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Design Flexibility for Hydroformed Automotive Structural Parts

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ABSTRACT

To simplify the number of design options that are available, decisions are often made early on to follow a particular system or set of design rules. This often builds in design compromises and extra costs that those involved either do not realize or have to live with because they are committed to the ‘system’.

This thorough, relatively objective consideration of the relevant factors should lead to the technically best way to make a part with the most design flexibility and least cost for the part being analyzed.

INTRODUCTION

The objective of this paper is to clearly identify and discuss different aspects of design flexibility that all should be aware of and focus on when designing parts for automotive structural hydroforming. In this rapidly developing industry, some claims of superior design flexibility have not been supported by factual proof, end up being less than promised and often tell only part of the story. To date hydroforming design flexibility has not been broken down to improve understanding. Therefore, this paper should be useful to those that are new to the process and those wanting to learn more. The subject is discussed relative to the 2 dominant hydroforming techniques being used today. These are pressure sequence hydroforming (PSH) and high pressure hydroforming (HPH). A brief conceptual explanation is given for each process for those unfamiliar with how they work.

The main design flexibility categories that will be discussed include variable vs. constant periphery design, material type, properties, and thickness (overall and process caused variation), bending, finished part cross sectional corner sharpness, part features (forming severity), holes and dimensional stability. Others are process conditions, section expansion and future ability to adjust to design changes.

The most important concepts will be discussed in a systematic sequence to consider all significant concerns and facilitate well considered decisions. Use of illustrations, subject part photographs that are supplemented by material test data, experimental results, production data and other related information should provide a very relevant guideline for those not yet confident in using this technology.

It is paramount to ‘keep your options open’ and know the full scope and meaning of design flexibility when choosing how to most economically make parts, thus ensuring continued competitiveness.

HYDROFORMING TECHNIQUES

Hydroforming technology, often in prototype, low volume and plumbing applications, has been used for many years. A number of different part types have developed which show good potential for more economical manufacturing or a greater range of features using hydroforming. This paper focuses on automotive structural parts. In this industry, the technology is new and unfamiliar to many. This can lead to acceptance of partial information as complete fact, which can be detrimental and dangerous.

Part complexity tend to increase in order to minimize part count, as well as maximize economy and functionality. As it increases, containing the tubular blank inside the die cavity becomes more difficult. When it is not contained, part of the tube periphery gets pinched between the die halves, the cavity doesn’t fill properly and rupture may result.

Consequently, 2 distinctly different techniques were developed to avoid pinching, forming and rupture problems. They are pressure sequence hydroforming and high pressure hydroforming. The reference to pressure in each name misses the real difference, which is how they each get sufficient material in the die cavity to successfully form a part. The final or maximum pressure used is simply what is needed to complete forming the part.

PRESSURE SEQUENCE HYDROFORMING (PSH) – Most automotive structural parts need to be bent and some are preformed prior to hydroforming. This blank is placed in the cavity and the die starts to close. When the die is partially closed, the tube is partly crushed. The ends are sealed and low pressure fluid fills the blank, making it relatively incompressible and like a formable solid. The die starts to close again with the desired low pressure maintained while the part volume reduces. Low internal pressure during closure discourages pinching between the die halves in the same way that it is difficult to pinch a balloon. This liquid mandrel also resists or prevents unwanted inward deformation.

Closing the die halves generate mechanical forces that deform the starting tube. In addition, the cavity periphery is essentially the same as the starting tube. Combined with the benefits of low internal pressure, the forces are guided in a more useful direction. They act through the tube wall compressively around the cross sections to force material into the corners. When properly designed and managed, these factors cooperate to force the tube to take on a complex shape with far less pressure (typically 1/5 to 1/3) than is needed with other techniques. Normally the maximum pressure needed is less than 50 MPa (7,000 psi). The tube wall is guided to the desired location and shape with no wall thinning, because the cavity and blank are the same periphery, leaving no room to expand. A more detailed description has been given in previous papers cited in the reference section.

This process offers design flexibility that is superior in a number of respects to other hydroforming techniques, as will be discussed in more detail in the following sections.

HIGH PRESSURE HYDROFORMING (HPH) – Another way to avoid pinching between the die halves is to use a tube whose circumference is smaller (5-10%) than the die cavity periphery. When the die closes there is no pressurized fluid in the starting tube and it takes on the cavity shape to some degree. Some undesired inward deformation occurs and cross-sectional corners are not filled when the die is completely closed. Water is injected and pressurized until these corners completely form and any unwanted deformation is forced out against the die. Maximum pressure commonly exceeds 140 MPa (20,000 psi) and can go beyond 690 MPa (100,000 psi). What is actually needed is dictated by Equation 1, which shows dependence on material yield strength, wall thickness and the inside radius of the sharpest cross sectional corner.

The tube wall is ballooned or blown out against the cavity wall. As a result, material thickness becomes quite variable throughout the part. Much of the development effort ongoing in the hydroforming industry such as special materials, tube making, lubrication, simulation, etc. strive to minimize wall thinning and its variation. Earlier development efforts resulted in the use of end feeding, lubrication, annealing, surface texturing and lower-strength, high elongation materials. It is necessary to be aware of several issues that arise from these measures and techniques developed to minimize their detrimental effect. These are material formability, friction, tool design and wear and especially how these impact part design flexibility.

This process has superior design flexibility in some aspects, which will also be described more fully below.

DESIGN FLEXIBILITY

Design flexibility is a general term that has different meaning for each industry and for each type of product. Everyone knows its importance, but defining what it means and how it should be maximized is difficult. One must get to the details of what design flexibility means for the industry and part type in which you are interested to decide the most appropriate technique to use. Cutting corners here leads to unpleasant surprises later.

For the automotive structural component industry, the main categories of design flexibility to consider are variable vs. constant periphery design, material type, properties and thickness, bending, corner sharpness, part features (forming severity), holes and dimensional stability. Others are process conditions, section expansion and future ability to adjust to design changes.

Design flexibility as it applies to the subject part must be broken down to the best degree possible and assess these components to judge whether the best result is being achieved. In other words, to obtain flexibility of one sort, other types should not be sacrificed, or at least only after knowing what is being given up.

VARIABLE VS. CONSTANT PERIPHERY DESIGN

A presumption has developed that all hydroformed parts must be expanded. This is rooted in the fact that for HPH the starting tube must be smaller than the smallest cross section in the finished part to avoid pinching. Therefore, all cross sections are expanded to varying degrees to completely form the part. It is the forming of these corners that dictates that high pressure be used, not expansion itself. Expansion is also justified by increased yield strength and superior dimensional capability. Technical proof to substantiate such claims and support their worth is presently unavailable.

HPH – The maximum pressure level (P_i) that must be used for the HPH process is dependent on cross sectional corner radius (R_i), material yield strength (S) and thickness (T). Equation 1 below describes the relationship reasonably well. It shows that as the corners form more sharply the pressure must increase with the maximum when forming is completed. It does not apply to PSH because of the different forming mechanism used.

$$P_i = \frac{ST}{R_i} \tag{1}$$

Internal forming pressure has a large effect on overall hydroform processing cost, regardless of the technique. It is most economical to minimize pressure, especially for high pressure systems. Reducing wall thickness, yield strength and increasing cross sectional corner radii will accomplish this. Optimizing the latter 2 factors for minimal pressure may conflict with design intent and compromise part function. However, these design compromises must be rationalized with process viability and cost. Process cost factors include equipment cost, the energy needed to generate higher pressure and to operate the larger press that has to contain it. Cycle time increases to achieve higher pressure levels and because larger presses are slower.

Considered from the product design perspective, when material requirements change to higher strength steel, the direct pressure increase causes a corresponding increase in press size and cost, as well as the pressure delivery system. Higher strength steels have less elongation, which reduces possible stretching or increases the likelihood of rupture. As corners get sharper, even in a small area, required pressure must increase proportionately, as will wall thickness variation.

A number of techniques have been developed to reduce wall thinning and/or make it more even. These include special materials, end feeding (only effective for some distance from the end), lubrication, part or die texturing, preforming, annealing, and reducing bending severity to leave more elongation for hydroforming. Process simulation is imperative to predict the outcome. However, despite these measures, wall thinning still is highly variable in portions of many parts. Each can add cost and use should be minimized for best economy.

PSH – Pressure sequence hydroforming offers another approach to pinching avoidance. As described earlier, a cavity periphery essentially equal to the start tube combined with low pressure during die closure harnesses forming forces in a more efficient way. This dramatically lowers the amount of internal pressure required to form complex shaped parts. Pressure is normally one fifth to one third of that needed for a similar HPH part.

The result is that wall thinning does not occur during the PSH operation and the above techniques to control it are therefore unnecessary.

For a given material and part design, the bent areas of the start tube have the lowest material elongation, because they are worked the most. Therefore, they will have the most limited ability to be hydroformed. This problem is most likely to occur when using HPH because of additional stretching that must occur.

The percentage expansion that can be achieved with PSH will be greater than with HPH because elongation used to avoid pinching in the latter process is not used in the first one. While logically true, it is contrary to the understanding of most people getting into the industry.

An understanding has developed that there is an inherent benefit in designing variable cross section peripheries into all parts on the supposition that this single aspect of design flexibility makes the part more ‘efficient’, implying lower cost. This oversimplifies the situation. Designing the most effective and lowest cost part is more complex. Excessive concentration on one facet of flexibility without thorough and informed consideration of other effects must be avoided. What follows is a discussion of these other aspects.

An example of how material strength, corner radius and internal pressure relate for an HPH forming situation follows. By referring to equation 1 we can calculate that for mild steel (YS = 240 MPa [35,000 psi]) forming 5T corners will take 48 MPa (7,000 psi). This is given to illustrate that pressure needed to form a medium severity corner does not require ‘high pressure’. Forming corners using PSH does not depend on pressure and this equation does not apply. For an actual HPH forming situation, by the time the corner material had stretched to this point, the yield strength would be substantially higher and require accordingly higher pressure.

Parts designed with variable peripheries must be fully formed with internal pressure. Coupled with stretching an undersized tube to fill the cavity, a considerable number of challenges to successful forming can arise. Many parts that exhibit varying peripheries do not need them, but objective, knowledgeable judgement is exceedingly difficult to find. The luxury of designing and objectively judging the merits of a design for each technique can rarely be afforded, but would be best. Having the discipline of designing a constant periphery along the part length allows access to a number of benefits that otherwise are unappreciated.

MATERIAL

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

The way material is formed and needs to perform for successful PSH and HPH differs greatly. It is important to explain material behavior for each process to clarify how well this aspect of design flexibility is served.

PSH reforms the cross section of the tube by bending the tube wall from a normally round starting tube into the desired shape along the length of the part. The wall is bent from a smooth, relatively gentle curve to much sharper cross sectional corners common in structural parts, or flat portions in between. Forming of this sort will tend to put the outside surface of the corners in tension and the inside in compression. Much of this deformation is plastic. The pattern would be opposite for flat areas, but to a lesser degree since the change in curvature is less. Exactly how tension and compression end up in the final part depends on the way that previous operations like flat sheet production, tube making, bending and preforming have affected the material. All PSH prototype and production applications use material and tube made to normally available commercial standards with no special development to serve the needs of the process.

Material testing shows that the increase in yield strength from PSH is 5-10 %.

In the final analysis, the most concise and relevant way to assess the net effect of these residual stress patterns is to consider the dimensional stability of the part. This is described in detail later in this paper. Normally there is no wall thinning from pressure sequence hydroforming (Figure 1). There is only what is introduced by previous operations like sheet and tube making, bending and preforming. As a result, rupture does not occur during hydroforming.

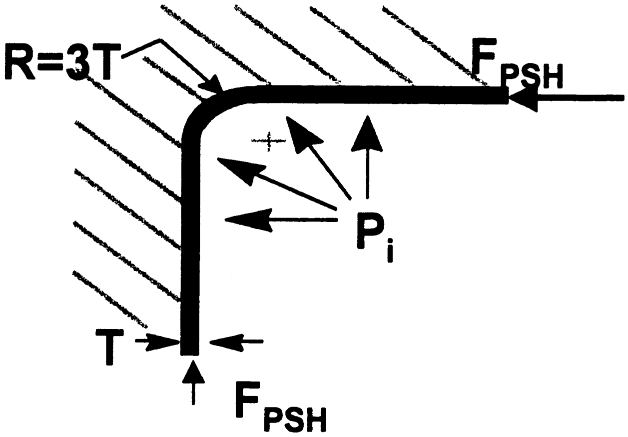

Figure 1.

For HPH, normally the tube is designed to be 5-10% smaller than the die cavity periphery. HPH stretches the starting round into the final cross sectional shape after the die is closed. The stretching pattern varies depending on the part shape, material type and properties, as well as lubrication, surface finish and several other factors. In general, the pattern appears as in Figure 2, with little or no stretching in flat regions of chosen cross sections. This occurs because the areas destined to become flat are usually the first to contact the cavity surface. Being pressed against the cavity surface by higher forming pressure causes friction that is too great to allow sliding. Corners exhibit wall thinning that increases substantially as the corners are approached. As a result, corners are most likely to rupture. Avoiding rupture is the fundamental reason behind the extensive effort being expended to develop ‘hydroforming steels’. The points mentioned earlier in this paragraph aim to improve the likelihood of making the stretching more even.

The tubular blank placed in the die will have seen previous deformation as in the PSH part. In most cross sections, all of the material is stretched by this hydroforming method, but to varying degrees as described above. More of the material will have a net tensile residual stress pattern compared to PSH. A high degree of dimensional stability is claimed, but difficult to judge since there is no publicly available HPH dimensional stability data that can be directly compared to the PSH data shown later in this paper.

As material is stretched, it work hardens and yield strength increases. Experiments have shown that for mechanically stretched mild steel this increase is roughly proportional to the percentage strain the material experiences. Hydraulically stretched material behaves similarly. On average around the cross section, YS gain would be the same as the percentage expansion (5-10%). Work hardening rates differ for other alloys, but mild steel is a common reference point.

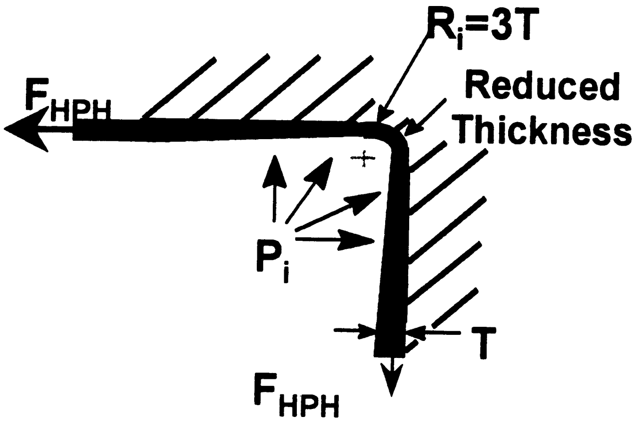

Figure 2.

Assertions that mild steel can be work hardened to be equivalent to HSLA should be scrutinized carefully. Buying HSLA normally means, the minimum YS of the steel is increased and mechanical property variability is dramatically reduced. Mild steel is noted for its relatively wide variation in YS, elongation and N value, which is one of the reasons it is so economical. It is unclear how a substantial increase in yield strength (more than 5-10%) and a reduction in the wider property variation of mild steel can be achieved reliably. A 3^{rd} factor is the variability of stretching and therefore the YS increase around a typical cross section. A range of 1-2% on some flats to 20% in corners would be common.

TYPE – The 2 main metal groups of concern in the automotive structural industry are steel and aluminum. Various alloys from each group exist that serve a number of purposes.

One of the most important differences between PSH and HPH is the effect of their forming mechanisms on material. Their ability to take best advantage of the benefits of a particular material differs. Selection of the right material is often fundamental to successful production; as well as best part economy and function.

The technique of cross section reshaping by bending employed by PSH has several benefits that widen the range of materials that are feasible for prototype and production. Lower elongation material can be used. N- values normally produced when making commercial quality, ERW mechanical tubing are satisfactory.

The PSH process makes low demands on the material, but is able to form complex shapes. In all production applications, material is selected by the customer. 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 the 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. It can be a more economical alternative to the other options detailed earlier. 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 in some cases is maintaining YS while improving formability.

Hydroforming simulation or finite element analysis (FEA) has become very important to provide some insight into what material properties are needed for a reasonably robust process.

The forming characteristics of aluminum can be challenging. HPH requires a cautious approach to successfully form aluminum because of the stretching nature of the process. Even expansion required to prevent pinching can be challenging.

The reshaping technique of PSH is more amenable to forming aluminum. The severity and range of features will be greater since all formability can be devoted to making them. In several instances, aluminum has been substituted for steel in production hydroforming dies with no change in tools or process conditions. Several alloys in the 5000 and 6000 series were used. This is important since it demonstrates that aluminum can be production hydroformed with no process development.

A wide range of materials can be hydroformed as long as they possess some ductility. A 310 MPa (45,000 psi) minimum YS HSLA has run in production for 4 years. Ultra HSLA and stainless steels prototypes have been made in production tools, demonstrating similar forming ease. Other lower elongation materials can also be formed, but bending is often the determinant of what can be done. One production die normally running with mild steel was used to make a number of aluminum and ultra HSLA parts with no process change.

PROPERTIES – A number of material properties are important to varying degrees when tube hydroforming. These are yield stress or strength (YS), elongation, n-value and perhaps, r-value.

YS is the point at which the material starts to plastically deform to eventually form as shown in Figures 1 and 2. Large changes have no effect on the process conditions of the PSH process. For example, required internal pressure remains the same when YS doubles. This is a tremendous advantage in an industry that is placing increasing importance on HSLA as a way to lose weight and gain strength.

For HPH, YS increases as the part progresses toward full formation since material is strengthened in corners along the way. Internal pressure must be elevated accordingly to continue forming.

For steel, as YS increases, elongation decreases and the amount of deformation that the material can withstand before necking and rupture is substantially reduced.

Elongation is the amount that the material stretches linearly prior to necking. PSH uses a small amount of elongation to reshape the part cross section, even in its most severe case. As a result, lower elongation materials can be used, such as HSLA steel, ultra HSLA steel, and aluminum. Also where expansion is required the amount that can be achieved is greater.

HPH requires substantially more elongation for successful basic forming. The most severe forming occurs in the cross sectional corners, which is what we must go by. Where the linear part of the stress-strain curve is exceeded and necking approaches, an area of concern exists. When forming goes beyond this point rupture will occur and the part is scrap. Minimizing this occurrence is obviously necessary to avoid adding cost.

However, a problem of greater concern because of the difficulty of detection, is when this almost occurs. There will understandably be little elongation left in this region. The stresses that the part experiences in service may cause premature fatigue cracking, perhaps propagating further along the part. The severity of consequences and cost can be formidable and designers must be vigilant about where it may occur and prevent it.

N-value is the work hardening exponent, which expresses material behavior as it is plastically deformed. Higher n-values indicate that as stretching commences, a particular element stretches to the point where it gets too strong. Any continuing strain is ‘shared’ with elements surrounding it. Spreading strain more effectively allows larger expansion and thus this property describes a materials ability to ‘balloon’. Material with lower n-values causes stretching to concentrate locally and burst more readily.

This property is always important for HPH because expansion is done on every part, whether it be to avoid pinching, vary the periphery, or form larger expansions. It is a concern for PSH only where expansion is designed in the part.

N-value also plays a role in how quickly a part can be formed. Higher values indicate that faster forming is possible while lower values will dictate a longer cycle time to avoid rupture.

R-value quantifies material drawability and is applicable to large expanded sections, normally only achievable at the part end where end feeding is most effective. Attention to maintaining a specified range of values may be necessary for some application, particular for HPH.

Tube manufacturers normally buy steel with the required YS of the final part and elongation sufficient to survive the subsequent operations performed on it after which some should remain for process robustness, part toughness and reasonable fatigue life. It is not normal tube making practice to track what happens to the N or r-values, but can be done at probable increased cost.

They do not plan or depend on work hardening of the material during processing to bring YS up to the specification. Ensuring a minimum strength is needed from a part design perspective, but is difficult and risky to guarantee considering the variability of each step in the progression to a hydroformed part. These include sheet and tube making, bending and preforming.

THICKNESS – The effect of start tube wall thickness on these hydroforming techniques is dramatically different, as is the effect of each process on the final thickness.

Equation 1 shows that thickness has a directly effect on HPH process pressure, with thinner material allowing less pressure to be used. As discussed above, alterations to material thickness can be dramatic.

As can be seen in Figure 2, the material thins in the corners. Depending on the degree of expansion and the available elongation, stretching may exceed the linearly plastic region of the stress–strain curve to the onset of necking. Exceeding this point will cause rupture. Even approaching it creates a strong possibility of dramatically reduced fatigue life of the part.

This problem is particularly worrisome because of the difficulty of detecting parts that have not ruptured but are very close to it. Subjecting such parts to cyclical loading, almost guaranteed with automotive structures, may cause premature fatigue failure. Concern about how far the material can be stretched before this occurs and how to manage production variability adds to the uncertainty.

Another item to consider concerns the minimum material specification required of most components. Wall thickness consistent with the specification will be too thin in the cross sectional corners by the amount of the thinning. To adhere to the minimum, starting wall thickness must increase accordingly. This carries a significant weight penalty (ie 20 %). This conflicts with assertions that buying a tube that is smaller (5-10%) and expanding it makes a lighter part. When combined with the near rupture situation discussed above it is wise to scrutinize this area carefully.

It is common to weld stamped brackets to structural parts. Variable wall thickness affects MIG welding stability. A good quality weld in a thicker area may burn through in a thinner one, or good quality in a thin area may give a cold weld where thicker. Also any YS gains planned on from processing the part will be lost where normally stress is highest because of the local annealing effect welding.

Consequently, effective process simulation is very important to give the best indication of problems during part development before prototypes are made. This is especially true for HPH, predominantly because of the wall thinning effect. It can be understood that the difference between a good part and rupture is very small. It is affected by a number of variables like material elongation, N-value, and consistency (properties and thickness). Others are blank and tool surface finish, lubrication and process equipment parameters.

BENDING AND CROSS SECTION PREFORMING

BENDING – Bending is a necessary preforming operation for almost all automotive structural parts. A number of different tube bending techniques are in use in various industries, but the most common and advantageous for these parts is CNC rotary draw bending. The chief benefits are speed, accuracy, repeatability and relatively good control of wall thickness variation from bending (thinning on the outside of the bend, thickening inside).

Product design focuses on bend radius and angle as well as the amount of straight length between the tangent points of adjacent bends as shown in Figure 4. The first 2 factors use some of the material elongation. As the radius decreases and bend angle increases, the amount used increases.

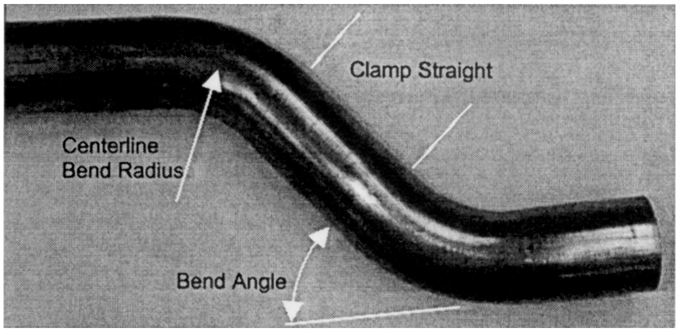

Figure 3.

This can be a problem when subsequent operations such as hydroforming also require a significant amount of elongation to form successfully.

Elongation requirements for HPH are substantially higher than for PSH, because of the elongation used to expand the whole tube to avoid pinching. Several ways have developed to handle these conflicting requirements.

Annealing returns the material to a high elongation, lower strength state that the material was in before work hardening was caused by operations like sheet rolling, tube making, bending and preforming. Although the whole part can be annealed, it seems that local (probably induction) annealing focuses on the bends that are worked the most.

When annealing, a cooling period of up to 20 minutes or more is necessary to prevent quenching the material. Annealing must be done in an oxygen free environment to prevent the formation of black scale.

A second approach is limiting bend angle and radius to prevent elongation from dropping too low. Doing this can prevent the need to anneal but may require a multi-part assembly where one could do the job. In addition, the number of useful features that can be designed into the part, such as abrupt indents and local sharp cross sectional corners may limit the part's utility. These are some of the main benefits of hydroforming and may cause difficult choices.

A third approach is to develop a special material to have a higher starting elongation and end up at a suitable residual after the interceding operations are complete. Although this may introduce additional cost for material with a given YS, it may be the best alternative.

CROSS SECTION PREFOMING – Preforming the tube cross section over some or all of the part length may be required to aid in avoiding pinching some of the tube between the die sections. There are at least 2 reasons and ways that this is done.

The first squeezes the round perpendicular (to make an oval shape) to the direction of die travel because a section in the cavity is too narrow for the start tube OD. It has little effect on elongation. This style of preform uses a hydraulic cylinder to compress the section in the direction desired and let it form freely in the other directions.

Alternatively, the cross section can formed close to the desired shape with some unwanted deformation, then hydroformed to complete forming and remove these deformations. This is done in the context of HPH where the difference between blank and final part peripheries is inadequate to prevent pinching along the length of the part when the die is closed. When the blank is compressed in one direction, it is also constrained in the others. The forces required to do this are substantially higher and therefore preforming of this type will be done in a press.

FINISHED PART SECTION CORNER SHARPNESS

Corner sharpness is often expressed as a multiple of the wall thickness similar to the norm in the stamping industry. As can be seen in Figure 4 sharp corners relative to wall thickness can be achieved in a production part. The wall thickness shown is approximately 1.2 mm and outside corner radius is as low as 3.5 mm.

Figure 4.

This factor is a key determinant of the maximum pressure required to completely form the part after structural demands of material YS and thickness have been satisfied (Equation 1).

Sharper corners increase internal pressure for HPH style processes. Therefore, economic considerations encourage larger corners.

Several reasons favour sharper corners. One is extending flat surfaces for hole placement near a corner. Structurally, sharper corners improve the rigidity of a particular section. A less tangible reason is that the part looks sharper, better defined or of higher quality.

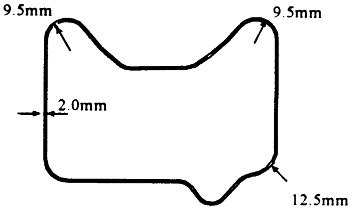

Figure 5.

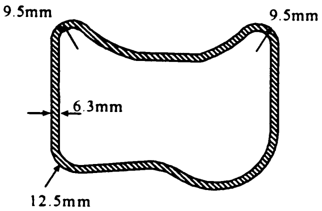

Figure 6.

Table 1.

Fig #	Material Grade SAE	Wall Thk. Min. = T mm	Internal Pressure MPa	Outside Corner Radius	Yield Stress MPa
6	1010	2.0	37.2	4.75T	263
	1010	3.0	37.2	3.2T	296
7	1026	6.3	41.4	1.5T	386

Internal pressure used in the PSH process is not sensitive to corner sharpness. In fact as seen in Figures 5 & 6, as well as Table 1, corner sharpness can decrease 30% with no effect at all. Even a decrease of 70% generates only a 10% pressure increase.

PART FEATURES (FORMING SEVERITY)

HPH techniques are well suited to bulge forming as evidenced by many prototype parts that have been publicized. Examples are plumbing fittings, in particular Tee's, bicycle frame nodes, camshafts among others.

Protrusions like those found on the above parts would seem to be beneficial on automotive structural parts. It is unclear if their inclusion is technically or economically feasible in larger, normally steel, structural parts. Several designs including them evolved into production designs without them, which implies that they are not.

Indents that cannot be formed with a solid portion of the die can be done by moving a portion of the cavity wall after the die is closed. Die lock features are an example. It is best to form such features when internal pressure is highest. Actuation units must be proportionately larger with HPH with possible limitations on in die hole punching or die integrity.

PSH is better suited to forming sharp corners, punching large numbers of holes, and creating severe indents as described above. High strength materials as well as those with lower elongation can be formed with the same pressure and press size used for lower strengths.

HOLES

Holes are an essential, functional requirement for nearly all structural, automotive components. They can be used for self-threading fasteners, pushpins, wiring clips, plug welding, clearance or several other purposes.

Attaching the component being hydroformed to the rest of the structure is an important reason to introduce holes. Attachment of other components is probably even more frequently required.

Any hole can be cut into a part in any quantity desired. The only issue is how they will be put in. The most dimensionally stable, robust and economical way to introduce holes in a tube hydroformed part is to punch them in the hydroforming die during the forming cycle. This is analogous to normal stamping practice. Situations will arise where some holes cannot be punched during hydroforming, due to either tooling restrictions or unsuitable characteristics of the hole. The rest of this section will focus on hydropiercing options.

A number of different hole styles are achievable. Three are shown below, with the slug attached to the first two. This is done to prevent their presence causing tooling problems, marks in the surface of subsequent parts or inexplicable rattling problems in the vehicle, among other difficulties.

Figure 7 is the cross section of a pierced hole. There is some indenting around the edge of the hole since fluid acts as a less than perfect die button. It can be used for clips, clearance and draining among other purposes.

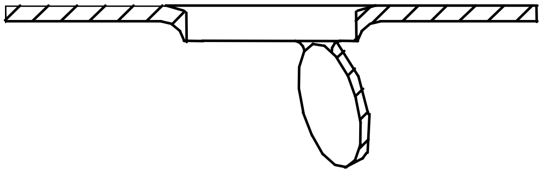

Figure 7.

The hole in Figure 8 uses a punch that pierces a small hole and pushes a larger shoulder through to form an extrude. This provides a longer land for better self-threading fastener engagement, which is the most common purpose of this type.

Fluid leakage around each of these hole types can be very small, allowing many holes to be punched in the same part while maintaining needed pressure in the tube. Production dies exist with as many as 64 holes of many shapes and sizes in an 1800 mm long part.

Figure 8.

Figure 9 shows a slug being pushed out from the cavity by internal pressure. Fluid leakage from hydropiercing such a hole may be considerable, which will limit the number that can be reliably produced in the same part.

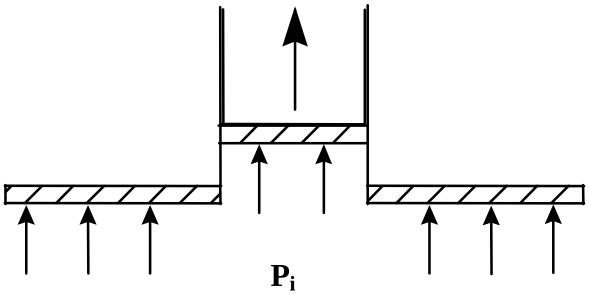

Figure 9.

Holes of this style can also be produced by piercing through both walls of the tube and carrying the slugs out of the tube to prevent the problems mentioned above.

Many different shapes are in production including round, oval, rectangular and hexagonal. Hole size is only limited by what is reasonable given the part geometry.

Higher forming pressures reduce the amount of indenting around holes like those in Figures 7 & 8. High pressure requires larger punching units, which in turn lessens how closely they can be grouped together. Another very important consideration with high pressures is the die remaining strong enough to resist the large forces experienced at maximum internal pressure. Failure to do so will cause the tool to crack and break. This can also restrict hole count and placement.

Maximum flexibility in hydropiercing is very important for the best and most economical product. Holes that cannot be hydropierced must be introduced as a secondary cutting or piercing operation at additional cost and reduced repeatability. Flexibility in this sense means hydroforming dies with a minimum of wear inserts and other separate parts that impede punch unit placement.

DIMENSIONAL STABILITY

Dimensional stability is an issue of great interest to designers and particularly manufacturing and assembly personnel. Its importance escalates as the drive to increase various aspects of vehicle quality and reduce build tolerances and problems progresses. One of the primary benefits of hydroforming is a significantly lower variability level. Compared to tubular structures assembled from several stampings, Tolerances can be ¼ or less for a given feature type and capability level.

It is important to understand that a complete description of dimensional stability must include the tolerance and the capability level that is being maintained. The type of part being considered, its datums, production rate and the sampling period also can have a large effect on what the numbers really represent. Vigilance to these details early on will reduce the possibility of unpleasant surprises later.

For most current automotive part production, the most common capability expectation is ± 5 sigma ($C_p = 1.67$) short term and ± 4 sigma ($C_p = 1.33$) long term. The tolerance that can be maintained at these capability levels is the clearest indication of process stability. The tolerance ascribed to the feature of interest and capability levels that exceed those indicated above can confuse comparisons. The greatest concern is usually long term capability

Following are 3 diverse examples of the tolerances that can be achieved using PSH. A full explanation of the part type, shape and measurement circumstances, along with a number of statistical values is given. These include capability at the tolerance specified, and most importantly the tolerance that can be delivered at a 'normal' long term capability level of 4 sigma.

ENGINE CRADLE CROSS SECTION WIDTH – Table 2 shows the impressive precision of hydroforming. It must be realized that it only presents part of the normally required position information. The size of a cross section is not normally as important as where those surfaces are located in space relative to a CAD or nominal position. It is mainly applicable where surface location opposite a datum is critical or a bracket fits around the tube and is located relative to it. The 6 month sample period should give a high degree of confidence.

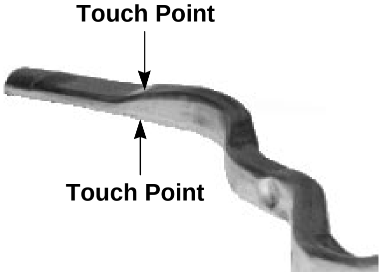

Figure 10.

Table 2.

Sample Period	6 Months
Sample Size	30 pcs.
Tolerance	±1.0 mm
Range	0.09 mm
Std. Dev.	0.024
C_p	13.60
C_{pk}	12.35
At $C_p = 1.33$ Tol. =	±0.10 mm

RADIATOR ENCLOSURE SURFACE LOCATION – The high C_p results from a higher than normal tolerance of ±1.5 mm and excellent repeatability. Production during this period was 80,000 pieces.

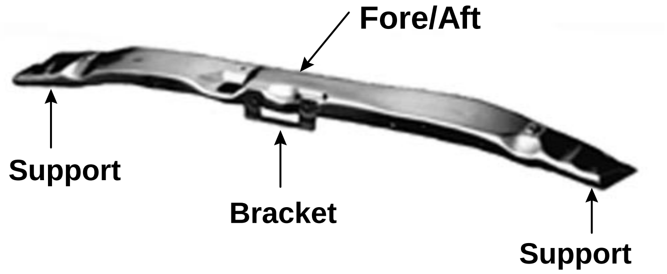

Figure 11.

Table 3.

Sample Period	2.5 Months
Sample Size	185 pcs.
Tolerance	±1.5 mm
Range	0.40mm
Std. Dev.	0.04
C_p	11.45
C_{pk}	9.98
At $C_p = 1.33$ Tol. =	± 0.16mm

This result is remarkable because the span is 1260mm. The tolerance at C_p = 1.33 is ±0.16mm. The tube is 76 mm, 1.3 mm wall thickness and the material is SAE 1008/1010 galvanneal.

INSTRUMENT PANEL BEAM SURFACE LOCATION (BEFORE WELDING) – This part uses 50.8 mm diameter, 2 mm minimum wall thickness, SAE1008/1010 mild steel tube. Cycle time is less than 17 seconds and has achieved a volume of 780,000 parts per year on 2 shifts with a partial third. This third iteration of a part that has been in production for 8 years runs in one press in a single cavity die with no backup tooling. Manufacturing scrap rates from bending, hydroforming with hole punching in the die and shearing total 0.5%.

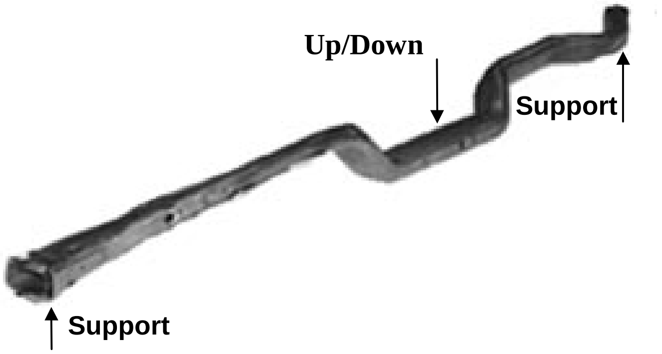

Figure 12.

Table 4.

Sample Period	3 Months
Sample Size	1000pcs.
Tolerance	±1.5 mm
Range	1.10mm
Std. Dev.	0.17
C_p	2.94
C_{pk}	2.47
At C_p = 1.33 Tol. =	± 0.68mm

Comparable production information is not available for HPH parts to support claimed high levels of dimensional stability and repeatability. Only when it becomes available can comparison between these processes be made.

PROCESS CONDITIONS

The single most important process condition in most minds is internal forming pressure. Attention to all else seems to pale in comparison.

Maximum pressure needed to form a part using the PSH technique is relatively constant despite radical changes that may occur in YS, wall thickness, sharpest inside cross sectional corner radius or even all 3 at the same time. Therefore, the main criterion to determine press clamping force size is the vertically projected area of the part. The size of the part also determines the bed size.

Maximum pressure needed to form a part using HPH is dependent on YS, wall thickness, minimum corner radius and projected part area. Determining the necessary pressure level is obviously a crucial factor and has a large effect on capital, tool and part cost and flexibility.

The energy needed to generate pressure and contain it with a press is a major factor in process cost. Higher pressure costs substantially more as detailed in a previous paper.

SECTION EXPANSION

Section expansion of hydroformed parts has attracted a lot of attention and has been closely associated with the need for high forming pressure. For tube diameters and wall thicknesses that are normal for structural parts, it is typical that pressure to expand in the round is low. Referring to Equation 1, a 3” diameter mild steel tube (YS= 240 MPa [35,000 psi]) with wall thickness of 1.5 mm will only need 10 MPa (1500 psi) to expand. For a given material and wall thickness, it is the reduction in effective radius that dictates elevating the pressure to completely form the part. In other words, forming the corners drives the need for high pressure.

It is also seems to be understood that expansion in the die is the best and most economical method, but this may not be the case. Expanded sections of 10% and above are only available at the component end or close to it and extra material is normally fed in. Anything that increases friction like bends, low, wide rectangular shapes or increasing distance from the end impede feeding additional material in and limit what can be done. Expanding in the die requires large end feeding cylinders and hardened inserts to withstand the intense abrasive forces that are generated. Also needed are likely longer cycle times for end feeding and special material to meet the deformation challenges.

End fed expansion in a PSH hydroforming die up to 41% has been successfully done with normal mild steel. Expansion of 27% with 345 MPa (50,000 psi) HSLA and through a 20° bend have also been prototyped.

Production feasibility of large expanded sections in HPH parts may be more challenging than it seemed in prototype.

Designs with expanded sections extending beyond the first bend or reducing in size through that bend are more likely to be best done in the die. If expansion is contained to the first straight portion of the part, it would be beneficial to consider mechanical expansion prior to placing the blank in the die. It would prevent the potential drawbacks listed above and allow access to the benefits of PSH.

FUTURE DESIGN CONSIDERATION

An understanding has developed that to maximize future design flexibility and utility of the equipment beyond the program parts being made on it, HPH must be used with the largest press possible. Changes in YS, wall thickness and corner radius that happen as part design evolves can dictate substantially higher pressure and clamping force equipment. The product that succeeds the one the equipment was bought for can more easily need substantially higher pressure, larger press and pressure delivery system.

Another approach to consider is that for PSH, equipment designed to run an engine cradle type part, for example, will be suitable to make any similar sized part in the future, regardless of how the design changes.

The paradox is that using low pressure, commonly viewed as a limitation, becomes a strength when using PSH because the pressure and therefore the equipment size will not need to change. It also provides a more efficient process coupled with the wide range of design flexibility detailed above.

CONCLUSION

Design flexibility is a multifaceted concept that usually receives insufficient consideration when different manufacturing techniques are being evaluated. This is probably more true than normal for tube hydroforming because of its relative recent rise to prominence. A conventional wisdom has not developed yet.

After consideration of all the factors cited in this paper more insightful and confident decisions can be made. These factors included variable vs. constant periphery design, material type, properties, and thickness (overall and process caused variation), bending, finished part cross sectional corner sharpness, part features (forming severity), holes and dimensional stability. Others were process conditions, section expansion and future ability to adjust to design changes.

Asking questions based on this framework will also improve knowledge and how it all works. Both processes discussed have strengths that should be accessed when needed. PSH has a number of subtle strengths that must be understood before they can be used. These include high degrees of flexibility with respect to material, part shape and severe shaping, dimensional stability, expansion and continued equipment viability.

Knowing these things will lead to more efficient and effective component manufacturing.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

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).
Hydropiercing: Punching holes in the wall of a hydroformed tubular component inside the hydroforming die using hydraulically actuated punches and internal fluid pressure to support the tube wall.
P: Maximum pressure level
R_i: Inside corner radius
S: Material yield stress or strength
T: Material wall thickness
HSLA: High strength, low alloy steel. Assures higher minimum yield strength even when fully annealed combined with more controlled mechanical properties. Normally yield strength up to 414 MPa (60,000 psi) minimum.
Ultra HSLA: Ultra High strength, low alloy steel. Yield strength exceeds 414 MPa (60,000 psi)
ERW: Electrical resistance welded. Common, economical seam welding process