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New Apparatus and Method for Forming Tailor Welded Blanks

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ABSTRACT

Tailor welded blanks offer a unique opportunity to reduce manufacturing costs, decrease vehicle weight, and improve the quality of stampings through the consolidation of multiple formed, then welded, parts into a single stamping. However, tearing near the weld line often occurs in this type of blank when formed with a traditional deep drawing process. Therefore, some adaptation to the existing sheet metal forming process must be developed in order to reap the numerous benefits available from tailor welded blanks. In this paper, numerical simulation are presented for a newly contrived tailor welded blank forming process where several hydraulic mechanisms apply distinct clamping forces along the weld line during forming. Excellent results demonstrate the effectiveness of the proposed method.

INTRODUCTION

Today's automotive industry is an extremely competitive market played out on a global stage. Customers demand high performance cars at minimal cost. Coupling these requirements with the ever constricting government environmental regulations, automakers are left scrambling to come up with innovative solutions to lower manufacturing costs, improve product performance, and reduce vehicle weight. One of the promising possibilities to meet these challenges is tailor welded blanks.

In the conventional fabrication of automobile body component assemblies, several stampings are formed individually and subsequently spot welded together in order to obtain the material and strength requirements at various locations in the assembly. Alternatively, the various materials can be welded together prior to the forming process to produce what are known as tailor welded blanks (TWBs). This term is derived from the notion that the automobile designer will be able to "tailor" the location in the stamping where specific material properties are desired. These differences can be in the material's grade, gauge thickness, strength, or coating, for example galvanized versus ungalvanized [1]. TWBs have generated enormous interest in the automotive industry as of late due to the substantial benefits they produce. These include reduced manufacturing costs due to fewer forming dies, elimination of downstream spot welding operations, and reduced scrap; weight reductions due to the combining of parts into a single component; improved dimensional part consistency from the reduction of inaccurate spot welding processes; improved corrosion resistance through the elimination of lap joints by integration of reinforcements [1]; and improved crash test results due to the increased stiffness of laser and mash-seam welds in comparison to traditionally used spot welds [2].

However, because the material properties in the heat affected zone, HAZ, adjacent to the weld and in the weld itself are significantly less desirable from a forming standpoint compared to the base metal, creating a failure free deep drawing process for TWBs is difficult. For the case of steel TWBs, material hardening in the weld and the HAZ limits the formability of these stampings. In particular, potential elongation of the blank in the direction along the weld line can be reduced to half of what is normally available for the given steel [3, 4]. In this research, Aluminum blanks are welded together to produce the TWB in order to obtain the maximum weight advantage. While there are not specific published studies on the formability of Al in TWB applications, the effects on the mechanical properties of welding Al alloys has been studied [5, 6]. Significant reductions in the potential elongation transverse (i.e. perpendicular) and longitudinal (i.e. parallel) to the weld line have been reported. In addition, unlike steel, the strength of Al in the HAZ decreases due to welding [5]. For a 6XXX Series Al Alloy, the tensile strength in the HAZ can be reduced by as much as 40% of the base metal's value [5]. This reduction however varies greatly based on the filler alloy used in the welding, post weld heat treatment or aging, and other welding process parameters, such as amount and length of weld heating.

Another concern in TWBs is weld line movement. Whether produced with steel or Al, the stronger material in the TWB will resist deformation more than the weaker material causing the weld line to "move" in the stamped part. This effect limits the ability of the designer to position the specific material properties in the final stamping where desired and may create other forming problems such as wrinkling, tearing, and uncontrollable springback.

Despite these formability concerns, TWBs are incorporated into the automobile body where prudent to reap the potential rewards they offer. Some of the components where TWBs are currently being utilized are body side panels, motor compartment rails, center pillar inner panels, and wheelhouse/shock tower panels [1]. Another prime example of a component that can be improved through the use of TWBs is a door inner panel. Stronger material is required near the hinge to support the weight of the door and to provide reinforcement for the mirror. As a reference to the potential manufacturing cost savings available, General Motors estimated that a tailor welded door inner panel saved the company $4.9-million through the elimination of fourteen dies, weld fixtures, and check stands [2]. This estimate was even conservative since other intangible costs such as reductions in die storage, materials handling, and die maintenance were not taken into account. A separate technical cost analysis showed a savings of $6.3-million for the manufacturing cost of a hypothetical TWB door inner [9]. For an idea of the possible structural improvements, an automotive manufacturer reported a 9% improvement in the elastic sag and 30% improvement in the plastic set when a 90-kg load was applied to the latch of an assembled tailor welded door [8].

In order to overcome the failures encountered during forming, attempts have been made to modify a traditional forming process to improve the formability of TWBs. Ahmetoglu et al. [10] investigated forming round cups with TWBs. In their work, the circular blank holder plate was cut, or segmented, in two with respect to the side with the thicker, stronger material and the side with the thinner, weaker material. Three nitrogen cylinders where positioned under each portion of the blank holder plate to vary the blank holder force applied to the two different material gauges. The thicker material was subjected to a lower blank holder force, thus allowing more material to flow into the die cavity. This process modification was successful at reducing the weld line movement and delaying tearing failure along the weld line compared to the case where a uniform binder force was applied to the TWB.

In another effort to improve TWB formability, Munzen [11] used the lower die cushion from a production triple action stamping press to clamp on the weld line during the forming process. The die cushion supported the weld line when the blank was initially placed across the die cavity. The part of the punch opposite the die cushion would then contact the blank prior to or just as deformation of the blank occurred. Once clamped, the part was formed entirely before the weld line was released. This clamping prevented the weld line from moving during forming. However, this process required that the weld line be at the highest point on the stamping in order for the clamping to occur successfully.

In this paper, a novel approach to modify the forming process is proposed to improve the drawability of TWBs. In this system, hydraulic cylinders apply clamping forces to specific locations along the weld line of the TWB during the forming process. Here, numerical simulation results are presented for both a typical stamping process and the newly contrived system. The analysis shows excellent promise for the clamping method to alleviate the tearing forming concerns associated with the part in this study.

PROPOSED APPARATUS FOR FORMING TWB

Our proposed system uses hydraulic controlled cylinders to clamp on the weld line during the forming of TWBs [12]. Figure 1 shows a schematic of the process with a hydraulic cylinder above and below the blank, incorporated into the punch and lower die respectively. While Fig. 1 only shows one set of opposing hydraulic cylinders, multiple sets could be used to clamp along the weld line in several locations. Having multiple sets of opposing hydraulic cylinders allows the weld line to have any shape, as opposed to simply a straight line. Also, as Fig. 1 shows, this system allows the weld line to be anywhere in the curvature of the formed part, not necessarily at the peak of the punch. Furthermore, the hydraulic cylinders would allow the weld line to be released prior to reaching the final forming depth in order to allow limited strain in the material near the weld line, which is desirable for part integrity.

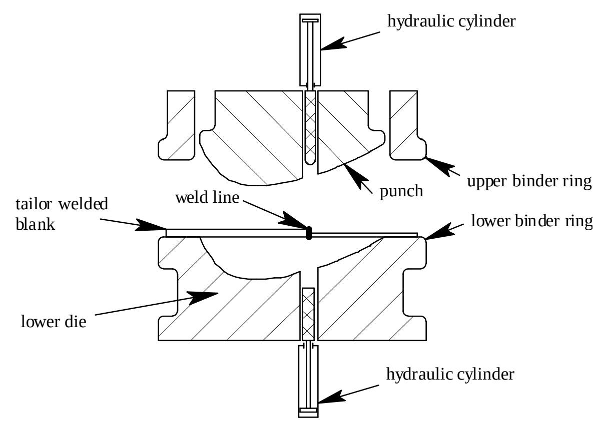

Figure 1. Schematic of proposed clamping mechanism.

DOOR INNER GEOMETRY

As previously mentioned, one of the most popular applications of TWBs is a door inner. Therefore, this part geometry was chosen for the numerical analysis and subsequent verification experiments to be performed in the near future. A schematic of the punch used in the simulations is shown in Fig. 2. The size of the punch was limited by the punch opening in the 150-ton HPM hydraulic stamping press where experiments will be performed, and maximized in order to allow sufficient room for the hydraulic cylinders. The various dimensions were scaled to that of door inners found in industry [7] including the curvature of the stamped part. Figure 2 also shows the location where the weld line will initially contact the punch. Note that the weld line is in the direction of the punch curvature; therefore, opposing cylinders will not necessarily contact the punch at its peak. Also, notice that the weld line is more complicated than simply an uni-directional straight line, thus optimizing material usage of the thicker gauge material. In most of the current applications, there is only one vertical weld line in the door inner [7]. This design is due to the limitations of current forming technology, not because of functional requirements.

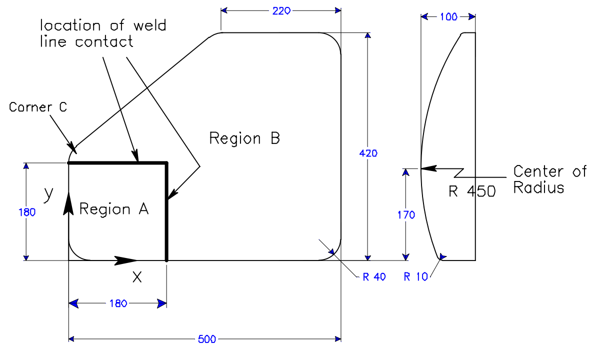

Figure 2. Punch geometry and initial weld line position on punch surface. Dimensions in mm.

The blank material used in this research was arbitrarily chosen as Al 6111-T4 with a thickness of 2 mm in Region A and 1 mm in Region B (Fig. 2). A step in the upper and lower dies accommodated this variation in material thickness. The clearance between the punch and the lower die was set at 30 mm, and the radii, both of the punch and die, over which the material was formed is 10 mm. A 100 mm distance was maintained between the edge of the blank and the opening of the die around most of the punch shape to allow for sufficient binder force area. Figure 3 shows the dimensions of the blank used in the simulations. A cut in the blank near Corner C (see Figs. 2 and 3) was required to reduce the tendency of wrinkling.

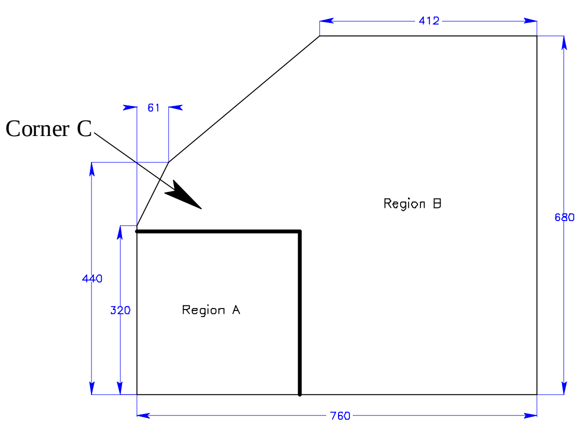

Figure 3. Dimensions of Tailor Welded Blank in mm.

FINITE ELEMENT ANALYSIS

In order to examine the potential of our proposed clamping mechanism for improving the formability of TWBs, metal forming simulations were conducted. This finite element analysis was performed on the commercially available software package, LS-DYNA3D. Figure 4 shows the mesh for the TWB. Belytschko-Tsay [13] shell elements were used in the analysis. The punch, lower die, and upper die were modeled as rigid bodies with surface to surface contact for the interface between the blank and the tooling [13]. The material model used for Al 6111-T4 has a Young's Modulus of 71 GPa, a Poisson's ratio of 0.3, and obeys Barlat's yield function for representing the anisotropic behavior of sheet metal under a plane stress condition [14]. The strain hardening is modeled by the power law with a strength coefficient of 520 MPa and a strain hardening coefficient of 0.26. A velocity profile, shown in Fig. 5, was used with a maximum velocity of 20 m/sec and an average velocity of 10 m/sec to allow the simulation to finish in a reasonable time while minimizing the dynamic effect. The zero acceleration at the beginning and end of the punch stroke also serves the same purpose. Other variables used in the analysis include a friction coefficient of 0.12 for Coulomb's friction law, a depth of draw of 100 mm, and a binder force of 400 kN.

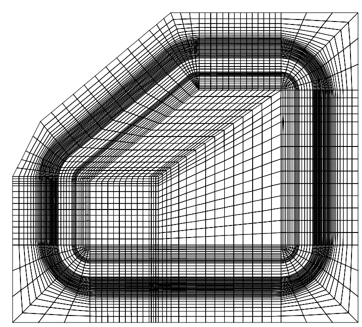

Figure 4. Mesh of Tailor Welded Blank.

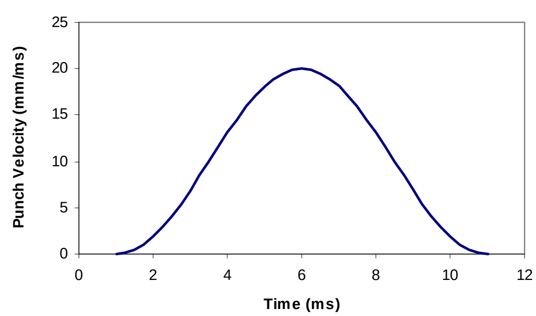

Figure 5. Punch velocity profile versus time.

RESULTS

Finite element analysis provides a powerful tool for evaluating the potential to form a TWB with the proposed modification to the process. Two cases were simulated. A typical metal forming process without a weld line clamping force, the Free Case, and the Fixed Case where the nodes in two locations, Clamping Areas 1 and 2, were restricted from moving in the *x*- and *y*-directions to simulate a clamping device. Figure 6 shows where these clamping areas were located along the weld line with respect to the punch profile. The location on the vertical weld line was chosen because this region had the maximum vertical weld line movement for the Free Case. The clamping area on the horizontal weld line was placed as close to the punch edge as possible, while leaving sufficient room to accommodate a hydraulic cylinder, since both the maximum engineering strain transverse to the weld line and weld line movement occurred near Corner C for the Free Case. These clamping areas were approximately circular in shape, limited by the location of actual nodes in the mesh, with a diameter of 45 mm. This geometry was chosen since hydraulic cylinders with circular piston rods will be used to apply the clamping force in subsequent physical experiments. The piston rod diameter value of 45 mm is one of the possible sizes for Parker-Hannafin HMI Series metric hydraulic cylinders.

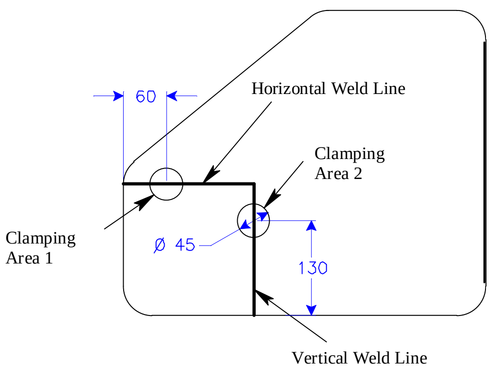

Figure 6. Location and size of clamping force areas. Dimensions in mm.

Figure 7 shows the final strain state of all the elements adjacent to the weld line in the thinner material for the Free Case and Fixed Case plotted as a Forming Limit Diagram, FLD. The Forming Limit Curve, FLC, for Al 6111-T4 with an elongation limit in plane strain, FLD_0, of approximately 25% and the marginally safe region are also plotted for the base material. As previously mentioned, welding will reduce the maximum potential elongation in the HAZ so the actual forming limit curve in the as-welded condition will be below these curves. However, since there is not experimental data specifically for Al 6111-T4 in the as-welded condition and maximum elongation is dependent on loading direction, only the FLC for the base material is shown. Figure 7 indicates that several elements, all of which are near Corner C, are in approximately a plane strain condition and would fail or be close to failure due to tearing for the Free Case. In contrast, no elements for the Fixed Case are near the FLC. As is seen in this FLD, clamping on the weld line significantly reduced the major principal engineering strains along the weld line, thus increased the possibility of avoiding tearing failure.

To address the concern about the reduction of elongation due to welding, engineering strains transverse and longitudinal to the weld line were investigated. Metzger [6] found that the maximum elongation transverse and longitudinal to the weld line for Al 6061 could be reduced from the original material's maximum elongation value by 80% and 60% respectively. These percentages were used as a guide to determine the maximum allowable engineering strain for Al 6111. Tests on the mechanical properties of welded Al 6111 will be performed in our future experimental study. Figure 8 shows the amount of engineering strain transverse to the weld line for the elements in the thinner material directly next to the weld for both the Free and the Fixed Cases. The zero for the weld line distance axis is at the punch edge and goes to the intersection of the horizontal and vertical weld lines at 180 mm. As this figure shows, the maximum engineering strains transverse to the weld line are 33.6% and 23.7% for the horizontal and vertical weld lines, respectively. In comparison, the maximum engineering strains for the Fixed Case are 12.4% for the horizontal weld line and 3.7% for the vertical weld line. Assuming that the limit strain of the weld line for Al 6111 has the same percentage drop as that of Al 6061, 80%, the allowable strain transverse to the weld line for Al 6111 would be approximately 5% (80% X FLD_0 = 80% X 25% = 5%). Then, the Free Case would have a maximum punch depth of 18.3 mm where as the Fixed Case could be formed to 27.0 mm before a transverse strain of 5% was reached. Hence, the Fixed Case significantly improved the potential forming depth for this particular part.

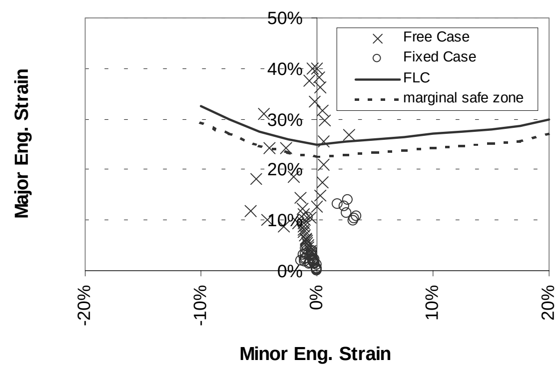

Figure 7. Forming Limit Diagram for elements adjacent to the weld line in the thinner material for the Free and Fixed Cases.

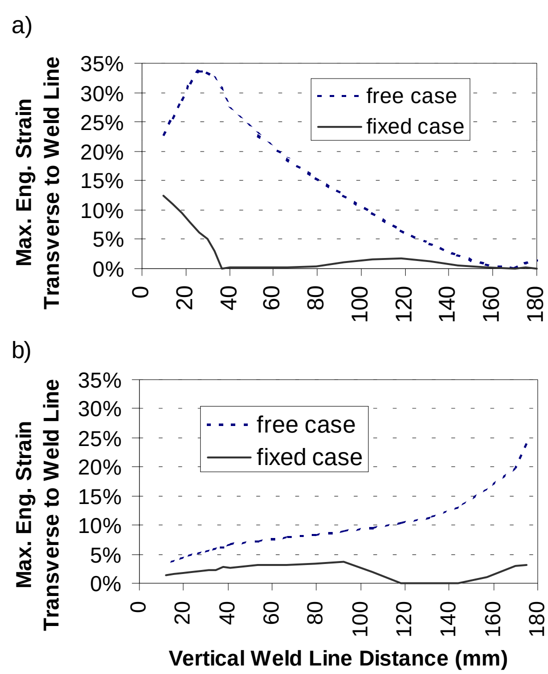

Figure 8. Maximum engineering strain in the thinner material transverse to a) the horizontal weld line and b) the vertical weld line. The distance axes are from the punch edge to the weld line intersection.

The maximum engineering strain longitudinal to the weld line, shown in Figure 9, was also examined. Taking into account the potential reduction in maximum elongation due to welding, the maximum value of elongation before failure would be approximately 10%, 60% of the FLD_0 value. This figure shows that clamping on the horizontal weld line actually increases the longitudinal engineering strain significantly in the area directly next to the hydraulic mechanism near Corner C. However, the maximum value longitudinal to the horizontal weld line was still reduced from 16.1% for the Free Case to 11.2% for the Fixed Case. For the vertical weld line, longitudinal strains were slightly negative indicating compression; therefore, tearing failure due to excessive elongation is not a concern. This compression is caused by this particular part geometry and the large strain transverse to the vertical weld line. Since the transverse strain is more critical than the longitudinal strain for this particular part, a similar potential forming depth analysis as was conducted for the transverse strains was not performed.

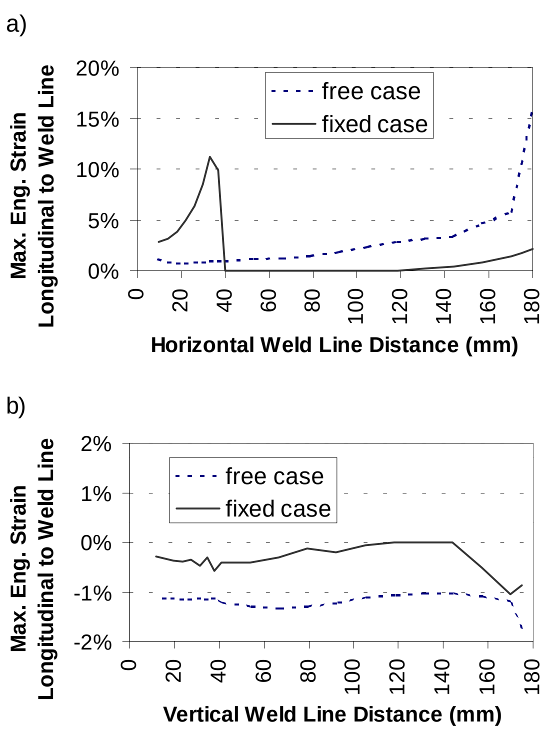

Figure 9. Maximum engineering strain in the thinner material longitudinal to a) the horizontal weld line and b) the vertical weld line.

Another good assessment of failure is the percentage of thickness reduction in the formed part. Figure 10 shows the results for the Free Case where thickness reduction increases as the gray scale becomes darker. Note that the location of the weld line is visible on this plot due to the large thickness reductions near the weld line in the thinner gauge material while the thicker material has significantly less thickness reduction. The maximum thickness reduction was 28.2% and occurred near Corner C in the thinner gauge material. In comparison, Fig. 11 shows the distribution of thickness reduction for the Fixed Case with the same color scale as used in the Free Case plot (Fig. 9). The weld line is almost invisible in this plot compared to Fig. 10 since clamping on the weld line causes the thicker gauge material to stretch more than in the Free Case. The maximum percent thickness reduction was reduced to 20.0% for this case, still occurring near Corner C but now in the thicker gauge material.

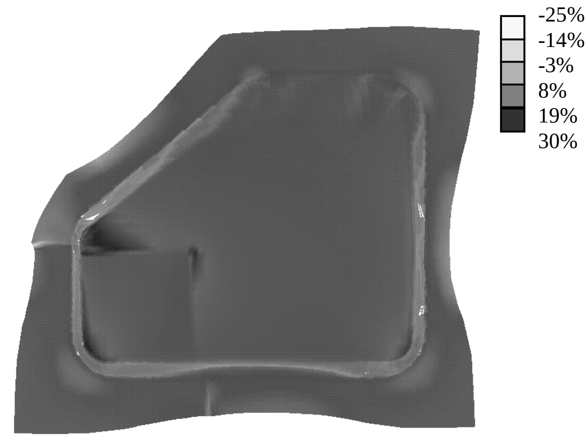

Figure 10. Percent thickness reduction for Free Case.

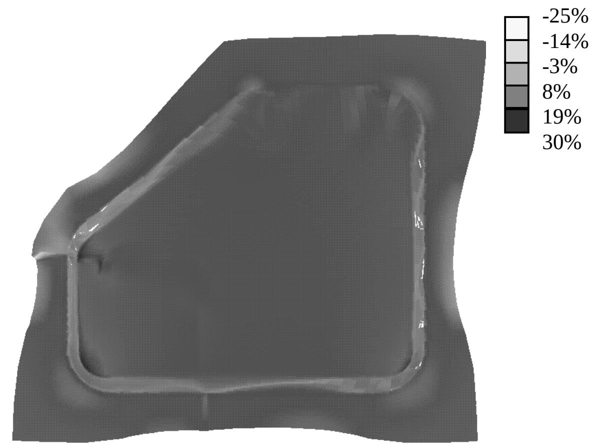

Figure 11. Percent thickness reduction for Fixed Case.

Finally, Fig. 12 shows that amount of weld line movement on the punch surface that occurred for both the Free and the Fixed Cases. The maximum values of movement for the Free Case were 12.23 mm in the *y*-direction for the horizontal weld line and 15.98 mm in the *x*-direction for the vertical weld line. For the Fixed Case, the maximum weld line movement values were reduced to 0.82 mm for the horizontal weld line and 0.97 mm for the vertical weld line.

Therefore, by clamping on the weld line, the tearing failure associated with this TWB part can be significantly delayed, the strain distribution is more uniform between the thicker and thinner gauge materials, and the weld line movement was dramatically reduced so that accurate placement of material properties in the final part geometry is possible. Table 1 summarizes the numerical results comparing the Free and Fixed Cases.

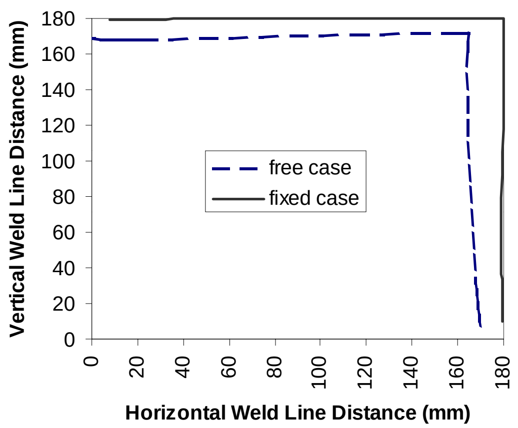

Figure 12 Weld line movement for the Free and Fixed Cases.

VARIABLE	FREE CASE	FIXED CASE
Max. eng. strain transverse to horizontal weld line	33.6%	12.4%
Max. eng. strain transverse to vertical weld line	23.7%	3.7%
Max. punch depth before 5% eng. strain transverse to weld line reached	18.3 mm	27.0 mm
Max. eng. strain longitudinal to horizontal weld line	16.1%	11.2%
Max. eng. strain longitudinal to vertical weld line	-1.7%	-1.1%
Max. percent thickness reduction	28.2%	20.0%
Max. horizontal weld line movement	12.2 mm	0.82 mm
Max. vertical weld line movement	15.9 mm	0.97 mm

Table 1. Results of numerical simulations.

ANALYSIS OF CLAMPING MECHANISM

The ability of the clamping mechanism to provide an adequate clamping force to resist weld line movement and to withstand reaction forces at the clamping areas is critical to the success of the proposed system. Therefore, the clamping mechanism was analyzed. Parker-Hannafin HMI Series hydraulic cylinders with a bore diameter of 80 mm, a maximum pressure of 210 bar, a stroke of 125 mm, and a piston rod diameter of 45 mm were specified as the mechanism that would supply the clamping force. The piston rod is made of 1050 steel, and the mechanical properties of this material are an ultimate tensile strength of 636 MPa, yield strength of 365 MPa, and Young's Modulus, E, of 207 GPa [15]. From the Fixed Case simulation, the reaction forces at each step of the forming process were calculated for both clamping areas by summing the reaction forces at each node in the given area. Clamping Area 1 had a reaction force, F_R, of 32.4 kN in the plane of the sheet while the value at Clamping Area 2 was 22.5 kN. Since Clamping Area 1 represented the worst of these two areas, its value was used in the analysis of the clamping mechanism.

Whether the hydraulic cylinder could produce enough force to resist the weld line movement is critical for the success of the clamping mechanism. To resist weld line movement, the cylinder must produce enough frictional force, F_f, to off set the reaction force found in the Fixed Case simulation. In order for the piston end to conform to the sheet metal during clamping, a rubber end will be attached to the hydraulic cylinder. The friction coefficient, μ, between metal and rubber was assumed to be 0.35. This value would be easily obtained or surpassed by the choice of the rubber material. With this μ, the normal force to resist weld line movement was calculated by Coulomb's friction law, $F_N = F_f / \mu$, to be 92.5 kN. Based on its physical dimensions, the hydraulic cylinder could produce a force, F, up to 105.5 kN. Therefore, the specified hydraulic cylinder would be able to resist weld line movement.

Next, The ability of the piston to withstand the maximum stress encountered when the piston rod is extended to its full length was analyzed. The maximum bending stress that the reaction force would produce in the piston rod is given by $\sigma = (Mr)/I$. In this formula, M is the moment produced by the maximum reaction force at the maximum distance, r is the radius of the piston rod, and I is the moment of inertia of a circular cross section which is equal to $(\pi r^4)/4$. Using the above equation, the maximum bending stress in the piston rod due to the reaction force is 248 MPa. Also, the opposing hydraulic cylinder would produce a compressive stress in the piston rod equal to the force, F = 92.5 kN, divided by the area F is acting over, the circular area of the piston rod with a diameter of 45 mm. This compressive stress is equal to 58 MPa. Adding these two stresses together, the maximum stress in the piston rod is 306 MPa at its base. This value is less than the yield strength of the steel; therefore, the piston rod can withstand the one time static application of these forces. Furthermore, the ratio of this stress divided by the ultimate tensile strength of the 1050 steel is approximately 0.5; therefore, there is also not a concern for fatigue failure in the piston rod [15].

Despite the fact that the weld line will not move, the piston rod will deflect slightly due to the application of the reaction force based on the formula $\delta = (F_R L^3)/(3EI)$, where L is the length of the extended piston rod. Using this equation, the reaction force would produce an end deflection in the piston rod of 0.227 mm. Due to this deflection, there is an eccentric buckling load applied to the piston rod. In order to evaluate the stability of this rod, the secant formula:

$$\sigma_{yield} = \frac{F_{cr}}{A}\left[1+\frac{e}{r}\sec\left(\sqrt{\frac{F_{cr}}{EI}}\frac{L_e}{2}\right)\right] \tag{1}$$

was used to calculate the critical force that would produce buckling in the piston rod. In this formula, F_{cr} is the critical force to cause buckling, A is the cross sectional area of the column, e is the eccentric distance from the centerline of the column to the axis of loading, and L_e is the equivalent length based on loading conditions. L_e was set to be twice the actual piston rod length, 250 mm, since the end against the sheet metal was considered free and the end in the hydraulic cylinder was deemed fixed. With the secant formula, the critical buckling load, F_{cr} was calculated as 356.2 kN. This is well above the maximum clamping force required to resist weld line movement (92.5 kN); therefore, buckling is not a concern.

The above calculations show that the hydraulic cylinder would be able to resist weld line movement, withstand the stresses exerted on the piston rod, and resist buckling. Table 2 lists the critical limits for these considerations, the actual values encountered, and the corresponding safety factor for the given criteria.

CLAMPING MECHANISM CRITERIA	LIMIT	ACTUAL	SAFETY FACTOR
Resist weld line movement	105.5 kN	92.5 kN	1.14
Withstand stresses in piston rod	365 MPa	306 MPa	1.19
Resist buckling	356.2 kN	92.5 kN	3.85

Table 2. Analysis of clamping mechanism results.

CONCLUSION

Tailor welded blanks provide numerous benefits including reduced vehicle weight, lower manufacturing costs, and improved structural integrity. However, formability concerns cause current applications to be limited. In this research, simulations were conducted for a TWB deep drawing process with a geometry similar to a door inner. First, a standard forming process was simulated by applying a binder force around the perimeter of the TWB and displacing a punch to form the part. Tearing failure occurred near the weld line where the thicker, stronger gauge of material caused the thinner, weaker gauge material to withstand much of the deformation. Then, a clamping mechanism was simulated by constraining nodal displacements at locations along and near the weld line where the maximum weld line movement occurred in the Free, non-clamped, Case. These constraints simulated the force of a hydraulic cylinder clamping the weld line in the specified locations. The results show that this clamping force on the weld line significantly delayed the tearing failure concern in this application and produced a more evenly distributed strain distribution in the thicker and thinner gauge materials. A stress and instability analysis then confirmed that the specified hydraulic cylinder could withstand the resulting stresses and resist buckling while providing the necessary clamping force to eliminate weld line movement. This research demonstrates the potential for the newly contrived system to fabricate TWBs while avoiding tearing failures. In addition, our proposed clamping mechanism on the weld line allows for increased possibilities and benefits for TWBs since non-straight weld line can be used, clamping forces can be applied on a non-peak location of the part, and the clamping force can be released prior to full punch stroke depth. Finally, the determination of clamping locations is an extremely straight forward and therefore diverges from a trial-and-error approach. While only simulations are shown in the research presented here, experiments will be conducted in the near future at Northwestern University's Advanced Metal Processing Laboratory (AMPL) to verify the formability improvements claimed here.

ACKNOWLEDGMENTS

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