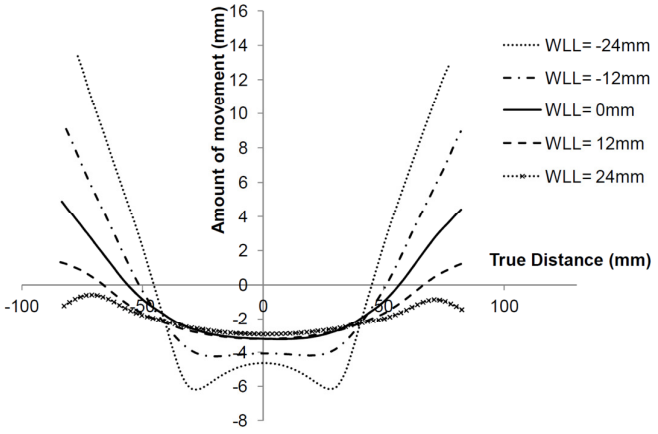


**Fig12.** Comparison of the weld line movement of the optimum blanks in various WLL.

## Conclusion

In the present work the optimum blank shape for Tailor-Welded Blanks (TWB) are determined. Using the three-dimentional geometry of the given product, an initial blank is approximated and the forming process is simulation using this blank. The initial blank is iteratively optimized based on the distance of the boundary nodes to the target edge contour. The optimum blank shape is obtained for a TWB with dissimilar materials and uniform thicknesses and also for a TWB with similar materials and non-uniform thicknesses. It can be concluded from the present work that:

- The weld line location affects the optimum blank shape of TWB.
- The blank optimization reduces the weld line movement.
- When the weld line location (WLL) is on the centerline of the drawing die, the optimization converges to the smaller shape errors, while when the WLL is not on the centerline, it is converges to the larger shape errors. When the WLL is far from the centerline, the blank optimization may not converge.
- In deep drawing of TWB with dissimilar materials and uniform thicknesses, when most of the blank is made of the weaker material the weld line movement is maximum and when most of the blank is made of the stronger material, the weld line movement is minimum.
- In deep drawing of TWB with similar materials and non-uniform thicknesses, when most of the blank is made of the thinner sheet metal, the weld line movement is maximum and when most of the blank is made of the thicker sheet metal, the weld line movement is minimum.

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