

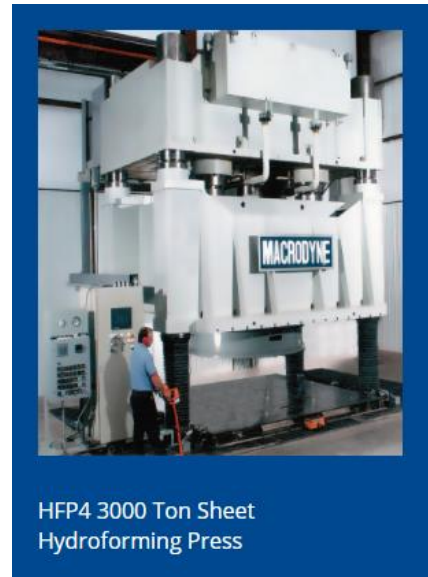
Hydroforming 101

An introduction

Hydroforming is a cost-effective metal fabricating process that can form complex geometries in tubular based parts and extended deep draws in sheet metal-based parts.

Hydroformed parts allow for parts consolidation, the reduced number of subcomponents reduces assembly costs and increases strength and stiffness of the final assembly. Tolerances will differ based on the application chosen and the size of the component but in general hydroform is capable of reduced tolerances versus traditional stamping /assembly methods.

Most of the parts that can be formed using hydroforming can also be created using other forming processes or with multiple component fabrication, so it is important to consider the costs, advantages, and disadvantages of each. Hydroforming will generally be viable when it can be used to reduce the number of component parts in a fabricated assembly.



The Process

The hydroforming process employs a hydraulic press with a specialized die, combined with an integrated water and control systems for high-pressure fluid, which causes the metal blank to conform to the shape and contours of the die.

Process parameters depend on the application and material selection, but as an example for sheet hydroform, it is estimated that the clamping force required to deform metal into automotive parts such as roofs, hoods, and other panels is between 5,000 to 10,000 U.S. tons.

For tube hydroform there are high- and low-pressure process methods. Low-pressure applications typically utilize pressure under 700 bar and require presses up to 2,500 tons. High-pressure applications typically utilize pressures up to 1,500 bar and require presses up to 10,000 tons. There are specialized systems that go up to 4,000 bar, requiring specialized equipment and higher tonnage presses.

Material selection is important to establish process parameters as materials that can be formed are limited (finite element analysis "FEA") by their formability characteristics and the requirements of the final part shape. Advancements in hydroform processes have made forming low elongation materials such as aluminum and high strength steels feasible.

Temperature also plays into the calculation of the forming forces required and the formability limits of the material. With cold forming operations like hydroforming, more force is required for materials at room temperature as they are less malleable.

Hydroforming has typically been a cold forming process, but warm hydroforming is becoming increasingly commonplace. Warm hydroforming uses fluids at temperatures a few hundred degrees above ambient conditions. This process is more costly overall, given the process complexity. If temperatures exceed 350 degrees Celsius, gas is used in the place of a fluid.

Hydroform metal forming simulation is often done using common Sheet Metal Forming Feasibility analysis methods. In addition, by using process windows and load path calculations, process parameters can be established.

Process windows and load paths are developed out of simulations (finite element analysis "FEA") and experimentation, using the material properties and geometry of the parts being produced. Process windows offer a range of values, displayed graphically to instruct the press system on the pressure versus displacement path to follow during the forming process. The sequence of values will be used by the process controller as to how much fluid pressure (and axial force in the case of tube hydroforming) are required in the application.

Forming limits diagrams provide a machine-free view of the process capabilities. They are produced by analyzing the way a material will stretch during the hydroforming operation and allows process parameters to be defined through the observation of the limits of the material and the process.

Another consideration that will have implications on the process parameters is the interaction of surfaces and lubricants, which will play a role in the performance of the hydroforming process overall. The goal is usually to reduce friction to allow material flow, but friction can be useful to the process by controlling material flow and preventing material thinning in important areas.

Hydroforming Categories

There are two distinct categories of hydroforming: tube and sheet, named for the blank geometry used in the process. These categories can be broken into subcategories with distinct processes with different process variables and equipment requirements.

- Tube: Electro Hydraulic, High Pressure THF, Hot Gas Tube Hydroforming, Hybrid Hydroforming, Impulsive, Hydroforming, Low Pressure THF, Tube Expansion, Warm Hydroforming, With Counterpunch.
- Sheet:
 - Cavity: Double Blank, Electro Hydraulic, Hot Gas Hydroforming, Impulsive Hydroforming, Moveable die/Counterpunch, Multi-stage, Warm Hydroforming.

- Punch: Hot Gas Hydroforming, Hybrid Double Blank, Hybrid Single Blank, Impulsive Hydroforming, Multi-stage, Warm Hydroforming.

Cycle times typically range from 15 seconds to over 1 minute, depending on component complexity. Pressure will depend on the application and the material, but greater force is required in the sheet hydroforming process given the larger active blank surface areas.

Tube Hydroforming

Historically, tube hydroforming was reserved for the production of plumbing parts, but over the years it expanded to include other applications. The process is characterized by the application of fluid pressure to the inside of a tube that is held by dies. The dies are closed on the tube, the ends are sealed, and the tube is filled with hydraulic fluid at predetermined pressures that will force the tube to conform to the dies.



Axial force is applied to the end seal plugs as the internal pressure is increased, creating compressive stress in the axial direction to deform the tube. The pressure is typically controlled accurately with a pressure intensifier according to the process parameters identified by the forming simulation.

Process Parameters

Process parameters are established through simulation and experiential means and seek to establish a balance between fluid pressure and axial force to determine a “working-zone” where the part will be optimally produced without buckling, bursting, or experiencing a seal failure.

The main process variables in the tube hydroforming process are the fluid pressure settings, axial pressure or displacement of the seal plug, lubrication, and in some cases temperature. Pre-forming processes which flattens the tube in certain areas is sometimes necessary so the tube will fit properly in the hydroform die. Preform is also used to shape the tube ends to match a seal plug that can be the same cross section shape as the final formed part.

There are two major practices in tube hydroforming, known as “High pressure” and “Low pressure”

In high-pressure forming systems, the tube is fully enclosed in a die prior to the pressurization of the tube. The tube is generally slightly smaller in circumference than the die to prevent wrinkling or buckling. High internal pressure allows the tube to conform to the die shape with tube expansion within the forming limits of the material. The material expansion generally results in material thinning and even material splits if the forming limit is exceeded. The high-pressure process is generally limited to lower strength, higher formability materials and requires thorough simulation analysis to ensure splits do not occur.

In low-pressure forming systems, the tube is slightly pressurized during the closing of the die, causing the tube to conform to the die shape as the die is closing. The process begins by filling the tube with pressurized fluid and then using the closing force of the press to form the tube. Since the tube forms directly from the round shape the part shape with no expansion, higher strength, lower materials can be formed versus the high-pressure process. With the “Low pressure” process there is less of a need for forming simulation because there is very little chance of a material split. However, the circumference of the part design must be a very accurate match the circumference of the original round tube.

Low-pressure applications require smaller presses, they consume less energy, have shorter cycle times, and occupy less floor space.

How to determine the pressure required to expand metal tubes:

$$P_{\max} = Rm \cdot t / R$$

Rm = The tensile strength of the material

t = Nominal wall thickness

R = The radius of the die cavity in the area where the tube is to be expanded

P_{max} = Forming pressure

How to determine closing force in the tube hydroforming process:

Ram force = $P_{\max} \cdot \text{tube length} \cdot \text{tube inside diameter}$ (approximate)

Ram force = $P_{\max} \cdot \text{projected area of inside of tube based on CAD}$ (accurate)

The pressure exerted by the press ram must balance the effect of force created by the hydraulic pressure acting within the tubular blank.

How to determine axial sealing force in the tube seal plugs:

Axial force on the seal plug has three purposes:

- Maintain contact to the end of the tube to seal the tube for pressurization
- Impart a compressive stress on the end of the tube to feed tube into the expanded areas
- Overcome the hydraulic force of the internal pressure on the sealing plug

To calculate: Determine the sum of the forces corresponding to the compressive stress required at the tube end and the hydraulic force due to internal forming pressure.

$$F_s = [\pi (d-t) \cdot t \cdot Rc] + [P_{\max} \cdot \pi (d-2t)^2 / 4]$$

F_s = Seal Plug force

d = tube diameter

t = wall thickness

R_c = required compressive stress at tube end

Additional Process Steps to Consider in Tube Hydroforming:

Thickening and thinning are common to any cold forming process and by setting accurate parameters, can be prevented from occurring or maintained within material limits. While these issues can be managed by optimizing process parameters, there are a number of design features that require consideration:

1. **Tube Bend Location:** In tube hydroforming, a design with bends near the tube end decreases the axial feeding motion's ability to replace material that thins during tube expansion. Tube expansion with end feed is only practical between the tube end and the first bend. Secondly, for economical bending there needs to be a straight length of tube between bends. Minimum straight length is 1.5 times tube diameter. Straight lengths less than this are possible but require contoured clamp dies on the bender
2. **Small Radius Bends:** Material changes that take place in the tube bending process can have implications on the ability to form during the hydroform process. When the bend radius is less than 1.5 times the tube diameter, it is important to evaluate material thinning along the outside of the bend.
3. **Sharp Cross-section Radii:** The smaller the radius, the more pressure required to form it and the more complex the process will be, the higher the forming pressure and the higher the die forces. Higher forming pressure requires a higher tonnage press, which comes at a greater expense. A general rule of thumb is to keep the radii to at least three to four times the material thickness for high-pressure process and seven times or more for low-pressure process.
4. **Excessive bulging:** The physical expansion of the material is contingent upon the material properties, but also the initial **tube** size and final geometry. A good way to estimate the greatest point of expansion before the material fails is to conduct a forming simulation.

Sheet Hydroforming

Sheet hydroforming has been considered standard manufacturing equipment in the U.S. since the 1940s, though its history dates back much further. Throughout its evolution, sheet hydroforming has greatly improved its capacity for deeper draws. Hydroforming machines can now achieve ± 0.002 of an inch with draw depths of ± 2 percent.

Sheet hydroforming operates using one tool instead of two, which reduces die cost when compared to other cold forming processes.

Rolled sheet metal, cut to size, serves as the blanks in the sheet hydroforming process, the size and shape of which is determined by the results of simulations which will be conducted to determine process parameters to optimize material flow.

Sheet hydroforming is typically performed using a cavity die or a punch. Punch hydroforming is also known as hydromechanical deep drawing. To determine whether a punch or a cavity will be used, the geometrical complexity and draw depth of the part being formed will have to be considered.

Cavity dies are selected if a part has complicated surface features like bulges and punches are applicable if a part has a cylindrical geometry and a simple surface. Punch presses are disadvantageous from a size perspective as they usually have a smaller bed size and can only draw simpler shapes. The advantages are deeper draws and less material thinning.



Process Parameters

The key process parameters include pressure, the variation of pressure over time, and temperature, though when using a punch hydroforming process, the punch displacement is also to be considered.

How to determine the force required to deform sheet metal:

$$F = \frac{LT^2}{W} \text{ (UTS)}$$

T = Sheet thickness

W = Width of the die opening

L = Total length of the bend

UTS = Ultimate tensile strength of the material

Setup Variables:

- The use of spacers or beads.
- The pressure for the counterpunch, if applicable.

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- Blank holding force (in instances where the blank is physically held).
- Lubrication condition and friction.
- Blank shape.
- The use of a bladder or direct fluid contact (DFC).

Bladder versus Direct Fluid Contact (DFC)

Sheet hydroforming can be performed using a flexible bladder to prevent the fluid from contacting the blank, or using fluid that is in direct contact with the material, which often leads to the need for secondary processes like degreasing and results in better surface quality.

Bladders prevent lubricant from mixing with the working fluid and enables the use of certain forming techniques, such as circular pressure intensifiers that can tighten radii. Without the bladder, this would not be possible as the bladder prevents the fluid from leaking around the pressure intensifier, instead of applying a firm force.

While there are certainly advantages of bladder versus DFC processes, the bladder has a finite life and will need to be fixed when broken which reduces process efficiency. It also requires heavier presses. Regardless of which is chosen, however, it will have little impact on the draw ratio.

Hydroforming Applications

Tube hydroforming is typically selected for applications such as automotive suspension cradles, A-pillars, body structure components, exhaust components, rotating engine components, and bumpers. Tube hydroforming allows for components with variable cross sections without the need for secondary processes, like welding. This reduces the number of components required to produce the final part.

Sheet hydroforming is attractive because of the formability and surface finish it can achieve as a near net shape manufacturing process. It is used to produce door panels, roofs, and body side fenders.

Materials

Different metals will produce different outcomes in different processes. Thus, material choice plays an important role in determining the process parameters for hydroforming processes. For instance, the stronger the material, the greater the pressure required to produce desired geometries.

Materials that are used in other cold forming processes can be hydroformed, including aluminum, brass, steel, stainless steel, copper, Inconel, exotics like Hastelloy and high nickel steels, cobalt, lead, zinc coated steel and bronze.

Specific material characteristics that are beneficial for the hydroforming process are high ductility, uniform elongation, a large strain hardening coefficient, fine grain structure, and a significant difference between yield and tensile strength.

Material Formability and Pressure Required:

In the calculation of process parameters, the material properties of interest are ultimate tensile strength (UTS), conventional yield stress, proportional elongation under maximum force, and total elongation below maximum force.

When compared to other traditional pressing processes, such as stamping, hydroforming is more suitable for processing metals like titanium, copper, and other high nickel alloys. High elongation steel performs better than mild steel, but it also comes at a greater price tag. Likewise, materials like stainless steel will allow for deeper draws than other materials because of its formability and ductility.

Chromium hot working steel has a working hardness of between 400 and 500 HV making it a ductile and tough tool steel, as it has the ability to withstand continued exposure to temperatures up to 540 degrees Celsius and can maintain tensile strength levels of ~5MPa at this temperature. Aluminum and magnesium wrought alloys offer the highest strength of non-treatable alloys with a UTS of 230-280 MPa and a tensile yield of 130-180 MPa.

Advantages of Hydroforming

The primary advantage of hydroform is parts consolidation, multiple components can be redesigned as a single part, reducing or eliminating assembly and welding processes. In many applications part strength and stiffness is increased because the cross section is homogeneous rather than welded half shells. Many of the newer hydroform systems further reduce costs by forming the tube end-to-end and eliminating process scrap of cut-off tube ends.

The hydroforming process has an advantage in its ability to control and vary pressure based on the optimized load path and other process parameters. The pressure from the fluid is also applied evenly across the entirety of the blank surface to promote even material expansion and provides forming force in orientations contrary to the forming direction to enable the creation of additional prominent features.

Like other cold forming processes, hydroforming results in high levels of work hardening, which increases the yield strength of the base material.

Hydroformed components are lighter weight, stiffer and stronger than assembled stamping parts and for this reason are often used in automotive roof rails to prevent roof crushing in the event of a vehicle roll over.

To learn more, visit Macrodyne's website at <https://www.macrodynepress.com/hydraulic-presses/hydroforming-presses/>

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