Research Directions in Hydroforming Technology

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Abstract. This paper both summarizes and explores the literature published between 1995 and 2015 on enhancing and extending hydroforming technology. Many different research areas have been proposed, all of which try to enhance the well-established manufacturing process by either improving formability or reducing costs. Each of the technological variations are first described and then their uses, benefits, drawbacks, and applications are discussed and summarized.

BACKGROUND

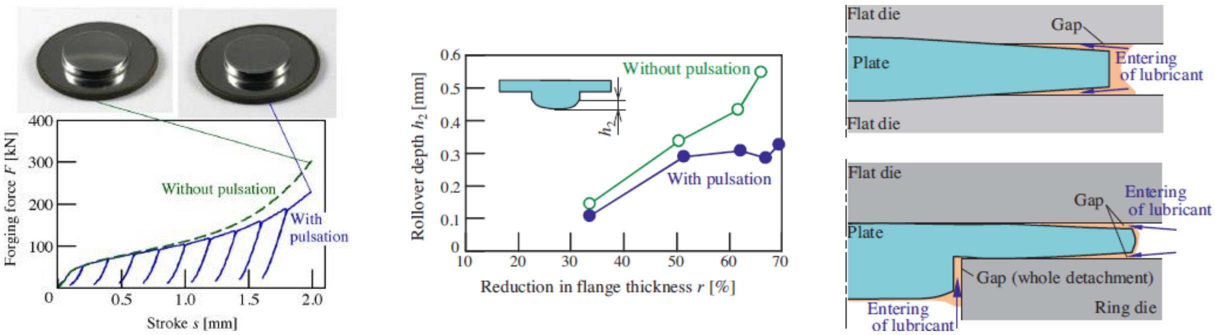
Hydroforming is a near net shape manufacturing process that uses large amounts of hydraulic pressure to form metal from readily available "blank" shapes into net or near net shape geometries. While the first examples of hydroforming can be traced all the way back to the 1890s and the first patent was issued in 1940, most of the technological development has taken place after 1950 (Zhang & Danckert, 1998).

Hydroforming's benefits stem from two key physical phenomena; the first is the ability of fluids to exert pressure on a surface completely evenly and in all directions and the second is the capacity to have a complicated pressure loading cycle which can vary pressure over a predetermined and optimized timeframe. These physical phenomena translate to distinct realizable advantages most notably in formability where in the sheet hydroforming process the limiting drawing ratio (or LDR, a key measure of formability) is improved from roughly 2.2 to 2.6 or in some specific cases can even be closer to 3.2 when compared to traditional pressing processes (Zhang, et al., 2004). The main disadvantage of hydroforming as compared to pressing are the increased costs which appear in two distinct areas, the initial cost of the capital equipment and the additional costs imposed by longer cycle times and lower throughput on machinery. The way to determine whether to use a hydroforming or a conventional forming process lies in weighing the additional formability gained by using a hydroforming process against the additional costs imposed by the entire manufacturing method including subsequent operations which can differ substantially (Bell, et al., 2015).

This paper's scope is limited to literature regarding hydroforming technology that has been published in conference proceedings or journal papers over the last 20 years with proven results. Consequently technologies for which either no industrial application or experimental trials exist were not included.

Impulsive Hydroforming

Using an impulsive method of applying force to the metal blank can significantly increase formability and produce a much more uniform material expansion. In traditional forming operations this is done by loading and unloading the press and has been shown to be effective in processes like stamping. By using cyclic loading (repeated loading and unloading) some of the benefits of an incremental process can be utilized in what has traditionally only been a single action process. For example Maeno, et al. use a pulsating load achieved via servo drive during a forging process of a stainless steel sheet. As can be seen below in figure 1 they show a noticeable decrease in required forming force during the operation and hypothesize that this is due at least in part to lubricant entering through gaps between the workpiece and die which are created due to the difference in elastic recov ery of the respective materials.

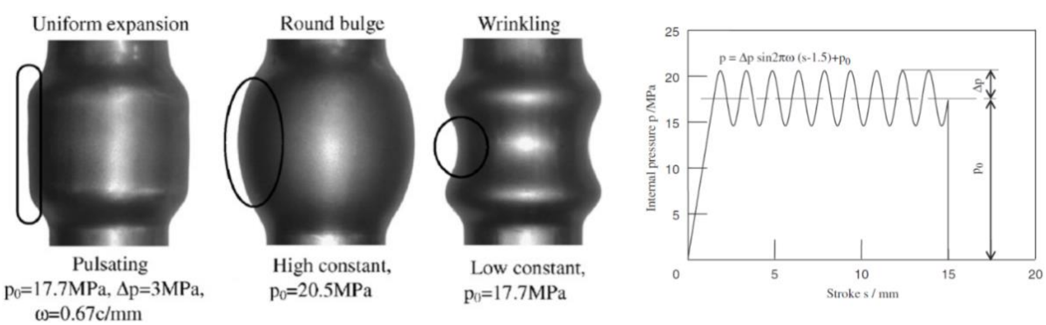


a) b) c)

FIGURE 1. Examples of lower load, increased quality and entering of lubricant during impulsive forging (Maeno, et al., 2014)

Physically speaking this impulsive process can also be applied to a hydroforming operation in several ways but the most common is to utilize a complicated fluid pressure cycle which increases and decreases fluid pressure. It is worth noting that it can be difficult for older equipment to alter fluid pressure with the rapid but precise changes that are necessary to perform an impulsive hydroforming operation. In one case Xu, et al. experimented with different impulsive loading patterns during a tube hydroforming operation and instead of bursting at 120Mpa, the material was able to refrain for bursting through the 140Mpa required to complete the operation.

This process can not only increase the formability of materials but it can also stabilize the material expansion and make it more uniform. This is particularly useful when the material blank is bulging into free space and not against a die. This concept has been shown in research performed by Mori, et al. wherein the authors bulged tube samples into free space at different pressures including low and high static pressure and one pulsating load which regularly oscillated between a higher and lower pressure as seen below in figure 2. The pulsating pressures seemed to expand the workpiece much more uniformly.

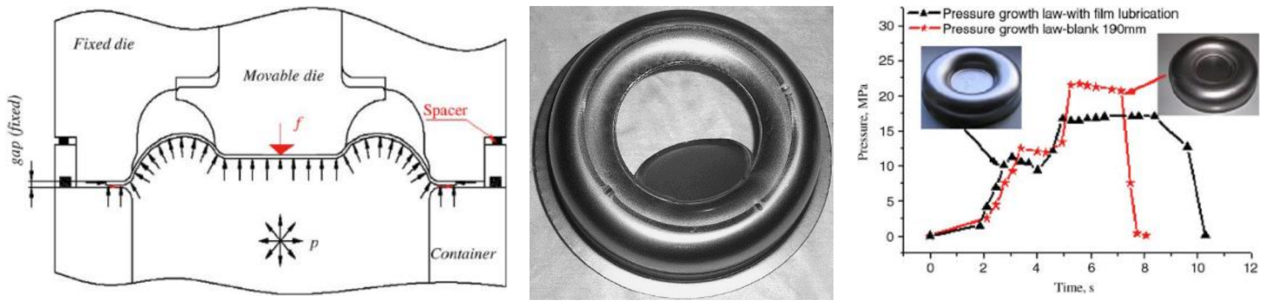


a) b) c) d)

FIGURE 2. Pulsating versus various other expansion pressures & pulsating schematic (Mori, et al., 2007)

Moveable Die

Several papers have suggested introducing moving mechanical support during a hydroforming operation which would both limit material flow in specific vulnerable areas and increase the amount of support for the material during the operation. In practice this could be done by using a ram or moveable die which was pressed against the sheet metal during the forming operation and retreated slowly while the material was expanding. This would allow the sheet metal to expand in more desirable and controlled fashion. This kind of mechanism was created and used to produce hemitoroidal (doughnut-like) shapes which proved that the concept was viable (Palumbo, et al., 2006).



a) b) c)

FIGURE 3. Schematic, failure due to excessive moveable die force, and pressure cycle (Palumbo, et al., 2006)

Multi-Stage Hydroforming

Several researchers have investigated the possibility of creating more complicated geometries using a multistage hydroforming process. One paper by Liu et al., suggests that by first stretching material in the opposite direction of the forming operation, a more complicated shape can be generated because generating more material in the working area before the operation yields more material to use once the operation begins. This is seen below in figure 4.

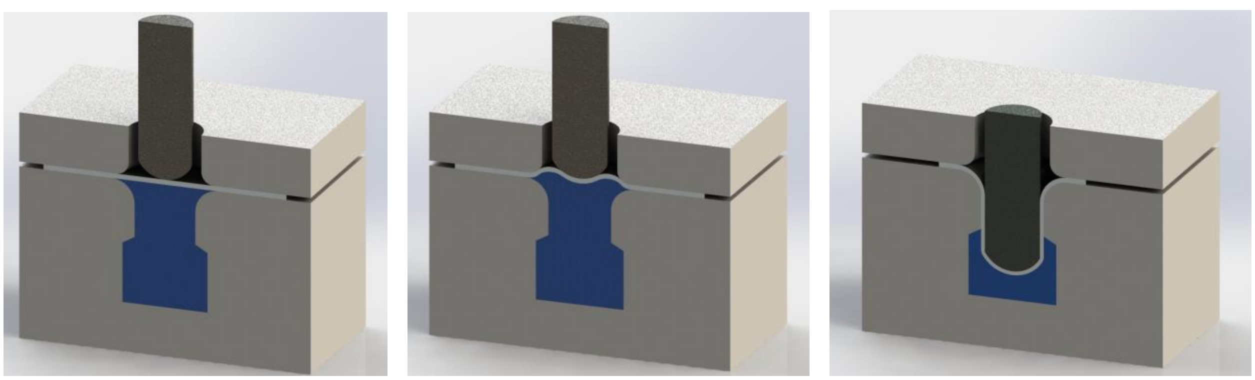


FIGURE 4. Schematic of pre-bulging in the opposite direction of the forming direction before hydroforming

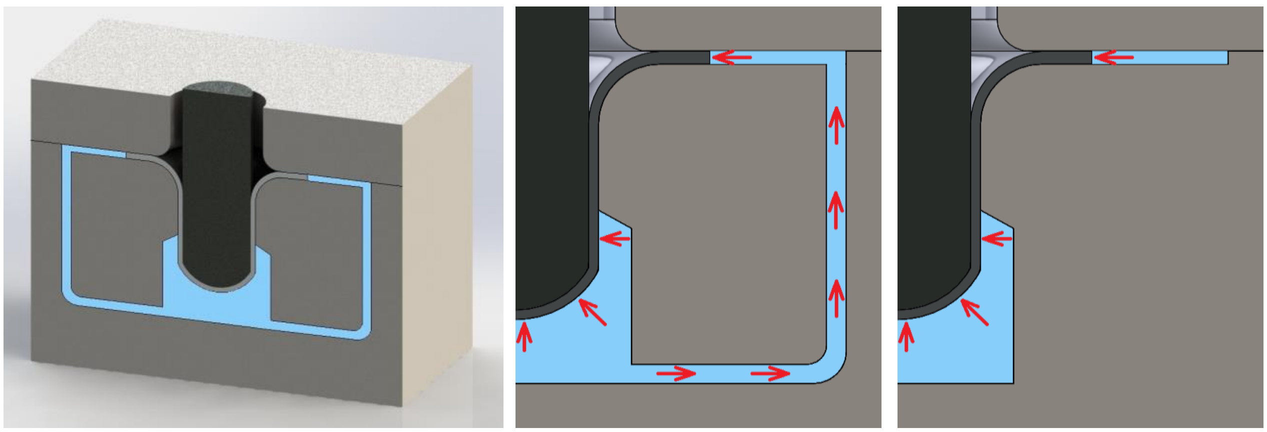
A study published by Golovashchenko, et al. takes this same principle a step further by showing an example of a very complicated shape which is manufactured with a hydroforming process. First a geometry was given which was difficult to form due to the sharp radii and a long vertical portion which required lots of material stretching as well as high pressure to fit into the tight corners. Traditional single operation hydroforming did not produce a successful component as the material tore while bulging into the tight corner. However when a 4 step operation was used which included inter stage stress reliving heat treatments, a successful final geometry was produced without fractures. The geometry, the single stage hydroforming process, and a four stage process are shown in figure 5.

a) Geometry b) Single Stage Hydroforming c) Four Stage Hydroforming

FIGURE 5. Multi-stage sheet hydroforming (Golovashchenko, et al., 2011)

Hydro-Rim Deep Drawing

Another clever adaption from conventional hydroforming is known as "hydro-rim deep drawing" in which fluid pressure is exerted on the back side of the flange. Usually this is done by connecting the space behind the blank and the space between the dies with a fluid channel (seen in figures 6a and 6b below) but can also be done indirectly (shown in figure 6c below). This allows for two distinct advantages over a normal sheet hydroforming operation. First, the fluid exerts increasing pressure on the back side of the flange which pushes additional material into the working area to replenish material that is being bulged downwards (Thiruvarudchelvan & Travis, 2003). This advantage is mildly analogous to the one seen during a tube hydroforming operation when axial pressures are exerted on the workpiece to induce additional material flow from the periphery to the inner portion of the tube. The second advantage this technique provides is to assist in lubrication between the workpiece and forming dies by forcing fluid into any available gaps which reduces friction.



a) Hydro-Rim Deep Drawing b) Direct c) Indirect

FIGURE 6. The difference between direct and indirect Hydro-rim deep drawing

Warm Hydroforming

It has been known for centuries that elevating the temperature of a work piece during a forming operation softens the work piece and makes it more malleable. Consequently this phenomena has been studied in detail in the deep drawing industry where a large body of work now exists which details applications where using higher temperatures dramatically increases the formability of certain materials and makes possible the creation of previously unformable geometries. One example published by Takata, et al. details a series of experiments which used an aluminum alloy in a deep drawing operation. In the experiments the authors performed the operation across a range of temperatures between 25 and 250 degrees and assessed the material formability which found that the LDR doubled between the least and most formable cases. This principle is now being trialed with hydroforming technology but there are certain difficulties which are unique to the hydroforming process. For example there are inherent difficulties that come with requiring heated surfaces to be placed adjacent to liquid especially when the temperature required is above the boiling or flash point of most commonly used liquids and oils. While these challenges have limited the development of warm hydroforming to the fairly recent past, the results have been very promising.

Traditionally hydroforming has been mostly used as a cold forming process and this is the area where the majority of both research and industry operates but the potential of hydroforming at elevated temperature is quite apparent and has been well documented in many sources, some of which suggest that materials like specific grades of aluminum and magnesium can only be meaningfully formed at an elevated temperature due to their low formability at low temperatures (Koç, 2008).

There are several ways in which heat can be applied to the hydroforming process but one of the more novel approaches, shown below in figure 7, is to heat the outer flange of the blank while cooling the middle of the blank where most of the operation is taking place. Because the blank is more ductile when warm the material is able to be drawn in from the warmer flange region instead of thinning in the middle.

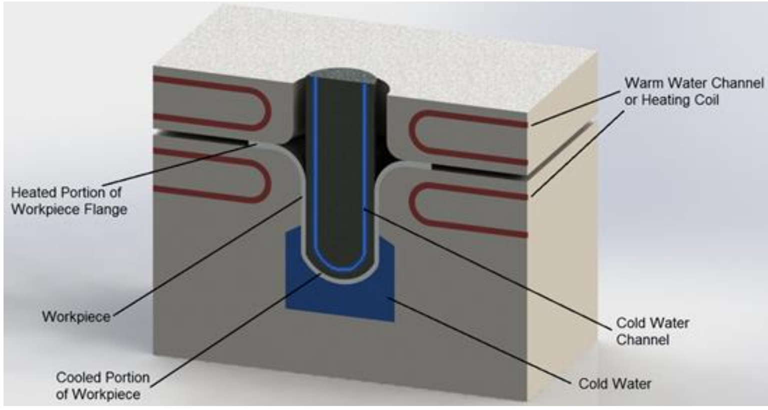


FIGURE 7. Warm hydroforming schematic

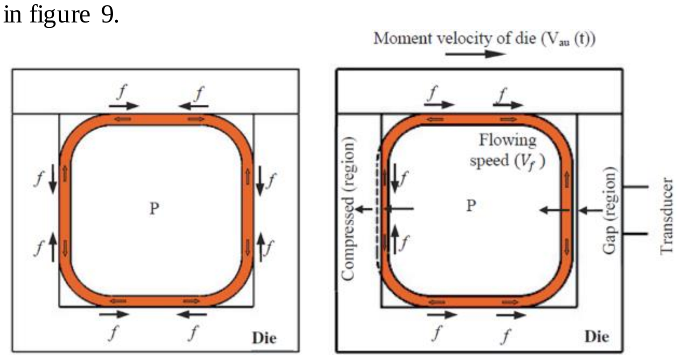
Alternatively it is also possible to warm the dies, the fluid, or both to perform a warm hydroforming process. In one such case both a cup and a box were trialed with an aluminum alloy (AZ31) at 0 and 230 degrees. While at zero degrees the cup does not even contact the upper surface before failing is observed but at 230 degrees it forms completely which is a good illustration of the benefits of hydroforming at elevated temperatures (Koç, 2008).

a) b)

FIGURE 8. Normal vs. elevated temperature hydroforming operations of cups and rectangular sections (Koç, 2008)

Ultrasonic Tube Hydroforming

A recent development in hydroforming technology is the use of ultrasonically induced vibrations during the forming operation which enhances formability by improving the contact condition between the blank and die. This enhanced formability manifests itself tangibly as both a more uniform wall thickness and better corner filling during the forming process. These advantages are particularly important as they are considered areas of concern in hydroforming operations and occur because high frequency vibrations result in a tiny opening (or gap) between the tube and the die for just a fraction of a second which in turn causes a momentary change in the condition between the tube and die which subsequently allows for easier expansion (Eftekhari Shahri, et al., 2014). Using this method Shahri et. al. were able to see a considertable increase in the corner filling ratio of a tube with a square cross section shown schematically below in figure 9.



a) b)

FIGURE 9. Hydroforming without (left) and with (right) ultrasonically induced vibrations (Eftekhari Shahri, et al., 2014)

Electrohydraulic Forming

A useful variant of hydroforming is called electrohydraulic forming which is a process whereby a blank and two electrodes are placed in a bath of liquid, the current is turned up between the two electrodes, and a shockwave is created in the water which in turn creates a momentary increase in pressure inside the chamber. This pressure travels to the blank through the liquid and the metal is deformed against the die.

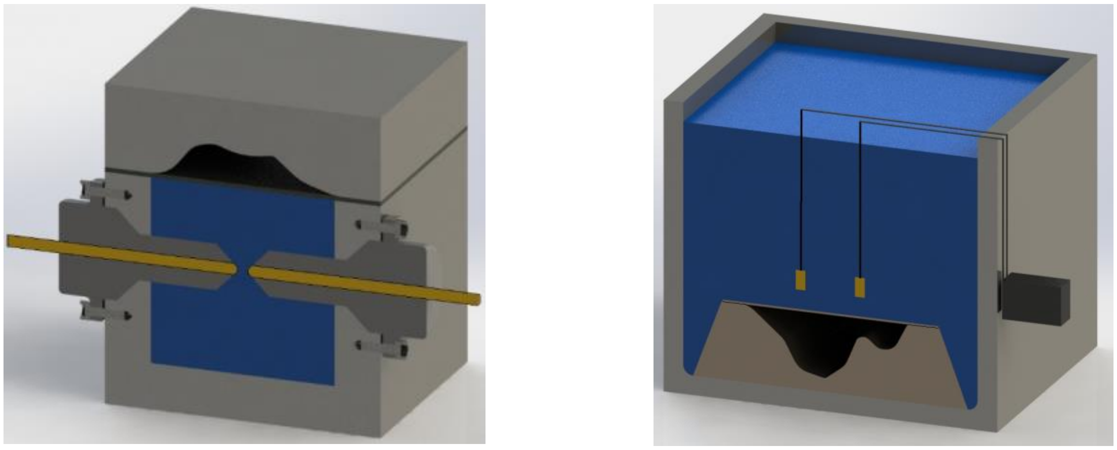


FIGURE 10. Electrohydraulic forming schematics

CONCLUSION

This paper summarizes and discusses the principles behind various technologies that are currently being pursued within the hydroforming industry. While all of these technological alterations are different in their application of forces and physical geometries, they all have the same objective which is to expand the forming capability of the hydroforming process. With the advent of these and other hydroforming technologies a better and more competitive manufacturing method capable of producing more complicated, higher quality, and more cost effective components is possible.

Technology	Pros	Cons
Impulsive Hydroforming	Lowers maximum required forces, Increases formability	Requires high control over pressure loading cycle, increases complexity of operation and simulations
Moveable Die	Increases formability	Only works on specific geometries, mechanically complicated, difficult to implement
Multi-stage Hydroforming	Does not require modifications to existing hydroforming equipment	Requires additional steps and potentially die changes
Hydro-rim	Increases LDR significantly, increases material feed from flange region	Requires specialized tooling
Warm Hydroforming	Increased formability especially for certain brittle materials, greatly increases material feed from flange region	Increases complexity of operation and simulation, can be difficult to heat correct areas, heating a fluid or heating metal nearby a fluid adds challenges
Ultrasonic	Increases corner filling, reduces thinning variation, bulges have more equal and even expansion	Increases complexity of forming operation and simulations, requires specialized ultrasonic equipment
ElectroHydraulic Forming	No moving parts during forming operation	Lack of traditional forming forces, presumably complicated simulation

TABLE 1. Summary of proposed hydroforming technologies

AUTHOR'S NOTE

Figures 1, 2, 3, 5, 8 & 9 were published in the original work. Figures 4, 6, 7 & 10 were created by the authors to illustrate the technologies described in the various publications.

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