

Hydroforming High Strength Steel Tube for Automotive Structural Applications Using Expansion

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ABSTRACT

The need for lighter, stronger, more rigid vehicle structures will increasingly require complex hydroformed structural tubes to increase strength, and decrease weight, cost and part count. This effort will increase the use of high strength, low alloy (HSLA) steel, in place of SAE 1006/1008 or 1010 steel. Traditional hydroforming techniques require the higher elongation of the latter materials. An alternative tube hydroforming process has been developed to successfully use these, and HSLA grades from 310 (945XF) to 552 (980XF) MPa minimum yield stress. This paper concentrates on hydroforming steel with a focus on HSLA. It will demonstrate to automotive designers available features such as local section expansion and reduction, hole piercing, achievable cross sectional shapes and the relationship between tube size, corner radii, and wall thickness.

INTRODUCTION

It is the purpose of this paper to illuminate how automotive structural steel parts can be hydroformed into complex cross sectional shapes that can vary dramatically along the part length, focusing on several HSLA grades. Available part design features, insight into how the process works, as well as the required internal pressure and press size are discussed.

Box section structures have long been an integral part of designing and constructing a motor vehicle. This need has been satisfied to some degree by assembling several stampings into closed sections, with the requisite joint flanges and overlaps. Extra section size or wall thickness are usually used to compensate for the weakness inherent in the assembly joints. In the past there has been no viable way to mechanically form a tube into the complex part shapes required with the quality levels demanded.

Tubular hydroforming removes this constraint and extends tube use into these applications. Benefits such as increased strength, reduced weight, reduced tool cost, variability reduction, and part consolidation with all their attendant advantages are often realized in the same part. Overall tool and part cost is reduced, and running design changes, such as altering material thickness, are often easier to accommodate.

As crash, weight reduction, as well as, bending and torsional rigidity requirements become more stringent, hydroforming's predominant virtue of making more efficient use of metal is paramount. Manufacturing scrap is routinely below 10%, and part weight savings compared to stamped assemblies result from eliminating joint overlap which also inherently improves structural properties. This in turn allows reduced section size and/or wall thickness.

Most hydroformed parts have used SAE1006/1008, 1010, or other low strength, high elongation steel. Extending the principle of more efficient metal use logically leads to using HSLA grades of steel. Weight saved by using HSLA results in a significantly lower net material cost despite the higher unit weight cost. When cost and weight can be reduced simultaneously it makes sense to maximize HSLA use. A natural extension is to use a process that gives maximum design flexibility for high strength, lower elongation material.

A tube hydroforming process that offers these features, while increasing achievable part complexity, has been developed and presently produces a number of high volume parts. These include an engine cradle with relatively complex surfaces using 310 (945XF) MPa min. yield HSLA steel. Experimental work has been done using 552 (980XF) MPa min. yield, 621 MPa ultimate tensile strength steel. Mechanical expansion prior to the hydroforming operation, and hydroexpansion during the hydroforming operation are two methods that will be discussed. Notable characteristics of these parts will be discussed, as well as other desirable features that can be designed in to satisfy particular needs.

TRADITIONAL HYDROFORMING

Traditional hydroforming systems use high internal pressure so that the tube hoop stress at the corner radius is higher than the material yield strength. The result is that tensile forces acting parallel to the tube wall, stretch material into the corners of the die using internal pressure only. This causes section expansion and local wall thinning. The formula given below (the hoop stress formula for a thin walled pressure vessel) is a good approximation of the relationship between material yield stress (S), internal pressure (P), effective internal diameter (Di), and wall thickness (T) for this

type of hydroforming system. As the tube forms, the corner radii inside the tube are 1/2 the applicable Di figure.

$$S = \frac{P D_i}{2 T}$$

Figure 1 shows a complex shaped cavity closing on a tube without pinching because the tube periphery is somewhat smaller than that of the die cavity. As the increasing pressure forces the tube to the final shape, friction between the tube and the die prevents sliding which causes the reduction in tube wall thickness shown in Figure 2.

Cavity oversizing usually prevents the tube wall from pinching at the die split line. High fluid pressure is required to force the material to fully form the cavity corners, with its accompanying wall thinning and higher equipment cost. It is the only means of forcing the tube to fill the cavity.

For an average expansion of 5% the localized corner stretching may be as much as 15-20%. The material must have sufficient elongation to prevent bursting with a reasonable degree of production robustness. The internal pressure requirement increases dramatically as the corners form, since the material work hardens, and inside corner radius decreases. As higher yielding grades of HSLA are considered, available elongation decreases and tube bursting can cause a serious scrap problem.

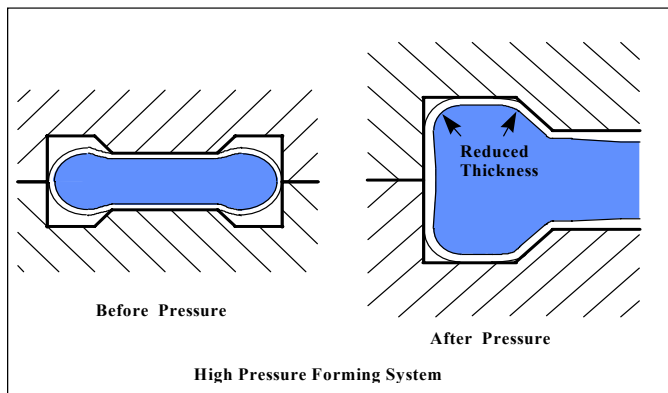


Figure 1

A second effect of using higher strength materials is that the internal pressure needed to exceed the yield strength of the material, to allow forming, increases the same amount. Thicker walled tubes, and sharper cross sectional corners also increase the pressure requirement. As these three factors combine, the pressure requirements increase rapidly. The resultant press size to contain this pressure increases in proportion. As press tonnage increases, purchase cost escalates dramatically and cycle time inherently lengthens. For example a 3 x wall thickness (3T) outside cross sectional corner formed in 345 MPa HSLA steel requires about 258 MPa internal water pressure. A Ø76.2 mm tube that is 1800 mm long would require an approximately 5000 tonne press.

Section expansion (beyond the 5% discussed above) is achievable during hydroforming. This can be done by using sufficient internal pressure to force material to the cavity surface. A second method is to axially feed material from the

end to lessen wall thinning that results from the first method. The latter method is only available at the part ends, but can achieve a larger section expansion. Both need high elongation material and often, in-process annealing, lubrication and cleaning. High elongation steel has low levels of carbon or other work hardening constituents, meaning the work hardening rate is low. The yield stress increase resulting from expansion or any other deformation is relatively small. High elongation materials have the legacy of low strength when they are in the vehicle. Relatively small deflections result in permanent deformation. This is contrary to the logical design direction of the industry toward high strength steel.

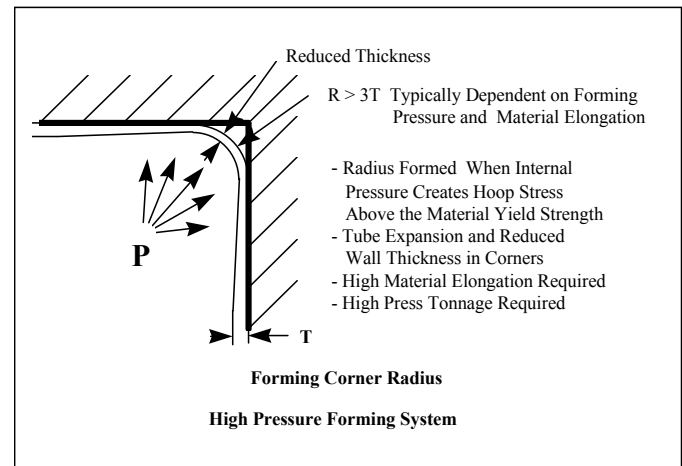


Figure 2

PRESSURE SEQUENCE FORMING

Formability can be achieved by using a first stage pressure while the die is being closed, and a second high pressure stage after the die is fully closed. This sequenced forming pressure creates the part shape by forcing the tube wall to flow into the corner areas of the die without stretching or expanding the tube to fill the die cavity as shown in Figure 3. The corners are formed by compressive forces, acting parallel to the tube walls, causing the material to deform in a bending mode. Internal water pressure supports the tube wall to prevent buckling. The tube is forced to do this because the cavity is designed to be the same periphery as the start tube.

This efficient combination of mechanical and fluid forming offers distinct advantages over the traditional process that uses internal fluid pressure only. Using higher strength material, thicker tube walls, and sharp (3T or less) corners have a small effect on the internal pressure needed to form the part. Illustrative examples will be discussed later in this paper.

The need for high elongation materials is reduced since the forces acting are compressive, and section expansion is not normally required. Elongation requirements are further reduced since material at the corners is not thinned. These process features are well suited to forming lower elongation HSLA steels. For a specific application the risk of bursting is significantly reduced without annealing.

This method prevents the tube from pinching at the die split line by judiciously applying the right pressure at the

appropriate time. The application of very high pressure to sharpen cross section corners, as is traditional, is unnecessary because the periphery of the tube and the die cavity match.

This process advance means that for most applications *forming a similar part* requires internal pressure that is much lower than for the traditional process, as is the size of the requisite equipment.

Friction plays a large role in limiting the amount that can be fed into a die during the hydroexpansion process (explained later), and the resulting final wall thickness. When lower pressure is used, the frictional force that opposes end feeding is smaller, which in turn should translate into less wall thinning. This can result in a more robust process, annealing prevention, or a higher achievable expansion percentage.

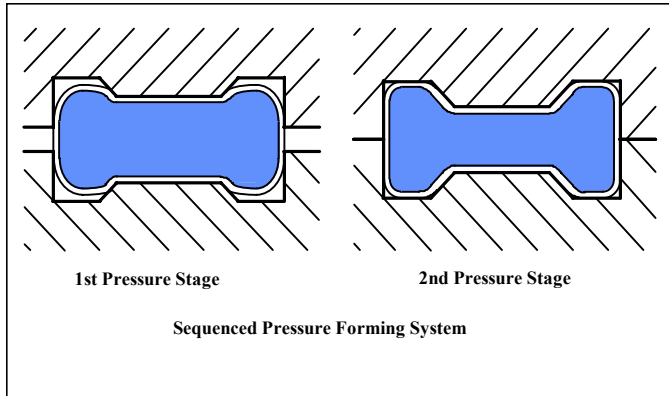


Figure 3

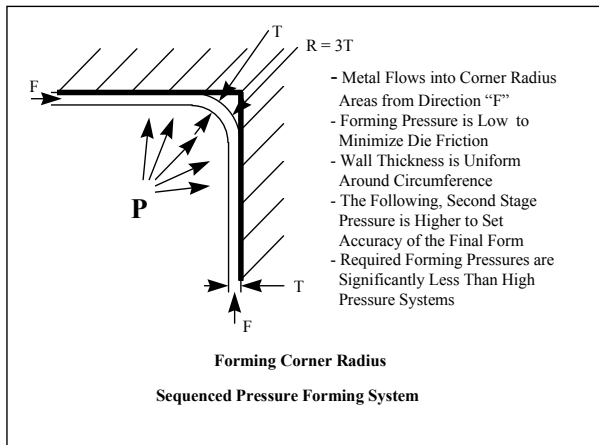


Figure 4

Figure 4 shows the die corner and how the pressure forms the radius in the tube by compressively forcing the tube into the corner area. The free flow of metal in direction “F” allows an outside corner radius to be formed equal to 3 times metal thickness. During the first stage, pressure is low, resulting in lower die friction, which is important to allow the metal to slide along the die surface and into the corner. The final formed tube has uniform wall thickness around the circumference including the corner radii. After completion of the first stage, a higher pressure is required to completely form the sides of the tube. During this time, holes are pierced in the tube by punches mounted in the forming die where required.

The previously discussed, Ø76.2 mm welded seam tube with 3T corners requires 48 MPa internal fluid pressure and a 1000 tonne press.

Tube expansion without end feeding during the hydroform process can be done between the first and second pressure stages. Expansion using end feed can also be done in the hydroform die in a third intermediate stage.

PRODUCTION FORMING HSLA 310 MPa STEEL

An engine cradle shown in Figure 5 is presently in high volume production using pressure sequencing in North America and Europe, using HSLA 310 MPa min. yield stress steel. The complex shape of this part reveals several interesting features.

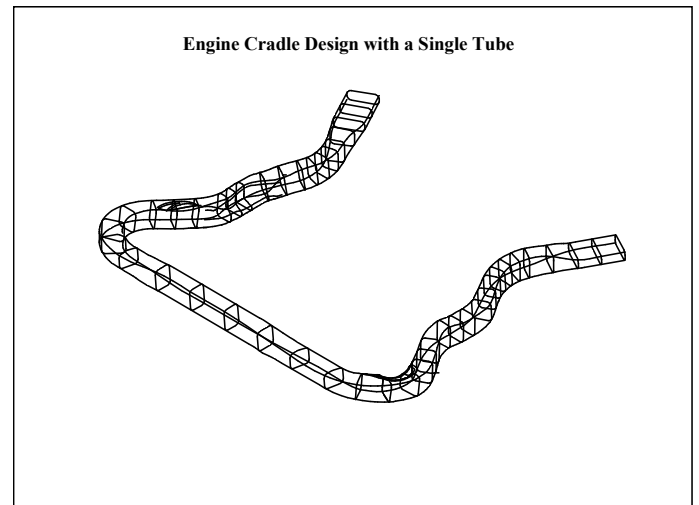


Figure 5

A total of 21 holes ranging in size from Ø5.1 mm holes to 8 x 12 mm slots, are all punched in the hydroform die.

	Yield Stress	Ult. Tensile Stress	Elong.
Flat strip	372 MPa	452 MPa	31.0 %
Round tube	407 MPa	465 MPa	30.0 %
Hydroformed tube	433 MPa	486 MPa	25.0 %

Table 1

The sections shown in Figure 6 give a range of shapes, including two that are undercut in die travel. The corners are mostly 5T, and bends are 2D with as much as a 120° bend.

Mechanical properties in flat stock, welded seam round tube, as well as after bending and hydroforming are shown in Table 1 and illustrate that the yield strength increases about 10% while being converted to a round tube. The yield increases as much as another 20% from forming the tube, as does the ultimate strength, while the elongation reduces.

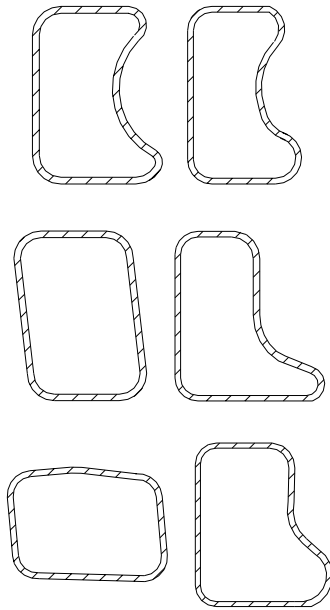


Figure 6

Hydroformed tube	610 MPa	727 MPa	11%
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Table 2

Comparison of 9 SPC points show a Cp value range of 1.4 - 2.7 (average 2.0) for 1008/1010 steel production material and 1.8 - 4.3 (average 2.6) for 552 MPa steel. The Cp measurements actually improved on average. Cpk's were not placed properly but would be recentered were this to be a permanent change.

As the tube is formed from its original round shape into the final part shape, all of the tube is subject to plastic deformation which stabilizes the part by eliminating spring-back of the cross section.

The tube diameter is $\varnothing 38.1 \times 1.0$ mm min. wall. The bend radius of $1.5 \times$ tube diameter (D) and a 65° angle of bend in this part are reasonably severe. Wall thickness changes on the inside and outside of the bends were similar to the production SAE1010 material.

The part has 23 holes ranging in size from $\varnothing 3.4$ mm to $\varnothing 21.7$ mm, all punched in the part during the hydroforming operation.

Aluminum grade 6061 tubes have also been bent and formed and all holes punched in the same production die with no significant problems.

HYDROEXPANSION

Hydroexpansion uses sufficient water pressure inside the tube to radially yield the material so that it assumes a periphery larger than that of the starting tube. It takes place inside the hydroforming die and the expanded section simultaneously takes on the cavity and finished part shape. Up to 15% expansion may be designed along the length of the part with unannealed tube, but the increased periphery comes at the expense of reduced wall thickness. The degree of homogeneity of this wall thinning has a strong effect on process robustness. Some factors that affect wall thickness consistency and likelihood of success are proximity to, and severity of a bend, concentricity of the expanded section with the starting tube, and the formed shape. Several experiments have shown the feasibility of this approach, but material and weld seam quality remain very strong uncertainty factors requiring resolution for production viability.

HYDROEXPANSION WITH END FEED - Forcing supplementary material into the cavity from the end improves this situation, by reducing or eliminating wall thinning and increasing the achievable expansion percentage. This takes place during the hydroforming process and extends the process cycle time slightly.

Expansion upwards of 40% have been achieved with, unannealed tube, but production viability is undetermined.

Referring to the hoop stress formula (repeated for convenience) again, it can be seen that for a $\varnothing 50.8 \times 1.5$ mm wall welded seam tube with a yield stress of 413 MPa the tube starts to expand at:

$$P = \frac{2T S}{D}$$

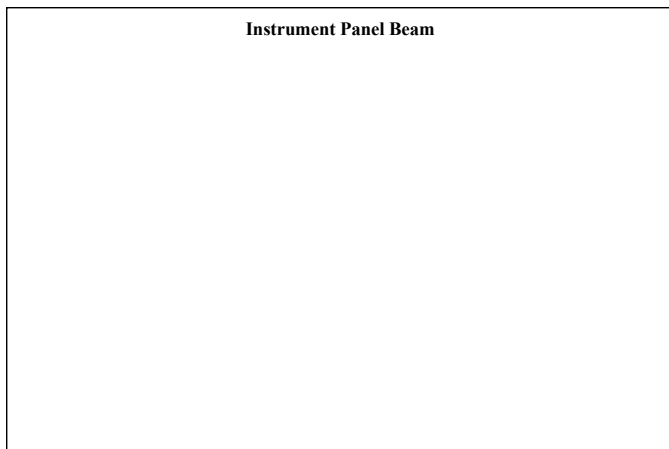


Figure 7

FORMING HSLA 552 MPa STEEL IN A PRODUCTION DIE

Sequenced hydroforming pressures have been used to form the instrument panel beam in Figure 7 using 552 MPa minimum yield strength steel. The tube was used directly from an ERW tube mill, then bent, formed and pierced without any in-process annealing or heat treatment. Table 2 contains the mechanical properties of the tube before and after hydroforming.

A statistical study that compared variation in hole position and size, and surface location showed no loss of dimensional control when 552 MPa was substituted for SAE 1010 steel.

	Yield Stress	Ult. Tensile Stress	Elong.
Round tube	600 MPa	706 MPa	17%

$$P = \frac{D_i}{47.8} \cdot 414$$

$$= 26.0 \text{ MPa}$$

As the tube expands, the pressure it takes to sustain expansion gradually increases. This results from work hardening caused by material deformation, and the decrease in effective diameter while the part forms into the section corners. The effective diameter becomes the inside of the cross sectional corners as they form. For SAE 1010 steel, pressure below 55 MPa was adequate to fully expand the part in Figures 8 and 9. Higher pressures than this will only serve to make sharper cross sectional corners.

As the minimum yield strength goes up, the elongation goes down, and the achievable expansion would logically decrease as well. More work is necessary to determine the applicable relationship.

The shape of the part hydroformed to give a 25% end feed expansion and the corner radii is shown in Figure 8. The mechanical test results are shown in Table 3.

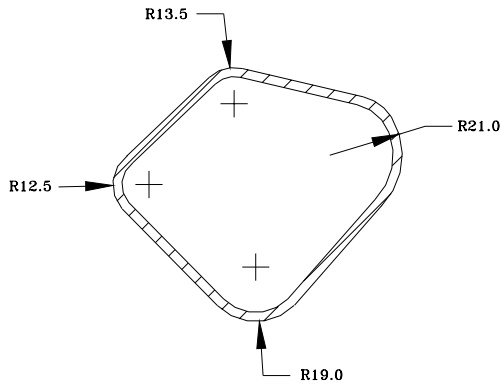


Figure 8

	Yield Stress MPa	Ult. Tensile Stress MPa	Elong. %	Wall Thinning Average %
start tube	297	383	38.0	-
formed tube	348	467	15.5	7.2

Table 3

Similarly, the 40% expanded shape and corners are shown in Figure 9. Table 4 shows the mechanical test results.

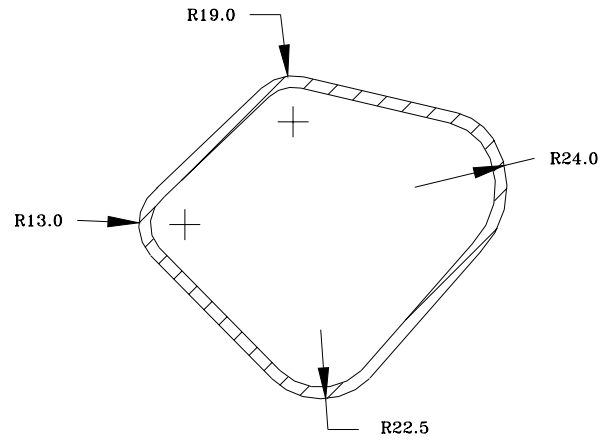


Figure 9

	Yield Stress MPa	Ult. Tensile Stress MPa	Elong. %	Wall Thinning Average %
start tube	297	383	38.0	-
formed tube	414	526	11.0	14.0

Table 4

Further efforts are underway to improve this ability. Continuing to explore new localized expansion situations will stretch the present achievable envelope. The focus is to increase knowledge, minimize concerns and extend the range of parts and features that can be economically built into hydroformed parts.

HYDROEXPANSION WITHOUT END FEED - Some applications may require section expansion in an area that does not allow additional material to be fed in. This situation arises in the engine cradle shown in Figure 10. Prototypes were made with SAE 1010 $\varnothing 70$ mm x 2.0 mm min. wall welded seam steel tube.

Expansion of this type makes the highest demands on the material since the expanded periphery comes completely from thinning the tube wall. The average peripheral expansion is 15%, designed to increase section height by 40% as required to increase vertical rigidity. The desired final shape will tend to cause uneven wall thinning as it deviates from being concentric and round. An element of further difficulty is that the expansion is in one direction as shown in Figure 10. The challenge is to make wall thinning as even as possible while maximizing the ability to make parts. Corner radii were made large to avoid adding a third cause of uneven wall thinning. Material was not annealed for any forming trials.

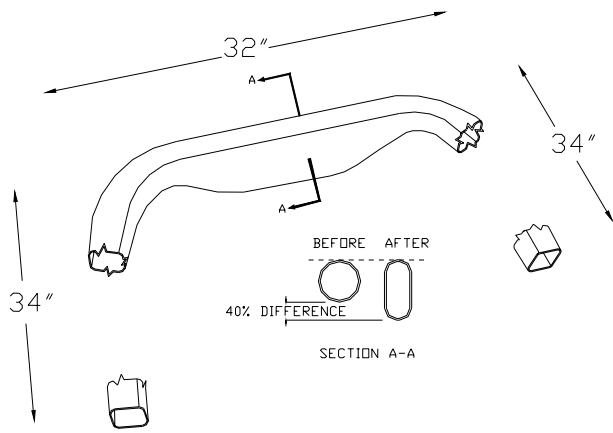


Figure 10

Parts were successfully made and the mechanical test results show in Table 5 that little elongation is left in the formed material. This indicates that a significantly larger expansion would be unachievable without annealing, even at a prototype level. Process robustness would be insufficient for production with the present amount of expansion. Higher elongation steel and/or in process annealing would probably be necessary for production. It is important to note that the volume of steel per unit length of the part remains unchanged regardless of extent of expansion.

	Max. Yield Stress MPa	Max. Ult. Tens. Stress MPa	Elong. %
Start Tube Axial	320	391	33.0
Radial	309	391	39.0
Formed Tube Axial	541	586	4.5-7.0
Radial	434	510	8.0-19.0

Table 5

MECHANICAL EXPANSION

The primary purpose of these experiments is to explore the process conditions, and limits of mechanical expansion to locally increase the tube periphery prior to hydroforming. For production use this method has a number of attractive features compared to hydroexpansion. Expanding prior to hydroforming makes all design features for unexpanded parts available. These in-die efficiencies or advantages with their attendant lower equipment costs include lower pressure forming, resultantly better wall retention, more severe expanded section formation (indents, sharper corners, flatter cross sections, etc.), and in die hole punching. Also the amount of expansion achievable with out annealing will tend to be higher or process robustness will be improved. For a specific expansion size it minimizes the need for high

elongation, low strength steels, or in-process annealing prior to hydroforming, especially if the expansion is in the middle of the part.

Wall thinning is as even as possible around the expanded periphery because the tube is round and the internal forces are equal in all directions. There are no external friction forces resisting end feeding as is found with hydroexpansion. The end forming force resolves into two components. The radial force acts to expand the tube. The axial component acting along the tube centerline via friction between the forming element and the tube inner surface provides an end feed force that results in minimal wall thinning in the same direction as the expansion element.

Using this method prevents the cycle time increase required for hydroexpansion. Sharper corners and thicker walled tubes are more easily handled. It seems likely that for many applications the percentage of wall thinning will be less than with hydroexpansion, since die surface to part friction is a major restriction on the amount of material that can be forced in the die. From Table 6 note that at 25% mechanical expansion loses 4.2 % of the wall, while hydroexpansion is 7.2% (Table 3). At 40% the difference (5.1 % vs. 14%) is even greater (Table 6 and 4).

A typical test blank is shown in Figure 11.

SAE 1010 STEEL- The tube used was $\varnothing 50.8$ mm x 1.5 mm wall welded seam round tube. No parts were annealed before or during the forming process.

Experiments have successfully expanded up to 90% with a resulting wall thinning up to 11%.

Mechanical properties and wall thinning data are contained in Table 6.

Expansion	Yield Stress MPa	Ult. Tens. Stress MPa	Wall Thinning %	Elong. %
25%	361	439	4.2	16
40%	445	550	5.1	15
47%	422	521	6.7	11
67%	414	553	7.3	11

Table 6

HSLA 345 MPa STEEL- The same methodology and tools were used to form this high strength steel. The tube used was $\varnothing 50.8$ mm x 1.5 mm wall welded seam round tube. No parts were annealed before or during the forming process. The maximum expansion achieved was 67%. See Table 7 for wall thinning, and mechanical properties.

Further research is proceeding to supplement the knowledge gained. This will focus on maximizing the advantages of this method cited earlier.

Although this section focuses on the merits of mechanical expansion, choosing between mechanical and hydroexpansion must be done on a situational basis to arrive at the best function/cost balance.

Expansion	Yield	Ultimate	Wall	Elong.
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	Stress MPa	Stress MPa	Thinning %	%
25%	455	515	6.5	13
40%	555	621	5.5	12
47%	543	636	6.2	14

Table 7

TYPICAL MECHANICALLY EXPANDED TEST SAMPLE

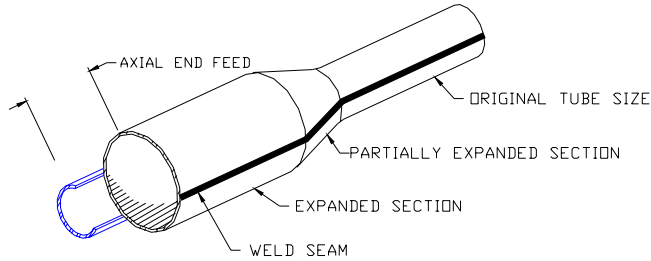


Figure 11

MECHANICAL REDUCTION

Mechanical reduction can be formed on the part ends, similar to expansion, if desirable for packaging, or structural reasons. Due to the nature of the reducing process, the majority (i.e. 75% or more) of the material in the starting tube is retained in the reduced section via thicker walls. The length of the reduced section does grow a small amount and the material is work hardened.

There is no viable alternative for this that can be performed in a hydroform die.

VARIABLE WALL FORMING

These results illustrate the relationship between initial material grade and strength, wall thickness, cross sectional corner radii, and internal hydroforming pressure.

SAE 1026 steel was selected for this exercise since its properties are similar to HSLA 345 MPa steel and its easy availability. A prototype die with a reasonably severe cavity shape was used for the three sections shown in Figures 12, 13, and 14. The start tube was $\varnothing 101.6$ mm, part length approximately 2080 mm and was formed on a 720 tonne hydraulic press. The material test results are from unformed tube samples. The tubes formed were not annealed before or during this experiment.

The final internal forming pressure and outside cross sectional corner radii expressed as a multiple of wall thickness are shown in Table 8, and the material test results are listed in Table 9.

Figure #	Final Forming Pressure	Outside Corner Radii
12	37.2 MPa	4.75T
13	37.2 MPa	3.2T

14	41.4 MPa	1.5T
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Table 8

Figure #	Mat'l Grade SAE	Wall Th. Min. mm	Yield Stress MPa	Ult. Tens. Stress MPa	Elong. %
12	1010	2.0	263	341	42.0
13	1010	3.0	296	396	38.0
14	1026	6.3	386	496	26.0

Table 9

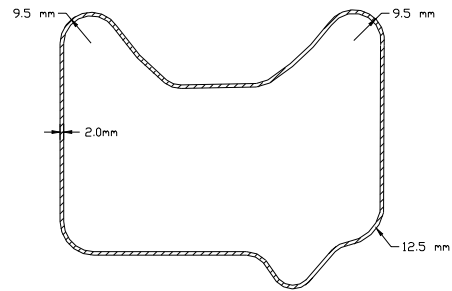


Figure 12

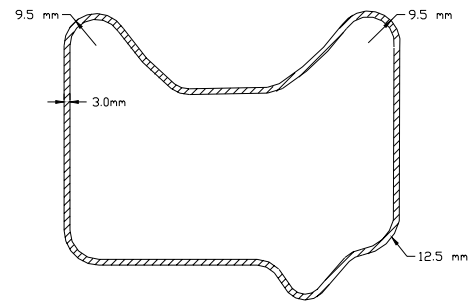


Figure 13

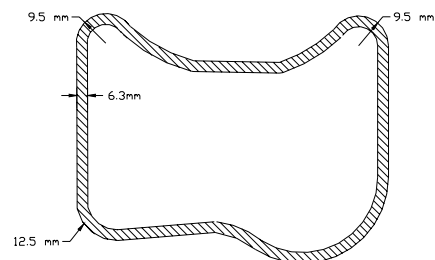


Figure 14

Figure 14 is shaped slightly differently than the others because the press tonnage was insufficient to close the die completely. The shape is complete enough to show the ability to form material that is high strength, as well as having a wall thickness that exceeds most automotive applications.

The results in Tables 8 and 9 point out that a dramatic increase in material strength and wall thickness have little effect on required pressure and that the corners form to the cavity shape. The 1.5T corners on the 6.3 mm part were formed with no sign of cracking. This is a result of forming the shape using compressive forces, unlike stamping where corner forming always uses tension and therefore creates cracks as the radii get smaller. Forming the same shape with traditional hydroforming would require approximately 966 MPa internal pressure and a 20,000 tonne press.

OTHER PART DESIGN FEATURES

There are a wide range of characteristics that can be built into pressure sequence hydroformed parts to allow the most functional, economical part possible. These attributes are applicable to HSLA grades of steel, as well as, regular steels, aluminum, and any other material with enough elongation. Coordinating these features with expanded sections creates some uncertainty about their effect on each other.

Welded seam tube prototype sizes range from 38 mm to Ø152 mm. Wall thickness ranges from 1.0 mm to 6.3 mm.

The range of possible section shapes is quite extensive. Many cross sections from parts in production are rectangular. This arises from mounting requirements to attach other parts to the hydroformed tubes. Most shapes can be accommodated and transitions between differing sections can be executed reasonably.

When a nearby part interferes with a hydroform tube, a reasonably severe indent, using a solid or sliding surface can be used to create clearance. This method can also be used to create undercuts in the die, shapes to fit after forming assembly pieces, mounting or datum surfaces, etc..

Holes of any shape and size are candidates to be pierced in the tube wall. Piercing all holes in the production die minimizes part cost as well as hole size and position tolerance. The cost and position stability benefits are extensive. Holes can have all common shapes such as round, hexagonal, square, rectangular, oval slots and some uncommon shapes. They can be clean pierced, or extruded to give a longer support collar, or for a self-threaded land. A method has been developed to remove slugs from larger holes in certain circumstances.

High volume production parts today have as many as 57 holes in one part, that range in size from Ø3 mm to 40 x 45mm holes. These are the present requirement, not extreme limitations. Development trials are used to broaden the envelope of achievability.

End trimming can be developed to match a mating part surface, or to cut out welding flanges using a laser or plasma cutter. It can be as simple as a single shear cut, or even no cut at all if the end condition is acceptable. This latter situation

would eliminate scrap. Cost and structural integrity will decide the appropriate method.

SUMMARY

Hydroforming is an emerging technology that meshes well with the automotive industry's drive to make more efficient material use. The application of this concept to structural parts leads to tubular box sections replacing stamped assemblies and replacing low carbon steel with high strength, low alloy steel (HSLA).

Hydroforming low strength and HSLA steel with a pressure sequencing system offers a number of advantages. The ability to form parts with a fraction of the pressure necessary for traditional hydroforming, using economical welded seam tube, without annealing, is economically attractive. The relatively small effect of using HSLA, thicker walls, or sharper corners on required internal pressure shows a compelling efficiency. Section expansion in the die, with and without end feeding, may be advantageous for some applications. Mechanical expansion prior to hydroforming offers some attractive features. Less wall thinning, more severe potential section shapes and in die hole punching are among the available benefits.

ABOUT THE AUTHOR

Gary Morphy is a Project Engineer at VARI-FORM's Technical Center in Woodstock, Ontario, Canada. He has worked at Vari-Form since 1992 on prototype and production part programs. A Mechanical Engineering degree from the University of Waterloo in Ontario was earned in 1985. He is currently working on a number of projects to further develop hydroforming technology. VARI-FORM started high volume production in 1990 and produces approximately 3 million hydroformed parts per year.