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Change in Material Properties and Tribology of a Material Undergoing Hydraulic Forming

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Abstract: ***With the advancements in science and technology during the Industrial Revolution, mechanical manufacturing processes also saw a revolution as new forms of processes were used to manufacture new machinery and tools to meet the demands of the rise in technology. One of the most prominent processes which came into light was forming. It is a process which is used to give shape to a material by overcoming stresses and causing a plastic deformation in the body to give a new and permanent shape. It is even used extensively today for myriad manufacturing processes. One of the most common types of the forming process is hydraulic forming, better known as hydroforming. A more detailed explanation on hydroforming and its various types along with their applications in the real world are given in this paper. The crux of the paper is devoted to the mechanical properties of the material observed once the forming process and the physical permanent deformation of the material takes place. An analysis of both microscopic and macroscopic properties is carried out. This entails major aspects of viewing material properties like stress analysis, stress - strain tests and even the surface finish and view. Even in hydraulic forming, different types of the process like vacuum forming and deep drawing and sheet hydroforming end up with a slightly different set of material properties and tribology, the particulars of which are beyond the scope of this paper. Lastly, we conclude about the advantages and disadvantages of the hydroforming process mainly in line with the properties of the material observed after the process.***

Keywords: Hydroforming, Hydraulic Forming, Plastic Deformation, Material Surface, Material Tribology, Stress, Strain, Hardness, Strength

1. History of Forming

Since the advent of humanity in the world, metals have played a crucial role from the development of our ancestors to the modern world as we see it. From the Bronze Age to the Industrial Revolution, and now today's world with huge skyscrapers and supercars, nothing would have been possible if man had not known how to exploit metals to his use.

However, metal as mined from the ground has not much value unless it is purified from its ores to an extent and then the required shape is given to it to satisfy its purpose. One of the ways to obtain the required shape of our metal is by forming. **Forming**, **metal forming**, is the metalworking process of fashioning metal parts and objects through mechanical deformation; the work piece is reshaped without adding or removing material, and its mass remains unchanged. Forming operates on the material science principle of plastic deformation, where the physical shape of a material is permanently deformed. The earliest records of forming come from an ancient copper pendant. Copper was hammered until it became brittle, and then heated so it could be worked further. This technology is dated to about 4000 - 5000 BCE. In the historical period of the Egyptian Pharaohs, gold and copper coins which were widely in use were formed by consistent hammering of slightly heated metals to derive the required shape.

[1]Ancient Egyptian Coins

Even today, after centuries forming is still an integral part of metal shaping though many more advanced techniques of the same are in use now. This is because of the large number of advantages metal forming provides to us:

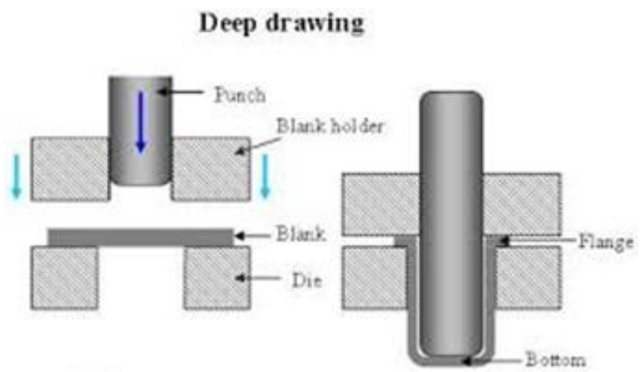
- There is no wastage of metal. All the metal is reshaped into the required product. The mass and volume of a non - porous metal remains unchanged after forming.
- Better material properties are obtained along the way. The metal gets hardened.
- Forming using machinery is a very fast process. It can give high production rates if appropriate machines are in use.

From many of the current existing forming techniques, some of the most commonly used methods are:

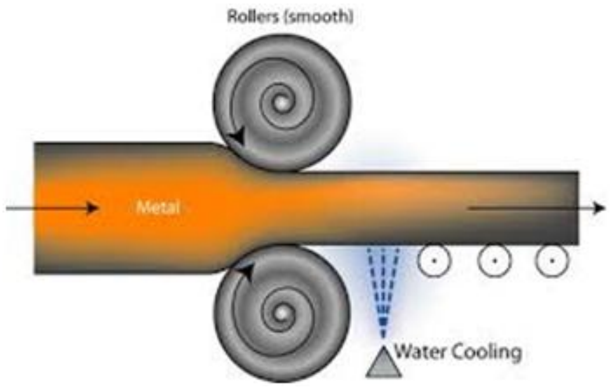
Bulk forming processes: Forging, Rolling, Extrusion and Wire drawing

Sheet metal forming processes: Deep drawing, stretch forming and Bending

Hydroforming or hydraulic forming is one of the hottest inventions in metal forming which has taken a lot over the forming industry.



[2] Sheet Metal Deep Drawing



[3]Bulk Metal Rolling

Hydraulic Forming

Hydraulic forming or hydroforming is a metal fabricating and forming process which is used for shaping ductile metals and alloys like aluminium, brass, copper and stainless steel. It is a highly cost - effective and specialized die forming method that uses a high - pressure hydraulic fluid to shape the metal into the die and give us the required shape.

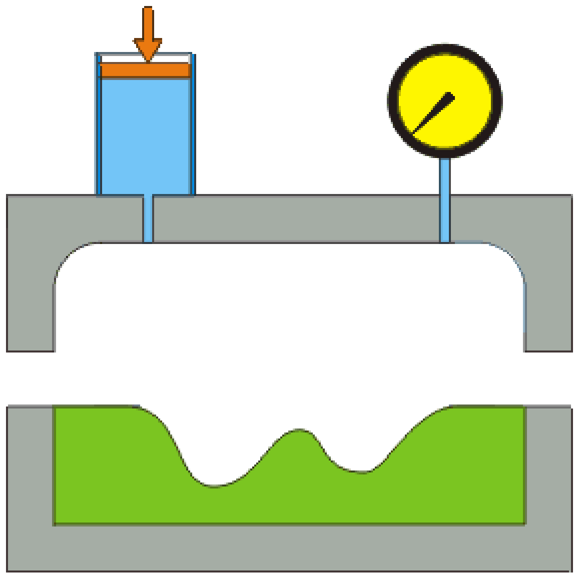
Earliest uses of hydroforming date back to 1950s where it was used to shape kitchen spouts. This is because it gave better metal strengthening and gave a better metal surface finish with less rough grains on the surface.

Soon afterwards, the success was replicated in the automobile industry. It was exclusively used in the sports cars industry as hydroforming was able to supply much lightweight, compact and complex car parts with increased strength and better surface finish.

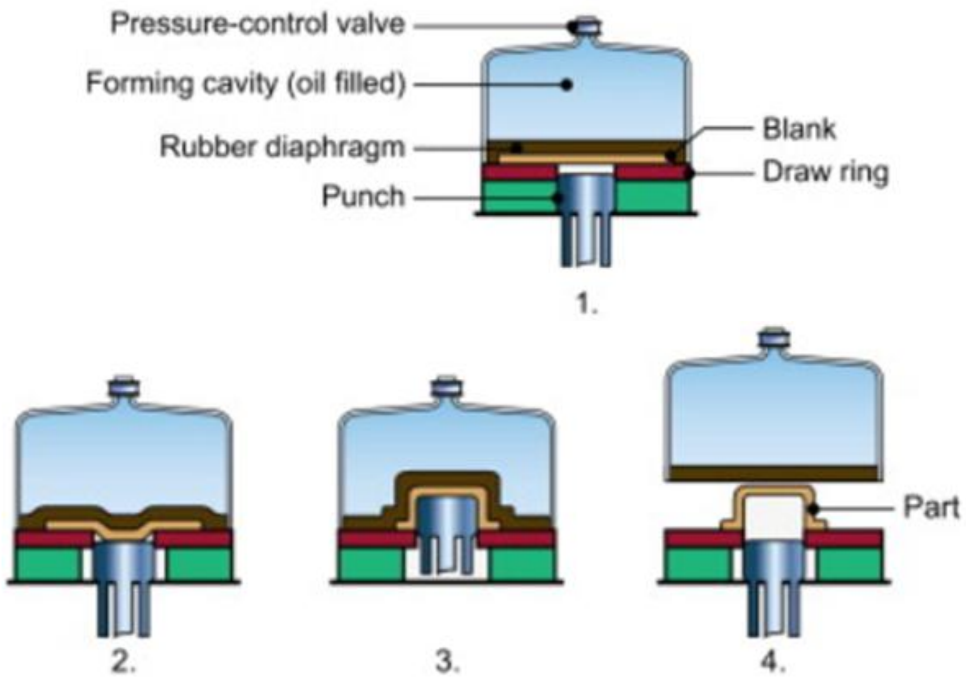
As of now, there are mainly two types of hydraulic forming which are in use today -

Sheet Hydroforming: In sheet hydroforming, we use one die on which the required pattern for print or the shape is already carved. From the opposite side of the die, highly pressurized fluid is driven onto the blank metal sheet which then is pressed against the shaping die and the sheet takes on the shape of the die.

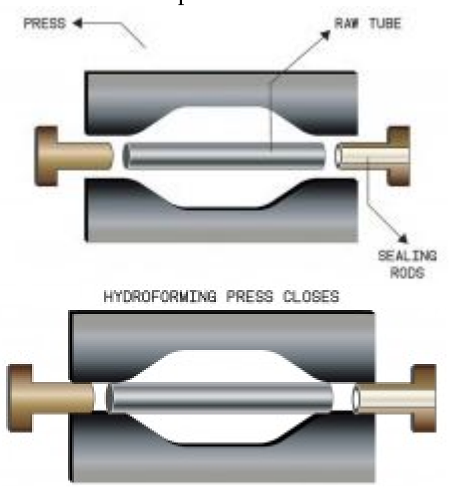
This process is also called **bulge forming** as the metal sheet takes the shape of all the crests and troughs and bulges of the die’s geometry.

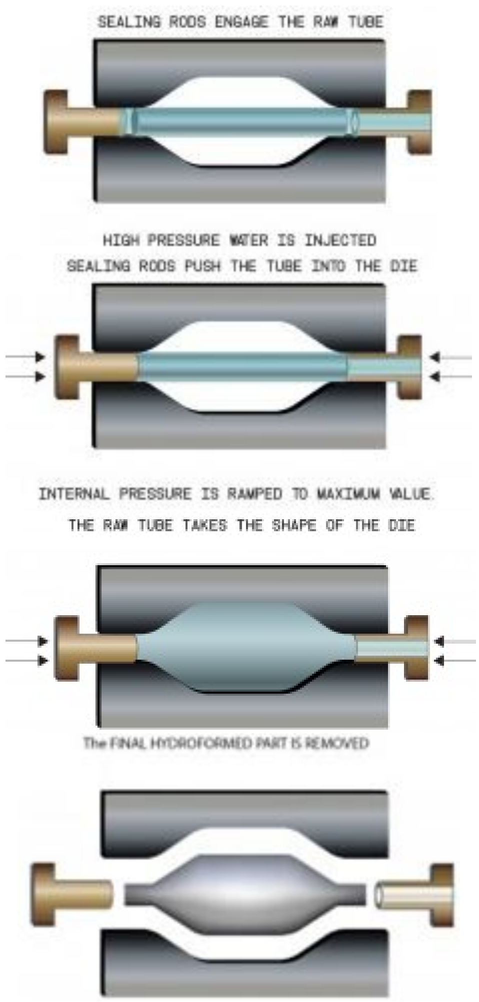


Hydro - mechanical deep drawing is another such process in which instead of direct contact of the metal sheet with the fluid, the fluid’s hydraulic pressure is used to power a shaping tool like a punch. The work piece is placed on a draw ring (blank holder) over a punch where we wish to cause the deformation. A hydraulic chamber surrounds the work piece and a relatively low initial pressure is kept around the work piece against the punch. The hydraulic chamber is kept out of direct contact with the work piece by a rubber diaphragm which is kept above the work piece. The punch then is raised into the hydraulic chamber and pressure is increased to as high as 100 MPa which forms the part around the punch. Then the pressure is released and punch retracted, hydraulic chamber lifted, and the process is complete.



Tube Hydroforming: In tube hydroforming, a hollow tube of the required metal is inserted into the forming die. The die has the shape which we wish to pass onto the metal tube when it expands inside the die. The tube is fit inside the die press and sealed on both ends by die clamp seals. Out of these one of the seals is perfectly solid which completely blocks the metal tube from the surroundings. Whereas the other seal which has the same cross - section as that of the tube allows water to enter the tube. Once the arrangement is set up, highly pressurized water is injected through the hollow seal which then passes on to the interior of the hollow tube. High internal pressure ramps up into the tube setup. Both the clamp seals must be held on tight so that they don't pop out due to the high pressure. Due to the high fluid pressure inside the tube, the metal is forced to expand. It expands until it takes the shape of the die. Once we get the required shape, the water and the seals are removed and the two halves of the casting die are separated to reveal the hydroformed part. However, we must be sure that the die used here is not too big else the metal will not be able to expand as much as the shape of the die.





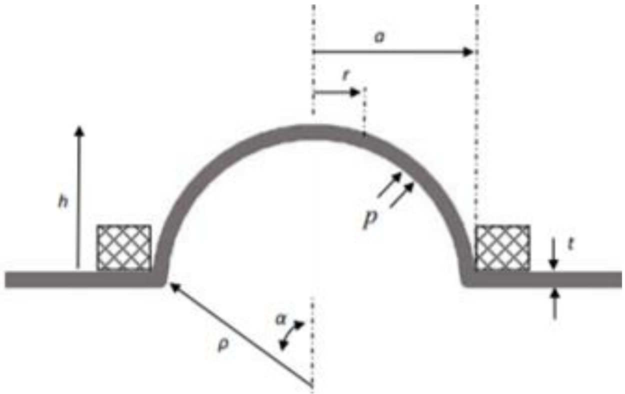
Tube hydroforming process provided a better alternative to craft complex and lightweight parts than sheet metal forming. This method offers a high degree of design flexibility with respect to generating the desired shape. We are able to get accurate designs and relatively complex shapes and geometry. It is widely used in plumbing applications where we get copper t - shape tubes by the additional use of counterpunch.

Material Tribology

Due to the growing use of hydroforming for manufacturing, scientists tried to study the properties of the material after the process and generalize a transition of the process's effect on the material. To get the results on material surface and relation between applied hydraulic pressure (P) and deformation (height h) caused by it, an experiment was performed.

The experiment setup for the open die hydroforming consisted of the top and bottom dies in which the required design is already carved out, workpiece, O - rings to prevent the leakage between the bottom die and workpiece, pressure intensifier and hydraulic pump. The experiment was repeated many times with different pressures and the height of the bulge was noted. After hydroforming, the strains on the workpiece were analyzed by:

- All the workpieces were electrochemically etched by microscale grids. After the process, the deformation of the micrograms were analyzed by analytical methods.
- The thickness strain at the bulge poles was observed by these grids.
- The electrochemically etched grid was inspected under a fine - etched atomic force microscope (AFM) probe.
- All the workpieces were sectioned along the cross - section area and were placed under the AFM probe. The cross - section of the workpiece was examined under 50x and 100x magnifying power and the average grain size was determined using the ASTM standards.

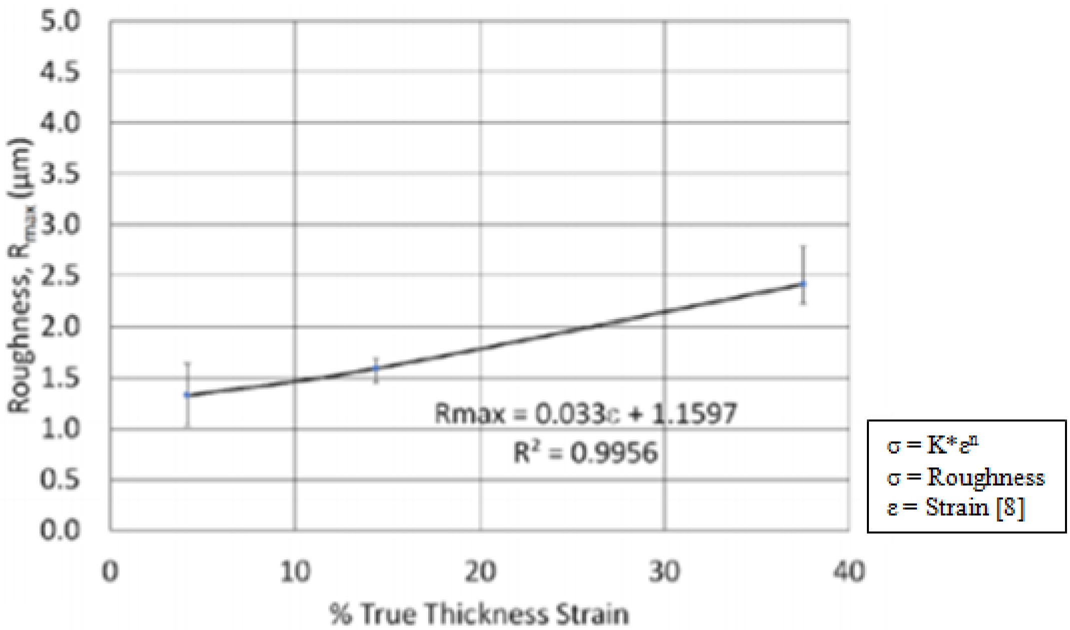


[7] Open die sheet hydroforming deformation experiment

On 50x magnification of the sheet magnification, it was observed that the cross - section had significant amount of thinning at the poles of the bulge. It was also thin at the base of the bulge where the workpiece entered the die cavity. This is due to a condition called *locking*. In this when the metal expands or tries to assume the shape of the die, it first comes in contact with the die shoulders. A combination of high stresses develops in the sheet when it tries to expand beyond the shoulders into the die cavity which the sheet has to overcome to fit into the cavity and get the required shape.

Upon doing the 100x magnification, we are able to see the grain structure of the metal sheet. Using this, we can calculate the ASTM grain size and also the thickness of the sheet at various cross - sections. On inspecting the grains closely, we see that after the hydroforming process instead of elongation of the grains, the grains become more rounded in shape.

During further analysis on the surface of the sheet, we see microscopic orange peeling on the surface. This causes the surface roughness to increase after the process. This is due to the stresses acting on the randomly oriented grains due to which mechanical properties change across the surface. The relation between the degree of roughness and the strain is obtained experimentally to be a power law function.



Post - Process Material Properties

One of the main problems faced in hydraulic forming is the decentralization and localization of hydraulic pressure. Both in sheet and tube hydroforming, the end products have low cross - section and are therefore not quite different from sheet metal. Due to this similarity, the products of hydraulic forming are subject to strain localization and necking. For quantitative analysis of the stresses, various forming limit strains experiments and analytical tools and procedures are used. These tests often point towards strain localization occurrences, non - zero normal and through - thickness stresses. Two different hypotheses have been investigated using their respective mathematical literature and tools to gain insights on the prevailing non - zero normal stresses in hydroforming. They are:

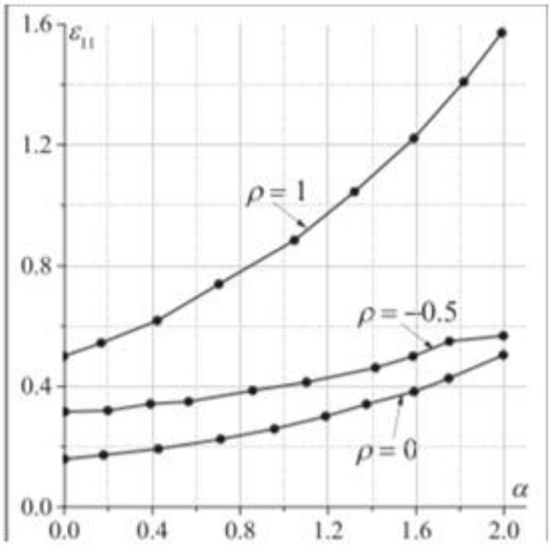
1) Flow Theory of Plasticity: The elasticity of the sheet metal is considered negligible. The mechanical behavior of the sheet is rigid. The rate of strain tensor É is given by the flow theory by:
   Έ=$\varepsilon eq(\partial\sigma$eq $/\partial\boldsymbol{\sigma})$
   ε eq is the equivalent strain rate.
   σ eq is the equivalent stress.
   $\boldsymbol{\sigma}$ is the Cauchy stress tensor.

The plasticity of the material is assumed to be isotropic and the yield point for the material is given by the Von Mises criterion.

2) Deformation Theory: The constitutive equations for principal stresses and strains were formulated. The formulation is only restricted to those materials in which the principal components of stress align with the principal components of strain i. e. isotropic materials. In this, the material is subjected to stresses in two principal directions and a non - zero principal stress acts in out of the plane direction. The additional assumption which we make for the hydroforming process is that there is constant pressure distribution along the distribution of the material surface.

Based on both the hypothesis, and their corresponding strain and stress relations, we have been able to come in agreement with the following conclusions based on the investigations:

- As the hardening parameters of the materials decrease, there is a significant increase in the formidable limits. This is clearly evident and logical as the hard materials have less tendency to break down under high stresses.
- The use of only normal hydraulic stress by the pressurized fluid in tube hydroforming can cause irregular tube buckling as the assumption that the pressure is uniformly distributed inside the tube is not true due to end point criterion. Therefore, normal compressive stress is used here. Early compressive stress can be used efficiently to prevent proper forming averting all the risks of buckling and necking due to erratic pressure distribution.
- Several comparisons of the result with other analytical tools provide us the required confirmation and additional validation for all the theory and tools used by us.
- It has also been speculated that tube and sheet hydroforming result in hardening of the material. Various theoretical tests also prove the same. Due to out - of - plane stresses developed in the metal; there is high increase in the forming limit strain. The forming limit strain gives a qualitative estimation on the strength of the material. Therefore, applying early normal compressive stress develops an additional out - of - plane stress for the tube and increases the forming limit strain. This is an additional advantage of pre - hydraulic pressure normal compressive strain.



[9] Effect of normal compressive stress on the forming limit strain

2. Conclusion

All in all, hydroforming is a very promising technique for forming metals. Since its inception in 1950s for making sports cars equipment, it has come to use in almost every industry. Tube hydroforming is in fact a cheap replacement to casting metal to give thin sheets and then welding them together. It allows the sheet to assume complex shapes with concavities, which would be almost impossible if we use solid die stamping. Since pressurized liquid is used in here, there is no sudden change of pressure or force acting on the metal and therefore no damage occurs to the metal. Instead the grain properties of the metal change in such a way that the metal becomes harder.

Also the tool required in this process is minimal. For sheet hydroforming we just need a punch and drawing tool and for tube hydroforming we just need a small casting die. Only little amounts of machining and surface polishing is required to neutralize irregularities on the surface. The current application of sheet hydroforming is in making satellite antennae and lighting fixtures in reflectors and houses. Tube hydroforming is used widely in the automobile industry and in fighter aircrafts due to its high strength and lightweight properties. It's also used for making bicycle rims for the same advantages.

However, the process comes with its own set of drawbacks. Since the process is relatively new, all its capabilities have not been studied yet and therefore it has not been investigated by an economic and scientific viewpoint for each part. Besides since pressurized water is used for forming, the process is slower and has a long cycle time due to deforming pressure building time. Also the method can be used to develop only oblong parts of specific ductile materials as thin tubes have a maximum limit beyond which expansion is not possible.

Hence, I would like to conclude that the hydroforming technique requires further in - depth primary research to further explore the science behind it and exploit it to its full potential.

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