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The Prediction of Weld Line Movement in Deep Drawing of Tailor Welded Blanks

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Abstract

Tailor welded blanks (TWBs) include welded metal sheets, for the purpose of obtaining the desired structure of materials, decreasing product weight and increasing process flexibility and efficiency. Weld-line movement in TWBs during process is always considered as a challenging problem. Weld line movement is one of the influencing parameters, having effect on sheets formability. The subject of this study is presenting numerical model for predicting weld line movement and thickness distribution in TWBs sheet during deep drawing process. In this paper, by applying the finite element approach, ABAQUS software, a method has been developed for predicting weld line movement in TWBs. Design of experimental method (DOE) was done based on sheet thickness, radius of die, and experimental design matrix parameters has been used for obtaining weld line movement prediction model. Experimental tests were done to confirm the correctness of the simulations. Finally, the effect of punch and die radius, weld-line situation and thickness rate, on weld line movement and thickness distribution in square TWBs have been reported.

Nomenclature

E	Coefficient of elasticity	ρ	Density
ϑ	Poisson coefficient	K	Strain hardening exponent
n	Strain hardening exponent	r_0	Anisotropic parameter 0
r_{45}	Anisotropic parameter 45	r_{90}	Anisotropic parameter 90
R_d	Radius of die	R_p	Radius of punch
WLL	Location weld line	Fbh	Force of blank holder

1. Introduction

During recent decades, auto-manufactures have faced a by-Law for both decreasing automobile weight and improving fuel utilization, as well as increasing safety and performance. Furthermore, car's body blanks are made of several smaller parts, each made separately; consequently, most of them are welded into each other to make the considered blank. This way suffers from expensive costs of providing die and materials. In addition, it shall be a cause of lack of dimensional precision in assembling process. For removing these kinds of needs, tailor-welded blanks were introduced to auto-industry, in early 1980's [1].

TWBs consist of two or several sheets of materials having different thickness or strength. Before the forming process, they are welded to each other. Subsequently, the welded sheets turn into the desired shapes

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by deep drawing process. Many studies have been done regarding this field that some of them are mentioned in the following.

Saunders et al. [2] investigated weld line displacement and effective parameters on the process of forming combined blanks. It was declared that welding properties do not affect the calculation of weld line displacement significantly and it is possible to consider it as a simple boundary condition between both materials. Kinsey et al. [3] presented a new method for preventing weld line movement by using a hydraulic controlling system concerning combined blanks plasticity. It was asserted that using such system for preventing weld line movement decreases tearing probability and increases strain distribution uniformity in combined blanks. Choia et al. [4] investigated the weld line movement of the welded sheets throughout the deep drawing process for two types of blanks with three different weld line positions. It was asserted that the amount of weld line movement and the distribution of strain thickness is less in central and diagonal directions and strain along thickness is less for the combined circular blanks compared to the square ones. Heo et al. [5] investigated the effect of dimensions of drawing brake on weld line displacement. It was stated that by increasing the dimensions of drawing brake in thinner sections of combined blanks, weld line displacement decreases. Kampus et al. [6] investigated the deep drawing of combined blanks without sheet-holder with four different materials having different shaping properties. It was claimed that concerning deep drawing of the combined blanks without sheet-holder, cup fraction always occurs at the bottom or through the wall of the cup. Padmanabhan et al. [7] investigated the anisotropy effect on the deep drawing of soft steel combined blanks. It was asserted that the required punch force for anisotropy combined blanks increases compared to that of non-anisotropy. The current of insufficient materials at the bottom corner of the cup leads to its thinning. Weaker materials are influenced by larger shape changes; hence, weld line moves toward stronger materials in the cup as well as thinner ones in the flange. Weld line thinning in the combination of isotropic materials is preferable than anisotropic materials. Chen et al. [8] investigated the effect of steep sheet holder and pin of the weld line's holder on the plasticity of combined blanks. It was stated that the finite element simulation can predict the plasticity behavior of combined blanks precisely. Moreover, using a steep sheet-holder can potentiality reduce wrinkling. In addition, using a steep sheet-holder and holder pin simultaneously improves the plasticity of the cup. Panda et al. [9] investigated the plasticity of combined blanks in biaxial stress by numerical and experimental methods. It was claimed that the fracture occurs perpendicular to weld line in combined blanks with similar thickness and different materials which moves toward the weaker sheet. In biaxial drawing, weld line displacement is toward the stronger sheet. Therefore, the highest weld line displacement occurs in the center of the cup and increases when thickness rises. Abbasi et al. [10] presented a new analytical method for predicting weld line movement in a circular section TWBs. It was stated that weld line movement decreases considerably by increasing the width of TWBs.

Additionally, by increasing the thinning rate, strain distribution shall be uniform and weld line movement increases, by getting closer to the weld center. Kagzi et al. [11] investigated the effect of thickness and strength proportion on the movement of weld line in different combined blanks. It was stated that the movement of weld line in combined blanks always occurs with a tendency toward the stronger metal. Furthermore, strength and thickness have remarkable influence on weld line; this is while welding itself does not affect weld line remarkably.

Satya et al. [14] studied effect of temperature difference between parts of TWbs on weld line movement. In their research, stronger part of TWB was heated and weaker part was cooled. So, because of ease of material flow toward die cavity, considerable decrease in weld line movement was seen.

Paten et al. [15] studied formability of TWBs in 3 directions containing longitudinal, transverse and 45° from longitudinal axis. TWBs sheet were made of Aluminum alloy and welded by friction welding. It was presented that angle between weld line and principle stress direction played an important role in FLD values in TWBs sheet. It was also shown that TWBs had the highest forming limit curve in longitudinal direction and the lowest curve in transverse direction.

Abdollah et al. [16] investigated effect of welding parameters on TWBs formability and selected optimum welding parameters based on Taguchi method. Optimum welding speed, according to this study, was 75-135 millimetre per minute. Beside, it was stated that by increasing strain hardening coefficient, formability of TWBs increased. As it is seen in the literature, there are some reports about effect of parameters on weld line movement in TWBs. But there is not a comprehensive model for predicting weld line movement based on deep drawing parameters. In this study, by using 3D fem simulation and experimental study, a model for weld line movement prediction is presented based on deep drawing process parameters. DOE method is used for providing model. This study has considered the effect of different parameters on weld line movement and thickness distribution, in various parts of TWBs. These parameters are as followed: punch and die radius, thickness combination. TIG weld was used for making TWBs. A three-dimensional simulation of limited elements was performed. A comparison between the numerical and experimental results was made in different thickness and different weld line situations.

Table 1
Mechanical properties of St12 steel based on power-law method ($\sigma = k\varepsilon^n$).

Sheet thickness (mm)	E (GPa)	$\rho\left(\frac{kg}{m^3}\right)$	ϑ	K (MPa)	n	Anisotropy parameter		
						r_0	r_{45}	r_{90}
1	203	7800	0.3	435.3	0.150	1.324	-0.118	1.089
1.5	203	7800	0.3	433.83	0.196	0.898	-0.167	0.624
2	203	7800	0.3	412.11	0.191	0.771	-0.215	1.318

Finally, the effect of punch and die radius, weld line situation and thickness rate on weld line movement and thickness distribution in square TWBs was studied, by helping surface-response way.

2. Materials and Methods

2.1. Material Properties

Table 1 indicates the mechanical properties and plasticity parameters of steel(steel grade St12), such as final strain and hard work coefficient. The experimental results of this table were obtained according to ASTM-E8 test procedure [12]. In all test procedures, ram speed was set on 2mm/min.

2.2. Tailor Welded Blanks

According to Fig. 1, different sheets with different thicknesses and positions of weld lines were welded to each other by TIG welding.

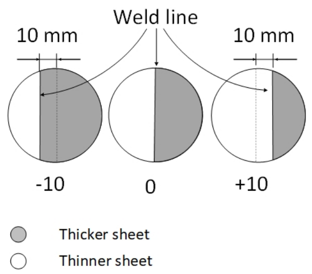

Fig. 1. Tailor-welded blank lay-out.

In order to make sure of the quality of the welding, tensile test according to ASTM-E8 [12] was conducted on a sample in which the weld line was in the center. There was no tear in welding, after drawing the sample (it indicates welding-quality).

Table 2 presents the mechanical properties of this sample based on power-law method.

Table 2
Mechanical properties of tailor-welded blank based on power-law method ($\sigma = k\varepsilon^n$).

Material	K (MPa)	n	Yield strength (MPa)
ST37 1.5×1.5mm	409.337	0.041	206.7

2.3. Deep Drawing Die

Fig. 2 shows the punch and die of the experimental setup. Different parts of the die are shown in Fig. 3, schematically. Blank holder was designed to apply 2000N. A fixed ring supplying a 12000N force by springs was exhibited.

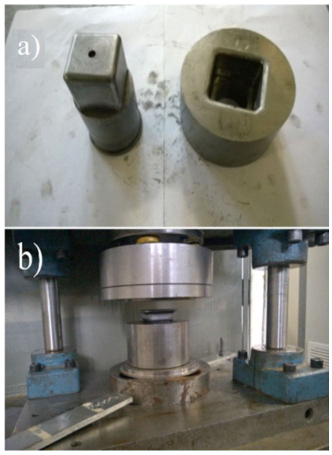

Fig. 2. a) Punch and die of the experimental test, b) Experimental test set.

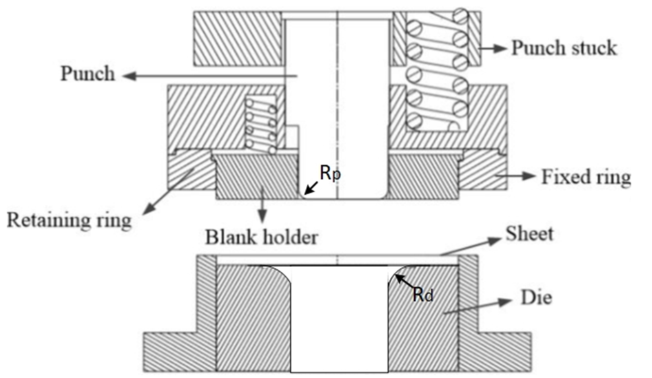

Fig. 3. A schematic view of the die.

2.4. Measuring Method for Weld Line Movement

For the measurement of weld line movement, image processing technique was applied. AutoCAD software was used for this purpose. This method was calibrated using gauge with precise size.

2.5. The Finite Element Simulation

Numerical simulation was done by ABAQUS/EXPLICIT software. In the simulation, by considering a symmetrical plane, one can manage the 3D modeling of symmetry of half of the die. Die dimensions were selected as depicted in Table 3.

Table 3
Dimensions of parts of the die.

Part	Dimension (mm)
Punch	40×40
Die	44.5×44
Radius of punch	R_p
Radius of die	R_d
Height of punch	30

The sheet was considered deformable and other parts were considered rigid. For this purpose, S4R and S3RD elements were used for sheets and other parts, respectively.

Fig. 4 shows FEM model. Because of the fact that the area of the welding region was small, in comparison with the area of the whole sheet, changing materials properties in HAZ (Heat Affected Zone) was neglected in the finite element simulation [13]. For all surfaces, friction-coefficient was set to 0.05. Mesh size independency was studied by investigating internal-energy changes. Fig. 5 shows boundary conditions of the simulation.

3. Designing Test

Response Surface Method (RSM) was used for obtaining correlation between parameters. Table 4 presents levels of parameters that were used in RSM. Weld line position was determined according to Fig. 1.

4. Results and Discussion

4.1. Measuring validation

Fig. 6 indicates the experimental results and simulation of thinning for 2 combinations of thickness (1mm×2mm and 1.5mm×2mm), by weld line location of -10mm, from cup-center in two paths of 0 and 45 degrees. As indicated in this figure, maximum thinning is related to the corner of punch and diagonal way. Minimum thickness in any part of 1mm×2mm sample is 22 and 33% of thickness amount, in thin part and the thick one, respectively.

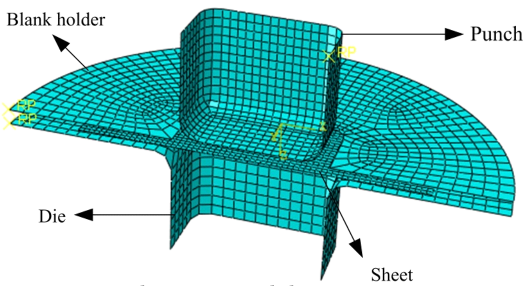

Fig. 4. Finite element model.

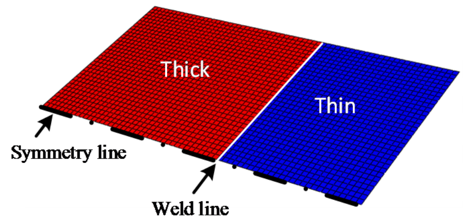

Fig. 5. Boundary condition of the sheet.

Table 4
Parameters level.

Level	Unit	Level 1	Level 2	Level 3
Sheet thickness 1	mm	1	1.5	2
Sheet thickness 2	mm	1	1.5	2
Weld line location	mm	-10	0	10
Radius die (R_d)	mm	4	5	6
Radius punch (R_p)	mm	4	5	6
Force blank holder(b h force)	N	2700	3400	3950

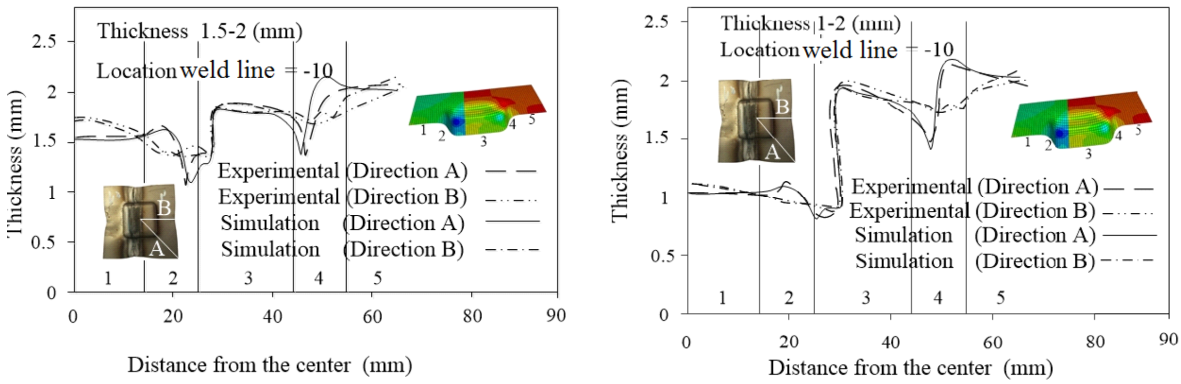

Fig. 6. Experimental and numerical results of thinning, in thickness combination of 1.5-2mm, 1-2mm, location weld line -10.

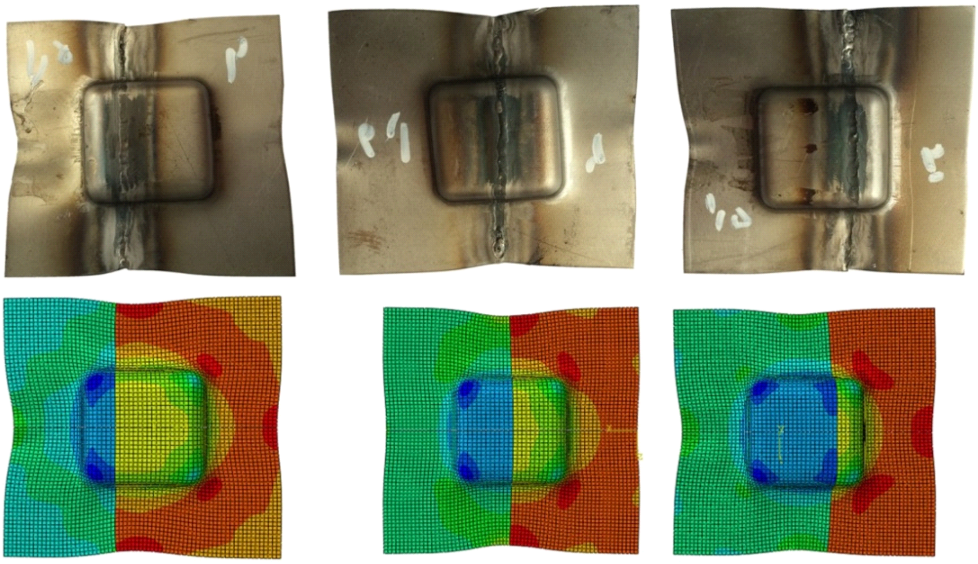

Fig. 7. Simulation and experimental results of weld line movement.

Table 5
Considering the correctness of the relations for thinning in thickness of 1-2mm.

Sheet	Weld line location (mm)	Radius die (mm)	Radius punch (mm)	Blank holder force (N)	Experimental value	Simulation value	Error percentage
1	-10	5	5	2000	0.8	0.74	7.5%
2	-10	5	5	2000	1.3	1.32	1.5%

Table 6
Considering the correctness of the relations, for thinning in thickness of 1.5-2.

Sheet	Weld line location (mm)	Radius die (mm)	Radius punch (mm)	Blank holder force (N)	Experimental value	Simulation value	Error percentage
1	-10	5	5	2000	1	1.05	5%
2	-10	5	5	2000	1.2	1.32	10%

Table 7
Considering the relations and the correctness of thinning in thickness of 1-1.5.

Sheet	Weld line location (mm)	Radius die (mm)	Radius punch (mm)	Blank holder force (N)	Experimental value	Simulation value	Error percentage
Center	10	5	5	2000	2.38	2.002	15.8%
Walls	10	5	5	2000	1.5	1.348	10.1%
Flanges	10	5	5	2000	1	0.849	15.1%

Table 8
Considering the relations validation of thinning in thickness of 1-2.

Sheet	Weld line location (mm)	Radius die (mm)	Radius punch (mm)	Blank holder force (N)	Experimental value	Simulation value	Error percentage
Center	10	5	5	2000	-2.7	-3.44	27.4%
Walls	10	5	5	2000	-2.3	-2.78	20.8%
Flanges	10	5	5	2000	0	-0.07	7%

Fig. 7 indicates the numerical and experimental results of weld line movement in the cup after its drawing. As it shown in this figure that the weld line turns into a thicker sheet in the wall and floor of the cup; but concerning the flange, the weld line turns into a thicker sheet as a result of remaining the thicker sheet in the flange, in comparison to thinner sheet. In every condition, the maximum weld line movement is related into the weld line location of +10.

The weld line movement shall increase the thickness difference, between 2 initial sheets. This is proved in both the experimental case and simulation.

Table 5 and 6 indicated the comparison between the obtained results from the experiment and simulation of thickness of two part samples.

As it is clear from Tables 5 and 6, the deviation between experimental and simulation has a less difference (about 7.5%).

As indicated in Table 7, the difference between the operational and numerical amounts is about 15%. Its reason is simplification of simulation condition and experimental measuring error.

As it is clear from Table 7, the difference between experimental and numerical results is about 20%. The reason is the simplification of simulation condition and experimental measuring error.

4.2. The Effect of Parameters on Thinning Tailor Welded Blanks

As indicated in Fig. 8, maximum thinning occurred in corners of the punch, because friction force, being provided into metal by edges of punch, shall be more than its flat part. Moreover, it is more observable in the die wall, in comparison with the cup center.

There are different effective factors on thinning tailor welded blanks (TWBs), which are considered in the following part:

4.2.1. Radius of Punch and Die

Fig. 8 indicates the effect of punch and die's radius on thinning, in two thin and thick parts. As it is clear from this figure, the maximum thinning decreased, in two parts of sheets by increasing the punch radius. Additionally, the maximum strain decreased by increasing the radius. Because by growing corners, sheet bending decreases in corners, therefore, sheet-flow is less in this region. These conditions shall decrease the material strength against changes in shape, and that's how thinning decreases. Fig. 8 indicates the validation of this subject.

As indicated in this figure, by a 50% increase in punch and die's radius, thinning percentage of sheet decreased to 11.5, 14.6, 19.72 and 16.85 percent, respectively. It is indicated that the maximum thinning occurred in sheet 2.

4.3. Blank Holder Force

According to Fig. 9, thinning of sheets 1 and 2 increased by increasing the blank holder force. The reason is related to increasing friction between sheets blank holder and die which shall be the cause of the difficulty in material flowing. Wrinkling occurs if there is a thickness difference between two sheets. Extreme increasing of blank holder force, for preventing the wrinkling of thin sheet, shall be the cause of the early tear of materials. The main reason of the tear is that whenever the thinner object is subjected to plastic strain, the thicker sheet is in the elastic region, therefore a breaking occurs in part with maximum thinning.

According to Fig. 9, by increasing the blank holder force to 46.3%, thinning of sheet 2 increases from 37 to 41% and 33 to 37%, for sheet 1. It means there is an 11% increase in thinning of sheet.

4.4. The Effect of Parameter, on Weld Line Movement

It is possible to explain weld line movement, in accordance with tension nature in the sheet. Tension is an effective factor in moving weld line.

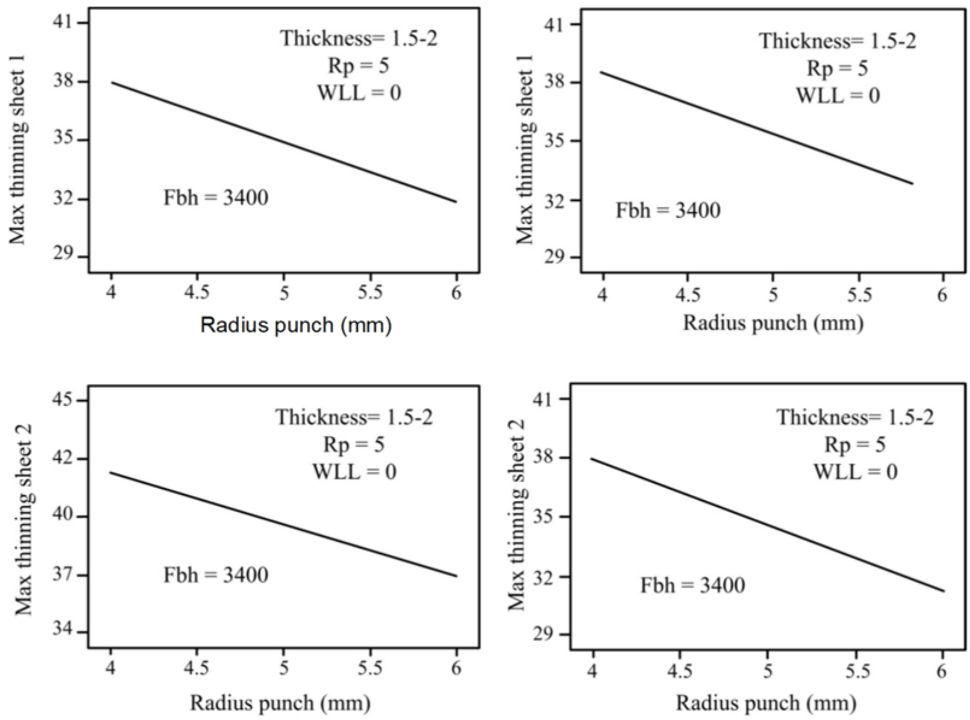

Fig. 8. The effect of punch and die's radius, on the percentage of sheet 1 and 2 thinning.

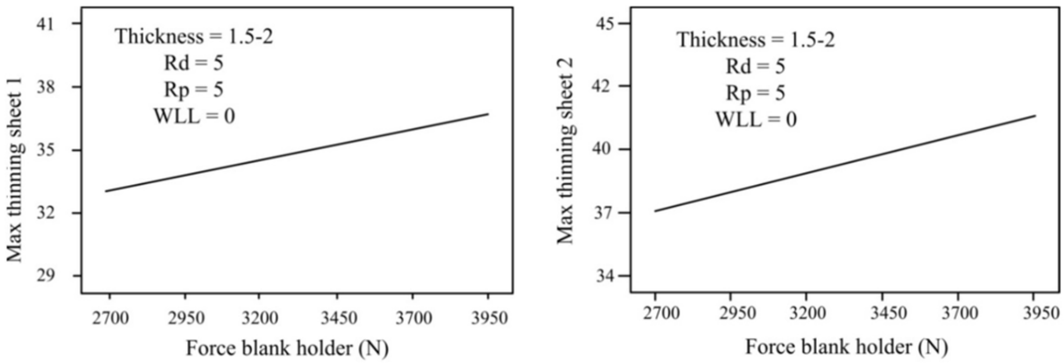

Fig. 9. The effect of the force of blank holder, on the percentage of thinning.

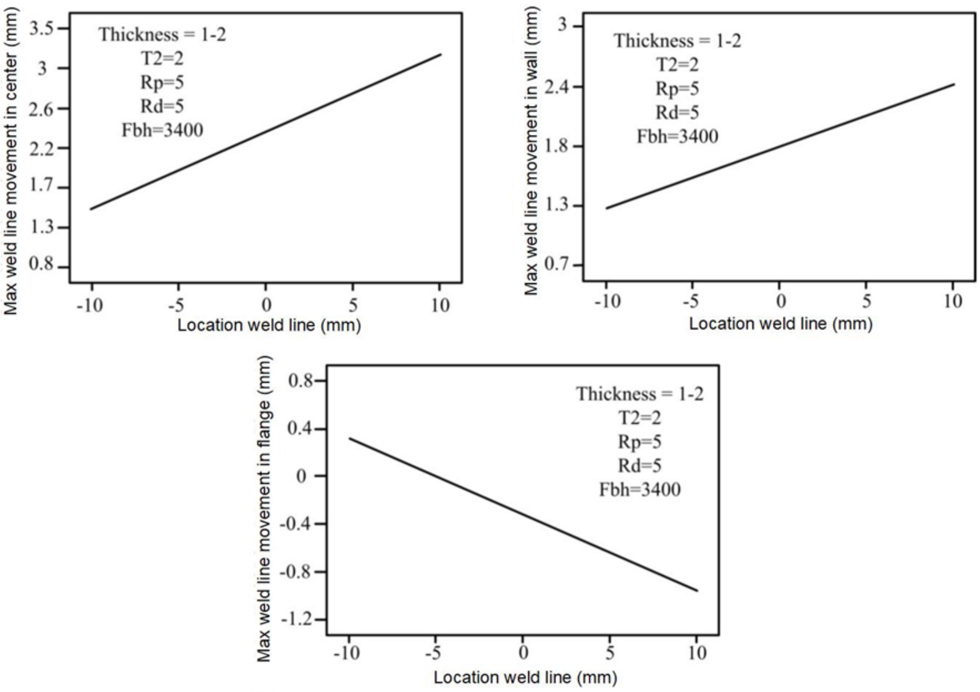

Fig. 10. The effect of punch radius on weld line movement.

4.4.1. Punch Radius

According to these figures, the maximum strain decreased by increasing radius. The reason is that by growing corners, sheet bending is decreased in edges; therefore, material flowing shall be simple and sheet drawing is less in this region. Consequently, material strength will be less against shape changes and weld line moving in decreased.

Shape of thicker sheet changes difficulty, but thinner changes easily. So, the most of the changes is related to the thinner sheet and the weld line is moved into the thicker sheet. As drawing tensions is considerably more in the center of the weld line, in comparison with the wall, the weld line movement is increased from the wall into the center. In the flange, the kind of tension is pressed once, so the weld line is moved into thinner materials. The validation of this subject is indicated in Fig. 10.

By numerical simulation of 1-1.5mm thickness combination, it was indicated that with 50% increasing of punch radius the weld line movement in the center, wall and flange decreased 13.6, 6 and 23%, respectively.

4.4.2. Weld Line Location

Fig. 11 indicates the effect of weld line location on its movement. By changing the weld line location into the thicker sheet, its movement shall increase as a result of decreasing the relation between the thicker sheet, die and blank holder. It is indicated by increasing the weld line location from -10 to 10, movement into sheet 1 is increased from 1.5 into 3.2 (in center). In the walls, it increases from 1.25 to 2.43mm and decreases from 0.319297 to 0.972182mm in the flange.

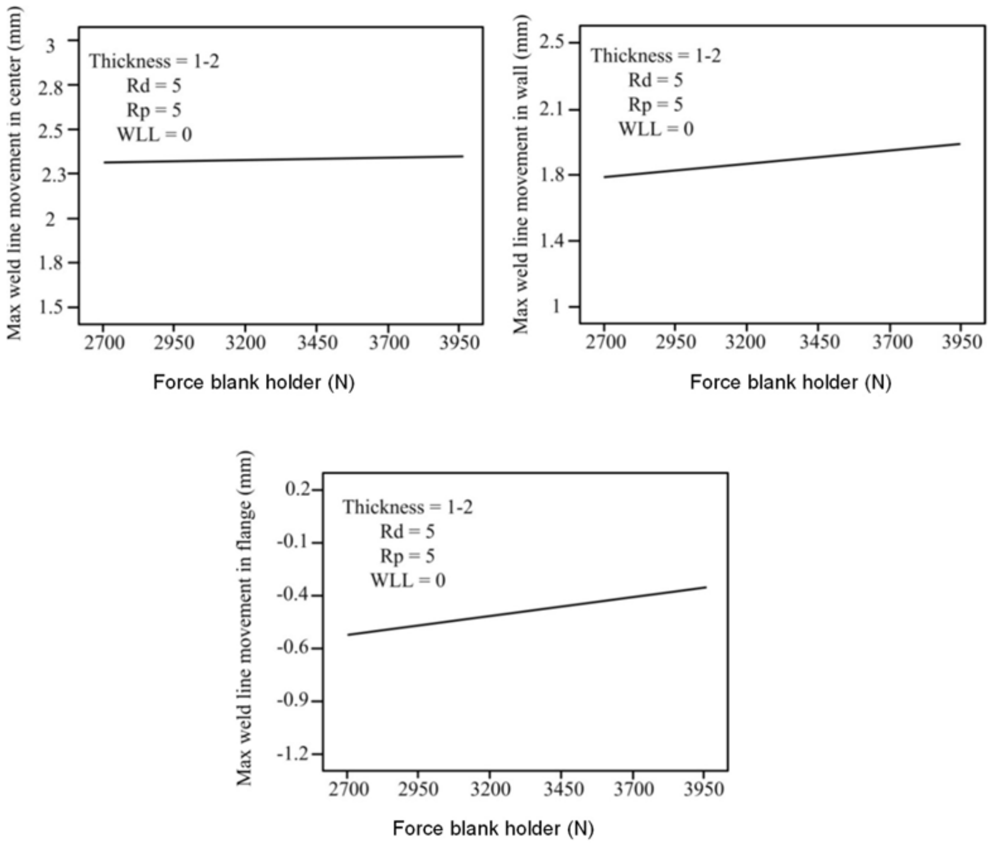

Fig. 11. The effect of weld line location on its movement.

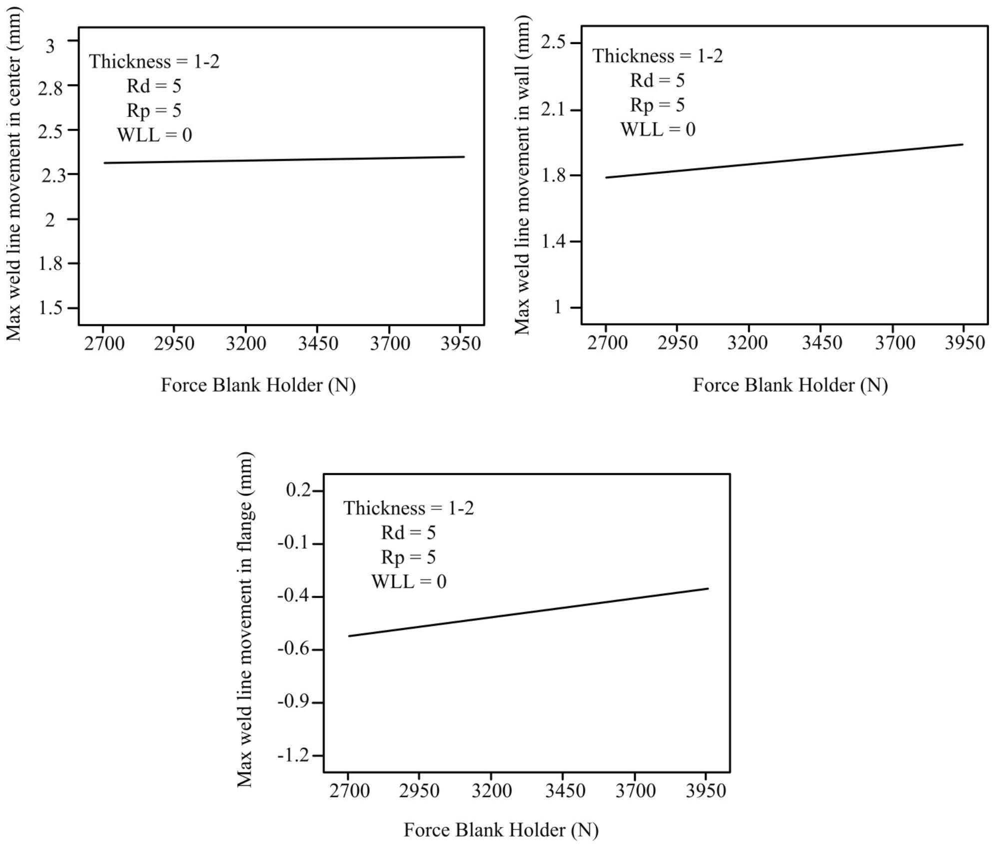

Fig. 12. The effect of blank holder force, on the weld line movement.

4.4.3. Blank Holder Force

By increasing the blank holder forces, the amount of the movement for the thicker sheet into die is decreased; as a result of increasing friction between the sheet and the die's structure, the material flowing into hole shall be decreased and the weld line movement is increased by growing the blank holder force.

In accordance with Fig. 12 (being related to the simulation performing for a thickness of 1-2mm). It is indicated that by increasing the blank holder force, the weld line will turn into the thicker sheet. Furthermore, by a 46% increase in the blank holder force, the weld line movement increases into the thicker sheet, after a 1.5% drawing in the center of the cup (11% in the walls and 43% in the flange).

5. Conclusions

In this study, the effect of deep drawing parameters on weld line movement and thinning of Taylor Welded Blank (TWB) was studied both numerically and experimentally. TWB sheets were made of ST37 sheet. For this purpose, numerical simulation was performed, using Abaqus commercial software. For providing statistical model, Surface-responding method was used for numerical results. Numerical results were validated with experiments. Good accordance was seen with experimental and numerical results. Results show that by increasing the blank holder force, the amount of thinning is increased in both part of TWB. Furthermore, thinning part in thicker part is more. A 50% increase in the punch radius decreased the weld line movement in the center, wall and flange into 13.6, 6 and 23% respectively. By changing the weld line location from -10 to +10mm (distance from centerline), the weld line movement in sheet 1 increased from 1.5 to 3.2%, in the center, 1.25 to 2.43 in the wall and, 0.319247 to -0.972182 in the flange. Moreover, by increasing the blank holder force from 2700 into 3950 (N), the weld line movement in the center of the Cup, walls and flange increased to 1.5%, 11% and 43%, respectively. (after drawing)

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