**Proceedings of American Society of Manufacturing Engineers International Congress and Exposition:
9th Symposium on Crashworthiness, Occupant Protection & Biomechanics
November 5-10, 2000, Orlando, Florida**

OPPORTUNITIES FOR CRASHWORTHINESS IMPROVEMENT USING TUBE HYDROFORMING

Gary E. Morphy
Vari-Form Inc.
Technical Development Centre
Woodstock, Ontario, Canada
(519)421-0400 ph, 519-421-0040 fax
gmorph.vf@bundy.com

ABSTRACT

The automotive industry has and continues to make advances toward the sometimes conflicting goals of make our vehicles safer to use, lighter and better able to perform while achieving attractive appearance and downward cost pressure.

Benefits that hydroforming offers that can improve crashworthiness are reviewed. Brief descriptions of 2 hydroforming methods are given followed by a more detailed examination of wall thickness and cross section expansion. Others include the influence of part design on forming pressure, materials that can be used and part surface complexity.

INTRODUCTION

The automotive industry has and continues to make advances toward the sometimes conflicting goals of make our vehicles safer to use, lighter and better able to perform while achieving attractive appearance and downward cost pressure. Tools that help attain these goals should be used fully.

Tube hydroforming is one such tool. It's place and a common sense or knowledge of what can be done with it is still developing in the automotive market. It is already recognized that in a number of applications a reduction in weight and cost while increasing performance can be realized. What is not as well understood is that other capabilities are presently available without substantial development.

Wide material choice is important for design flexibility to best satisfy the part requirements. Maximizing the range of cross section shapes may also be crucial. Is important to understand how costs can be assigned to different part features so that the best decisions can be made to minimize overall cost.

Examples of hydroformed ultra HSLA and aluminum parts, which can be useful for structural improvement or weight reduction, will be examined in some detail. HSLA use is common in door and bumper beams, engine cradles, and frame rails to name a few. Relatively severe forming examples will be shown to illustrate what types of designs are feasible. The relationship between process conditions and how part features are formed will be explained. Different ways of using the steel in a tubular structure to the greatest effect is considered, whether it is for general structural rigidity or energy absorption in a vehicle crash.

NOMENCLATURE

PSH – Pressure sequence hydroforming

HPH – High pressure hydroforming

Hydroexpansion – Expanding or increasing the periphery of a part cross section from that of the starting tube inside the hydroforming die (can be done with and without end feeding).

P - Maximum pressure level

R_i – Inside corner radius

YS – Material yield stress or strength

MYS – Minimum yield stress or strength

T – Material wall thickness

HSLA – High strength, low alloy steel. Assures higher MYS (even when fully annealed) combined with more controlled mechanical properties. MYS up to 414 MPa (60,000 psi).

Ultra HSLA – Ultra high strength, low alloy steel. MYS exceeds 414 MPa (60,000 psi) combined with more controlled mechanical properties.

HYDROFORM BENEFITS FOR CRASHWORTHINESS

The most obvious benefit of tube hydroforming is its ability to make more efficient use of material than was possible with previous technology. Each of the benefits cited also impacts the ability of the part to absorb energy in a crash and improve crashworthiness.

As shown in Figure 1 (left side), making tubular structures consisted of making a series of stampings and welding them together. This was done to make parts with required cross

Copyright © #### by ASME

section complexity and provide the quantity, location accuracy and style of holes needed. Location accuracy of the part surface and holes suffered when assembled because of tolerance build up and particularly, weld distortion.

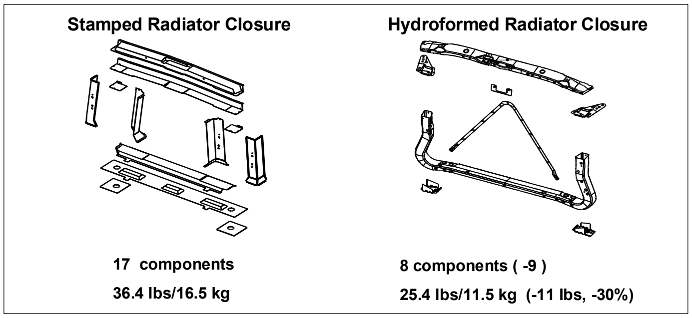


Figure 1

Hydroforming addresses some of these difficulties and provides the opportunity to make a tubular structure from a tube. It overcomes the difficulty of only having access to one side of the material. This offers several benefits, some of which are shown in Figure 1 (right side). The total number of parts is reduced, to less than half of the stamped version. This impacts cost directly by making 2 hydroformed tubes rather than 8 stampings and assembling them. It also provides a significant performance improvement to rigidity and structural integrity. This gives the opportunity to reduce the wall thickness and/or the starting tube diameter to reduce weight if the performance increase is unneeded. Table 1 provides some information that may guide the designer to making the most effective choice for a given product.

Generally speaking, occupying the same cross sectional space and reducing the wall thickness to meet the criteria required for the application at hand makes a more efficient structure. Two examples in the first and second column show the benefit of wall reduction compared to the initial situation in column 3. Other restrictions such as being able to make good quality tubing, stable welding of assemblies or sufficient fastener thread strength may prevent taking full advantage of these potential weight savings. When this occurs it makes sense to reduce tube size, but as can be seen in the rightmost column, weight reduction is smaller. In some instances the strength of the part may pose a problem for occupants because it is too great. In this instance the best method is using thinner wall or smaller tube since it reduces weight, but crash initiators or holes may be needed to create the crash behavior desired.

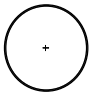
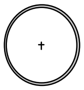
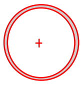
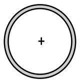
Tube Cross Section			Initial 	
OD – in. (mm)	2.75 (70.0)	2.5 (63.5)	*2.5 (63.5)*	2.25 (57.2)
Wall Th. – in. (mm)	0.041 (1.03)	0.056 (1.42)	*0.079 (2.0)*	0.079 (2.0)
OD / Wall Th. Ratio	67.1	44.6	*31.6*	28.5
Mass – lbs/ft (kg/m)	1.19	1.47	*2.05*	1.84
Weight Reduction %	42	29		10
Displacement from Load	100% of Limit	100% of Limit	*72% of Limit*	100% of Limit
Max. Stress From Load	100% of Limit	91% of Limit	*66% of Limit*	82% of Limit

Table 1

From the point of view of crashworthiness, joint elimination parallel to the tube centerline substantially elevates the ability of the given section to absorb crash energy. One of the main reasons for performance improvement is that joints add flexibility to the structure and is eliminated when they are. A typical automotive structural part centered around hydroformed tube(s) will flex at tube to stamping, or tube to tube joints, but the net effect is usually a substantial improvement. The resulting part also takes up less space, as shown in Figure 2. Dimensional stability is dramatically improved, because of the welding not done, which avoids accompanying distortion.

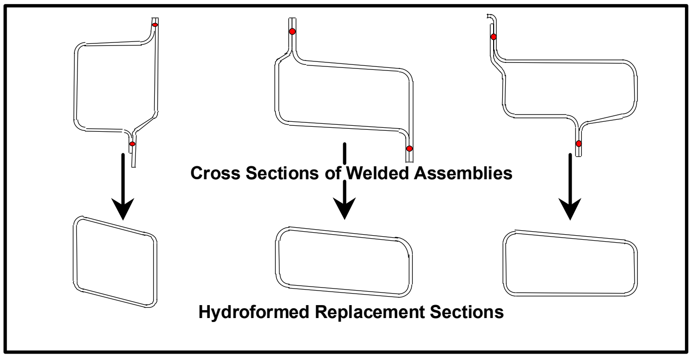


Figure 2

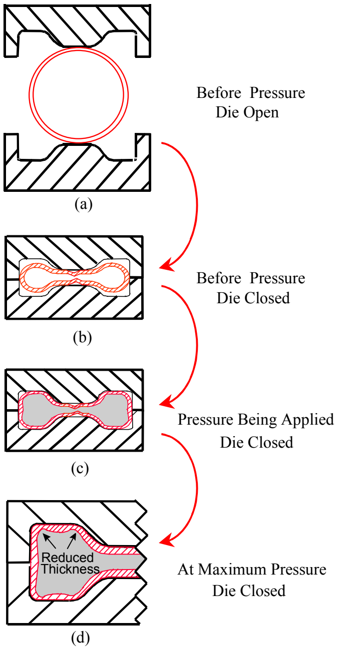
INFLUENCE OF HYDROFORMING TECHNIQUES

There are 2 hydroforming methods that dominate the manufacture of automotive structural hydroformed parts. It is important to distinguish them because of their different effects on wall thickness, material yield strength (YS) and part design flexibility, which affects how parts can be made more suitable for crashworthiness. They are commonly referred to as high pressure hydroforming (HPH) and pressure sequence hydroforming (PSH).

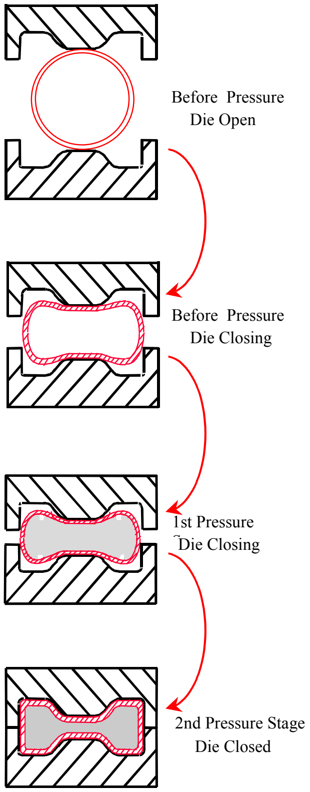
HPH (Figures 3) normally uses a tube that has a slightly smaller periphery than the desired part cross section, bends it, possibly preform it, closes the hydroforming die, fills the tube with water and pressurizes it to expand (stretch) the material to fill the cavity. Stretching causes tensile forces to act through the wall (F_{HPH} Figure 5).

Copyright © #### by ASME

PSH (Figures 4) uses a different forming mechanism to achieve complex forming with a fraction of the pressure needed for HPH. It starts with a tube that has essentially the same periphery as the die cavity along the length of the part. As the die closes, the tube is sealed and filled with low pressure water (ie 1000 psi). The die continues to close while low pressure is maintained. The water acts as a liquid mandrel that simultaneously discourages pinching and collapsing, which forces the tube into the cavity shape. After closure is complete, pressure is increased (ie 5000 psi) to complete forming flat areas and punch holes. Constant final part periphery along the part length is essentially equal to that of the starting tube. It is done to provide a high degree of surface forming complexity while reducing cost.



Figures 3 - HPH



Figures 4 - PSH

The latter process is more difficult to ‘picture’. These differences are important to understand in order to make sense of their effects on the characteristics mentioned above (described in more detail in following sections).

INFLUENCE OF WALL THICKNESS

The thickness of the tube wall is crucial to structural integrity and component performance in a crash. Automotive manufacturers routinely simulate part performance and crash scenarios on computer systems. This leads to the goal of eliminating some prototype stages and most crash testing, as confidence increases that the results are a true representation of reality. Confidence in simulation is high and growing.

Wall thickness consistency in different areas of the same part and knowing how it varies is very important. Normally a structural part will be bent and possibly preformed prior to hydroforming. Bending thins material on the outside of the bend and thickens it on the inside. The magnitude depends on the severity of bending and the bending techniques used. Some types of preforming do not change the wall while others do.

Wall thickness variation around the cross section is inherent with expanding the tube in the hydroforming die. The corners get thinner (Figure 5) because the material is stretched to form the larger periphery of the finished part.

All of these variations must be known to ensure that the proper wall thickness pattern is included in FEA work. The minimum values must be used for analysis so that in the worst case the part meets performance requirements. Failure to do so results in real part performance that is less than what FEA predicted. This discrepancy may not cause a problem, but it could be sufficiently serious for the part to fail. The most serious source of thinning seems to be what occurs in the hydroforming die, presumably because of its effect of the cross section corners. It may be necessary to increase the starting wall thickness so that the corners exceed the minimum after hydroforming.

Various measures have been developed to reduce wall thinning during hydroforming, such as end feeding, lubrication, special materials, annealing and preforming. These are effective to some degree depending on the part design and manufacturing details, but rarely is thinning eliminated. The fact that the thinning effect concentrates in the corners as shown in Figure 5 increases the importance. Cross sectional corners are normally considered to carry a disproportionately large portion of the total load compared to flat areas, and give more resistance to deformation in a crash.

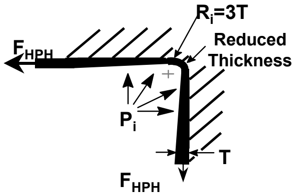


Figure 5

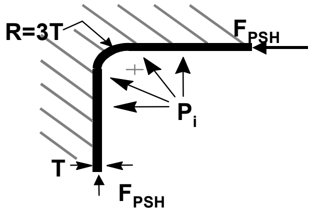


Figure 6

Figure 9 shows thickness measurements around the periphery of the parts in Figures 7 & 8 in the locations shown. These sections give a clear picture of thickness variation introduced by PSH and HPH since they are not on a bend. End feeding (only used for HPH) does not help in the crossbar area since frictional resistance (from bends, bumps, etc.) exceeds the buckling strength of the tube.

Variation from part to part at the same location was also present, but steel strip thickness variation probably explains much of this difference.

Copyright © #### by ASME

The data points for the PSH part shows variation of approximately 0.1 mm. This is due to variation in the flat steel strip and tube making. PSH does not add wall thickness variation. Part to part variation at any location changes with the starting tube thickness, but is unaltered by PSH. As a result, only wall thinning from bending need be considered.

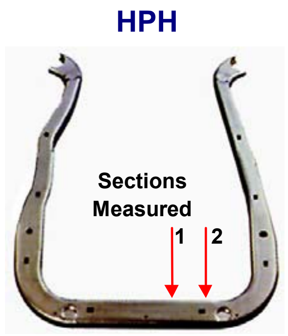


Figure 7

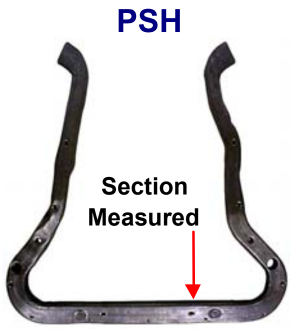


Figure 8

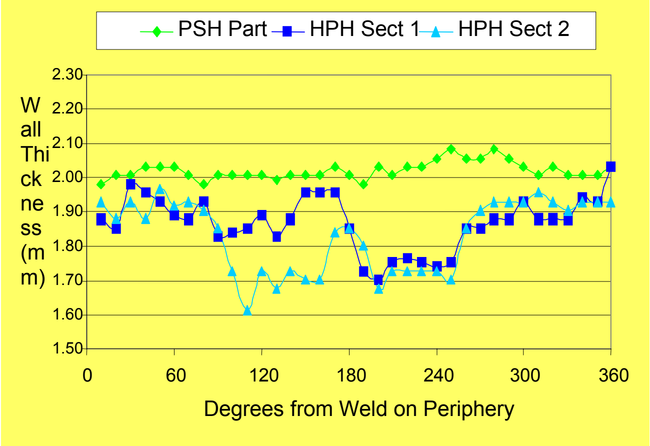


Figure 9

PART CROSS SECTION EXPANSION

Expanding tubular cross sections has received a lot of attention in the automotive hydroforming industry, particularly by part designers. Expansion is attractive because it can increase part effectiveness and can make part design easier. It also increases cost, but may be well worth it because of greater functionality.

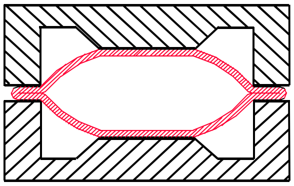


Figure 11

There are 3 fundamental reasons to expand the cross sectional periphery of a hydroformed component. The 1st is that HPH normally expands the tubular blank to prevent squeezing part of the tube between the die blocks or 'pinching' as shown in Figure 11. Pinching forms an undesired sharp ridge(s), making it less likely that the cavity will fill and likely the tube will rupture. This process is explained related to Figures 3.

The 2nd and 3rd reasons are to respond to part requirements. These requirements usually aim to increase section strength and/or improve mounting conditions for mating parts. Greater section strength receives most of the attention and variable periphery part designs strive to provide larger sections where stresses are higher and thereby improve material use efficiency.

Figure 12

There are several different ways to expand tubular cross sections. Figures 12 & 13/14 are methods used in the hydroforming die(hydroexpansion). The part in figure 12 was made without end feeding since it was U-shaped and material could not be effectively fed into the crossbar shown. Expansion is achieved by thinning the wall, with substantial variation in the amount. The amount of expansion that can be achieved mainly depends on formability, part design, die design and lubrication. The maximum expansion that can be achieved with reasonable process robustness will be 15-18%. In the part shown section height is increased by 40%.

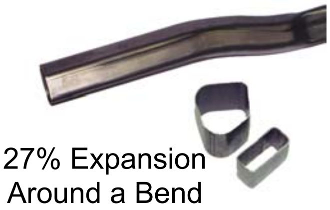


Figure 13

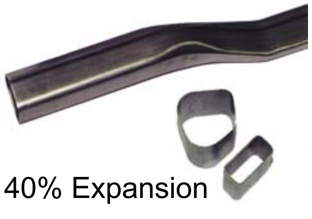


Figure 14

Figures 13 and 14 show hydroexpansion with end feeding. The 2 main benefits of doing this is that wall thinning is substantially reduced and the expansion percentage that can be attained is dramatically higher (40% Figure 14). In addition to the extended cycle time and other factors mentioned above, other difficulties to be aware of are tool wear, higher scrap rates and in-die hole punching limitations.

Figure 13 shows that some material can be pushed around a small angle bend, but this amount will decrease as the bend angle increases.

Expansion (common in HPH parts) in the hydroforming die is considered by some to be 'free' but the correctness of such an assessment depends on the viewpoint. When using

Copyright © #### by ASME

HPH it seems free because equipment etc. has to be put in place for pinching avoidance.

Relative to PSH, which normally has a constant periphery (no expansion) along the length of the tube, there are several items that must be provided to expand that add cost. One of these is that friction opposes feeding additional material in the die, which usually dictates using lubricants (and often cleaning followed by rust inhibitor application). Wall thinning during HPH may require additional starting thickness. Use of high pressure to complete forming and reduce springback (calibration) seems to be the result of the need to expand. Press size (to hold the die closed), the water pressure delivery system and equipment operating costs increase proportionately.

The hydroforming die is considered by many to be the most efficient place to expand. There are several reasons why this may not be true, including frictional resistance to end feeding in the hydroforming die. The method illustrated in Figure 15 can push more material into the expanded zone since it is done prior to inserting the blank in the hydroforming die. Friction between the internal forming mandrel and tube inner surface acts in the mandrel travel direction and assists end feeding.

Some portion of the total hydroforming cycle time is used to do end feeding. It is 'part of the forming process', but extends the total cycle time (compared to a process without end feeding) to balance the effect of end feeding and pressure application. Therefore, parts without expansion tend to be produced at a higher rate. Pre-expansion (Figure 15) is often considered an 'extra' operation, but it prevents a hydroforming cycle time increase and equipment is relatively inexpensive. In some situations it would provide a net saving.

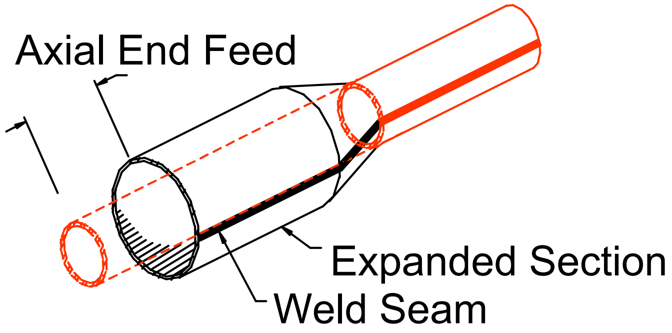


Figure 15

PART DESIGN INFLUENCE ON FORMING PRESSURE

For parts designed according to HPH criteria the sharpness of the sharpest cross sectional corner helps determine the pressure required to form the part. The relationship between pressure-P, inside corner radius-R_i, YS, and wall thickness-T is shown in Equation 1.

$$P_i = \frac{YS\ T}{R_i}$$

Equation 1

Some part shapes may present difficulties such as 2 pictures in Figure 17 (left top and bottom middle).

All cross sections shown in Figure 17 are made with PSH. The section at right bottom has corners that are 2T on the outside, very sharp by hydroforming standards. Equation 1 does not apply to PSH because of its fundamentally different method of forming. Dramatic changes in YS, T, and R_i have little effect on forming pressure and therefore press size and the pressure delivery system can be a common size for a wide range of parts. Part size most commonly dictates press size.

This different method also uses lower forming pressure (1/3 to 1/5 of what would be required for a similar HPH component). This in turn makes it possible to use smaller, faster, lower cost equipment.

ELIGIBLE MATERIALS

Material selection is a very important aspect of design flexibility when striving to fulfill part functionality requirements including energy absorption during a crash situation. Maximizing the range of choices is fundamental to making the most effective, efficient part.

Another concern can be the way material is formed and needs to perform for successful PSH and HPH, which differs substantially. The automotive structural industry is mainly concerned with steel and aluminum. Various alloys of each serve a number of purposes.

The PSH technique of cross section reshaping by bending has several benefits that widen the range of feasible materials for prototype and production. This is possible because the wall is not stretched, allowing lower elongation material to be used. N- values normally produced when making commercial quality, ERW mechanical tubing is satisfactory.

The PSH process is able to form complex shapes because of these low demands on the material. In all production applications, the customer selects the material. Commonly, mild steel is chosen because it provides the most rigidity for the least cost. Special material is only needed when it is dictated by part function, not production process requirements. However, PSH will be able to use special materials developed for other processes, because they normally enhance formability, elongation and n-value.

HPH places higher formability demands on material, thus requiring higher elongation and n-values to form a given part. Special material is often needed to address formability issues, but it can be a more economical alternative to the other options, such as annealing. As formability increases, YS tends to decrease. This is a process benefit since it reduces the pressure needed to fully form the part, but may not be consistent with the functional needs of the part. A challenge of material development is maintaining YS while improving formability.

Figure 16 shows an instrument panel beam made from 3 different materials. They are from right to left, 80 ksi (552

Copyright © #### by ASME

MPa) MYS steel, SAE 1010/1008 mild steel and 6061 aluminum. Each part was made in a production die with the same process conditions, including internal pressure. Table 2 shows the mechanical properties from the first 2 pieces and the hydroforming pressure used.

Figure 16

Material		Yield Stress MPa	Ultimate Stress MPa	Elong. %	Internal Pressure MPa
Mild Steel	Start	318	389	33	
	Formed	403	429	16	33
552 MPa	Start	600	706	17	
	Formed	610	727	11	33

Table 2

It is notable that elongation of 17% is more than enough to accommodate the reshaping needed to make this relatively sharply formed part. It is expected that this would be insufficient to prevent rupture when using HPH.

This is particularly important for occupant safety and designing how a vehicle structure responds in a crash. It shows that existing high strength steels can be hydroformed without having to develop special alloys. In applications where a complex tubular part shape is important for fit or better performance, high strength steel can be used.

Aluminum is another material that generates a lot of interest for structural applications. It most recognized asset is weight reduction, but it does not 'like' to be stretched. In similar fashion, PSH does not stretch it, thus allowing forming with no process change.

PART SURFACE FORMING COMPLEXITY

Automotive development is characterized by trying to fit more into a smaller space. Desire to reduce weight, manufacturing cost, improve performance and fit with, and among other surrounding components provides some of the motivation. Contradictorily, strength of the vehicle structure is often reduced by having to 'go around' other components. Hydroforming can offer more shaping flexibility to partially offset this.

Figure 17

As a result, the need for the widest range of options when shaping the part surface is important. Figure 17 show 7 production and prototype parts that are formed with the wall almost touching, substantial changes in cross section or sharp corners relative to the wall thickness. Each of these features can serve a purpose for parts that are important in crash.

Figure 18 shows 2 perpendicular views of a production part section that has a constant periphery. The desire for more vertical rigidity generated this design. Section depth increased more than 60%. To maintain constant periphery the width decreased substantially. The part length shown is approximately 19" (483 mm).

It is not surprising when the limits of technology, including hydroforming are being pushed. Hydroformed part design limitations are often due to bending. Although many difficult bends can be done, cost should steer the designer to simplify the bending method to that of conventional rotary draw bending.

Copyright © #### by ASME

Figure 18

As seen in Figure 19, the 3 main product design concerns are bend radius, bend angle and straight length between bends.

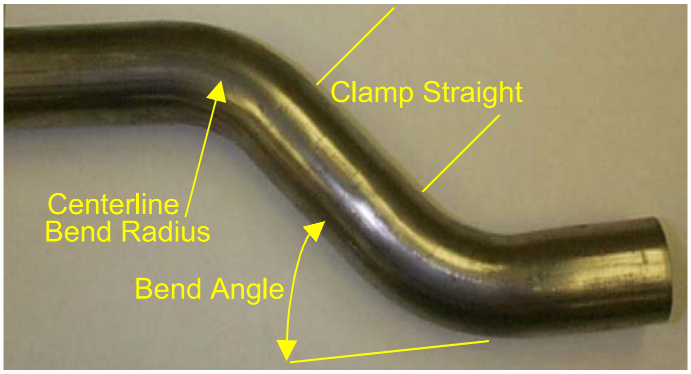


Figure 19

The combination of these factors determines bend severity and the amount of formability (indicated by elongation and/or n-value) that is used. This has a direct effect on the formability that remains for preforming and hydroforming. Generally, PSH requires less residual formability because it does not stretch the material. Alternatively, bending severity can be higher than for an equivalent HPH design and have enough formability left for hydroforming.

CONCLUSIONS

Hydroforming offers the potential to improve performance and reduce cost and weight simultaneously. It is not automatic, easy or obvious how to design and make the most efficient part. As with any other technology there are many ways to misapply it. The best way to ensure best application is to learn as much as possible about different methods to allow logical judgement of the merits of each approach.

REFERENCES

IBEC98 Conference and Exposition, Cobo Hall, Detroit, MI., Sept. 29- Oct. 1/98, **Tube Hydroforming: Efficiency and Effectiveness of Pressure Sequence Hydroforming**

SAE 1999 International Congress, Cobo Hall, Detroit, MI, March 1-4/99, **Design Flexibility for Hydroformed Automotive Structural Parts**

IBEC99 Conference and Exposition, Cobo Hall - Detroit, MI, September 28-30, 1999, **Expanded Sections In Hydroformed Automotive Components: Manufacturing And Cost Considerations**

Copyright © #### by ASME