

Tube Hydroforming: Efficiency and Effectiveness of Pressure Sequence Hydroforming

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ABSTRACT

Tube hydroforming is a technology that is new to many and proving its merits as a viable and often superior alternative to welding tubular assemblies from stampings.

This paper discusses how pressure sequence and high pressure hydroforming techniques work, how two functionally similar parts made by its respective technology compare and the dimensional stability of parts made with pressure sequence hydroforming.

Data comparing the 2 processes show a substantial benefit when using pressure sequence hydroforming considering processing steps, hydroforming equipment, energy consumption, cycle time and floor space requirements. PSH dimensional stability compares very well with welded assemblies. High pressure dimensional data is unavailable which prevents comparison.

Comparisons using specific information that has only recently become available should be interesting and valuable to anyone wanting to learn more about this emerging industry and technology.

INTRODUCTION

Tube hydroforming provides many advantages compared to structures composed of stampings that are welded together. These are lower weight, capital, tool and piece cost and higher strength, rigidity, and dimensional stability. These factors have driven this new technology to assume an abruptly high profile in the automotive industry.

Two main hydroforming methods have developed that each offer differing advantages. The distinction between the two revolves around achieving reasonable part design complexity while containing all material within the confines of the desired die cavity. How much pressure is applied, and when, constitutes the heart of the difference between the processes.

Pressure sequence hydroforming provides opportunity to realize a number of efficiencies. These are not available with other technologies without significant increase in process complexity and cost, if at all. Efficiency will be shown by discussing a pressure sequencing hydroforming high volume production cell making an automotive structural part. This will be compared to a high pressure hydroforming production cell.

Examples show part design complexity, necessary equipment, cycle time, and dimensional capability among other interesting features.

The inherent efficiencies of pressure sequence hydroforming are not well understood. It is important to improve understanding to ensure that the most informed judgment is made about the most advantageous technology for a particular part. This choice should achieve the best balance of minimizing capital, tool and part cost as well as weight while maximizing part design and material selection flexibility.

The potential for less informed decisions is increased because the industry is in its infancy and the wisdom of experience is less prevalent than is desirable.

HYDROFORMING

As the design of any automobile body structural part develops complexity normally increases. This happens because of unforeseen conflicts that arise between the various requirements of the part and its related components. Hydroforming techniques were developed to make parts that are beyond the capabilities of tube and sheet metal forming methods available at the time.

The fundamental strength of tube hydroforming is the ability to make supporting members that use material and energy efficiently while positioning surfaces and holes accurately and repeatably. This ties in well with the industry trend to increasing part complexity and more efficient processing.

As part shape complexity increases, the tube resists being contained by the forming die. Where it squirts out,

the situation in Figure 1 occurs. Two disadvantages that occur are an undesirable sharp ridge or pinch following part of one or both split lines and the cavity may not fill. Preventing this is obviously necessary.

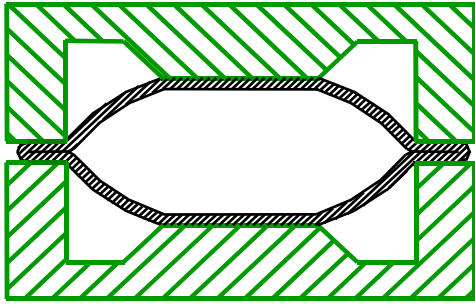


Figure 1 'Pinching'

Two distinctly different approaches have been developed to prevent these problems and greatly improve achievable forming complexity. They have been described as pressure sequence hydroforming (PSH) and high pressure hydroforming (HPH). It has been common to focus purely on pressure used during the processes, but it is only part of the story. The fundamental technical distinction between the 2 processes is how pinching is prevented. Both use a combination of cavity sizing relative to the starting tube diameter and internal pressure after the die closes, while PSH also uses low pressure water filling the tube while the die is closing.

The following explanation of both processes has been presented conceptually previously. It is included because it is important that the reader understand the difference between the processes and how the economic benefits of pressure sequence hydroforming can be accessed without compromising design flexibility. In a number of ways PSH design flexibility is superior.

PRESSURE SEQUENCE HYDROFORMING (PSH)

This method of preventing pinching is less intuitively obvious than the other. Pinching is avoided by filling the tube with low pressure water as the die closes on the tube, which is minimally smaller than the die cavity.

As seen in Figure 2, the die halves contact the round tube in view (a). The normally round starting shape is forced toward the intended shape as the die closes as in Figure 2(b). Up to this point there is no water inside the tube. The tube is filled with water (signified by shading) at stage 2(c) and low internal pressure is applied while the die continues to close.

This is the key difference that distinguishes this process. The periphery or circumference of the starting tube is designed to be close to the desired periphery of the finished part. Coupling this with pressurized water to keep the tube wall in contact with the die cavity wall

effectively harnesses the large mechanical force caused by the closing press and die. This force resolves into

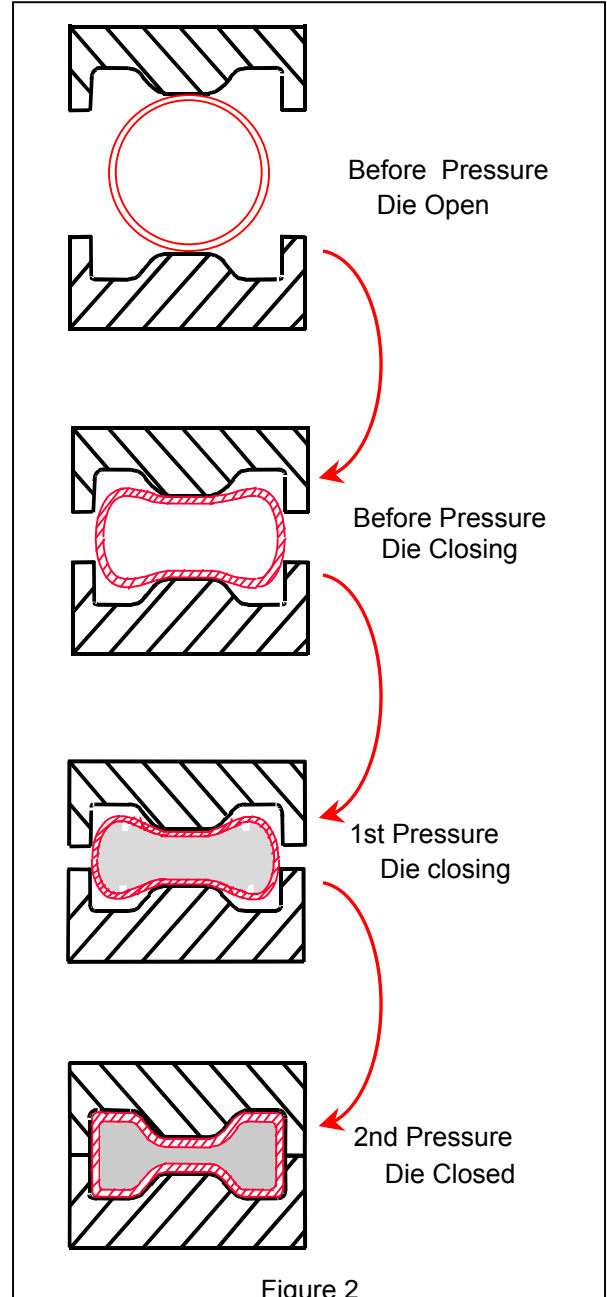


Figure 2

compressive forces that act parallel to the tube wall as shown in Figure 3, which is part of the reason it is so beneficial. Tensile or stretching forces usually used in stamping and other hydroforming techniques can cause material cracking. The closing die deforms the tube wall from the outside and water in the tube gives some level of control over the inside surface. The water resists unwanted deformation (ie crushing or ripples in the metal) and facilitates a controlled reshaping of the cross section throughout the length of the part.

This efficient combination of hydraulic and mechanical forces used at proper points in the cycle facilitates very complex part forming. Using low pressure water when

the die is closing allows material to slide on the cavity surface and get pushed into place using the power of the press. This forming mechanism is conceptually different than the 'ballooning' model often presumed to be used for all hydroforming. It offers a number of process efficiency and design flexibility improvements that must be understood in some detail to appreciate their value.

As the die comes closed, forming is almost complete. Pressure is increased to a higher level (normally 34-48 MPa) to produce the final form of the part as shown in Figure 2(d). Although this range is normal and all that is needed because of the mechanical forming force, any maximum pressure can be applied that is needed for the successful formation of an unusual part (ie 172 MPa). Any holes needed in the part are punched at this stage since the backing force provided by the water is greatest. The main reason for applying this higher pressure is to flatten the planar areas, not to finish forming the corners. As can be imagined, much less pressure is needed for the former than the latter.

Less internal pressure has several benefits including far lower stretching demands on the material, thus increasing the potential range of materials to include HSLA, ultra high strength and stainless steels, as well as aluminum and lower elongation materials. The tube wall can move over the cavity surface more readily and wall thickness is virtually unchanged from the bent tube blank placed in the die prior to hydroforming (Figure 3). Reduced springback results in dramatically improved dimensional stability relative to welded stampings.

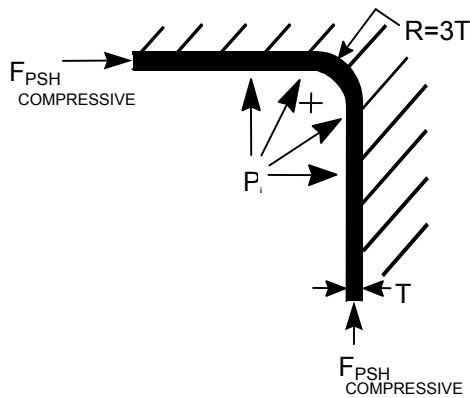


Figure 3

For processes that depend on internal pressure to 'balloon' the part, any change in these properties requires a proportionate change in fluid pressure. PSH is not sensitive to material strength, wall thickness and cross sectional corner sharpness. A dramatic change in any of these properties does not significantly change the required internal pressure.

HIGH PRESSURE HYDROFORMING (HPH)

This process avoids pinching by intentionally designing the tube periphery to be smaller than the desired

finished product. The steps of the process below shows starting with a round tube (a) and fully closing the die before filling it with water (b). Often one of the results is undesired ripples in the tube wall roughly perpendicular to the tube centerline such as those shown in (b) & (c).

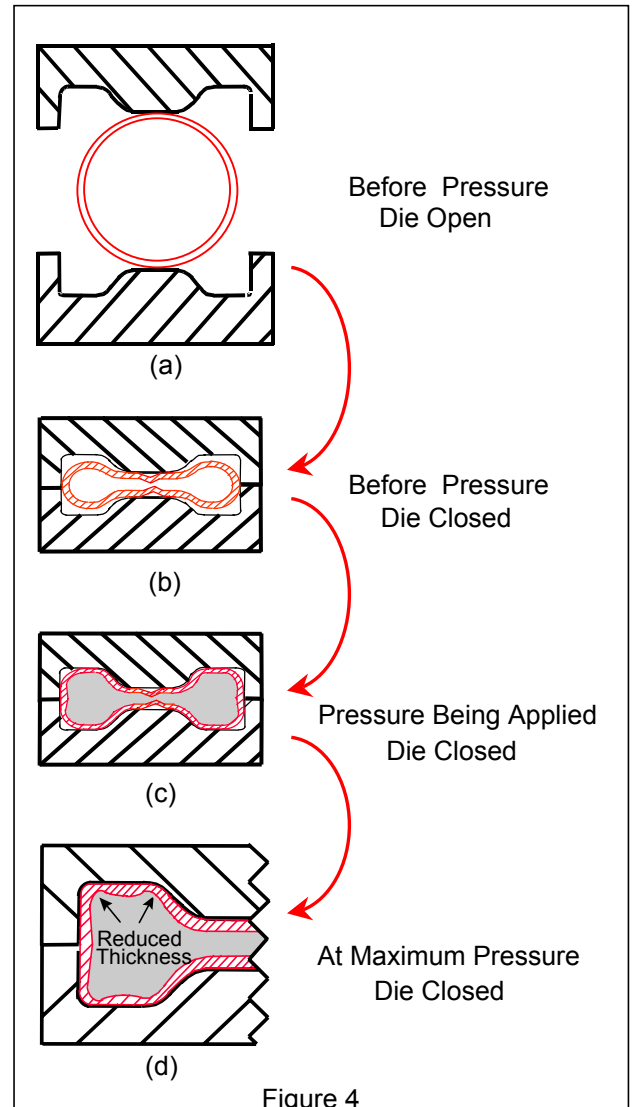


Figure 4

A 2nd more significant result is the difference between the tube and die cavity peripheries. This causes the situation also shown in Figure 4(b) where the cross sectional corners are left unfilled immediately after the die is closed, but the material thickness is still the same as the bent tube blank. When a flat die surface compresses a round tube, ripples such as those shown in (b) and (c) occur.

The next step is shown in Figure 4 (c) where water fills the tube. Pressure is applied such that material stretches into areas where the tube does not fill the die cavity. After pressure has been increased sufficiently to fully form the part, it appears as in Figure 4 (d).

A key result of this forming technique is that wall thickness becomes uneven, often in the pattern shown

in Figures 4 (d) and 5. The latter shows the internal pressure stretches the material into the corner, inducing tensile stresses in the tube wall. The wall thins because as forming progresses from 4 (b) to (c) and (d) the tube wall contacts the die cavity surface. Since the pressure needed to stretch the material is greater than is used at this stage of PSH, the material tends to stick to this surface. As a result the stretching concentrates on an increasingly smaller portion of material.

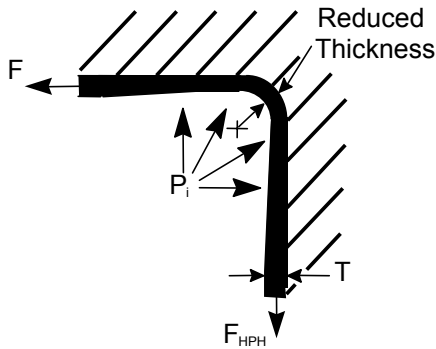


Figure 5

High pressure is needed primarily to push the material into the cavity corners. It is the only tool available to 'finish off' the part. The mechanical forces that are harnessed by PSH are largely unavailable because the cavity has to be bigger than the start tube to avoid pinching. Most of the expansion takes place at lower pressures. A secondary reason for high pressure is the need on many parts to iron out the ripples caused by closing the die on an empty tube.

The important benefits of HPH are reduced springback resulting in improved dimensional stability and that pressure is available to push material anywhere, provided the material is sufficiently formable. It is particularly well suited for 'T' and 'Y' shaped parts.

The biggest process challenge is reducing and living with the effects of wall thinning brought about by the start tube versus die cavity periphery difference. Forming with internal pressure makes friction an impediment since it causes the thickness variation shown in Figure 5. One way of reducing this problem is feeding additional material into the die which is only effective near the ends.

PART DESIGN AND PROCESS COMPARISON

Following is a comparison of 2 functionally and physically similar engine cradles shown in Figures 6 (PSH technique) and 7 (HPH technique) and the processes that make them. It is a clear and specific way to contrast some differences between these techniques.

The respective designs have several similarities and differences as described in detail in the sections below.

The Figure 6 part is 1090 mm wide x 1050 mm long. The periphery is the same as the starting round which is 220 mm and average corner radius is 4.4 times wall thickness (T) with some as low as $3.2T$. Corner sharpness as a multiple of wall thickness is a clear expression of corner severity independent of specific material considerations. The bending and formation of the front corners allows front body mount bushings to be welded in the tube, giving probable strength and cost benefits. Measurements taken on both parts half way between the cross bar and the leg end show they are the same width within 10 mm.



PSH
Figure 6

HPH
Figure 7

The Figure 7 part is 760 mm wide x 990 mm long. The periphery varies from 206 - 217 mm and the starting round is 204 mm. The average cross sectional corner radius is $6.7T$. The 2 benefits of these larger radii for HPH is that forming pressure and stretching demands on the material are reduced proportionately.

Brackets to attach the front bushings to the HPH tube are needed. The larger bend radius, excessive total material elongation requirements or other functional considerations may have prevented bending the tube to incorporate the bushings.

The cross section shapes are generally similar throughout each part, with some notable differences.

The cross bar of the HPH part is 2-3 mm smaller in height and width, as would be expected with a smaller start tube and no expansion. The cross sectional corners average $7.4T$ compared to $4.2T$ for the PSH part. These larger corners allow the section to be a little higher and/or wider, but reduce the width of flat areas and section strength.

The front bend regions of the PSH part are about 8 mm wider with the same height as the HPH part. The legs sections are roughly the same height and width and purely rectangular for HPH. By comparison, the PSH part includes significant indents to accommodate constraints imposed by nearby components. The corners average $4.3T$ on the PSH part vs. $5.8T$ for HPH.

The part in Figure 6 has been produced at a rate of about 600,000/year with 2+ shifts for more than 3 years. The production equipment for the Figure 7 part was designed to run 1,000,000/year on 3 shifts and has been

in production since Feb./98. Actual history for the latter is not available.

PROCESS FLOW DIAGRAMS - The process steps for PSH and HPH are shown in Figure 8 and 9. The differences of note are a simple preforming fixture vs. a small preforming press and the added steps of lubricating, cleaning, rust inhibitor application and drying. The last 3 operations were shown separately for clarity, but they occur in a single piece of equipment.

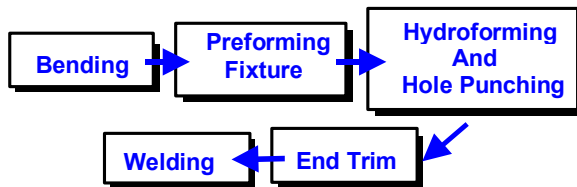


Figure 8: PSH Process Layout

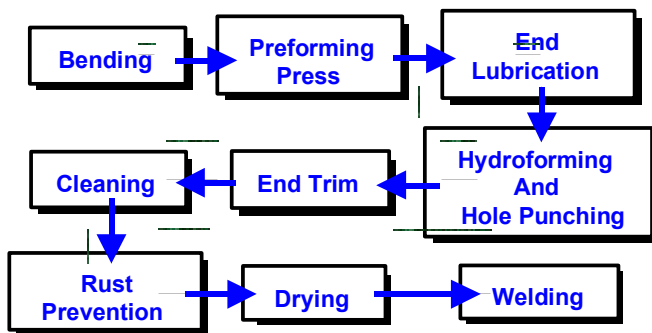


Figure 9 HPH Process Layout

These extra operations, and dealing with the lubricant residue from cleaning adds cost.

MATERIAL AND TUBE SPECIFICATIONS - The part in Figure 6 uses 300 MPa minimum yield HSLA steel, which was chosen by the customer based on part function with no process restriction. The tube is 70 mm diameter with 2 mm wall thickness. Normal commercial standards for cut length, cleanliness and seam weld quality are sufficient for PSH production.

The Figure 7 part uses 240 MPa boron mild steel in a 65 mm diameter with 2mm wall thickness. It is apparently dictated by the process and will cost more than mild steel, but comparison to 300 MPa HSLA is unclear. More stringent standards of cleanliness, length and weld quality are required which tends to increase cost.

BENDING - The respective straight, round tubes are bent on CNC benders to approximate the final part centerline profile. Both experience normal thinning on the outside of bends and thickening on the inside.

The PSH part has 9 bends, the greatest of which is approx. 140°. The centerline bend radius is approx. 115 mm. This more complex profile was worked out to

accommodate the function of the related components in the most economical way.

The HPH part has 5 bends and the largest is about 100°. The centerline bend radius is approx. 140 mm. The larger bend radius reduces demands on the material and leaves more formability for expansion during hydroforming. The simpler bending program means that bending cycle time is substantially less and allows the use of only 2 benders to produce this high volume part.

It is important to note that cycle time for a part may be limited by bending, like, for example, the PSH part where the number of bends is high. The cycle time for the hydroforming press can be faster, but is not taken advantage of because the benders cannot keep pace.

PREFORMING - The PHS part in Figure 6 is placed in a press loading fixture where it is made into an oval shape through the part legs by using simple blocks sliding perpendicular to press travel. This is done because the leg width is substantially less than the starting tube diameter.

The HPH part in Figure 7 undergoes a much more intense preform in a 200 tonne press. It is likely done to form the round starting tube closer to the desired rectangular shapes of the final part. This is necessary because the periphery is not expanded in this area and the steel would likely not be contained within the die cavity, or pinch. Using the PSH technique would make this type of preforming unnecessary

HYDROFORMING - Following preform the HPH tube ends are lubricated with oil before being loading in the press. Dramatically different forming pressures are required. The HPH part requires 152 MPa or 1,500 bar. This pressure over the surface area of the part is contained by a 3500 tonne hydraulic press which requires 630 kW/press to operate. The PSH part is not lubricated and needs only 48 MPa or 475 bar and an 1100 tonne hydraulic press at 94 kW/press.

The PSH part has 21 holes of varying sizes, the largest being 42 mm in diameter. The remaining holes are medium and small rounds, as well as rectangular, which are punched in the hydroforming die with slugs attached.

The HPH part has 22 holes with the largest being an 18 x 26 mm slot. The rest are small round, rectangular, and hexagonal with all slugs attached, indicating that all were punched in the forming die.

Both parts are then trimmed at an end shearing station and inspected for hole presence. Additional material is trimmed to accommodate rear mounting bushings. The HPH part requires washing to remove the oil followed by application of rust inhibitor and drying to complete the process, while the PSH part does not.

WALL THICKNESS DISTRIBUTION – Figure 10 shows the wall thickness pattern for each of the parts in the leg area where the HPH part undergoes expansion to avoid pinching as described previously. Measurements were taken in a straight section to avoid the wall thinning and thickening effect of bend areas which should give a clear comparison of thinning from hydroforming. They were taken every 10° for a total 36 readings around the circumference.

Wall thickness for the PSH part is virtually the same as the starting round tube, since there is no expansion. The section shown has a higher than normal range of 0.10 mm or up to 5% above the minimum reading.

The 2 sections on the HPH part vary substantially more (22%) from highest to lowest readings. The amount of expansion is approximately 5%. Even though sections 1 & 2 are approximately 40 mm apart there is a noticeable difference in the thinning pattern. Stretching in two of the cross sectional corners are the reason for the low measurements between 100 and 150° as well as 200 and 250°. The other 2 corners in these rectangular sections do not exhibit this pattern, perhaps because the start tube is closer to that side of the finished section.

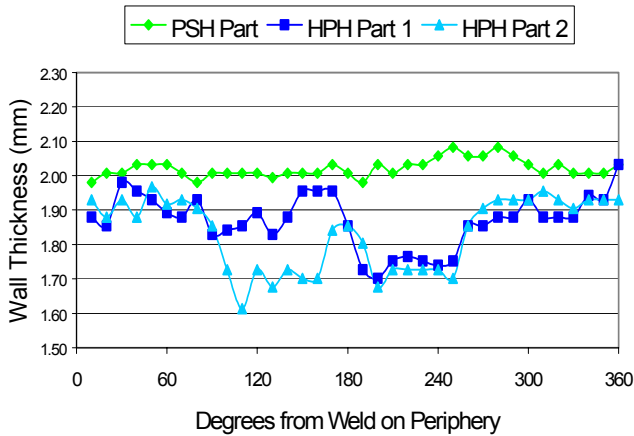


Figure 10 Wall Thickness Comparison

Failure or rupture in such sections normally occurs at the tangent points of the corner radii. It is noteworthy on section 2 at 200 and 250° and particularly at 110° that thickness abruptly drops, suggesting the onset of necking. Extending into this zone of plastic deformation may reduce the fatigue life of the product before cracking, depending on stress application.

Wide variation in wall thickness affects weld quality. Conditions set for thicker material in flat areas may burn through thinner corners or settings for corners may cause cold welding in thicker areas. Controlling this is important since many structural hydroformed parts have other components welded to them.

INTERNAL PRES. & HYDROFORMING EQUIPMENT - Figure 11 shows the large difference between PSH and HPH internal pressure and hydroforming press size. As

expected, press size is proportional to the pressure. The fact that PSH can use pressure less than 1/3 of the HPH need means that much smaller, faster equipment can be used as shown in the later cycle time section.

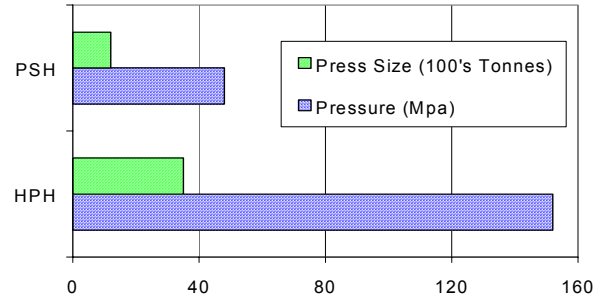


Figure 11

This benefit is compounded by the fact that changes like stronger material, thicker material or sharper cross sectional corners can be designed in a future product without changing pressure and being able to use the same PSH press. Presuming that using high pressures always maximizes design flexibility is not always true.

EQUIPMENT POWER & ENERGY CONSUMPTION - This is an important measure of the relative efficiency of the processes. Figure 12 looks at the presses since good comparable data is only available for them. The

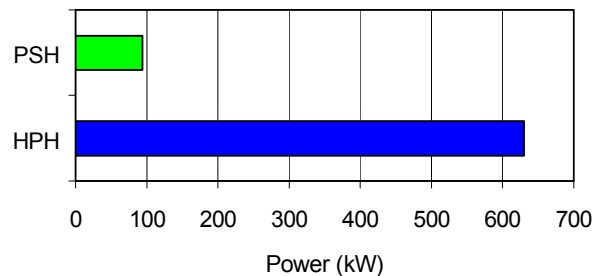


Figure 12

PSH value is for an 1100 tonne press and the HPH value is for a 3500 tonne unit. For the latter there are 2 which will double the energy consumption indicated.

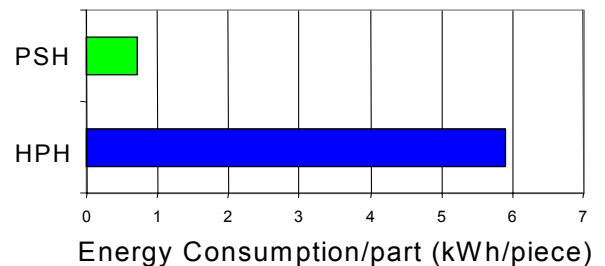


Figure 13

Figure 13 attempts to consider these factors together to give a clearer comparator. Energy consumption per part is important and is based on the rated power of the

respective units. These numbers are meaningful relative to each other but may not represent actual energy consumption. They give an idea of cost magnitude.

When considering the whole process, the difference shown here is only part of the story. Energy needed for the HPH equipment that preforms, lubricates, cleans and dries adds to the already large difference. Although not shown in Figure 6, the end trim is similar to Figure 7, so that assumably energy consumption is the same.

CYCLE TIME - PSH cycle time is <22 seconds while HPH takes >34 sec. or more than 50% longer. These times are for the production of one press for each process. As previously noted the HPH system has 2 presses for a line production rate of 17 sec..

This significantly longer time may be explained by larger presses being inherently slower, as well as the longer time it may take for the HPH sequence to complete forming, including end feeding. Due to the great similarity of the parts from the functional perspective it seems unlikely that this time difference is driven by some part design constraint. This greater cycle time has made 2 presses necessary to meet the volume requirements.

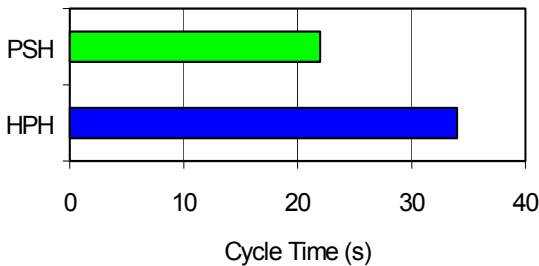


Figure 14

PSH could provide 800,000+ parts from one 1100 tonne press at a similar rate of use. The difference of 200,000 or fewer parts would have to come from a second press, but most of the available production time could be used for another part. Cycle time is a big factor in the part process cost, but also determines the production capacity of the equipment in the allotted time (ie 2 or 3 shifts). This in turn dictates the amount of capital that must be committed to produce a given part volume. Minimizing this expenditure and cycle time are important keys to financial efficiency.

REQUIRED FLOOR AREA - The PSH production cell occupies 240 m², while the HPH equipment needed to produce a functionally similar part requires 1090 m² as shown in Figure 15. This is because equipment required for HPH are not needed (ie no lubrication, cleaning, rust protection application or drying equipment, 2nd hydroform press or preform press) for the simpler PSH process.

The space occupied does not include assembly and welding operations for either process.

The cost associated with this additional space is considerable. For a proper comparison it must be remembered that the volumes are different and that for PSH, 'part' of a press, as explained earlier, would likely be needed to produce 1,000,000 parts/year. Even when including this, the PSH total space requirement would likely not exceed 325 m².

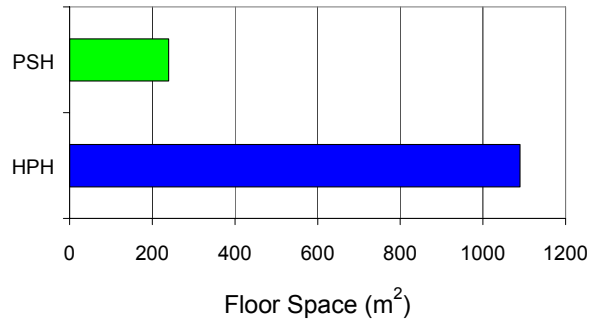


Figure 15

Presumably other related floor space requirements such as inventory of tubing and finished product would be comparable for a given part and annual volume.

DIMENSIONAL CAPABILITY

Comparative data from HPH components is not publicly available and therefore discussion of the respective parts is not possible. Instead PSH production data is discussed. In comparison to stampings that are welded together, hydroformed parts have a dramatically improved level of dimensional capability.

The following data is taken from 3 PSH production cells that show the capability levels that are being achieved on several types of part features. This data is included to increase awareness of capability levels being produced today. Such data gives a firm point of reference rather than promises.

CROSS SECTION WIDTH – When complete the part in Figure 16 is assembled with brackets. It uses 63.5 mm diameter, 2 mm minimum wall thickness, 310 MPa min. yield strength HSLA steel tube. Production cycle time is <22 seconds and about 250,000 parts/year are made in a single cavity die in one press in North America and 400,000 parts/year in Europe with a similar setup.

Manufacturing scrap from bending, hydroforming with hole punching in the die and shearing is 0.5%. All data is taken prior to assembly or welding operations.

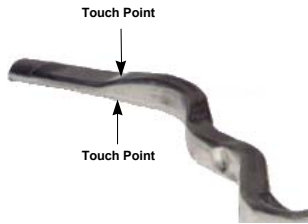


Figure 16

Cross Section Width

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

Table 1

SURFACE LOCATION, CENTER SECTION, 4 BENDS - Figure 17 shows a part with 1 bracket welded to the front surface. It uses 76.2 mm diameter, 1.3 mm minimum wall thickness, SAE 1010/1008 galvaneal steel tube. The cycle time is <18 seconds and is produced at a rate

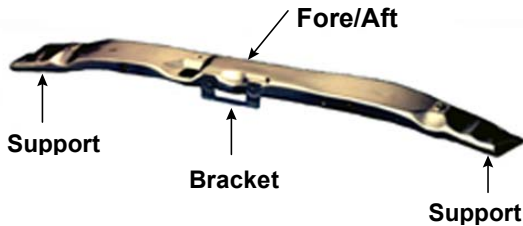


Figure 17

Center Section Fore/Aft

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

Table 2

of approximately 450,000 part/year. Manufacturing scrap rates from bending, hydroforming with hole punching in the die and shearing normally total 0.2%. Welding a bracket to the tube causes scrap of 0.4%. All data is measured prior to welding.

SURFACE LOC., CENTER SECTION, 11 BENDS - The part has three brackets welded as shown in Figure 18 and provides most of the structural strength for the instrument panel, supports the steering column and is part of the body in white structure. The part uses 50.8 mm diameter, 2 mm minimum wall thickness, SAE1008/1010 mild steel tube. Cycle time is <17 seconds and has achieved a rate 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 with a single cavity die and no backup tooling.

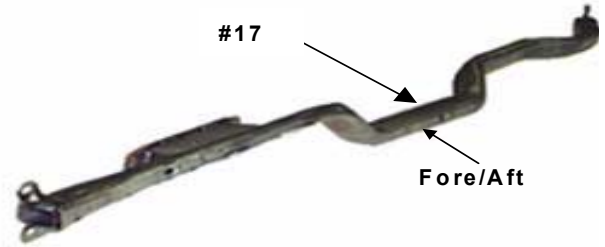


Figure 18

Center- Fore/Aft

Sample Period	4 Months
Sample Size	1200pcs.
Tolerance	±1.5 mm
Range	1.37mm
Std. Dev.	0.17
C _p	2.94
C _{pk}	1.87
At C _p = 1.33	
Tol. =	± 0.68mm

Table 3

Hole #17 (5.68 mm Diameter) At Tube Center -

Long Term			
	X (Surf.)	Y	Z
Sample Period	6 Months		
Sample Size	30 pcs.		
Tolerance (mm)	±1.5	±1.0	±1.5
Range	0.84	0.18	0.96
Std. Dev.	0.26	0.05	0.25
C _p	1.90	6.25	2.02
C _{pk}	1.56	4.42	1.93
At C _p = 1.33			
Tol. (mm) =	±1.04	±0.20	±1.00

Table 4

Manufacturing scrap rates from bending, hydroforming with hole punching in the die and shearing total 0.5%. Welding causes another 0.5%.

CONCLUSIONS

The preceding data is from production processes and the HPH information has been publicly released.

The process descriptions explain how the 2 technologies work from a purely technical viewpoint. It also explains why forming the part with low pressure applied at the right time provides a number of options, advantages and economies that are not otherwise available.

The process comparison section also shows that being able to use low pressure is a desirable goal with some big benefits if the functional requirements of the part are being met. The number and magnitude of the benefits should be compelling enough to encourage an objective assessment of which process offers the most benefit.

Process simplicity differences are shown graphically in the respective process flow diagrams. The additional HPH process steps add capital and part cost.

The last section uses long term production data in 4 different situations on 3 high volume parts that goes past what can be promised to show what is being done. Although comparable data is not available publicly for parts using the HPH process, this PSH data shows what is being done in daily production.

Presuming that design flexibility is always best served by using HPH oversimplifies the situation. Design flexibility has many facets and considering one too highly (surface placement and variable periphery along the part length) leaves the possibility that others are given too little consideration and the wrong conclusion is reached.

The 2 engine cradle parts being compared in this paper are similar in function and tube size. The PSH part length and width are greater. More demanding bending to provide for locating the front body mount bushings in the tube rather than on a bracket and the generally sharper cross sectional corners indicate more design flexibility. Wider choice of material is a major aspect of design flexibility that also favors PSH. Additionally, high strength or thicker material and sharper corners are design options with little or no impact on internal pressure or processing cost for PSH.

It is not apparent that section variation in the HPH part plays a significant functional role or provides a benefit.

Sections of the part can be expanded with PSH, depending on the requirements, but attention must be paid to ensure increased cost is justified. Where needed, an HPH process can be run on PSH equipment, but the economies and efficiencies discussed in this paper would not be available. It seems sensible to incur these additional costs only when needed rather than presume an HPH process must be used for all parts.

Pressure sequence hydroforming offers a high degree of design flexibility with an efficient, simple, effective process while delivering excellent dimensional stability.