2000-

Hydroformed Automotive Components: Manufacturing Cost Considerations

Gary Morphy, P. Eng.
Vari-Form Inc.

ABSTRACT

The primary motivation that drives the popularity of tube hydroforming, particularly in the automotive structural industry is the anticipation and expectation of significant savings compared to established methods, like stamping and welding. These potential savings can be divided into 6 main categories. They are capital (facilities and equipment), tooling and part costs, as well as, weight reduction, assembly simplification and performance improvement. Careful and knowledgeable consideration of these factors with the goal of achieving the best balance should lead to choosing the most advantageous manufacturing option. Overemphasis on one factor may lead to disappointing results in some of the others.

This paper concentrates on the 1st 3 categories examining the impact of design decisions on overall cost. Due to the 'newness' of hydroforming, the possibility that design decisions made with partial knowledge may build in extra cost is higher. The latter 3 receive less attention, limited to how they relate to the cost categories.

Each of the 3 cost aspects will be broken down to show how cost is incurred and give more insight into minimizing it. The tradeoff between functional features and cost will also be examined to rationalize when increasing the latter is justified by improvement of the former. This paper should help demystify a relatively new technology and facilitate understanding the most economical way to make parts for a particular function.

The most knowledgeable initial decisions are essential because once a manufacturing path is chosen, changing direction is more difficult with each passing step.

INTRODUCTION

The cost of making any product is fundamentally important, but usually it is difficult to know what the most cost effective alternative is. Generally, industry is compelled to reduce costs and/or increase performance or 'do more with less' to remain competitive. This is particularly true in the automotive industry. Tube hydroforming offers the potential to accomplish both simultaneously, with advantages over some stamped and welded assembly applications. Cost and the factors affecting it will be this papers focus.

Objective insight into overall costs can be difficult to obtain, particularly when trying to make an 'apples to apples' comparison of differing manufacturing processes. This difficulty is magnified when the detailed knowledge required to make this comparison meaningful is not common, as for tube hydroforming. It can be compromised by technology favouritism, where positive features are emphasized while disadvantages are downplayed. Lastly, insufficient time to properly weigh the options is a way of life in the automotive industry.

This last point is magnified when not knowing and understanding the available options limits effectively choosing the best ones. Also, if you do not understand where cost comes from and why it is necessary, the chances of minimizing or intelligently reducing it are slim.

This analysis will consider specific cost points, but it will do so qualitatively rather than quantitatively. This should help the understanding of how each factor affects overall cost. However, the magnitude of each cost factor will vary for each application. Ideally all costs will be determined, but where time prevents it, this paper will help make relative judgements. A 2nd reason for this approach is the understandably reticence of companies to detail their costs for competitive reasons. A 3rd is that each factor applies differently to each part and a decision making framework seems to be a more generally applicable and logical approach.

Costs can be attributed to 2 general causes; part and process design. Many factors are affected by both. It is important to understand the distinction, because part design driven features are required for the part to function properly. However, process driven features may be avoided by using alternate manufacturing steps.

Six factors stand out as most important when contemplating how to achieve the best balance between performance and economy. They are capital (or equipment), tooling and part costs, as well as, weight reduction, assembly simplification and performance improvement. Careful examination of these factors should lead to the 'best' option.

This paper concentrates on the 1st 3 categories and examines the impact of part or process design decisions on overall cost. Less attention is given to the latter 3, limited to how they relate to the cost categories.

HYDROFORMED PART COST CONSIDERATIONS

As with all automotive components, minimizing cost is an overriding principle that affects all else. The goal is to find the cheapest method to produce a part that achieves required quality, performance and delivery standards. Some general principles have a substantial effect on product cost and the wisest way to produce. Some even indicate if hydroforming is the most suitable method.

An important question is whether hydroforming a component is the most efficient alternative. The relatively abrupt popularity of this technology can cause a leap to the conclusion that a part should be hydroformed, even when it is not supported by objective cost comparison with other methods.

Increasing annual and overall volume, tends to reduce cost. Reducing part count by consolidating several parts into 1. Equipment uptime (the time that it is doing productive work) is a big manufacturing cost issue.

As with all manufacturing processes, many considerations intertwine to form the reason a part is made a certain way. In some situations, particular methods to handle these considerations are accepted as normal or 'the way' to do it with insufficient understanding of the interrelationships between them. Understandably, the most efficient and effective solution rarely results. Separating the threads and distinguishing them from each other is an important task to make sense of which add value (equivalent to or surpassing its cost) to the subject part and which do not.

Deciding the best part design accompanied by the process necessary to make it is tedious, but the ultimate reward of the assurance of competitiveness.

DESIGN FEATURES AFFECTING COST

A distinction should be made between design features that serve the part function and those that cater to one or more steps in the process. The first will be discussed in this section, while the latter will be listed at the end.

Bend placement relative to other bends (how close they can be), centerline radius and angle have a large influence on the utility and cost of the part. Cross section shape is also important for the most effective final product and can impact cost. This includes corner sharpness, which may aid in hole placement or improving welding conditions. Elevated material yield strength can be desirable for better crash energy absorption. Thin material reduces weight, while thicker can add sufficient section strength through areas that are too constricted for a more efficient design.

Dimensional stability is important and 'calibration' pressure is used to improve it in the expansive method described below. Hole placement is crucial for many components to become part of an effective structure. The best case is putting them in the hydroforming die. Where they cannot be, secondary techniques are available at increased cost and decreased position repeatability.

Cross sectional corner radii, yield strength, and thickness affect the maximum pressure needed when expanding. Hole quantity and position can be limited by the maximum forming pressure needed. Removing too much metal for punching units can weaken the die enough that the cyclic pressure loading could break it.

PROCESS FEATURES AFFECTING COST

The biggest influence on cost is how pinching is avoided for more complex part shapes (Figure 1), which includes most parts designed for automotive structural purposes. This in turn determines what maximum pressure required to properly form the part.

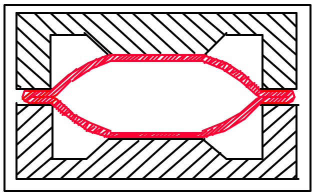


Figure 1

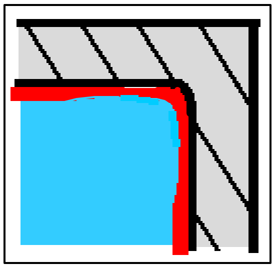


Figure 2

When the tube is expanded to varying degrees, the die is fully closed before water is injected. Cross section corners are not filled where expansion is to occur. Water is pressurized to stretch the metal to fully form the part, which thins the material, particularly in the corners (Figure 2). Pressure is usually further increased to 'calibrate' the part, meaning to improve dimensional stability. Maximum pressure impacts equipment, tools and part costs as detailed below.

When a part is not expanded the periphery of the bent tube and the die cavity are essentially equal along the length of the part. This fundamentally different method of hydroforming reshapes the tube cross section as the die cavity closes on the tube that is full of water (liquid mandrel) that is maintained at a low pressure. As a result, the required maximum pressure is reduced to 1/3 – 1/5 of the pressure needed for the expansive method. Since there is no expansion there is no wall thinning or the common methods to reduce it.

CAPITAL AND EQUIPMENT COST FACTORS

These costs include the equipment necessary to make the desired part in the volume required.

Automation has a number of attractive features, which mostly relate to reducing part cost, but requires a substantial equipment cost increase. Decisions can be made based 'on the numbers', namely that the piece cost savings 'justifies' the increased capital expenditure. Too often this approach ignores the peripheral issues that can change the final effect on overall cost. An example is minimizing direct labour during process design and having to increase skilled labour (maintenance/engineering) to address unforeseen issues to keep the line operating. Another can be process 'uptime' that is less than expected.

As with most things, the best approach should be reasoned out logically and carefully. Complete automation may not be the most efficient solution when things like defects in the straight/bent tubes, preforming or hydroforming may stop the production sequence.

MATERIAL – Tube hydroformed parts replace stampings that are assembled into a tube-like structure. As a result sheet metal coils that would have gone into making stamped and welded assemblies are converted to tubing enroute to hydroforming the final part shape. Generally, since engineered scrap is substantially lower for hydroforming, material use should be somewhat lower for a given number of parts. Also, material required will decrease since it is common for hydroforming to reduce final part weight. Therefore, it does not seem likely that material production capacity will need to increase to serve the hydroforming industry. The processing route merely changes.

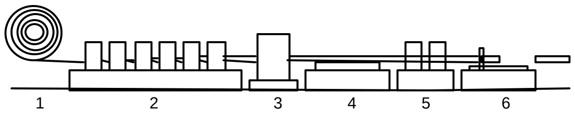
For applications where expansion is not needed or considered the best solution to the design problem at hand, normal existing grades of mild, HSLA or stainless steels, as well as aluminum can be hydroformed.

In order to satisfy the increased formability demands of expansion, new material compositions are often needed. It is expected that cost will increase, since 'special' usually dictates additional process steps, alloying elements, etc.. It is reasonable to expect that to accommodate these special needs that new equipment may be necessary. This will be reflected in the cost of the material.

TUBE MANUFACTURING – Where excess tube production capacity exists there is no need to add equipment to respond to the increased demand for tubing that accompanies the move to hydroforming. However, to respond to this demand it is likely that many tube companies are contemplating or have ordered additional tube mills. When specifying such equipment it is wise to include the ability to produce high diameter to wall thickness (D/T) ratios and ultra HSLA steels. Making efficient automotive structures will logically trend in both of these directions for applications that benefit from it.

Methods used to make tubing include seamless, high frequency, laser (continuous and batch), but the most common by a wide margin is electric resistance welded (ERW) tubing. Cost is the biggest reason. The others offer advantages such as superior weld seam integrity, smaller heat affected zone (HAZ), non-constant cross section, etc., at a higher cost. The applicable benefits must justify it.

Tube mills can also be specified to use more rolling stands to shape the round more slowly than is the case on most current mills. This uses less material formability (especially n-value), leaving more for bending and hydroforming, which is important when expanding the tube. Cost of the mill increases accordingly.



1 - Steel Coil, slit to required width
2 - Tube Forming Rolls, flat stock formed through roll sets into tube
3 - Seam Welder, high frequency with an induction coil
4 - Cooling Section
5 - Final Precise Sizing
6 - Flying Cut off, cut to length at line speed

Figure 3

The addition of new tube mills may or may not increase the cost of tubing directly, but it will likely have a positive effect on the quality of tubing and the ease with which it can be produced. New techniques of forming, welding and verifying its quality are the main reasons.

BENDING – This is a crucial aspect of the normal production sequence for a hydroformed structural part. There are a number of different approaches, but the most common is CNC rotary draw bending. It provides a combination of speed, accuracy, repeatability, some design flexibility and control of metal thinning/thickening that is attractive for this type of product.

They can be loaded and unloaded manually or fit with automated equipment, which reduces direct labour cost, while increasing equipment cost substantially. The manual approach has an operator who can observe and diagnose many problems and resume production relatively quickly. The automated approach may have difficulties achieving similar 'uptime' since any problem will stop production until maintenance or engineering can diagnose and correct it.

Standard CNC machines restrict part design as pointed out in the part cost section. Alternatives like machines with multiple tool sets lessen these limitations, but substantially increase equipment, tooling and part cost.

When the need for a shorter clamp straight or different bend radius is sufficiently high a multi-position style of CNC bender can be used. A regular CNC bender is fitted with a bend arm or bed that moves vertically with a stack of 2 or more tool sets. This addition increases the bender cost by 30% or more.

Another alternative to consider is a series of bending machines that are specially designed to lower part design limitations by doing each bend in a sequence much like a progressive stamping die. This method may achieve higher production rates than several CNC benders, thus making the equipment cost attractive. Available manufacturing space may also favour this sort of bending arrangement. It is an attractive option for applications where the sum of these 4 advantages is sufficiently high.

Other considerations are manufacturing cell flexibility and satisfying service requirements. For the first, equipment changes would be far more difficult than with a CNC bender (switch to another program) if one press needs to run 2 or more products. Also, this equipment must be stored and used periodically for service parts at least 10 years after the end of production.

A hybrid system that combines CNC and dedicated benders may be a wise choice for some applications.

PREFORMING – Preforming can be fit loosely into 2 categories. Figure 4 shows compression of a round cross section in 1 direction while allowing free forming perpendicular to that. The equipment arrangement is relatively inexpensive (because forces needed are low).

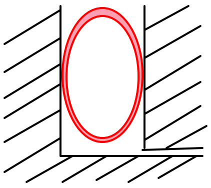


Figure 4

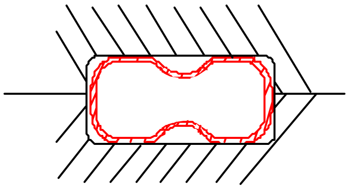


Figure 5

Figure 5 illustrates a situation where the cross section is fully constrained and formed more closely to what the desired final cross section is (in this case rectangular). The much higher forces exerted may require a small press and a tool that captures the affected portion of the part. This makes equipment, tool and part cost substantially higher. The main benefit is that the wall thinning pattern in Figure 2 and its accompanying challenges can be largely avoided.

A third type is hydroform preforming expands where needed from the starting round cross section to a larger round. The benefits are that wall thinning is in proportion to the amount of expansion, but relatively constant rather than the more normal pattern in Figure 2 and avoids the techniques to reduce this effect. The amount of pressure needed for this expansion is relatively low (for common tube sizes and wall thickness' 10-25 MPa). A press will be needed to hold the die closed, but may be able to be the same used for hydroforming with appropriately increased bed size and tonnage. This method will substantially increase equipment, tool and part cost, but may be more attractive than alternative solutions.

LUBRICATION – The detrimental effects of friction are avoided when the part is not expanded and therefore no lubrication is needed.

Applications that include section expansion and end feeding, commonly require lubrication of some variety. The goal is reducing the coefficient of friction as well as the tendency of material to thin more in section corners. The cost impact can be minimized by ensuring that application time is minimal (no waiting before next process stage) and that the lubricant does not have to be removed after processing.

The nature of the lubricant and how it must be applied affect equipment cost. Some lubricant types are petroleum based (ie oil, grease), chemical formulations (perhaps water soluble) and dry films. The first will almost certainly need to be cleaned from the part after forming is completed. The middle group may or may not need to be removed. The last category of lubes can probably be left on the part, but it depends on the situation.

The most common application methods are spraying, dipping or brushing. The latter is used for localized application, often manual in which case equipment cost is very low. As would be expected labour cost may be higher than for spray or dipping.

A 4th application method that is convenient, since no equipment is needed, is adding it to the hydroforming fluid. It likely provides less lubrication, but is sufficient for some situations.

Where lubrication is required over all or much of the part dipping is a popular option. Depending on how it is used, equipment may be a tray to dip the ends in (common with HPH parts to facilitate end feeding) or a dipping tank to immerse the whole part and a conveying system.

Spraying has some applicability, but also must include equipment to control the atomized fluid that does not land on the part. It can be used for local or total coverage.

For dry film lubricants (dissolved in water for application) dipping or spray must be followed by a drying period, which may be shortened by a drying system. Where such a system is not used drying storage is necessary to hold parts until they are dry.

ANNEALING – This is a method used to increase formability. When not expanding, formability requirements are low so that annealing is not necessary. However, expansion elevates the formability needed to avoid rupture. It is most commonly associated with steel and must be done in a nitrogen atmosphere to prevent oxidization with its undesirable black scale.

The tube can be purchased in an annealed state, which elevates the tube cost to run it through a nitrogen atmosphere furnace, at the tube supplier's facility.

It can also be done locally in the bent areas of the tube, since this material is usually the most aggressively stretched. This leaves the least residual formability for subsequent operations like hydroforming. The probable heating technique is induction because it can heat small areas rapidly.

The equipment must include an induction heating system with a special enclosure to flood the interior with nitrogen. This may be necessary for each bent area.

HYDROFORMING – Hydroforming equipment cost can be a large proportion of the total capital expenditure for a hydroforming line. The main components are the hydraulic press and the pressurized fluid delivery system. There is a wide variance in the cost of such equipment, but the chief determining factor is the maximum fluid pressure needed to complete forming.

When expansion is necessary, design changes such as lower yield strength material, larger cross section corner radii, thinner material or calibration pressure will reduce pressure requirements and equipment cost.

A normal hydraulic press size is defined in 2 ways that are roughly proportional to each other. These are the closing and holding force that the hydraulic cylinders can exert and the bed size, which dictates the size of die that can be accommodated. The first must increase in proportion to fluid pressure for a given part size and configuration in order to keep the die closed.

Other press designs have been developed to provide a low closing force with relatively small cylinder supplemented by a clamping arrangement to hold the die closed under much higher pressure. It appears that capital cost for such an arrangement is not substantially different from a similar sized conventional hydraulic press, but operating costs should be less.

Smaller presses are, not surprisingly, cheaper to buy than larger ones. Installation costs are also much less. Some perceive that it is best to buy a bigger press than is needed for the job at hand to avoid the situation where future part requirements might exceed the limitations of the press. What may not be understood is that beyond the higher purchase cost increased expenses such as cycle time and energy consumption impact production.

Generating the pressure to form the part requires another piece of equipment whose cost can vary widely. Two common ways to generate pressure are with a direct pumping system and using a low pressure pump and multiplies its effect using an intensifier(s). Both have their advantages, but it is difficult to identify a clear 'better' option until a part is selected.

It is safe to say is that cost increases as maximum forming pressure does (more than proportionately). The cost increase happens for several reasons including the size of piping, valves, fittings, pumps, number of intensifiers.

Being able to use lower pressure when not expanding to reshape the cross section substantially reduces equipment costs.

HOLE PLACEMENT – Holes are one of the most important features of a hydroformed part, for attachment to the rest of the vehicle or to other items. The method used to put holes in the part can play a large role in determining part quality and part cost. The 2 options are during hydroforming, or after as a secondary operation.

The most economical, positionally accurate and repeatable method is punching during the hydroforming cycle. Some of today's hydroformed automotive parts have all holes punched during forming. Others punch some and cut the rest after forming. Some punch 1 hole for location purposes and cut all others after hydroforming.

For the first scenario, equipment cost is relatively low since it is restricted to the hydraulic system needed to power the punch unit cylinders. These cylinders must be sized to shear the material around the hole edge and overcome the internal pressure. Extra hydroforming cycle time for piercing can be less than 1 second.

For the 3rd situation, equipment must be provided to cut the material at the required rate and the cutting mechanism must be guided to the proper position and trace the required hole profile. Several techniques can be used including laser, plasma arc and punching. For the first 2, cycle time is largely dependent on the total cut length, number of holes, sustainable cutting speed and the number of laser or plasma units doing the cutting. Decreasing cutting cycle time can usually only be addressed by adding more units.

Laser has a high capital cost. In addition to the laser, a means of guiding it is required, commonly a robot. The area must be enclosed for safety reasons. Cost for a cell, not including tooling can approach $1 million.

Plasma cutting equipment cost is a fraction of laser, but requires more frequent maintenance. It needs a similar guidance system and must be shielded as well. The total system cost is less than laser.

Punching holes can be done after hydroforming, but the metal must be supported on the inside. Therefore, this is only available near the part ends, but can make indented holes for self-threading fasteners. Cost is relatively low.

A common assumption is that slugs cut with either laser or plasma will fall into the part to be shaken out later. While true much of the time, it fails to happen often enough that a verification system is necessary to ensure that they are not there and to knock them out if they are.

The 2nd instance where it is a combination of in-die punching and post hydroform cutting, the punch unit hydraulic system is required for those holes punched in the die along with the hole cutting equipment described above. This method will probably be a medium equipment cost option.

END TRIMMING – Hydroformed parts require a piece of material beyond the finished part end. Its purpose is to provide a sealing surface and make a transition from the finished part end shape and the seal shape. There are several methods to remove it, including saw, laser or plasma cutting, as well as shearing.

Equipment investment will probably be lowest for saw cutting. Shearing is probably next, followed by plasma cutting and the highest cost assigned to laser cutting. The first 2 are only able to make planar cuts (can be at an angle), while laser and plasma are the candidates where more complex end trimming is required. Their higher purchase price is part of the additional cost of non-planar end trimming. Cuts with more than one plane can be achieved with 2 or more shear or saw stations.

Saw cutting and shearing require clamps to hold the finished part and the saw or shear blade must be advance through the part (probably do both ends simultaneously).

The part must also be held for laser and plasma, but probably rotated while the cutting proceeds, since cutting upside down is not a preferable condition. The cutting tip must be moved to trace the pattern of the desired edge and coordinated with the rotation. This will most commonly require a robot, but it may be more economical to build both movements into 1 machine. Both, particularly laser, need to be safety shielded.

These methods can be used together where warranted.

CLEANING AND CORROSION PREVENTION – When the tube is not cleaned (no cost) there is a residue oil from the tube rolling mill in the inner and outer surface. This combined with any rust inhibiting component of the hydroforming fluid gives reasonable rust inhibition for a limited period (ie 30 days) which is normally long enough to ensure the part is installed in the completed vehicle likely after e-coating for external applications.

Lubricant can be required for successful hydroforming, mainly when the tube is being expanded from its starting periphery. It is necessary to clean some lubricants from the part surface to address handling, welding, coating compatibility, mating plastic degradation or other issues.

The equipment will be likely have to be designed for the particular program, lube used and therefore how it must be removed.

Cleaning will very likely strip all substances from the material surface. This is a problem for steel, since it is corrodes easily. As a result a rust inhibitor will usually have to be applied, probably by dip or spray. This requires application, and perhaps drying, equipment.

TOOL COST FACTORS

Tooling must be properly made and durable enough to form metal in the desired shape for at least the program life of the part. It is a one time up front cost that is significant to the overall program cost for smaller production volumes, but becomes less so as volume increases.

The proper balance between tool quality and economy must be struck for best results. A high quality tool is never regretted by the people using it, but may cost more than it really needed to. Too much allegiance to the latter may cause problems of one sort or another for the life of the program.

MATERIAL –Tooling cost does not apply.

TUBE MANUFACTURING – Many tube makers have a large inventory of tube mill tooling. No tool cost should be incurred if design adheres to standard sizes (where tooling exists), forming techniques and welding methods.

It may be deemed sufficiently important to use a tube size for which tooling does not exist. This could be motivated by weight reduction, space restrictions or achieving the right balance between expansion to avoid pinching and minimizing wall thinning, among others. When warranted, a set of forming rolls must be purchased. Approximate cost may be $50 – 100,000, but may be fairly easily justified considering the savings over the life of the program.

BENDING – Bend tooling is not a large initial cost when rotary draw bending on a CNC bender, but increases as more complex bending scenario are used. A normal tool arrangement is shown in Figure 6. A full set of tools includes all those labeled below. Some of these, the mandrel body and balls as well as the wiper die are wear items that must be regularly replaced (discussed further in Part Cost/Bending section). Material toughness and abrasiveness affects this and may necessitate changing the pressure die, clamps or bend die occasionally.). The clamps and pressure die also may need to be cleaned periodically.

Multi-position CNC benders tool cost is higher due to the multiple tool sets.

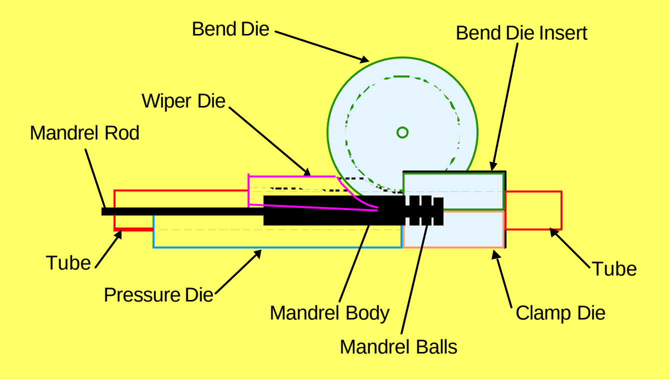


Figure 6

Specially designed 'progressive' bender cells will have substantially higher tooling costs than a standard CNC arrangement.

PREFORMING – Cross section preforming tooling can vary significantly. It depends on the style of preform and the amount of the part that will be affected. Tooling needed for the type of preform shown in Figure 4 is less expensive than is required for Figure 5 style preforming. The first normally consists of 2 curved plates that are pushed together with a hydraulic cylinder. In all cases only a portion of the part is preformed.

The second requires a tool that completely encloses the part, at least along a portion of its length. The cost would be higher due to the more complex surface that will need to be cut and much higher if it encloses the whole part from end to end.

The 3rd preforming option is hydraulic expansion. Tooling consists of a simple hydroforming die with a round cross section shape that bulges at the expansion location.

LUBRICATION, ANNEALING, CLEAN, CORROSION PREVENTION – Tooling is likely to be minimal, if any.

HYDROFORMING – Tooling for hydroforming can incorporate a number of different design approaches that can substantially affect tooling cost.

Some of these are overall size, strength (ability to contain pressure), hole punching, other moving die elements and wear inserts. The first is primarily determined by the part shape and size as well as accommodating mounting hole punching units .

Most dies are made of tool steel and cut to the desired shape, but some (ie prototype) may be cast. The number of holes punched in the die affect die cost dramatically. Even though the tool can cost much more, this addition is usually small compared to the equipment and tool cost of doing the holes after hydroforming.

Generally speaking, as the maximum forming pressure escalates, so do stresses on the die. To contain them the die must be strong enough. Discontinuities in the die, (ie punching units, wear inserts) weaken the tool and increase the possibility of fatigue cracking.

Lower maximum pressure as used when following a constant periphery design approach allows greater punch unit position and quantity flexibility, making it more likely that all holes can be punched in the hydroforming die. More detail on hole punching is given below.

When expanding it is common to feed additional material in the end of the cavity to reduce the effect of wall thinning. This and other factors can cause intense local abrasive forces. A logical response is to install separate inserts that can be made harder and/or more easily replaced. It increases cost a medium amount, but reduces complications later. The end feeding cylinders and mounting arrangements are large due to the high forces that must be exerted.

Moving forming elements within a die may allow more complex forming or undercuts that would create die lock. This increases tool cost, but can be a clever solution to achieve a challenging part feature. Moving pieces, wear inserts and movement of the metal relative to the cavity surface, also tend to reduce hole punching capability.

HOLE PLACEMENT – Tooling for hole punching in the die includes cylinders, punches and other punching components.

The cylinders must be sized to shear the material around the hole edge and overcome the internal pressure. Therefore cylinder size increases with hole size and internal pressure. The first is usually dictated by part design, but the process used and the maximum pressure required determines the latter. Cylinder size also helps determine how many holes can be punched in the die.

Piercing with fluid pressure pushing the slug outward (Figure 9- Bottom left) is another option with advantages like good flatness around the hole and removal of the slug. Tool cost may be higher than a normal punch unit. Piercing 2 holes in opposing walls that are too close together to fold the slugs back inside the tube can be done as well (Figure 9-Top right). Slugs are removed systematically from the die and cost is likely higher than a normal punch unit.

Holes cut after hydroforming have to be located on a fixture. Depending on the number and location of holes, the fixture may need to rotate or be a series of several fixtures. Cost would be much higher than for a simple stationary fixture.

END TRIMMING –Shearing has solid clamps on both ends, the outer face of which is located on the trim plane. Saw cutting and shearing use blades that have to be replaced or sharpened periodically depending on the toughness of the tube material, but the machines themselves are usually robust and require little attention.

Tooling for plasma and laser trimming is limited to fixtures that include a locating pin, pads and clamping. It is possible that the trimming can be incorporated into hole cutting after hydroforming but safe operating space for the number of robots needed or cycle time requirements may dictate otherwise.

PART COST FACTORS

This group of costs are the most important to understand and minimize, particularly with higher volume programs, because they continue for the life of the vehicle program. It can be considered worthwhile to incur higher equipment or tooling cost to facilitate reduced part cost.

MATERIAL – For hydroformed parts, material cost can exceed 50% of the total. As a result, the impact of a ‘small’ price difference is relatively large which makes this aspect very important.

Normal existing grades of mild, HSLA or stainless steels, as well as aluminum can be hydroformed when expansion is not needed. Most hydroformed parts presently are made of steel so that the rest of the discussion will refer to it. These existing grades will be widely available and the cost can be negotiated.

However, changes in the composition of such material are needed to satisfy increased formability demands of expansion. This will increase cost in several respects including cost of alloying elements and time for extra processing in addition to the possible equipment cost mentioned earlier. This is part of the cost of expansion that is often difficult to separate from the total.

TUBE MANUFACTURING – Tubing is the raw material for hydroforming and as such has a higher value added than is normally assumed for stampings.

Prior to tube hydroforming’s ascension to prominence a common tube specification for ‘good’ quality mechanical tubing was ASTM 513. When not expanding, it is still sufficient. Other hydroforming methods may require more stringent controls on length, cleanliness, surface finish or wall thickness. Expansion, or burst testing will also likely be required when all or part of the finished tube are expanded. All of these requirements add cost, but the amount varies.

The weld seam on the straight tube receives the most attention because of quality or integrity of the joint and the heat affected zone (HAZ) that is on both sides of it. When expansion does not occur, the normal lowest cost ERW type joint is often sufficient since no tension is exerted around the circumference of the tube.

When expansion is necessary, the weld region is the weak spot that may rupture with disproportionate frequency. The failure mode may be splitting at the metal edges due to inadequate weld adhesion or in the HAZ beside this that is softened by the heat from welding. Weld integrity can be increased by using a different welding method. These include high frequency, laser or eliminate the weld completely with seamless tube. All methods cost more than ERW.

The cost of non-standard size tubing may be higher relative to those that are more common. Setup costs are only assigned to 1 production run rather than sharing it as can be on common sizes.

BENDING – Restricting parameters (Figure 7) for economical tube bending often is a prime limitation on hydroform part design. The most restrictive is often the clamp straight, which has a recommended minimum of 2 times the tube diameter. Depending on tube diameter, wall thickness and yield strength, shorter clamps may be used. When too short, the leading edge of the clamp will dent the tube and not bend the specified angle.

Bend severity is mainly a function of centerline bend radius and angle and material strength. Decreasing the centerline bend radius increases the clamp straight between adjacent bends. High bend severity uses more formability in those local areas, leaving less for subsequent operations like hydroforming. This conflict between economical bending and overall process robustness is best resolved by achieving proper balance.

A part with no expansion can use a sharper bend radius, giving a longer straight or a larger bend angle (Figure 8) and thus a wider range of economical bend possibilities without resorting to annealing.

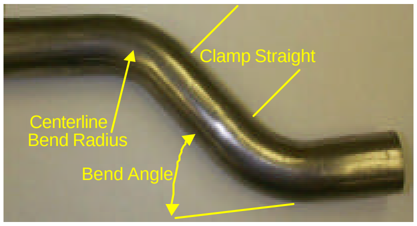


Figure 7

Bender cycle time depends mostly on the number of bends, bend angle and speed. It is common to need 2 or more benders to keep pace with the rest of the forming equipment, even though some production runs with 1.

For multi-position CNC benders, the most significant impact may be on piece cost, since bending cycle time increases to allow time to change the position of the tool stack or bed of the bender to access different tool sets. This would drive the need for an additional bender(s) or extended production hours for a given part volume.

The mandrel body and balls, as well as, the wiper die are wear items, usually made of bronze, which must be regularly replaced. Replacement rate depends mainly on bend severity, tube material abrasiveness, production rate, clearances, tool material etc..

CNC benders can be manually loaded adding labour cost to the operation or an automated system that doesn't, but may require additional technical support to maintain operation.

Specially designed 'progressive' bender cells can be made to form many types of prebent tubes in steps for the main advantage of higher production rates. Similar to CNC benders they can be manually or automatically fed, with similar benefits, but the intermediate steps would normally be automatic.

PREFORMING – The type of preforming shown in Figure 4 requires little space and can be added to a progressive bender cell or placed in a pre-load fixture for automatic press loading. There would be no labour, and equipment operating cost is expected to have a low impact.

The type of preforming shown in Figure 5 would likely require a small press. Cost would arise largely from equipment operating cost (ie electricity and labour if applicable).

LUBRICATION – The cheapest approach is no lubrication, which is normal when not expanding.

If it is beneficial or necessary to lubricate, it is best to choose one that does not need to be cleaned from the part later. Some types are petroleum based lubricants, water based solutions, as well as dry film (often soap) coatings. The first will likely need to be removed, but the others probably do not.

It is necessary to allow dry film lubes to dry. Since this takes a lot longer than a normal production cycle time allowance must be made, which will tend to increase processing cost.

ANNEALING – The most productive point to anneal in the process seems to be after bending. The bends are the regions that have the lowest remaining elongation and therefore where rupture is most likely to occur when hydroforming with expansion is performed.

Annealing adds substantially to part cost, because of the energy used and the fact the tube must be left to cool gradually prior to being hydroformed to avoid quenching. It seems probable that labour cost will be incurred.

HYDROFORMING – The biggest factor affecting cost is the internal fluid pressure used to form the part. The need to expand the tube cross section at least along part of its length is usually at the center of determining what this pressure needs to be.

Generally speaking, part cost increases as the required pressure does, because of the cost of operating the equipment. This is largely due to energy consumption, cycle time and manufacturing space needed. The electricity needed to operate a 5000 ton press compared to a 1000 ton can be 7 times greater, for example.

Cycle time seems likely to be longer. Possible explanations for this are slower movement of the ram, up or down, or longer time to end feed/expand and calibrate in order to complete the forming cycle. This impacts cost by taking longer to run a part, but also being able to make fewer parts before another press is required.

The amount of manufacturing space in 1 example is more than 4 times bigger for a part with small, expanded sections compared to a similar part without expansion.

HOLE PLACEMENT AND STYLES – The method used to place holes in a part play a large role in its cost and quality level. As mentioned previously, cost and dimensional stability are relatively low when punching holes in the hydroforming die. The part is completely fixtured against the die cavity surface by the fluid pressure. When there is no expansion the range of shapes (Figure 8), sizes, position and quantity (64 holes – 1 die) seems to be widest and is done in <1 second. There is no labour cost.

When expansion and accompanying higher pressure is required, hole design flexibility is more limited and the likelihood of hole cutting after hydroforming increases.

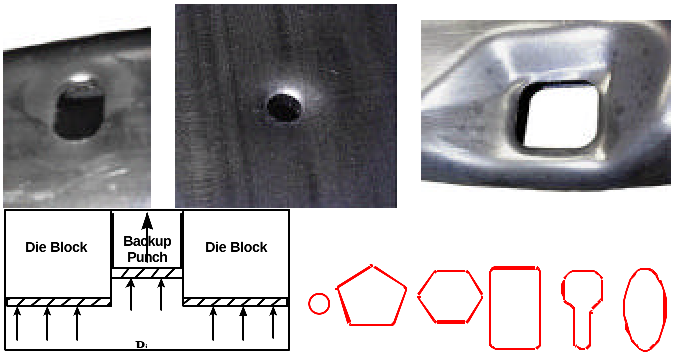


Figure 8

When considering the alternative post form hole making methods, the most popular seems to be laser cutting. Hole edge quality is good and hole size accuracy and location is determined by the guidance system, typically a robot. Hole count, size, material thickness and part volume determine how many laser cutting systems are needed. There may be labour cost depending on automation of part load, transfer between cutting stations if applicable and unload

All holes in Figure 8 are made in the hydroforming die.

When this is not feasible holes can be put in after hydroforming, usually by laser or plasma cutting. Extruded holes as shown at the middle top of Figure 9 cannot be done in this way, but most others can be.

END TRIMMING – Removing the scrap piece from the part end is often the last process step. Methods include shearing, sawing, plasma or laser cutting. The first is the fastest (ie 5 seconds including clamping and unclamping), but the speed is not used fully because cycle times of the other equipment are so much longer. It is clean (no cuttings), leaves one or 2 slightly burred edges and is usually done with 1 shear on each end.

Sawing is a medium speed operation, but will likely be done within the cycle time of the other equipment. It leaves cuttings inside the part, the amount of which depends on the application. Edge quality is similar to shearing with burrs on 1 or 2 sides, but a little rougher.

Plasma and laser cutting tend to be slowest since the single point cutter must trace the whole trim pattern, but offer flexible non-planar trim patterns. One cutting cell per end is probable, but where the combination of trim length, cutting speed and production volume are too great 2 cells may be needed at a substantial increase in equipment cost.

Edge quality is good with laser and plasma with no burrs, but spatter may stick to the part when using plasma.

CLEANING AND CORROSION PREVENTION – When the part must be cleaned to remove process lube, everything is removed. Cleaning usually means washing with a water/chemical mix. It must be followed by application of a rust inhibitor and drying. This sequence is likely to be automated, but will be loaded and unloaded manually or by automation.

It is usually not needed where lubrication is not applied.

FACILITIES AND SUPPORT COST FACTORS

This category includes the services that must be supplied to the production operation to make parts that satisfy customer requirements. These include engineering, quality, maintenance, material handling, as well as the building needed to house everything.

Engineering includes part and process design (including process simulation – needed for expanded parts), equipment and tool making and efforts to deal with day to day problems. Engineering effort can increase substantially when part design includes expansion. Ensuring that customer requirements and forming demands on material are satisfied with reasonable process robustness is usually more challenging. When expansion is not used, material demands are dramatically reduced.

Quality cost includes all testing, inspection and monitoring equipment, fixtures and personnel for incoming, in process and outgoing material. Cross section expansion may increase the effort necessary to ensure making satisfactory parts.

Increased automation decreases direct labour, but may increase support labour (ie maintenance and engineering staff) substantially.

The cost of the building needed depends on the space required for manufacturing, incoming and outgoing material storage, engineering, quality and maintenance. Manufacturing space can vary dramatically depending on the process used and the needed equipment. An example is hole cutting in the die where there is no cutting equipment requiring floor space or doing it after hydroforming when there is.

EXPANSION WHILE HYDROFORMING

Having the ability to expand the cross section of a part during the hydroforming operations has come to be viewed as one of the most important benefits of hydroformed parts. It is very attractive for a designer, but it can pose a big challenge to manufacturing, especially beyond 10-15%. It can be dealt with in a number of ways as described in some of the sections above. Some of these include special materials, tube making and specifications, bending, preforming, tooling, annealing, lubrication and possible limitations on part design. Process simulation is a must to predict if the chosen approach is likely to be successful.

These solutions add cost, but if the benefit of expansion is justified by reduced cost or increased performance elsewhere, it is ‘worth it’. Expansion during hydroforming extends production cycle time to feed material in.

For most parts that are expanded, the fundamental reason for expansion is to avoid pinching the tube between the die halves. Preforming is used in some cases to assist in this respect and may reduce the amount of expansion needed to address this issue.

Figure 9

Figure 10

There are alternatives that may be advantageous and/or cheaper, which should be considered. It can be done as a preform operation with possibly lower equipment, tooling and part cost. It may not be even necessary. More aggressive bending (Figure 9) and/or cross section reshaping (Figure 10) may satisfy the requirements of the packaging or rigidity issue that initiated the ‘need’ for expansion.

Expanding has the side effect of increasing the overall yield strength. Planning on doing this to approach that of HSLA should be considered carefully. Reasons are loss of strength at welds from annealing and a tendency to lose strength during cyclic loading.

WEIGHT REDUCTION

One of the benefits of hydroforming cited most often is weight reduction. Compared to an assembly of stampings the initial opportunity arises from elimination of extra metal for weld seams along the part length. A secondary gain that can exceed the first in magnitude becomes available when these joints are eliminated. If the resulting increase in rigidity exceeds the requirement, it creates an opportunity to reduce wall thickness and/or tube diameter. Thickness reduction achieves greater weight loss for a given degree of rigidity.

Additional weight reduction may be realized by using other materials like high strength steel, stainless steel or aluminum.

ASSEMBLY SIMPLIFICATION

Simplification of assembly takes several forms. The most obvious is consolidating 2 or more stampings into 1 hydroformed tube. Generally, justification for using hydroforming increases as a tube replaces more stampings. The sum of the individual stamping costs cannot be directly compared to the cost of the hydroformed tube. The cost of assembling these into a tubular structure must also be recognized. This may not be easy to do because of overlap between this type of assembly and what has to be done to join tubes or to add stampings to complete the hydroformed assembly.

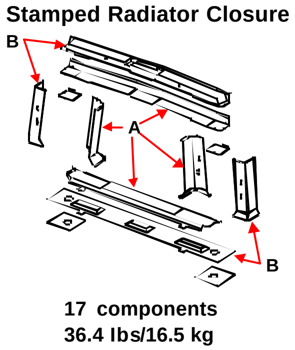


Figure 11

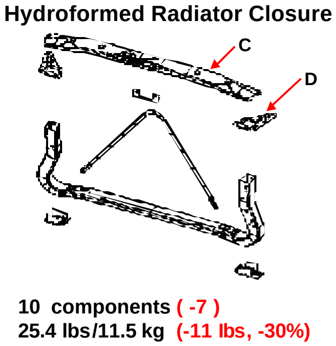


Figure 12

Some of the benefits are due to joints not made, simpler assembly fixturing, improved build tolerance and structure rigidity.

PERFORMANCE IMPROVEMENT

Performance can mean several things. The most obvious for automotive structural parts is rigidizing the vehicle body or at least facilitating it. This is a common claim for tube hydroforming due to joint elimination. Using the same cross sectional area for the hydroform design gives a substantial rigidity increase.

Dimensional stability may also be important. Vehicle assembly standards and customer expectations have become more critical over the years. The high degree of stability hydroforming can provide can be welcome addition to a challenging assembly operation.

Performance can also be related to how efficiently the part can perform its required tasks. Many hydroform applications exist where the amount of material used is reduced while improving structural strength.

CONCLUSIONS

The different cost aspects mentioned in this paper should be considered in the context of the part design being analyzed. This information should be tailored to judge how to make the simplest, cheapest and most functional part possible.

It is important to recognize that it is best to know what a particular feature costs and if it’s ‘worth’ it. Not knowing this leads to unconscious added expense, lack of competitiveness, and not being awarded the contract.

Once a path is chosen it gets succeedingly more difficult to change direction with each passing step. Therefore it is imperative to get as knowledgeable as possible about what the best design solution, the different options and analyze them objectively before choosing. Getting at least some firm idea of the real cost of each option is the best plan, but realistically time often does not allow this. Failing quantitative information, the next best thing is to know qualitatively what impact a part or process design decision will have. Competitiveness comes from intelligently applied knowledge rather than doing what everyone else does.