ENHANCEMENT OF SHEET METAL FORMABILITY VIA LOCAL ADAPTIVE CONTROLLERS

Brad L. Kinsey and Jian Cao
Department of Mechanical Engineering
Northwestern University
Evanston, IL

ABSTRACT

Tailor welded blanks (TWBs) offer an excellent opportunity to reduce manufacturing costs, decrease vehicle weight, and improve the quality of sheet metal stampings. However, tearing near the weld seam and wrinkling in the die addendum often occurs when a traditional forming process is used to fabricate this type of blank. Cao and Kinsey (1999) proposed a modification to the deep drawing process where a segmented die with local adaptive controllers clamps adjacent to the weld line during the forming process thereby increasing the material draw-in of the thicker and/or stronger material from under the binder ring. This in turn reduces the strain in the weaker and/or thinner material near the weld seam and thus alleviates the potential of tearing failure. In this paper, details are given for the experimental implementation of the advanced forming process on a non-symmetric test panel. Notable improvements were obtained compared to a traditional forming process. Also, a systematic approach for determining the local adaptive controller locations is proposed and verified as being effective through the experiments.

INTRODUCTION

A concerted effort has been made to reduce automobile body weight in order to meet Corporate Average Fuel Economy (CAFE) standards imposed by the United States government, while simultaneously improving crashworthiness to appease customer safety concerns. Tailor Welded Blanks (TWBs) offer a means to produce both of these benefits as well as reduce manufacturing costs, improve dimensional accuracy of the final part, and increase corrosion resistance. A TWB is fabricated by welding together two or more sheets of metal of dissimilar thicknesses, material grades, and/or coatings, e.g. galvanized versus ungalvanized, to produce a single blank, which is subsequently formed. A schematic of current and potential automotive TWB applications is shown in Fig. 1. It is estimated that 40 to 60 million TWBs were produced worldwide in 2000 (Das, 2000).

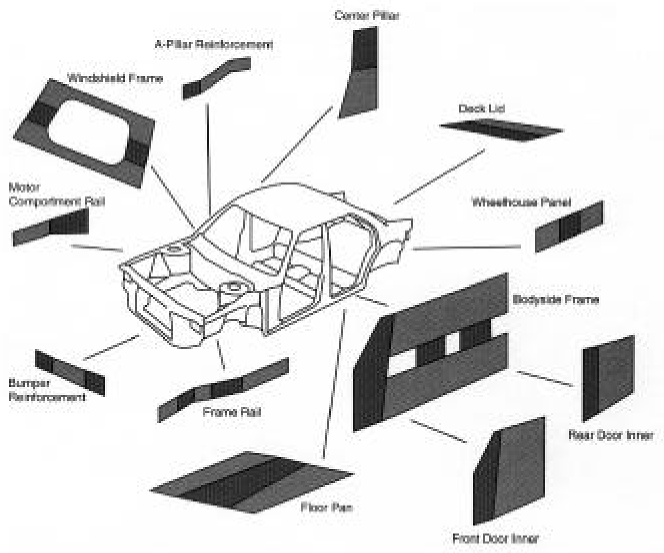

FIGURE 1. EXPLODED VIEW OF CURRENT OR POTENTIAL TAILOR WELDED BLANK AUTOMOTIVE BODY COMPONENT (AUTO/STEEL PARTNERSHIP, 1995).

The research surrounding TWBs has concentrated in several areas. In one area, improvements to the welding process to minimize material changes and produce consistent weld properties have been studied. Ductility across the weld is severely decreased in TWBs thus contributing to the concern of tearing failure. Research in this area has included the significance of welding parameters on the formability of TWBs (Eisenmenger et al., 1995; Bhatt et al., 1995), analytical and numerical simulations of weld line properties (Doege et al., 1996), and the effect of post weld processing, e.g. hot and cold planishing, on the formability of TWBs (Lee et al., 1996).

Other research has concentrated on the sheet metal itself investigating the formability of TWBs created from popular grades and alloys of material as well as searching for material that is less susceptible to the potential negative effects of welding. In this body of work, Aluminum TWBs have received significant attention due to the additional weight savings available; however, substantial reductions in the formability of the Aluminum blanks occurs due to material changes in and near the weld line. Venkat et al. (1997) and Wagoner (1996) investigated Aluminum alloys 5754-O and 6111-T4 that have the combination of being both weldable and formable. In our research, Al 5182-H00 (AlMg5Mn) has been used, because this particular alloy has been identified as an excellent choice for automotive components such as door inners and floor pans (Vollertsen et al., 1997) due to its superior deep drawability and weldability. Kridli et al. (2000) conducted tensile tests with Al 5182-H00 on standard size TWB specimens with transverse weld lines and miniature specimens which consisted of only the Gas Tungsten Arc Welding (GTAW) material to represent the potential formability of the weld material loaded longitudinally. In our research, our test panels were fabricated from Al 5182-H00; however, the welding was performed with a 3 kW YAG laser and a welding speed of 100-mm/sec. Since the type of welding process and welding parameters affect the TWB formability, we conducted our own material tests and created Forming Limit Curves (FLCs) for the Al 5182-H00 base material and TWBs based on Limit Dome Height tests. The potential plane strain elongation for the base material and TWBs was found to be 22% and 6%, respectively. Further details on the welding process for our TWBs and determination of the FLCs can be found in Kinsey et al. (2001).

Along with efforts to understand the welding process and material interactions, other research work has investigated modifications to the manufacturing process itself to improve the formability of TWBs. These attempts have focused on increasing the material draw-in to the forming area on the side of the TWB with the stronger and/or thicker material through the use of segmented binders or modifications to drawbeads (Pepelnjak et al., 1998; Ninforge and Dawance, 1998; Ahmetoglu et al.; 1995; and Siegert et al, 1995). These approaches showed promising improvements as potential forming height was increased due to reductions in the weld line movement. However, the determination of the optimal binder force distributions or drawbead profile to produce the desired result could be time consuming. Also, the reduced restraining force on the stronger and/or thicker material side results in less material straining and more compressive stress, which adversely affects the material's resistance to wrinkling, another forming failure mode.

Cao and Kinsey (1999) proposed an advanced process for forming TWBs that incorporated a segmented die with local adaptive controllers to create an additional boundary condition or constraint within the forming area. Figure 2 is a two dimensional schematic of the concept with hydraulic cylinders serving as the local adaptive controllers. The local adaptive controllers would be positioned such to reduce the strain in the weaker, thinner material adjacent to the weld line, thereby increasing the potential forming depth. Figure 3 shows the geometry of the TWB and punch for a non-symmetric test panel used in our research. Numerical simulations of the proposed process on this test panel geometry using two separate local adaptive controller locations and Al 6111-T4 provided excellent results, e.g. an increase in the potential forming depth of 52.9% and a decrease in the engineering strain transverse to the vertical weld line of 80.1% (Kinsey et al., 2000).

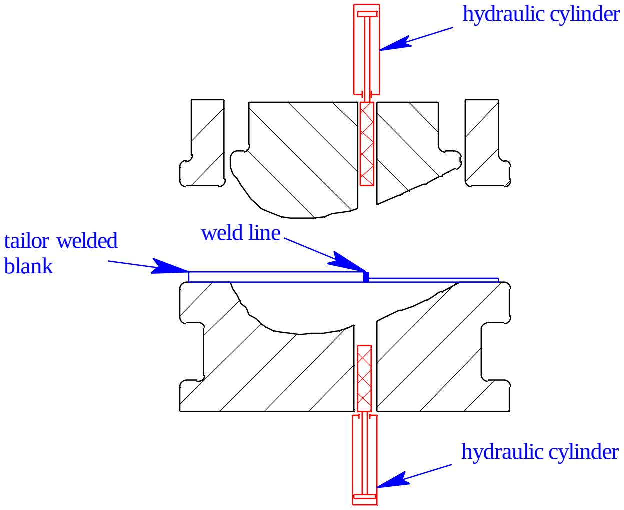

FIGURE 2. TWO-DIMENSIONAL SCHEMATIC OF SEGMENTED DIE WITH LOCAL ADAPTIVE CONTROLLERS.

In this paper, physical implementation of the segmented die with local adaptive controller process to improve the formability of TWBs is presented. A systematic approach for determining the local adaptive controller locations is also proposed followed by the design and selection of hydraulic system components to achieve our objective. This advanced forming process was successful at increasing the depth of draw of the test panel TWBs, reducing the strain in the thinner material along the weld line, and increasing the material strain of the thicker material.

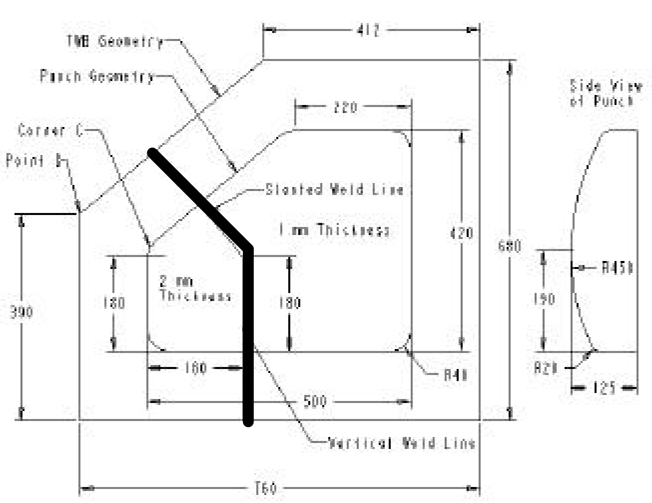

FIGURE 3. NON-SYMMETRIC TEST PANEL PUNCH AND TWB GEOMETRY. ALL DIMENSIONS IN MM.

DETERMINATION OF THE LOCAL ADAPTIVE CONTROLLER LOCATION

The determination of the locations of the local adaptive controllers is critical to the success of the forming process. In our previous work (Kinsey et al., 2000), the locations were determined solely based on the geometry of the proposed cylinders to provide the adaptive control. However, a more systematic methodology is needed in order to aid in the design of the process. The rational is the following.

The root cause for the reduced formability in TWBs, along with reductions in the ductility of the material due to the welding process, is the fact that the thinner and/or weaker material undergoes most of the deformation in the process while the thicker and/or stronger material does not deform as much. This leads to increased strain in the weak and/or thinner material and weld line movement. The reverse thinking process leads to the notion of restricting weld line movement by applying the local controllers at the location where the forces causing material stretching are the largest. Therefore, a numerical simulation of the proposed geometry was performed with all of the nodes along the weld line fixed in the plane of the blank to prevent weld line movement. The sheet material was modelled as Al 5182-H00. All the other simulation details were the same as those previously used in our work (Kinsey et al., 2000).

In post processing the simulation, the reaction forces of the fixed nodes along the weld line in the x- and y-directions were analyzed. The reaction forces were investigated because the force at the nodes directly corresponds to the strain in the adjacent elements and thus the cause of the tearing concern. Figure 4 shows the a) y-direction and b) x-direction reaction forces plotted versus distance from the coordinate system shown on the punch geometry in Fig. 4c). The area centroids for the force curves were calculated from the following equations.

$$\bar{x} = \frac{\int_0^{L_x} x \times F_y(x)\,dx}{\int_0^{L_x} F_y(x)\,dx} \quad , \quad \bar{y} = \frac{\int_0^{L_y} y \times F_x(y)\,dy}{\int_0^{L_y} F_x(y)\,dy} \qquad (1)$$

By intersecting the two area centroids on the part geometry, a proposed location for the local adaptive controllers is provided. An additional numerical simulation was then performed with nodes in the proposed segmented die area fixed to verify that acceptable strain and weld line movement values were obtained. One clamping location for the particular part geometry in Fig. 3 was shown to be adequate through this numerical simulation.

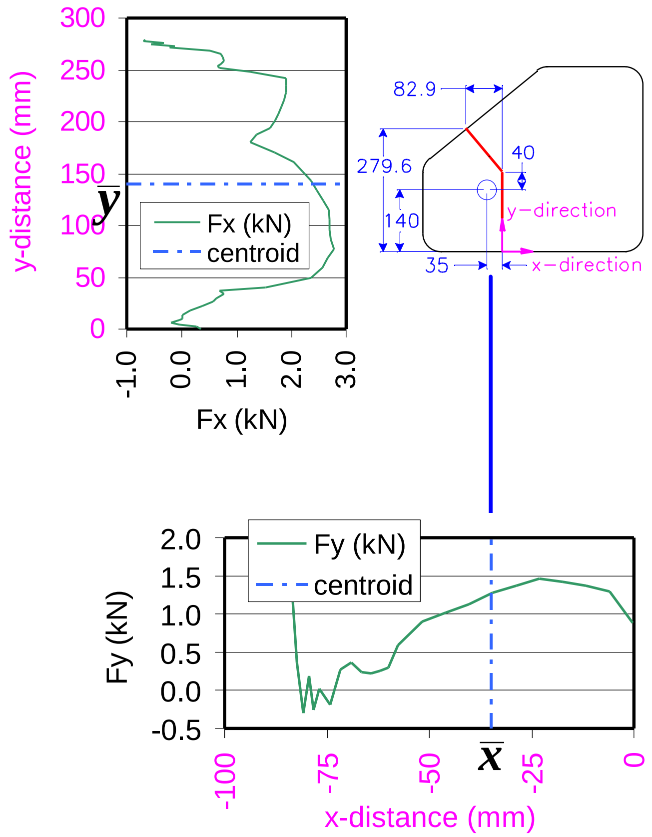

FIGURE 4. DETERMINATION OF ADAPTIVE CONTROLLER LOCATION BY INTERSECTING A) THE CENTROID OF F_X, AND B) THE CENTROID OF F_Y ON C) THE PUNCH GEOMETRY.

Note that one adaptive controller location will always be the most desirable, since this would reduce the complexity and cost of the process modification. However, if for some reason multiple adaptive controller locations are needed, for example if one set of hydraulic cylinders can not generate adequate restraining force or the required clamping area was too large for the curvature of the part, the methodology developed here is still applicable. In these cases, the curves of the reaction forces can be divided into segments and for each segment a centroid point can be calculated, which would correspond to a desired adaptive controller location. This method could also be utilized for a single, linear weld line on a part. The location along the weld line would be determine as above (e.g. the y-centroid), and the distance from the weld line (e.g. the x-centroid) would be chosen so as not to clamp directly on the weld line to allow for a flat surface to restrain the material. Future research will further evaluate this technique at determining multiple local adaptive controller locations for other part geometries.

HYDRAULIC SYSTEM FOR LOCAL ADAPTIVE CONTROLLERS

The local adaptive controllers, which act as a clamping device to provide an additional restraining condition within the forming area, were controlled with an auxiliary hydraulic system. The selection of the hydraulic components for this system was based on the reaction forces calculated from the numerical simulation with the nodes fixed in the local adaptive controller location area presented in the previous section. The hydraulic cylinders needed to be able to provide a sufficient clamping force to prevent weld line movement while being able to withstand the compressive force in the process, i.e. resist yielding or buckling. The auxiliary hydraulic system consists of a 5 HP motor, 30-gallon reservoir, and 2 fixed gear pumps. One pump supplies 2.2 GPM of oil so that the hydraulic cylinders advance fast enough to keep up with the punch speed of the forming process, which can be up to 25-mm/sec. The other pump provides a 4 GPM flow to an off loop filter and cooling system. The upper hydraulic cylinder is controlled by a proportional displacement valve and has a Temposonics L series displacement transducer imbedded in the cylinder rod to allow for closed-loop position control. The lower cylinder is controlled by a proportional pressure/force valve, thus allowing variations in the pressure held in the cylinder, with a pressure transducer to monitor the pressure value. Both cylinders have an 82.55-mm bore diameter, 44.45-mm rod diameter, and a maximum pressure capacity of 34.5 MPa.

EXPERIMENTAL SET UP

The experiments were performed on a 150-ton HPM hydraulic stamping press. Parts were formed with the punch geometry shown in Fig. 3 without a matching female die, with a clearance between the punch and the lower binder of 30-mm, a binder area of 100-mm around the perimeter of the lower binder die opening, a lower binder radius of 20-mm, a forming speed of 4-mm/sec, and a binder force of 260-kN. Urethane rubber was added to the ends of the hydraulic cylinders to prevent excess coining of the material and to increase the friction coefficient between the sheet metal and the clamping device (Kinsey et al., 1999). The binder plates do not have a step for the different thicknesses of the TWB, which would normally be incorporated in production dies to restrain the material properly. This was done so that experiments of this test panel geometry with a uniform material thickness could also be performed at a later date. Therefore, for these TWB experiments, 1-mm thick material shims were added in the binder area of the 1-mm section of the TWB to build up to the 2-mm thickness. This imperfect restraining of the material is partially the cause for the wrinkling behavior in the die addendum of our test panel.

The forming process was controlled and data acquired with National Instrument computer boards and Labview software. Voltages from the computer were sent to the cards for the proportional valves to control the location of the upper cylinder and the pressure in the lower cylinder. For the position control of the upper cylinder, experimentation found that a proportional constant of 12.5 and an integral control constant of 0.1 provided the best closed-loop control results. Also, data acquisition of press variables such as punch location from a Temposonics III displacement transducer and binder and punch forces from load washers were obtained.

The forming process using a segmented die with local adaptive controllers proceeded as follows. The blank was loaded into the press with the 1-mm shims used to create a uniform 2-mm material thickness around the flat lower binder plat. The lower cylinder was then advanced until it was against the TWB. At the beginning of the process, the upper platten that includes the upper binder plate, punch and upper hydraulic cylinder is well above the lower binder plate and lower cylinder. The upper cylinder is then extended beyond the punch surface, approximately 55-mm, and held at a fixed position. The press is then cycled which brings down the upper platten. The binder plates would come in contact, thus setting the binder force. With the punch and upper cylinder advancing in unison, the upper cylinder would eventually contact the lower cylinder prior to punch contact. Once the lower cylinder experienced 2.7 kN of force, the control program would send a higher voltage to the proportional valve of the lower cylinder thus building pressure and applying the clamping load. For these experiments, a 50 kN clamping force was applied with the hydraulic cylinders. At this time with the punch still advancing toward the material, the upper cylinder would retract into the punch allowing the clamping to remain stationary on the yet to be deformed TWB. When the upper cylinder had retracted to just before the punch surface, it would stop retracting into the punch and again would move downward in unison with the punch also forcing the lower cylinder to move downward to accommodate the same bore pressure. The process would continue forming until a depth of 95-mm at which time the upper and lower cylinders would retract releasing the clamping force. The punch would then advance to 100-mm and retract. This additional 5-mm of draw without clamping was performed in order to stretch out the slight dent caused by the clamping process. A video of this entire process can be viewed at http://www.mech.northwestern.edu/ampl/.

Two cases were tested, the free case where a traditional process was used to form the part without the local adaptive controller process, and the fixed case where the local adaptive controller process was implemented.

RESULTS AND DISCUSSION

For the free case, tearing failure occurred in several parts at approximately 80-mm of draw depth. Figure 5 shows a part with a propagated tearing failure, which initiated near the weld line intersection. Figure 6 shows a close-up picture of another sample where forming was stopped just as the tearing failure began. The thinner material taking most of the deformation in the process near the weld line caused this tearing failure. Figure 7 is a plot of the major engineering strain obtained by circle grid analysis in the thinner material adjacent to the weld line for a) the vertical weld line and b) the slanted weld line with the abscissa being the distance from the weld line intersection, zero, to the location where the strain value was measured. Figure 8 is a plot of the minor engineering strain again for a) the vertical weld line and b) the slanted weld line. (All the data in Figures 7 and 8 are averaged values from three parts ran at each forming case.) For the free case, the major strain levels, which were approximately transverse to the weld line directions, were largest at the weld line intersection point of the vertical and slanted weld lines and had an average value of 8% for the vertical weld line. As was previously mentioned, due to material changes caused by the welding process, the plane strain elongation limit for this Aluminum alloy and welding conditions is approximately 6% (Kinsey et al., 2001). The slight increase in the major engineering strain before failure occurred can be attributed to the fact that the test panel for the free case at the weld line intersection is not in a plane strain condition but has a slightly negative minor engineering strain, -5%.

FIGURE 5. FULL VIEW OF NON-SYMMETRIC TEST PANEL WITH SEVERE TEARING FAILURE AT A DEPTH OF 80-MM USING A TRADITIONAL FORMING PROCESS.

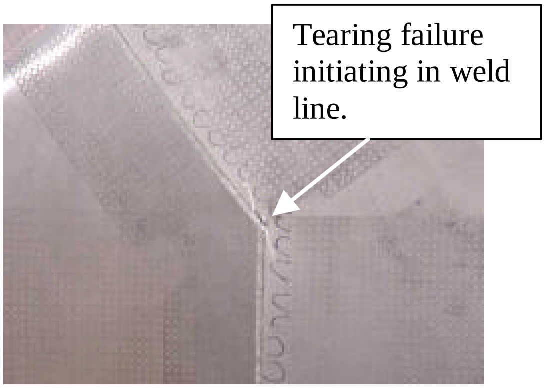

FIGURE 6. CLOSE UP VIEW OF FAILURE INITIATING IN THE WELD LINE AND PROPAGATING INTO THE THINNER MATERIAL AT A DEPTH OF 79-MM WITH A TRADITIONAL FORMING PROCESS.

With the fixed case, i.e. the implementation of the segmented die with local adaptive controllers forming process, tearing failure was avoided up to the maximum depth of draw for this tooling, 100-mm. This is a 20% increase in the forming depth compared to the free case. Plots of the major and minor strains for this case can also be found in Figures 7 and 8.

The strain state at the intersection is nearly plane strain and the major engineering strain value is close to the 6% limit. Therefore, these parts are perhaps near the failure limit of this particular TWB. Note that the lowest major engineering strain level for the vertical weld line to occurs at 40 to 50-mm away from the weld line intersection point. This coincides with the location of the segmented die in Fig. 3, 40-mm. While the slanted weld line does not have a sudden decrease in the strain level to coincide with the segmented die location, the strain level near the weld line intersection is more level compared to the free case where the strain is highest at the weld line intersection and then gradually decreases. Figure 9 shows a part that was formed to 100-mm with the segmented die and local adaptive controller forming process. Note that a slight dent was produced due to the clamping despite the use of the urethane rubber material. It is believed, however, that forming into a female die cavity, which was not the case in our experiments but is generally the case in industry, may improve this condition.

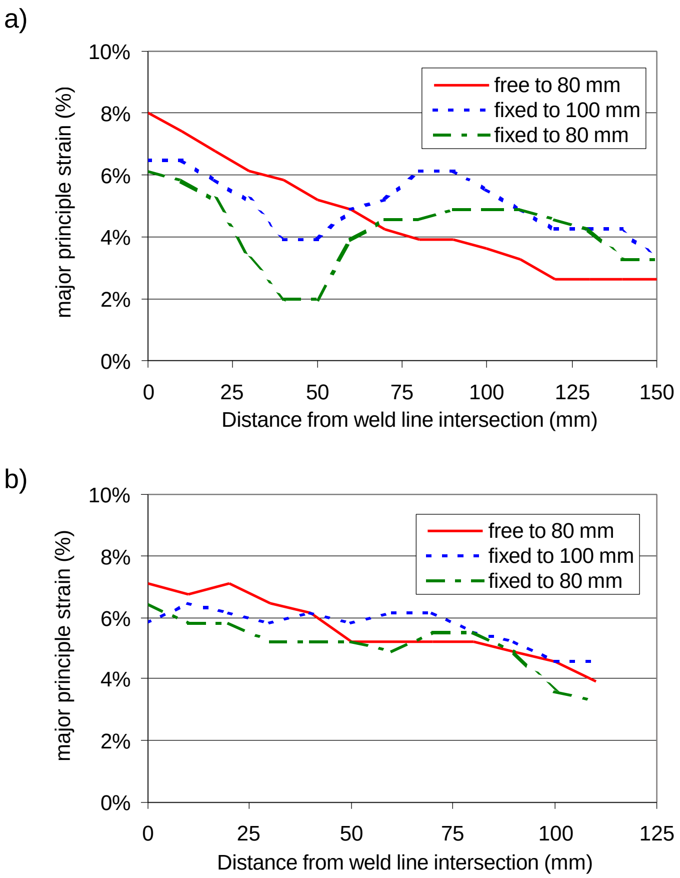

FIGURE 7. MAJOR ENGINEERING STRAINS IN THE THINNER MATERIAL ALONG THE A) VERTICAL WELD LINE AND B) SLANTED WELD LINE.

Experiments with the advanced forming process were also performed where forming was stopped at a depth of 80-mm to compare the strain state of the free case parts with those of the fixed case at the same draw depth. These plots are again included in Figures 7 and 8. The strain levels for the fixed case stopped at 80-mm are less than those of the fixed case at 100-mm of draw depth as would be expected and show the same pattern. The cause of the decreased engineering strain at the weld line is increased material draw-in from the binder force area and increased strain in the thicker, 2-mm material. Measuring both the free case and the fixed case parts formed to 80-mm, an average increase in the material draw-in at Point D (see Fig. 3) of 4-mm was observed. With respect to the strain at Corner C of the formed part, it would be expected that the major engineering strain would be decreased for the fixed case due to the increased material draw-in at Point D. However, the maximum major engineering strain at Corner C was increased from 6.7% to 12.3% for the free and fixed cases respectively. This indicates that less material is drawn from under the punch to form the stretch wall as a result of the clamping. Thus, the thicker, 2-mm material is undergoing more plastic strain in the fixed case compared to the free case. In most sheet metal forming applications, benefits from work hardening are actually welcomed as long as the strain level is below the forming limit

Table 1 illustrates the advantages of the segmented die with local adaptive controller forming process, the fixed case, compared to a traditional forming process, the free case, for this particular TWB test panel application. In this table, the average values for three parts formed at each of the free and fixed cases are given. For the maximum depth of draw, the fixed parts noted are the ones that were formed to 100-mm. For all of the other characteristics, the fixed parts formed to 80-mm depth of draw are used in order to compare characteristics at the same forming depth with the free case. Also, the percent improvement for each characteristic comparing the fixed and free cases is given. As was stated previously, these improvements can be attributed to the increased strain and draw-in of the 2-mm material produced by the local adaptive controller process which then allowed the 1-mm material to undergo less deformation and avoid tearing failure near the weld line.

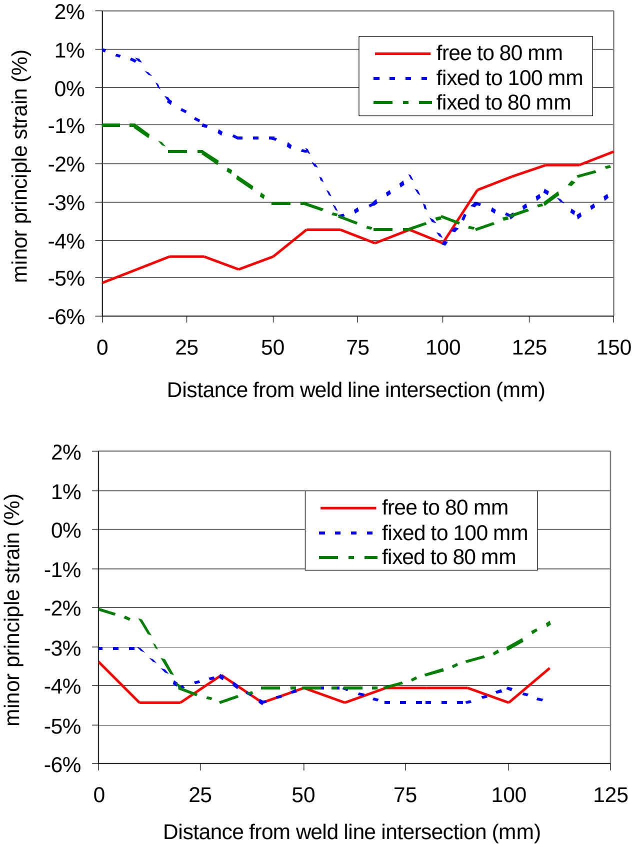

FIGURE 8. MINOR ENGINEERING STRAINS IN THE THINNER MATERIAL ALONG THE SLANTED WELD LINE AND VERTICAL WELD LINE..

FIGURE 9. FULL VIEW OF NON-SYMMETRIC TEST PANEL WITH LOCAL ADAPTIVE CONTROLLER LOCATION SHOWN FORMED TO A DEPTH OF 100-MM.

Characteristic	Free Case	Fixed Case	% Improvement
Draw Depth (mm)	80	100	20%
Major eng. strain vertical weld line (%)	8.3	6.3	32%
Major eng. strain slanted weld line (%)	7.3	6.7	9%
Material draw-in at Point D (mm)	25.4	29.4	14%

TABLE 1. COMPARISON OF CHARACTERISTICS FROM THE FREE AND FIXED FORMING CASES.

CONCLUSIONS

Tailor Welded Blanks (TWBs) offer an excellent opportunity for automakers to reduce manufacturing costs, decrease vehicle weight, increase crashworthiness, and improve dimensional accuracy of the final product. However, decreased formability due to changes in the material properties in the fusion zone and the heat affected zone of the weld prevents full utilization of this design option. In this paper, the implementation of an advanced forming process with a segmented die and local adaptive controllers to improve the formability of TWBs is investigated. First, a methodology was presented to determine the locations of local adaptive controllers. This step is essential in order to aid in the design of the process. Then, details were given for the hydraulic system used to create the clamping force adjacent to the weld line in the thicker material. The parameters for this system were determined based on numerical simulations of the process. Finally, experimental results comparing a traditional forming process, the free case, and the local adaptive controller forming process, the fixed case, were presented. The fixed case produced an increase in the potential forming depth due to less plastic strain being concentrated in the thinner material. Specific improvement values can be found in Table 1.

While the research here was conducted on an Aluminum TWB, this advanced forming process and methodology to determine the local adaptive controller locations could also be applied to steel TWBs. The formability concerns for steel TWBs are not as severe as those of Aluminium TWBs. Therefore, steel TWBs are currently being used in industry by placing the weld line at a location where less stretching is occurring. By incorporating the proposed modification into the forming process, designers would have greater flexibility in choosing the weld line location, thus optimizing on material utilization and further decreasing weight. Moreover, the essence of this advanced forming process is that an additional material constraining location is created inside the forming area, not just on the perimeter of the material in the binder force area. Therefore, this technique could be used to improve the formability of not only TWB applications but also traditional uniform gauge stampings as well.

ACKNOWLEDGMENTS

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