

A New Method for Controlling Weld Line Movement in Deep Drawing of Tailor Welded Blank

Shrouk Maghrapy

`shrouk.maghrapy.j@eng-st.cu.edu.eg`

Cairo University

Alaa El-Mokadem

Cairo University

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Abstract

This study concerns the weld line movement (WLM) in deep drawing of tailor welded blanks (TWBs). The movement of weld line always occur towards the stronger or thicker sheet side, leading to failure in the weaker or thinner side. This can be eliminated or reduced by different ways like using varying blank holder force or using special drawing beads. In this work a new method is proposed for controlling WLM by Experimental investigations in which a geometric compensation strategy-based on the measured WLM- was developed by precutting the sheets along a curved path opposite to the occurred WLM in actual forming process before welding and then forming. This new technique was performed on a real industrial component, a Nissan car door manufactured from mild carbon steel sheets with different thicknesses. The movement of the weld line results from the asymmetry in resistance to deformation between the welded sheets, causing geometric misalignment, stress concentration, and the onset of cracking.

The methodology integrates experimental work with numerical simulations using the finite element software ABAQUS/CAE. Laser welding and deep drawing operations were carried out, the movement of the weld line was quantified using a three-dimensional laser scanning technique.

The results showed that the proposed strategy reduces weld line movement, and through a trial-and-error optimization methodology, a nearly straight weld line was obtained after the deep drawing process. The numerical predictions agree reasonably well with the laboratory results in both the direction and magnitude of weld line movement.

This confirms the possibility of relying on numerical modeling in studying the movement of the weld line in welded metal sheets in detail.

Keywords— *Tailor Welded Blanks, Weld Line Movement, Deep Drawing, Sheet Metal Forming, Laser Beam Welding, Finite Element Simulation, Automotive Body Panels.*

1- Introduction

The automotive and aviation industries, both globally and locally, have witnessed numerous developments, meeting user requirements while ensuring environmental sustainability and minimizing manufacturing and operating costs [1]

Reducing vehicle weight to improve fuel efficiency has become a major objective in the automotive industry. One widely adopted approach is the use of **Tailor Welded Blanks (TWBs)** in the manufacturing of modern vehicle body panels, enabling enhanced performance while minimizing overall weight. TWBs are produced by joining several flat metallic sheets with different properties (parent sheets) prior to the stamping process used to form the final component. Despite their advantages, this process may lead to a reduction in formability due to the geometrical and material discontinuities created at the weld interface [2]

Tailor Welded Blanks (TWBs) have emerged. These are welded sheet metal blanks that differ in thickness, material type, coating material, or mechanical properties [3]. In this approach, the assembly and welding of the sheets are carried out **prior to the deep drawing process**. The welding process used to join these sheets is **laser welding**. Among the challenges associated with forming tailor welded blanks, WLM stands out as one of the most practically significant issues and therefore deserves special attention.

Weld line movement: This occurs during the deep drawing process due to the difference in deformation resistance between the sheets, this leads to the movement of the weld line away from its original position toward the thicker sheet. WLM is considered one of the major challenges facing the practical application of (TWBs), as WLM results in geometric mismatch of the product, concentration of mechanical stresses, and the occurrence of cracks in or near the weld region, leading to assembly and fitting problems and, consequently, product rejection due to non-compliance with the required dimensional standards.

Recent research on tailor-welded blanks has increasingly focused on controlling the non-uniform deformation created by differences in sheet thickness, strength, weld-zone properties, and contact conditions during forming. These differences produce unequal material flow on the two sides of the weld, causing weld-line movement, excessive thinning, stress concentration, springback, and fracture. In the present study, this problem is observed in a real automotive door panel, where the weld line moves mainly toward the thicker sheet during deep drawing. The proposed approach compensates for this movement by introducing an initially curved weld path opposite to the predicted displacement.

Many studies have been conducted to address WLM in TWBs. **Kinsey, Liu, and Cao [4]** divided the blank holder into independently controlled segments, establishing that weld-line movement should be controlled through asymmetric forming forces rather than a uniform blank-holder force;

the approach requires specially designed tooling and calibration for every material and thickness combination.

Choi et al.[5] examined square and circular laser-welded blanks with different initial weld-line positions, experimentally and numerically, and showed that weld-line movement and thickness strain distribution are strongly affected by the initial weld-line position and by the difference in deformation behaviour between the joined sheets.

Abdolazimzadeh et al.[6] developed a three-dimensional ABAQUS/Explicit model to predict weld-line movement and thickness distribution, investigating sheet thickness, weld-line position, punch and die radii, and blank-holder force. Agreement with experiment showed that finite-element analysis can predict weld-line movement well enough to evaluate TWB forming behaviour before experimental trials.

Kahhal et al. [7] proposed an adjustable drawbead whose penetration depth varies during the punch stroke, optimising its trajectory with a neural network and a genetic algorithm, and established that the restraining force can be modulated in time as well as in space. It demands an actively actuated die, and the network must be retrained for every new material, thickness ratio or geometry.

Wang et al.[8] controlled forming defects in an automobile rear door inner panel by edge and notch cutting of the blank contour, defining thinning, thickening and draw-in indices, and established that the material flow of a TWB can be corrected by modifying the blank geometry alone, without changing the press, the binder system or the die. The modification was applied only to the outer contour, however, and the weld line itself was left straight in its nominal position, so the residual weld-line movement was not addressed.

Tang et al. [9] developed a one-step inverse finite-element method that determines the initial blank and weld configuration from the required final geometry, accounting for blank-holder pressure, drawbead restraint, friction and the forces acting near the weld, demonstrating that numerical prediction can be used to modify the initial weld position rather than merely to estimate its movement.

Abbasi et al.[10] developed an analytical model for weld-line movement in stretch forming, validated against simulation and experiment, and showed that increasing the thickness ratio increases the movement because of the greater difference in deformation resistance between the two materials.

Zhang et al. [11] determined the laser power and welding speed window that avoids defect-prone microstructures in B1500HS/B340LA TWBs, and established that formability can be improved by selecting the welding parameters rather than by modifying the forming process; the work addresses bending rather than deep drawing.

Aminzadeh et al. [7] optimised laser power, welding speed, blank-holder force, material properties and friction simultaneously for dissimilar tailor laser-welded blanks, treating weld-line displacement as a response, and demonstrated the value of systematic numerical optimisation over trial-and-error parameter selection.

Phaoniam and Lawanwong [13] showed, for three weld-line positions in 590Y/980Y blanks, that the weld-line position changes the through-thickness stress distribution and therefore the springback angle in hat-shaped bending. The study covers equal-thickness sheets in bending and does not address the in-plane flow that produces weld-line movement in deep drawing.

Safdarian et al. [14] established that the failure location in laser-welded St12 blanks is governed by the volumetric heat input rather than by the individual welding parameters, and identified the heat-input window within which failure moves from the weld into the base metal.

Attique et al [15] compared thickness-differential and strength-differential TWBs in incremental forming and found the strength differential far more damaging, the strength-mismatched blanks failing at a few millimetres of depth against about thirty millimetres for the thickness-mismatched ones. This explains why, in blanks such as those studied here that differ only in thickness, the dominant defect is the geometric displacement of the weld line rather than early fracture.

The representation of the weld and the heat affected zone in the finite element model has received particular attention. **Jeon et al.** [16] derived HAZ properties from measured hardness and showed that this predicts the load to within a few per cent, though with a much larger error in displacement.

Eom et al. [17] showed that fracture remains in the base metal at nominal welding parameters but propagates into the HAZ at elevated heat input, so the HAZ must be modelled as a discrete material region above

A further group of recent studies attempts to remove the property mismatch after welding instead of accounting for it in the model. **Dong et al.** [18] combined cold rolling with solution heat treatment for aluminium alloy TWBs and raised the cupping value above that of the base metal, confirming that a treatment applied between welding and forming can reduce the discontinuity introduced by the weld.

Data driven methods have also entered the field. **Sekban et al** [19] investigated the formability of friction stir welded high strength steel using experiments, finite element analysis and an artificial

neural network, and reported that the trained network reproduced the measured load-displacement response at least as accurately as the finite element model, which supports the use of surrogate models for the forming response of welded blanks

Palmieri et al. [20] used in-line measurement of blank draw-in to estimate the instantaneous friction coefficient and set the optimal blank-holder force, establishing that a single correction, without an iterative feedback loop, is sufficient to obtain defect-free parts. The measured quantity is the draw-in of a monolithic blank, not the position of a weld line.

Finally, the metrology on which such compensation depends has itself been the subject of recent work. **Hawryluk et al. [21]** applied three dimensional optical scanning together with virtual gauges and numerical simulation to the inspection of formed parts, and established that the combination of scanning with virtual measurement significantly shortens the inspection time and increases its accuracy compared with contact gauging, while also detecting surface defects that conventional coordinate measurement does not reveal.

Together, these studies highlight practical strategies for better controlling weld line movement during the deep drawing of TWBs. All the Previous studies have tried to reduce WLM in TWBs, but most focused on general sheet forming rather than real automotive parts. In **the Nissan car door**, WLM still causes defects like necking and fractures, showing that existing solutions are not fully effective.

They use **special blanking dies, accurate laser welding, and online weld inspection** to ensure TWB quality.

In normal automotive production, the problem is handled during **die and process design** by:

- Adjusting the **blank-holder force and draw beads** to balance the flow of the thick and thin sheets, but it is an expensive technique.

This research therefore aims to study weld line movement during deep drawing of inner lining of car door parts :

This paper is organized as follows: Section 2 presents the used methodology, like the materials, preparation, forming process, and measurement techniques. Section 3 presents the results and discussion, and Section 4 concludes the paper by summarizing the main findings and outlining potential directions for future research.

2- METHODOLOGY

2.1. Research Framework and Overall Approach

The research framework of the present study is based on integrating experimental investigations with numerical simulation for a real industrial specimen _ Nissan car doors manufactured from TWBs_ to understand and find a solution to the weld line movement in tailor welded blanks (TWB) during the deep drawing process. The specimen is formed under conditions like those of the industrial application for which it is prepared, while the resulting movement of the weld line due to the deep drawing process is measured using laser scanning. Based on the laser scanning measurements and the identified direction of weld line movement, a geometric modification strategy for the blank prior to welding is proposed. The strategy involves laser cutting the blank using dimensions equal to the measured weld line movement, but applied in the opposite direction, followed by laser welding and repetition of the deep drawing process under the same previously used conditions. The outcome of this strategy is evaluated and repeated once again, after which the same experiments are conducted for the same type of specimen using numerical simulation with the commercial finite element software, ABAQUS/CAE. In addition, laboratory mechanical tests are carried out to determine the stress–strain behavior of the material under different loading directions, with the aim of studying the magnitude of weld line movement resulting from mechanical tensile forces applied in different directions relative to the weld line and under different tensile force.

2.1.1. Base Materials and Parameters

The base materials that are very popular in automotive industry; Advanced high-strength steel, High-carbon steel, Low-carbon steel, Galvanized steel, Stainless steel. In this study, mild carbon steel with different thickness was used. Outer sheets door that was used in Nissan car doors were Mild carbon steel sheets (JAC 270 E 45/40), as shown in Figure 1, JAC270 is a cold rolled Mild steel with a galvaneal coating having a minimum yield strength of 270 MPa. The specimens were prepared to be suitable for subsequent forming operations.

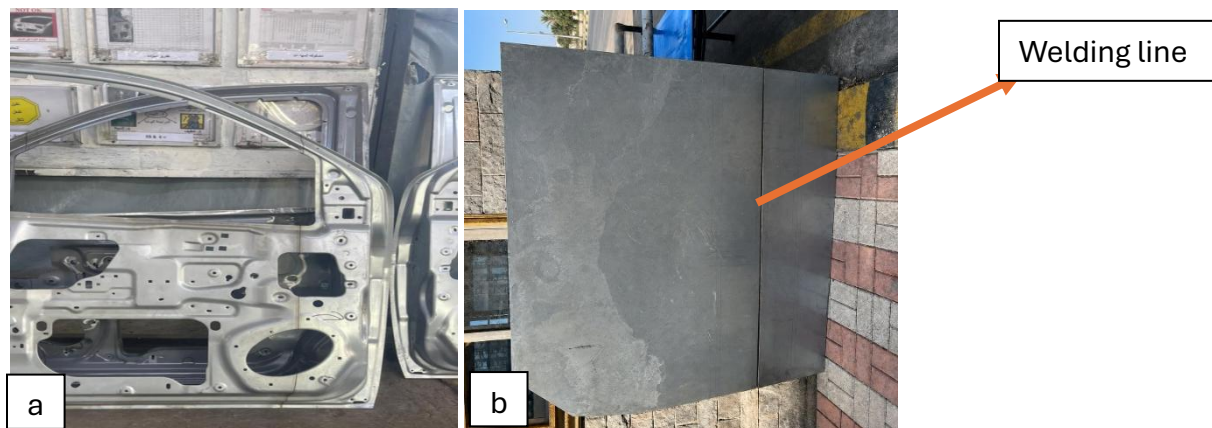


Figure 1: Nissan car doors inner after a) deep drawing ,and b) original TWB sheet.

2.1.2. The Tailor Welded Blanks (TWBs) Configuration

TWBs were prepared by welding the two sheets using laser welding, as applied in the production lines of automotive doors as shown in Figure 2 (a). The weld line was positioned at the center of the specimen to represent the baseline condition. The same specimen dimensions and geometric shape were maintained for all cases throughout the study as shown in Figure 2 (b).

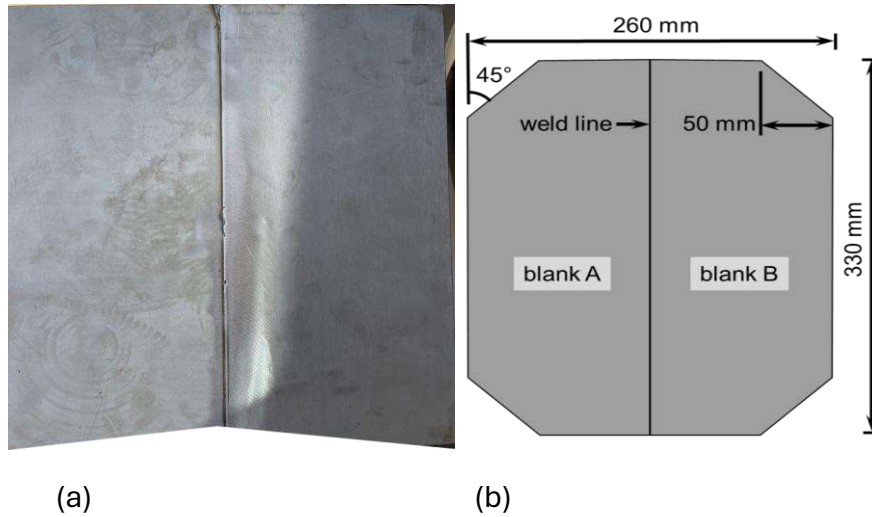


Figure 2:(a) the two welded sheets, (b) Geometric dimensions of the TWB for experimental work.

2.2. Experimental Procedure:

The objective of this approach is producing a perfect steel tailor welded blank without defects and failures that occurred due to the welding line movement during the deep drawing process, as an applied objective of the study, a specimen representing a Nissan car door was selected, as it is one of the components manufactured using TWB figure (3). The Experimental setup was including **Two Major Phase**:

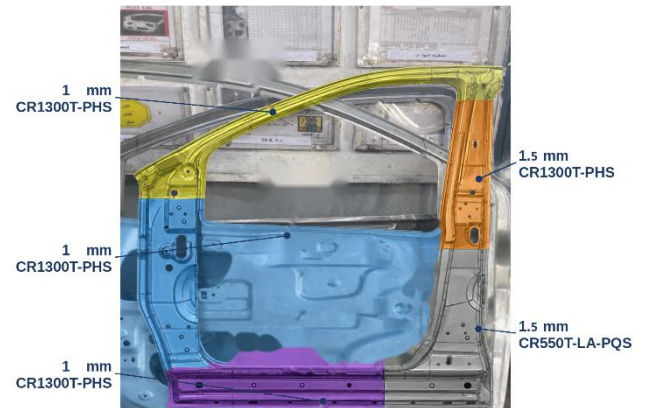


Figure 3: Side Panel made of steel tailored blanks.

2.2.1 Weld Line Movement due the deep drawing Process (phase 1):

TWB was examined in both its undeformed state and after the car door deep drawing process to analyze weld line displacement. The experimental work was carried out in two main stages. In the first stage, two metal sheets with predefined properties and dimensions were welded using a LBW (laser beam welding) machine as presented in figure 4. LBW process is frequently applied in the automotive industry. It is based on keyhole or penetration mode welding.

In this study, a LBW machine equipped with (Co₂) laser source, and Welding speed (3-6 m/min), were applied to produce butt joint with a gap tolerance of approximately 0.1mm, without the use of filler wire, and sheets clamped rigidly and The resulting heat-affected zone (HAZ) width was 0.5 mm, fusion zone width was about 1.2mm, and Total affected width from this process was 1.5 mm.

The position of the weld line in its original state was considered a basic reference for comparison with its position after carrying out the remaining steps of the experiment.

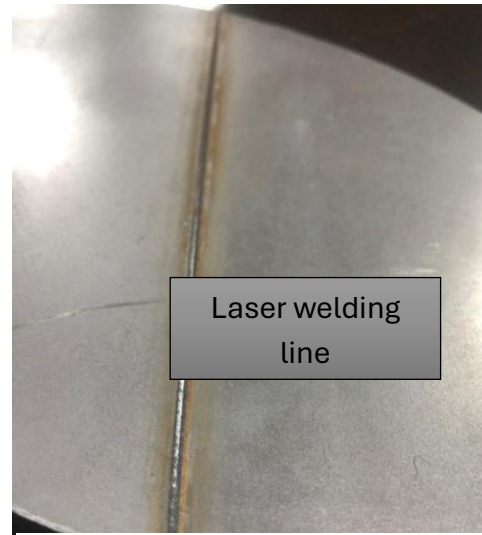
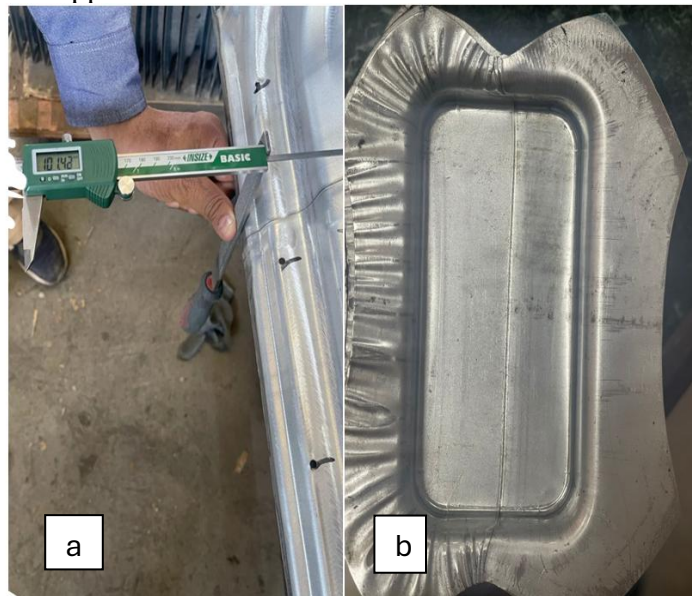


Figure 4: the original welding line position.

As shown in figure 5 (a), the depths of the tailor welded blank after deep drawing process is 4 cm from bottom, and this is the deepest depths that applied to the car door from bottom of the car door to the upper as shown in figure 5 (b).

After completing the deep drawing process, the position of the weld line was identified and measured using a 3-D laser scanner.

In this study, a 3D laser scanning Technique was employed to capture the geometric of the welded specimen. Through use laser scanner with Accuracy ($\pm 0.020 - 0.050 \text{ mm}$), resolution ($0.05 - 0.2 \text{ mm}$), and PolyWorks Inspector as a software.



Based on the data obtained from the scanning process, the movement of the actual weld line was quantitatively evaluated from its original position as illustrated in figure 6, and the dimensions of this movement were recorded in preparation for using these data in the second stage of the experiment. This approach allows accurate assessment of welding path movement and overall welding accuracy was determined. As all previous studies proven, the line moved toward the thicker blank and the higher strength one as a curved line.

In the second stage, two other metal sheets identical in properties and dimensions were prepared, where they were cut in a curved line toward the thinner blank, in a direction opposite to the measured weld line movement obtained from the first stage and with the same movement dimensions that were recorded using laser cutting. The sheets were cut using fiber laser cutting, the cutting accuracy was $\pm 0.03 \text{ mm}$. A fiber laser source was used with a cutting speed in the range of 6-12 m/min for 1 mm sheet thickness.

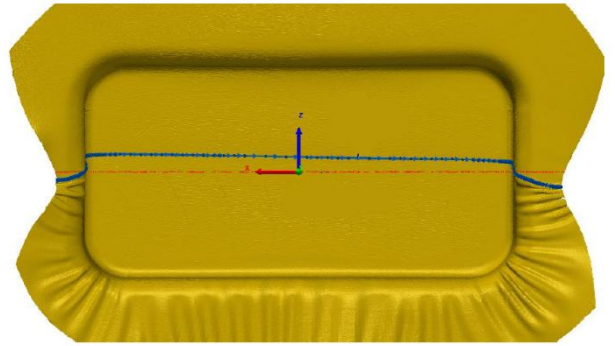


Figure 6:3-D Model Of The TWB Obtained From Laser Scanning And Analyzed Using Poly works Inspector.

After that, the same welding, deep drawing, and laser scanning steps were repeated as in the first stage, and the new position of the weld line movement was determined, and its dimensions were recorded for comparison with the previous results.

Then investigating TWB if the welding line movement is eliminated and become almost straight welding line, not curved and keep a trial-and-error strategy to obtain the perfect straight welding line by repeating the previous stage again with modifications to the cutting dimensions to be deeper (+2 mm) than the previous in order to improve the results, and the resulting values were recorded for comparison with the results of cutting with dimensions equal to the weld line movement, as well as with the results of the first experiment conducted without any modification to the weld line position, considering the reference weld line as the target position after performing the deep drawing processes.

Subsequently, the deep drawing process was performed using a punch and die in rectangular shape.

In the present study, a double acting hydraulic press and die deep drawing was employed. With maximum load (250 tons), Blank holder force (30 KN), Punch speed (15 mm/s), Punch and die in rectangular shape as shown in figure 7(b). with geometry 100 X 99 x 100 mm, and 200 x 300 x 50 mm respectively as in figure 7 (a).

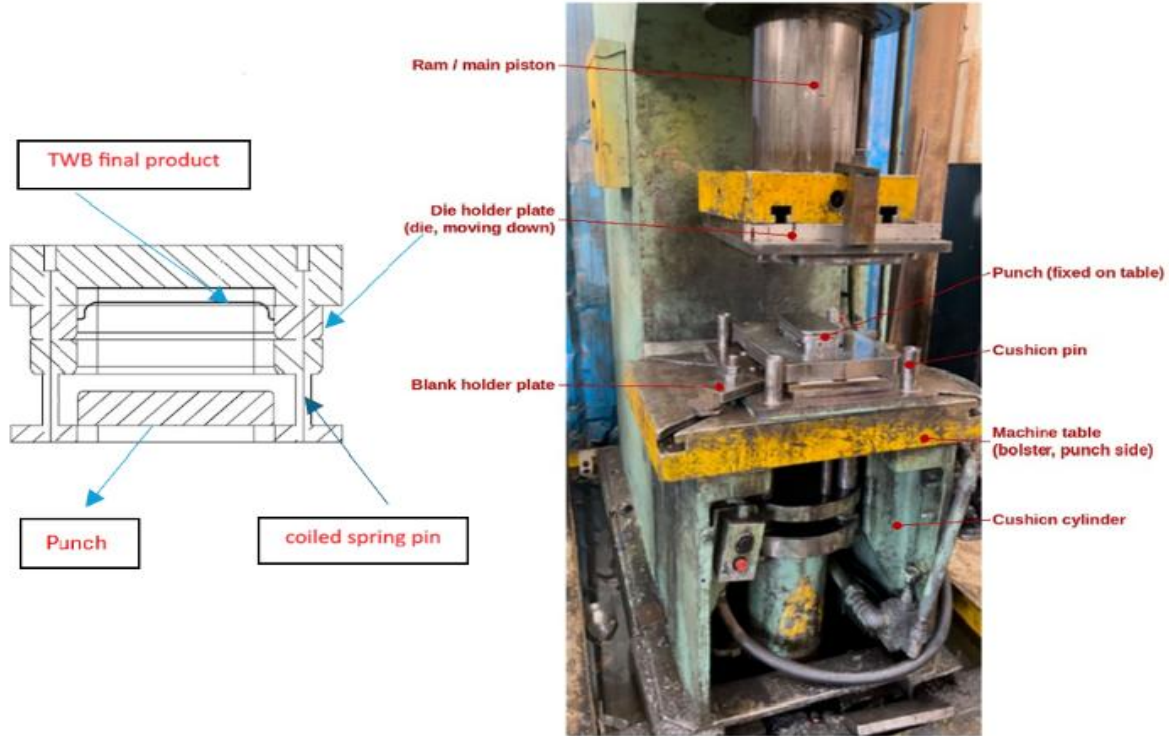


Figure 7:(a) schematic sketch for die deep drawing (b) Double-acting hydraulic deep-drawing press showing the hydraulic ram, punch and die assembly, blank-holder system, guide pillars, and hydraulic cushion.

2.2.2 Mechanical Characterization of the Weld Zone (phase 2):

In our study, four specimens of the same material (JAC 270 E 45/40) and with the same studied thicknesses were prepared to conduct the **tensile test**. Tensile tests were performed on a Wolpert (Amsler) hydraulic universal testing machine of 100 kN capacity, fitted with manual wedge grips and an analogue force dial, at a crosshead speed of 6 mm/min over a 100 mm gauge length figure 8.



Figure 8:standard tensile test machine.

These specimens included two tailors welded blank (TWB) specimens figure 9, where the weld line direction in the first specimen was parallel to the direction of the tensile load, while the weld line direction in the second specimen was perpendicular to the direction of the tensile load. The base sheets, with the aim of comparing the mechanical properties of the welded and the base sheets specimens and evaluating the effect of the presence of the weld line and its orientation on the material behavior.



Figure 9: four specimens with different condition.

2.3 Model Validation:

Model validation was carried out by performing a quantitative comparison between the experimental and the numerical simulation results. The weld line movement obtained from using 3D laser scanning in case of compression with modify blank geometry and without modify was comparing to the predicted weld line movement from the finite element models.

The commercial finite element software, ABAQUS/CAE, was used to construct a three-dimensional finite element model (FEM).

2.3.1 Finite Element Model of TWB with a Straight Weld Line at the Center (Model 1)

This model was used to simulate the box deep drawing operation of the Tailor-welded blank (TWB) and predict the movement of the weld line during this operation. The weld line in this model was a straight line positioned at the center of the TWB.

Material Model

The TWB was constructed from two separate steel blanks, labeled as blank A and blank B in previous Figure 2 (b). These blanks possess the same material properties, and a thickness ratio of 1.5 mm to 1 mm, respectively.

Table 1. provides the relevant material parameters for both blanks A and B.

Table 1 Material properties

Density	7800 kg/m ³
Young's Modulus	210 GPa
Poisson's ratio	0.3
Yield Strength	300 MPa
Strength coefficient	530 MPa
Hardening coefficient	0.26
Plastic potential [22]	$R_{11}=1, R_{22}=1.011, R_{33}=1.040, R_{12}=1.028, R_{13}=1, R_{23}=1$

Weld-Line Model

The TWB was discretized using S4R shell elements with 9 thickness integration points applying the Gauss integration rule. The maximum element size of the deformable TWB was determined through sensitivity analysis to be 5 mm. The weld line and the Heat Affected Zone (HAZ) were represented as an infinitesimally thin line with discrete nodes shared between the two sections of the TWB. The effectiveness of this model in predicting the movement of the weld line has been corroborated by comparing it with 3D solid models of the weld line and the HAZ [23].

2.3.1.1. Geometric Model

Die, punch, and blank holder were modeled as 3D rigid bodies, as shown in Figure 10 (a). The interaction between the rigid bodies and the TWB was modeled employing surface-to-surface contact with penalty friction of 0.1 and a shear limit of 100 MPa. The movement of these rigid bodies was controlled via reference points (RP), and the model was built while utilizing the geometric and load symmetry across the x-y plane as shown in Figure 10 (b).

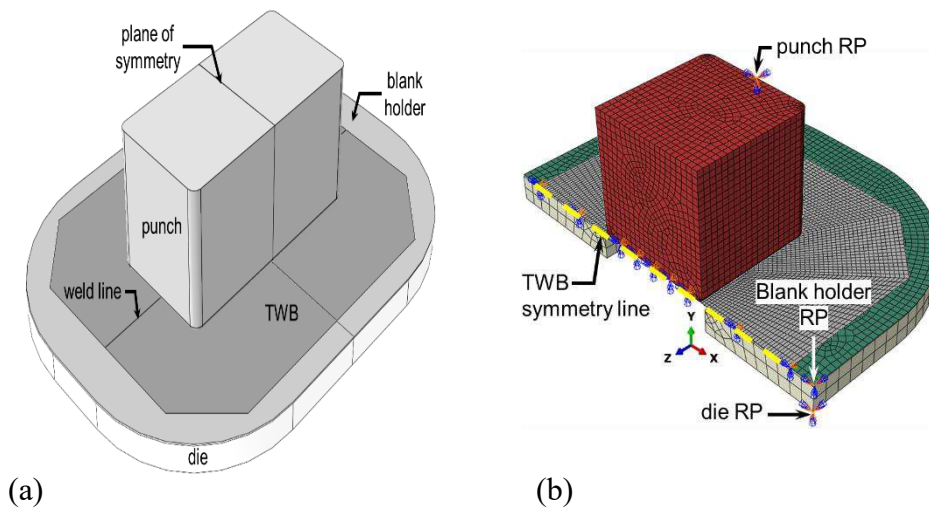


Figure 10:(a) The forming die, (b) FE model of the deep drawing process.

The simulation of the forces acting was applied as follows:

The blank holding force, which increases linearly to reach a maximum value of 30 kN, was simulated using the dynamic explicit formulation, then this force was kept fixed at this value, and the punch movement was simulated uniformly inside the die opening in the y direction at a constant speed of 20 mm/s until reaching its maximum specified displacement, which is 40 mm. The standard general formulation was applied to model the die retraction away from the TWB and the unloaded geometry of the TWB. The final position of the weld line with respect to the punch centerline was then extracted post unloading.

At the end of the dynamic step, the TWB's status was exported as the initial status for the unloading step.

2.3.2 Finite Element Model of TWB with Offset Weld Line (Model 2)

The FE model, as explained in the previous section, was employed in the same manner to simulate the process on another TWB. This TWB was made of the same blanks (A and B) but had a different weld line shape and location. The new weld line was created utilizing the same weld line nodes from the previous model, however, each node was moved in the opposite direction by a distance equal to its displacement in the previous simulation. The overall size and location of this new TWB relative to the die remained consistent with the original TWB. Comparison was then made between the final weld line movement between the two models.

2.3.3 Numerical Parameters and Assumptions

The unloading step was carried out while keeping the symmetry boundary conditions on the TWB symmetry line. The interaction constraints between the TWB and the rigid bodies were removed to allow the elastic recovery of the TWB. Throughout the unloading process, the weld line was allowed to move freely except the node intersecting with the symmetry line, which was fixed to prevent the translational rigid body motion of the TWB. The center line of the punch which coincided with the initial position of the weld line before the forming process, was used as a reference for locating the final position of the weld line nodes after unloading.

Key parameters such as the magnitude and direction of weld line displacement were used as validation criteria. The agreement between experimental measurements and numerical predictions was evaluated to assess the accuracy and reliability of the proposed simulation approach and the extent of the ability and efficiency of the numerical model to represent the actual forming behavior of the welded parts, with the aim of supporting the use of the numerical methodology to predict weld line movement under similar forming conditions.

3. RESULTS AND DISCUSSION

3.1. Weld Line Movement Behavior in the Baseline TWB (Without Blank Modification)

The TWB used in the Nissan car door was chosen without any engineering modification prior to the deep drawing process to adopt the result as a reference case for studying the weld line movement behavior during that process. The results of the measurements using 3D laser scanning technology, as shown in Figure 11, indicate that the weld line moved in a curved direction towards the thicker plate.

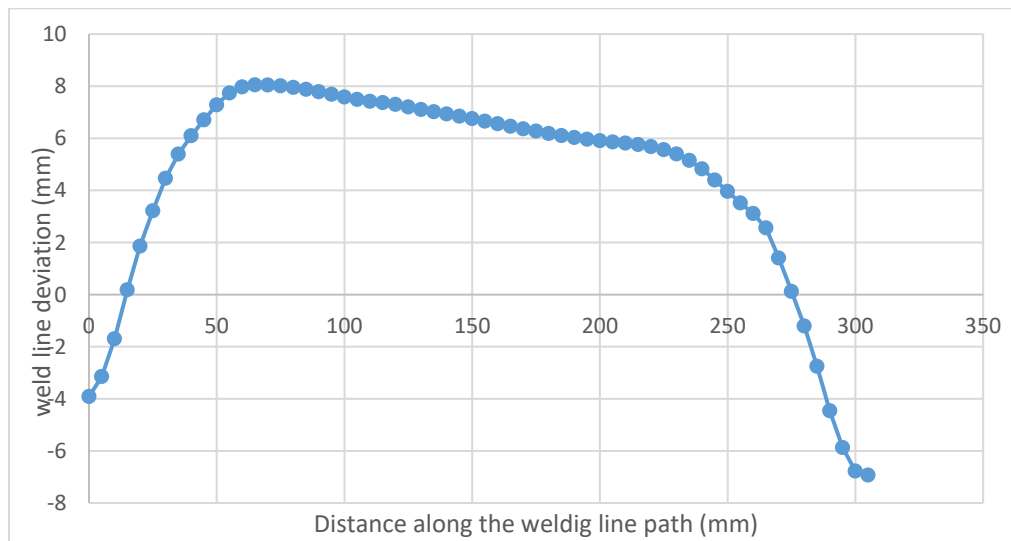


Figure 11: Welding line movement from the middle line (Idial welding line) measured at incremental 5mm steps along the welding line path.

The movement values were recorded at several points 5 mm apart along the weld line, as shown in Figure 11. It was observed that the highest value of deflection was in the deeper areas and those most exposed to mechanical stress during the pulling process, while this value gradually decreased towards the edges.

3.1.1 Effect of Blank Geometry Modification on Weld Line Movement

Based on the direction and magnitude of the weld line movement in the previous case (the reference case), a strategy was proposed to modify the blank geometry before the welding process in order to limit the weld line movement defects during the forming process.

This strategy is based on pre-cutting the blank with a curved path in the opposite direction to the expected movement direction, and with dimensions equal to the movement values measured in the reference stage.

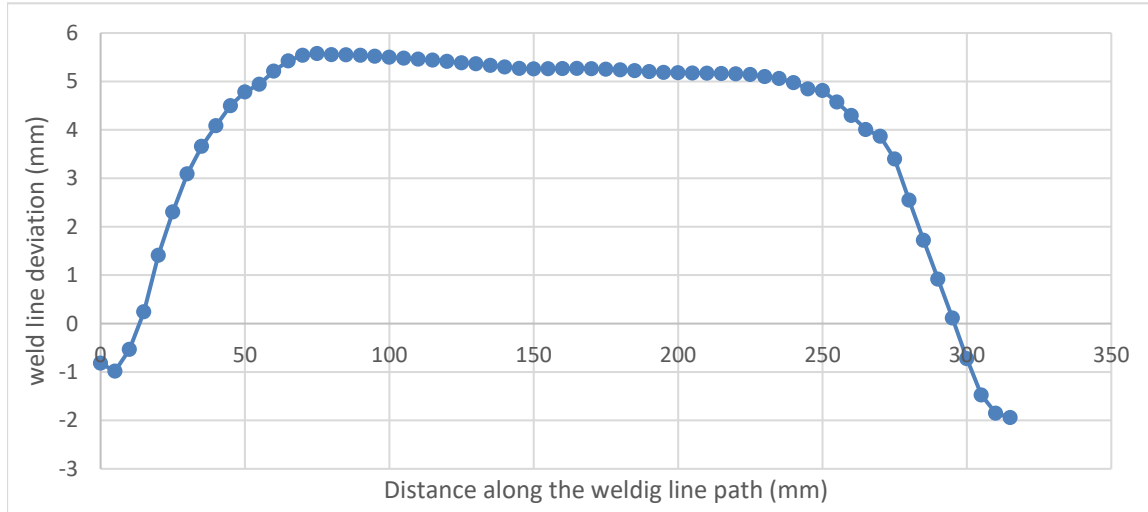


Figure 12: Welding line movement from the middle line (I dial welding line) measured at incremental 5mm steps along the welding line path.

After applying this strategy, then welding and re-performing the deep drawing process under the same previous operating conditions, the results showed a noticeable improvement in the weld line position after forming. The amount of movement was reduced compared to the reference case, and the weld line became closer to its original position before the deep drawing process, as illustrated in Figure 12.

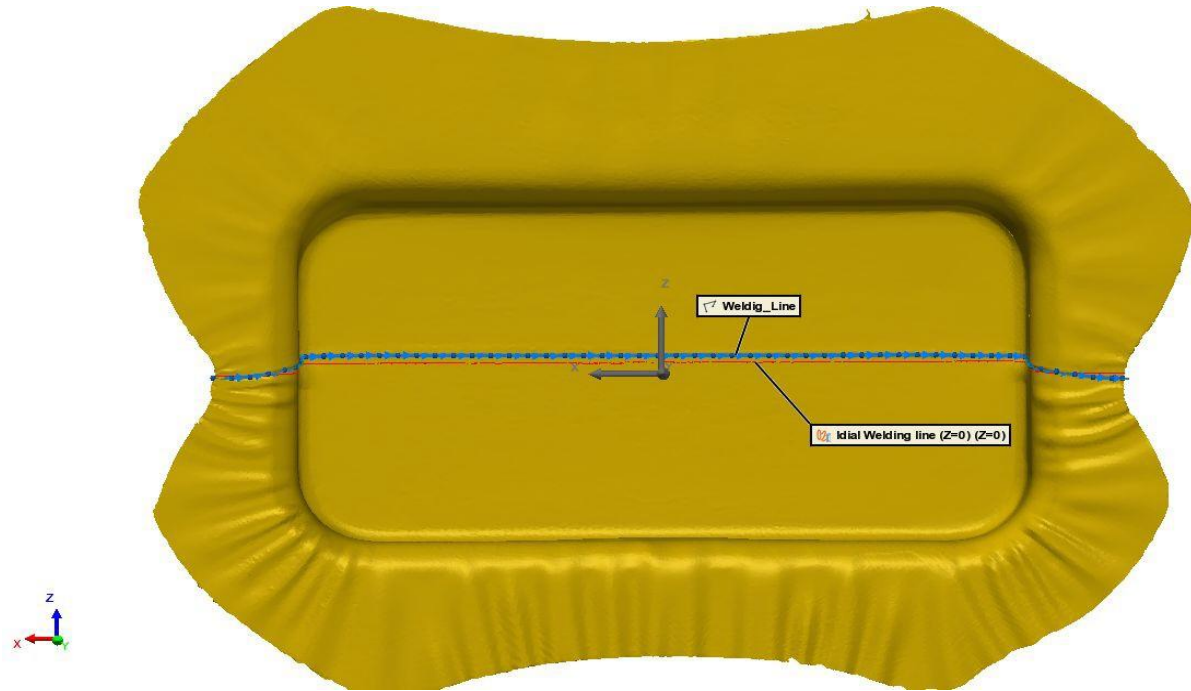
Although the pre-cutting method reduced the movement of the weld line from its original position. The movement of the weld line represents the accumulation of several variables, such as the deformation path of the two sheets, the local differences in stress distribution and deformation resistance of each sheet, as well as the contact conditions and friction coefficients with the die.

3.1.2. Optimization of the Curved Cutting Strategy

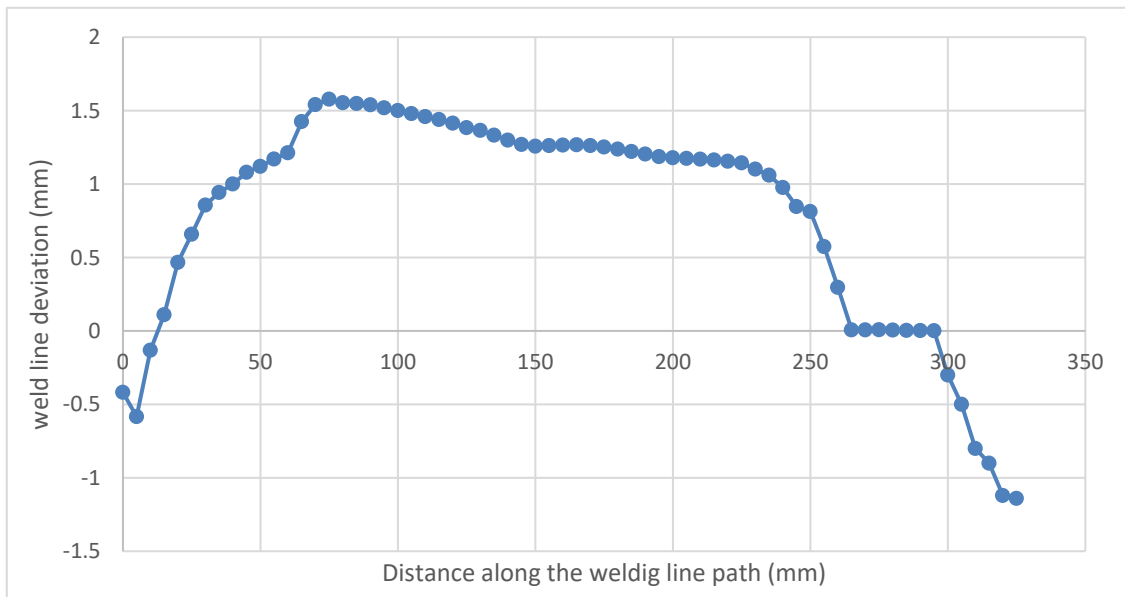
An optimization strategy based on the trial-and-error principle was proposed, in which the cutting path was modified to be deeper than the movement values measured in the first stage, as well as deeper than the cutting dimensions adopted in the previous stage, in order to overcome the accumulated nonlinear effects that occur during the forming process.

The results, as shown in Figure 13 (a), demonstrated that increasing the depth of the cutting path led to an additional improvement in the straightness of the weld line after forming, where the resulting movement became limited and within the geometrical tolerances that are industrially acceptable. However, excessive increase in the cutting depth may lead to a reverse movement of

the weld line, which highlights the existence of an optimal value for the cutting path that varies depending on the material type, its dimensions, and its properties.



a)



b)

Figure 13:(a) weld line movement after optimizing the Curved Cutting Strategy with Laser Scanning Measurement Technique (b) Welding line deviation from the middle line (Idial welding line) measured at incremental 5mm steps along the welding line path.

3.2 Numerical Prediction of Weld Line Movement

In the first model, the blank was represented with a straight weld line at the center, and in the second model, the weld line was shifted by an amount opposite to the expected movement values.

The weld line movement in the die opening zone, where the TWB contacts the punch, is directed towards the thicker side (blank A) of the TWB, driven by the greater resistance to flow on that side and complemented by the ease of flow of the thinner side (blank B) into the die. On the contrary, the area beneath the blank holder experiences compressive stresses, and these stresses are better resisted by the thicker side, causing the weld line movement towards the thinner side.

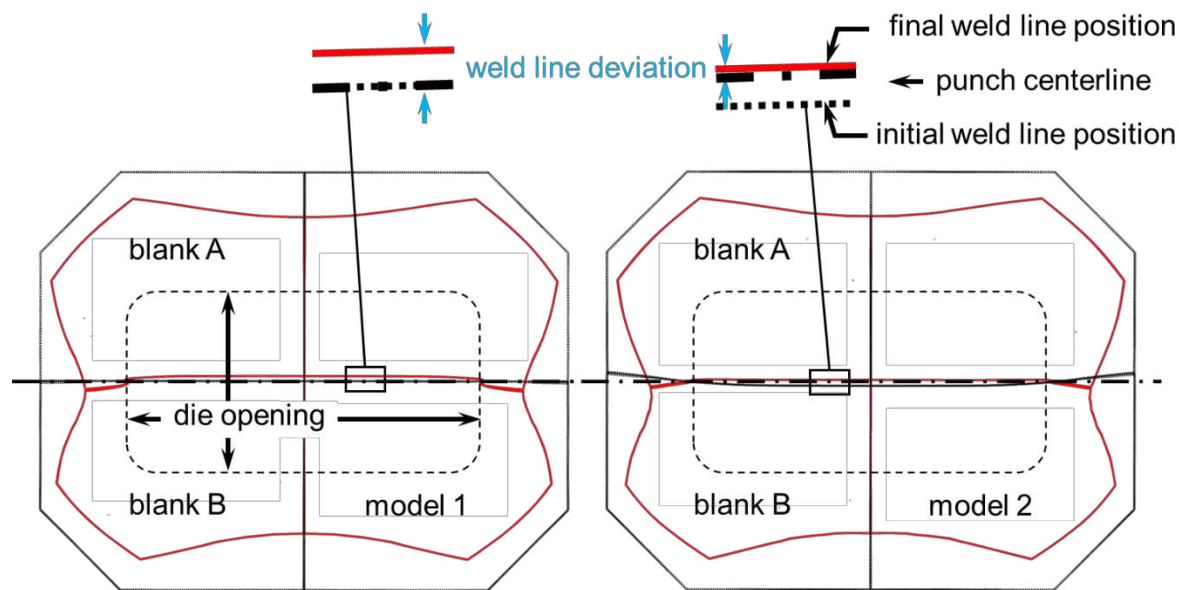


Figure 14: movement of the final weld line for model 1 and 2, representing an initially centered and offset weld line position respectively

The movement pattern is consistent in both models. However, the final location of each node on the weld line relative to the centerline of the punch is contingent on its initial position relative to the same centerline. For instance, when the nodes of the weld line were initially positioned at the centerline of the punch as depicted in Figure 14 (model 1), they always moved away from that centerline. Conversely, when initially positioned as shown in model 2, the nodes of the weld line moved towards the punch's centerline, resulting in less overall weld line movement from the centerline of the punch.

3.3 Experimental–Numerical Validation

The numerical simulation results were compared with the experimental results in order to evaluate the accuracy of the numerical model used. As shown in Fig. 15, the comparison showed a relative

agreement between the numerical and experimental values in terms of the direction of weld line movement and the magnitude of the maximum movement.

It is also evident from Fig. 16 that there are small differences between the results obtained from

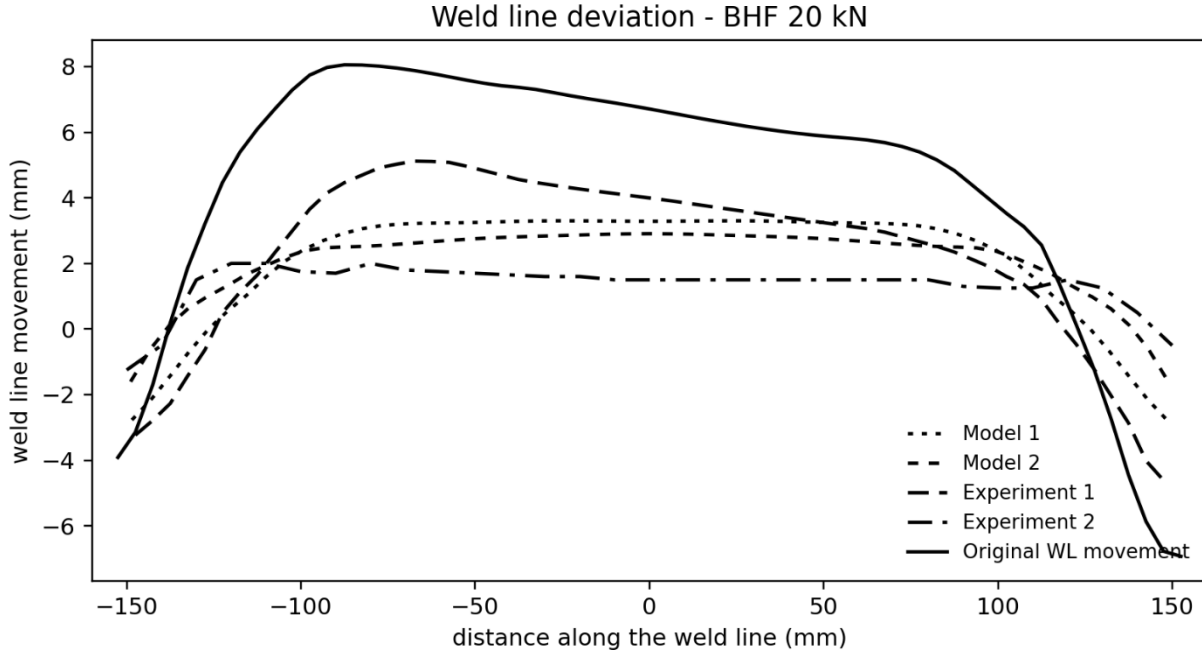


Figure 15: Weld line deviation for initially centered weld line (model 1 and experiment 1) and initially offset weld line (model 2 and experiment 2) and the original WL movement.

the numerical model and the results obtained experimentally. This is due to the assumptions on which the numerical model was built, such as the homogeneity of the weld zone properties and the lack of accurate representation of thermal deformations. Nevertheless, the level of agreement between the results confirms the validity of the numerical model in predicting the behavior of weld line movement under similar forming conditions.

3.4 Mechanical Behavior of the Weld Zone

The mechanical behavior of the weld zone was evaluated by mechanical stress and strain testing on welded and unwelded samples with thicknesses of 1 and 1.5 mm Figure 16 (a),(b) respectively with different directions of tensile forces applied relative to the direction of the WL.

The results, as shown in Figure 16(c), showed that the welded samples with a weld line parallel to the loading direction exhibited mechanical behavior _in terms of elongation and fracture resistance_ closer to that of the unwelded samples, this is because the weld line's orientation parallel to the load allows for a more uniform distribution of stresses across the weld zone, thus reducing the concentration of localized stresses.

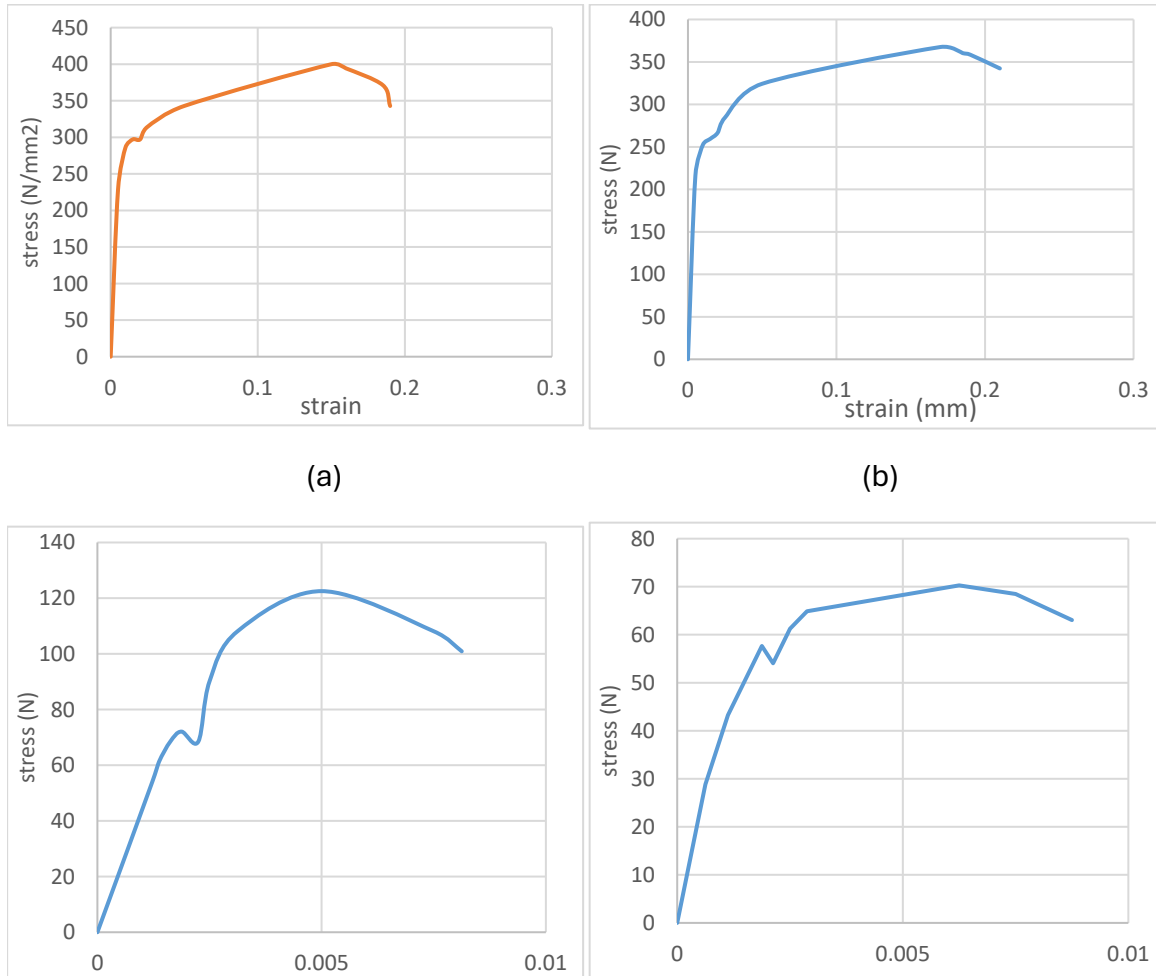


Figure 16: (a) stress-strain curve for unwelded sample with thicknesses of 1mm, (b) stress-strain curve for unwelded sample with thicknesses of 1.5mm, (c) stress-strain curve for welded sample with parallel WL, (d) stress-strain curve for welded sample with perpendicular WL.

The welding line acts as a potential weak point because:

The weld zone may not always exhibit the same mechanical strength as the base materials, depending on the welding process, material properties and weld quality.

The heat-affected zone (HAZ) around the weld often has reduced mechanical properties, leading to a decrease in overall strength. If the weld quality is good, it can still carry significant loads, but the weakness is pronounced if the weld is not uniform or has defects.

While the samples with a weld line perpendicular to the loading direction, as shown in Figure 16(d), showed a relative decrease in elongation before breaking, Due to the concentration of stresses at the welding area.

If the weld has good bonding and integrity, the strength might be higher, but if there is a weakness or a defect, this is a highly vulnerable area for failure due to shear forces.

These findings highlight that the direction of the weld line plays an important role in stress distribution during loading, which may indirectly affect the movement of the weld line during forming processes.

4. Conclusions

Tailor welded blanks used in the manufacturing of car doors showed noticeable weld line movement during the deep drawing process. The weld line moved toward the thicker sheet due to the difference in deformation resistance between the welded sheets. Experimental measurements confirmed that the weld line movement was higher in regions exposed to greater mechanical stresses, especially in the deeper areas of the formed part, while the movement decreased gradually toward the edges.

The proposed compensation strategy, based on modifying the sheet geometry before welding by applying a curved pre-cut path opposite to the expected weld line movement, proved effective in reducing weld line movement after forming. By applying a trial-and-error approach and increasing the depth of the reverse cutting path, the weld line movement was reduced significantly, and its final movement value was reduced to within industrially acceptable geometric limits. However, the results also confirmed that an optimum cutting depth must be selected carefully to avoid reverse movement.

The numerical simulation carried out using ABAQUS showed good agreement with the experimental results in both the direction and magnitude of weld line movement. This confirms the validity of the developed numerical model and its capability to predict weld line behavior during the forming process.

The stress–strain test results showed that the mechanical behavior of the welded specimens depends strongly on the orientation of the weld line relative to the loading direction. Specimens with a weld line parallel to the loading direction exhibited mechanical behavior closer to that of the unwelded specimens, while specimens with a weld line perpendicular to the loading direction showed a more noticeable change in mechanical response due to the direct influence of the weld zone on deformation and fracture behavior.

Overall, the proposed method provides a practical engineering solution for controlling weld line movement in tailor welded blanks. It can be applied in industrial production lines without changing the forming conditions or modifying

the production equipment, which increases its applicability in the automotive industry.

Future Work

Future work should focus on determining the reverse cutting depth required to achieve minimum or zero weld line max movement during forming. This can be achieved by developing a correlation between the mechanical properties of the welded sheets, the geometric dimensions of the blank, and the max reverse cutting depth. Such a correlation would allow the proposed compensation strategy to be applied more accurately and efficiently in industrial forming processes , also , other mechanical characteristics of materials like direction to rolling , anisotropy must be taken into consideration.

Declarations

Availability of data and materials

All data used shall be made available upon request.

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List of figures

Figure 1: Nissan car doors inner after a)deep drawing ,and b)original TWB sheet.	6
Figure 2:(a) the two welded sheets, (b) Geometric dimensions of the TWB for experimental work.	7
Figure 3:: Side Panel made of steel tailored blanks.	7
Figure 4: the original welding line position.	8
Figure 5: (a) the drawing depth of the car door 10 cm in 3 stages , (b) the applied depth on the test specimen.....	8
Figure 6:3-D Model Of The TWB Obtained From Laser Scanning And Analyzed Using Poly works Inspector.	9
Figure 7:(a) schematic sketch for die deep drawing (b) Double-acting hydraulic deep-drawing press showing the hydraulic ram, punch and die assembly, blank-holder system, guide pillars, and hydraulic cushion.....	10
Figure 8:standard tensile test machine.	10
Figure 9:four specimens with different condition.	11
Figure 10:(a) The forming die, (b) FE model of the deep drawing process.	12
Figure 11: Welding line movement from the middle line (Idial welding line) measured at incremental 5mm steps along the welding line path.	14
Figure 12: Welding line movement from the middle line (l dial welding line) measured at incremental 5mm steps along the welding line path.....	15
Figure 13:(a) wield line movement after optimizing the Curved Cutting Strategy with Laser Scanning Measurement Technique (b) Welding line deviation from the middle line (Idial welding line) measured at incremental 5mm steps along the welding line path.	16
Figure 14:movement of the final weld line for model 1 and 2, representing an initially centered and offset weld line position respectively.....	17
Figure 15:Weld line deviation for initially centered weld line (model 1 and experiment 1) and initially offset weld line (model 2 and experiment 2).	18
Figure 16: (a) stress-strain curve for unwelded sample with thicknesses of 1mm, (b) stress-strain curve for unwelded sample with thicknesses of 1.5mm,(c) stress-strain curve for	

welded sample with parallel WL,(d) stress-strain curve for welded sample with perpendicular WL.....	19
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