



## A Review on Tube Hydroforming (THF) Technology for Automotive Application

Ayub Ashwak<sup>1\*</sup>, Adesh Bhil<sup>1</sup>, V B Manjunath<sup>1</sup>

<sup>1</sup> Asst Prof, Dept. of Mechanical Engineering, Holy Mary Institute of Technology & Science, Hyderabad, India

\*Corresponding author E-Mail ID: [shwaq18@gmail.com](mailto:shwaq18@gmail.com), Mobile: 9966374266

DOI: <https://doi.org/10.34256/irjmt1912>

### ABSTRACT

Increasing use of hydroforming in automotive applications needs intensive analysis development on all aspects of this comparatively new technology to satisfy an ever-increasing demand by the trade. This paper summarizes a technological review of hydroforming method from its early years to terribly recent dates on numerous topics like material, tribology, equipment, tooling, etc., so that other research worker at completely different components of the globe will use it for additional investigations during this space.

*Keywords: Hydroforming; Tube; Lubrication; Friction; Formability; Pre-forming*

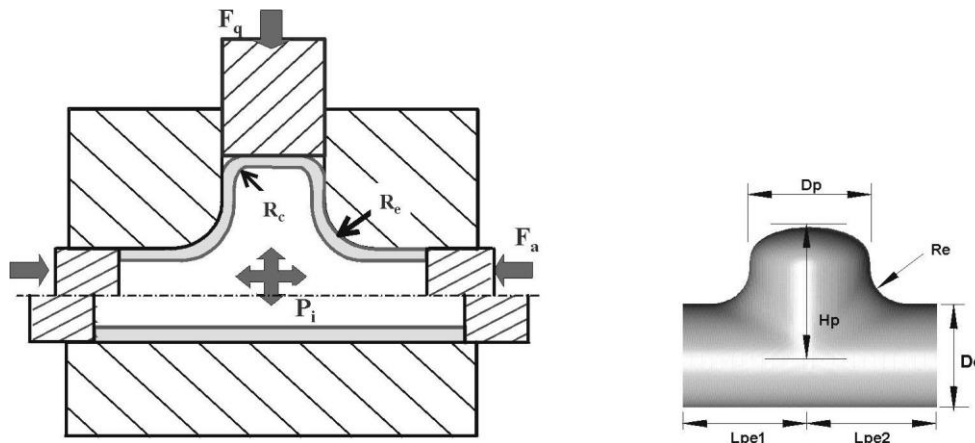
### 1. INTRODUCTION

Tube Hydroforming (THF) has been referred to as with several alternative names betting on the time and country it absolutely was used and investigated. Bulge forming of tubes (BFTs) and liquid bulge forming (LBF) were 2 earlier terms, as an example. Hydraulic (or hydrostatic) pressure forming (HPF) was another type of name used for a short while by some investigators. Internal air mass forming (IHPF) has been principally used inside German makers and researchers. In some periods, it was even called as "Unconventional Tee Forming". Throughout this paper, THF will be used to describe the metal forming process whereby tubes are formed into complex shapes with a die cavity using internal pressure, which is usually obtained by numerous suggests that like hydraulic, viscous medium, elastomers, polyurethane, etc., and axial compressive forces simultaneously, Fig. 1.

Even though THF process has been in practical industrial use only more than a decade, development of the techniques and establishment of the theoretical background goes back to 1940s. Manufacturing of seamless copper things with T branches was investigated using internal pressure and axial load by Grey et al. [1]. Davis tested tubes of medium carbon steel under internal pressure and tensile axial load to determine their yield and fracture characteristics [2]. Experimental and numerical studies were conducted to and the bursting pressure of thick-walled cylinders by Fuel Crosland and Dietmann during 1950s and 1960s [3±5]. In 1960s, experimental and theoretical investigations on instability of thin-walled cylinders were performed by many researchers at different countries [6±8]. Fundamental investigations on thin- and thick-walled cylinders helped theoretical enhancements in LBF operations. Use of hydrostatic pressure in metal forming processes for bulging of tubular parts was frets reported by Fuchs [9]. In this paper, he reported experimental studies on expansion and angling of copper tubes using hydraulic pressure.

Ogura and Ueda [10] presented their experimental results on LBF of Tee shapes from low and medium carbon steel. Different configurations and number of Tee protrusions were formed using internal pressure and axial compressive loading. Proper forming zones were defined for Tee protrusions using experimental results. Experimental results for forming of "different cases" were conjointly disclosed during this paper. In the same amount, Al-Qureshi and his team [11] performed bulging and piercing experiments of different materials including copper, steel and aluminum using polyurethane to provide internal pressure. They didn't report use of axial loading in their experiments.

In 1970s, research on different aspects of bulge forming continued both experimentally and theoretically by various authors. New shapes, materials, totally different tooling configurations and new machine ideas were introduced, whereas the fundamentals remained the same. For instance, instead of polyurethane, rubber and elastomer were used to provide internal pressure [12]. He given that bigger circumferential growth of thin-walled tubes was obtained mistreatment rubber forming ways than mistreatment hydraulic forming technique. Effect of friction between rubber and inner facet of the tubes was conjointly mentioned. Limb and his team [13] per-formed BFTs of different materials with changing wall thickness. They according that increasing the interior pressure step by step throughout the appliance of axial load offers the simplest results on dilution and complete filling. Thickening of tube wall at feeding zone was conjointly mentioned because of the friction between tube and die surface. In addition, experimentation of different lubricants such as PTFE film, colloid-dal graphite and Rocco RTD spray were carried out. In case of insufficient lubrication, low Tee protrusion heights were obtained as well as a bulged protrusion area resulted instead of a fully formed and that area. With proper lubrication, it was reported that a matter bulging of the Tee protrusion was obtained.



*Fig. 1. Elements of a typical THF process. (Fa): Axial force, (Fq): counter force, (Pi): internal pressure, (Rc): corner radius, (Re): fillet radius, (Do): initial tube diameter, (Dp): protrusion diameter or bulge width, (Hp): protrusion or bulge height, (Lp): distance between tube edge and protrusion.*

## 2. THF PARTS, TECHNOLOGY, PRESSES, HYDRAULIC AND CONTROL SYSTEMS

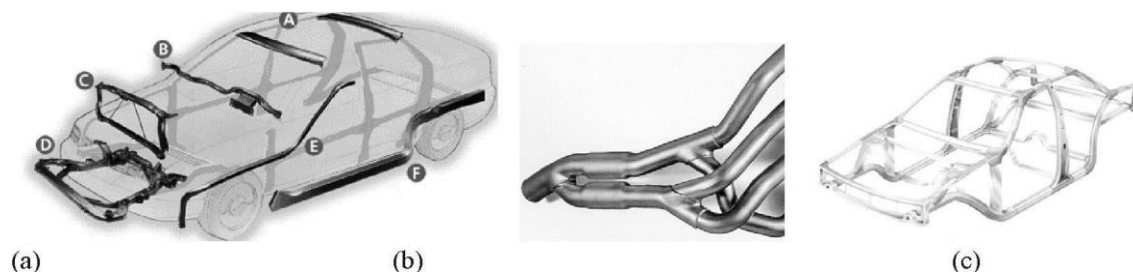
Various parts for automotive, appliance and plumbing are produced by THF technology as listed below:

- Exhaust system parts; usually made of stainless steel for obtaining required structural, thermal and corrosion properties: Exhaust parts, engine tubes, catalytic converters, pressure tubes, tail pipes, connectors and manifolds.
- Chassis parts; common material is low to medium carbon steels and aluminum for structural and cost related reasons: Frame rails, engine sub-frames (cradles), roof rails and bows, instrument panels, rear axle frames and radiator frames.
- Engine and power train components: Suspension cross members, hollow camshafts, drive shafts and gear shafts.
- Body and safety parts: Windshield headers, A/B/C pillars, space frame components, seat frames and shock absorber housings.

Design of the THF system is of special importance since high hydraulic pressures and complex shaped parts involved. The system needed for THF consists of the followings:

- presses or clamping devices for closing the dies, tooling,
- pressure system; intensifier,
- hydraulic cylinders and punches; for sealing the tube and move the material,
- process control systems; computers, data acquisition, transducers, etc.

Fig. 2 illustrates examples of THF parts for automotive applications. There are also a number of candidate parts in development, such as camshaft, crankshafts, differential casings and space frames



**Fig. 2. Examples of structural frame parts for automobile applications. In (a) roof headers (A), instrument panels (B), radiator frame (C), engine cradle and rear axle (D), roof rails (E) and lower rail frames (F) can be manufactured by THF [56], (b) exhaust part [59], (c) space frame.**

## 2.1. Presses or clamping devices

In contrast to other forming operations, in THF process, presses are used to open and close the die and to provide enough clamping load during forming period to prevent elastic deflections and die separation. Necessary tonnage of the press (or clamping device) is dependent on the required closing force. It is, in turn, a function of the maximum internal pressure takes place during forming, part size (i.e. diameter, length and thickness), and material. Large components with thick walls (i.e. chassis components) and intricate regions (i.e. small corner radii) need high closing forces up to  $7000\pm 8000$  t. At present, presses up to 10 000 t capacity are in operation at several plants in the world. Existing hydraulic presses with appropriate closing forces and bed sizes can be utilized for THF process [55,60± 64] with some necessary additions and changes in the system.

Clamping devices, other than regular hydraulic press systems, are being designed and tested for hydroforming purposes. The purpose of developing special clamping devices is to increase capabilities on process control, obtain better dimensional accuracy via high clamping load, access larger bed size, reduce cycle time, increase flexibility for different parts and reduce

investments, etc. In such a design, the ram with the upper die half is actuated up and down through a small cylinder, which would provide rapid motion and cost less. As the ram closes the dies at its bottom position, two opposite and horizontally positioned cylinders are actuated to lock the ram at its required location. More-over, several other small and short-stroke cylinders at the bottom of the press bed are moved up to further increase the clamping load capability. Such a design would not only be cost effective in terms of initial capital investment, but also would provide rapid stroking, which consequently contribute reducing the production cost. In principal, a THF press or machine must have the following features:

- appropriate die closing force;
- appropriate bed size to hold the dies;
- adjustable/movable axial punches with computer con-trolled positioning
- adjustable/movable rams for counter forces with free and position control;
- optional: automatic work-piece handling;
- high pressure (2000±5000 bar) and fluid pumping cap-ability with tight control.

## **2.2. Tooling**

Hydroforming tooling consists of die holders, dies, inserts, punches, protection systems and generally counter punches or movable inserts. Due to the high-pressure values involved in THF process, strong tooling systems are required to minimize die defection and part tolerance deviations. Hence, tool steel such as D2 are used for inserts, whereas 1045 steel is used for the dies. Inserts area unit typically hardened and polished to realize swish surface end to cut back friction and die wear. Design of half positioning and halving lines needs full attention since through that not solely necessary closing force may be reduced however conjointly formability of the part may be secure. For structural parts, diagonal positioning is one way of balancing the die defection between vertical and horizontal directions of the part. Because of confidentiality issues in this high demanding technology, limited information regarding tooling design is released to the public as it goes with other aspects of the technology. Hence, common guidelines known for forging and stamping technologies are applied in combination after necessary improvements and trials.

In general, the followings are main requirements for THF tooling [55,66±68]:

- High strength against stresses due to large internal pressure and axial loading;
- Good surface finish to minimize friction and increase formability;
- Flexibility by interchangeable inserts; good guiding systems;
- Balanced design to minimize the closing force requirements.

## **2.3. Pressure system**

The pressure system (pump, intensifier and control valves) should be designed and selected, so as to provide the required pressure levels for a wide range of parts to obtain flexibility in the system invested. The applied pressure should have a range from 2000 bar (30 ksi) up to 10 000 bar (150 ksi) depending on the parts in consideration. In many current industrial applications using pressures up to 3000 bar (45 ksi) are enough. The flow rate can reach up to 50 l/min in order to allow short cycle times. In order to increase the production rate, multiple intensifiers are used to shorten the pressurizing period and compensate time losses in case of rapid pressure increases when required by any part and process design.

## **2.4. Hydraulic cylinders and punches**

The axial punches are necessary to: (a) seal the end of the tube to avoid pressure losses and (b) feed material into expansion regions. They should feed the material into the deformation zone

in a controlled way, and in synchronization with internal pressure, i.e. pressure versus time and axial force versus time should be controlled and coordinated. Counter punches are sometimes used on bulged or protrusion sections to avoid premature fracture by providing a controlled material. Axial cylinders are expected to generate forces of up to 7000 kN (700 t) while counter cylinder limits extend up to 2000 kN (200 t). The smaller size also allows close control of the punch position. Various punch tip designs for effective sealing during hydroforming have been developed.

### 3. MATERIALS AND FORMABILITY IN THF

The overall success of hydroforming product heavily depends on the incoming tubular material properties. Material properties like composition, weld type, yield and tensile strength, ductility, anisotropy must be determined for tubes. Monitoring and controlling of tube rolling, welding and annealing processes should be conducted carefully to produce tubes with desired properties. Followings square measure the desired characteristics of hollow materials for quality THF applications:

- High and uniform elongation; high strain-hardening exponent; low anisotropy;
- Close mechanical and surface properties of weld line to the base material;
- Good surface quality, free of scratches;
- Close dimensional tolerances (thickness, diameter and shape);
- Burr free ends; should be brushed;
- Tube edges perpendicular to the longitudinal axis.

According to the requirements above, all alloys that are used in deep drawing or extrusion are suitable for THF. Table 1 tabulates some of the tubular materials used in THF process. In addition, available tube types can be listed as follows:

- Seamless drawn circular tubes; seamless drawn tubular profiles;
- Longitudinally seam welded circular tubes; longitudinally seam welded tubular profiles;
- Tailored tubes; round seam welded or longitudinally seam welded.

Different testing methods have been used to determine the quality of tubing for purposes other than THF process. These tests can be listed as follows: (a) tensile test, (b) expansion test (c) cone test and (d) bulge test.

**Table 1. Common materials for THF**

Material	US designation	German designation	Material No. DIN
Steels	AISI 1015	C 15	DIN 17007, 1.0401
	AISI 1020	C 22	DIN 17007, 1.0402
	AISI 1035	C 35	DIN 17007, 1.0501
	AISI 1045	C 45	DIN 17007, 1.0503
	AISI 1015	St 37	DIN 17007, 1.0100
	AISI 1020	St 42	DIN 17007, 1.0130
	ASTM A572-575	St 50	DIN 17007, 1.0530
	Alloyed steels	AISI 5120	21 MnCr 5
AISI 420		X 20 Cr 13	DIN 17007, 1.4021
AISI 304			
AISI 409			
Aluminum alloys	AA 1050A	Al 99.5	DIN 1712 (part 3)
	AA 5005A	Al Mg 1	DIN 1725 (part 1)
	AA 5056A	Al Mg 5	DIN 1725 (part 1)
	AA 5086	Al Mg 4 Mn	DIN 1725 (part 1)
	AA 7075	Al Zn Mg Cu 1.5	DIN 1725 (part 1)
	AA 5052		
	AA 5754		
	AA 6260 T4		
	AA 6061 T4		
	AA 6063 T4		



#### 4. FRICTION IN THE PROCESS AND EVALUATION OF LUBRICANTS

Structural frame elements with significantly long and with varied cross-sections need substantial axial feeding so as to make into die cavities while not a lot of expense of excessive dilution. Substantial cross-sectional changes from round-like to rectangular shapes demand minimum resistance against corner forming and material movement. Friction issues for such cases become very critical. Selection of associate degree acceptable lubricating substance and die coating is important to beat slippy friction, forestall sticking out and vexing to scale back tool wear, axial forces and excessive dilution.

Until recent years, there was not any reported testing methods or equipment development to measure or evaluate friction in THF process. However, effect of friction and different lubricants on formability and extend of protrusion height was mentioned at many occasions starting 1970s [13]. In the same source, thickening of tube wall at feeding zone was reported due to the friction between tube and die surface. In addition, experimentation of different lubricant such as PTFE film, colloidal graphite and Rocol RTD spray were carried out. In case of insufficient lubrication, bulging effect of the dome of Tee protrusion was found to be more pronounced. With proper lubrication, it was reported that a matter bulging of the Tee protrusion was obtained. The impudence of the following parameters on tribological conditions in hydroforming should be examined in detail to improve forming of a complex part:

- Lubricants; die coatings;
- Surface pressure; sliding velocity;
- Work piece and die materials

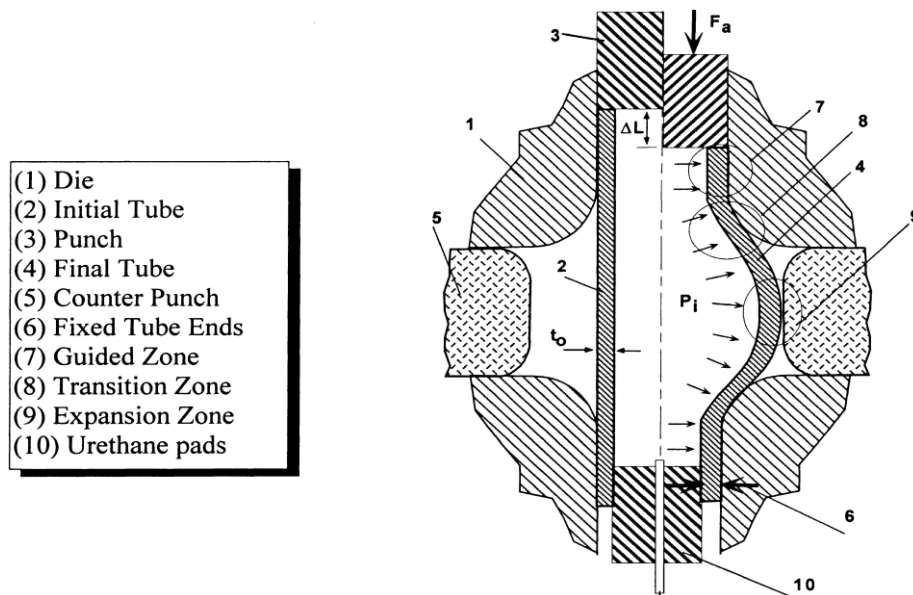


Fig. 3. Schematic of a basic tooling design for friction testing, and various friction zones during a typical hydroforming process.

#### 5. PRE-FORMING OF TUBES FOR HYDROFORMING PROCESS

Numerous THF tasks require a pre-framed cylinder with the end goal to: (a) fit the cylinder into the hydroforming pass on pit and (b) achieve the coveted shape toward the finish of the procedure. Pre-shaping of cylinders generally incorporates twisting and pounding tasks. Besides, tempering might be fundamental subsequent to bowing or squashing to expel remaining

burdens. With the end goal to consider the impacts of pre-shaping and to configuration parts, tooling and process parameters legitimately, examination of twisting and squashing of cylinders is fundamental. In writing, examinations around there have been dated to exceptionally late years, and in a constrained way. These examinations are predominantly trial or dependent on FEA of complex molded parts. Furthermore, there is sufficient foundation and involvement in cylinder bowing for different purposes. Diminishing and thickening of cylinders amid especially in twisting task may enormously influence the achievement of hydroforming process as diminished segments will most likely be unable to withstand inside weight amid extension, and therefore burst, while over the top thickening may prompt wrinkles on the bowed cylinder, and these may require high weight for rectifying.

With the end goal to examine the whole THF process, it is important to convey the consequences of bowing and smashing investigation into hydroforming stage. Utilization of FEA is so far the main method for accomplishing this. Properly chose FEA programming would convey the strain history picked up amid pre-framing straightforwardly into the hydroforming stage similarly as in real shaping of complex parts. Alongside FEA, hypothetical investigations can be additionally performed for straightforward cases or two-dimensional conditions like cross-area of a section.

## **6. INNOVATIONS AND TREND IN HYDROFORMING TECHNOLOGY**

Ongoing advancements are expected to enhance intensity of hydroforming innovation by decreasing starting speculation cost, expanding generation rate, and material use, combining more parts into single parts, and discovering approaches to dispense with downsides, for example, exorbitant diminishing.

As referenced previously, new press or cinching gadget ideas are being worked on and preliminary to diminish the measure of starting capital speculation and additionally increment the profitability by having quick strokes. Indeed, even some hydro-shaping frameworks without a press or clasping gadget are talked about and appear to be possible just for low creation rates.

With the end goal to expand the material usage and keep away from unnecessary diminishing, after advancements are being tried and utilized these days: (a) decreased (funnel shaped) tubes for long auxiliary parts having considerable extension degrees between two closures, (b) tailor-welded tubes for limiting diminishing at high development zones which are as a rule at the center areas of a long part for which different developments can't be used for all intents and purposes, (c) twofold tubing is utilized to build the quality of the last part while limiting the weight. Especially utilized for front rails where additional consideration must be taken for magnificent accident properties, (d) numerous tubing is by all accounts an imaginative method for delivering entire gatherings on the double, which is an amazing method for combining more parts into one. Containers of various pre-framed shapes are associated with one another and put into a hydroforming bite the dust out and out. Endless supply of hydroforming, all parts of a gathering are produced and collected. Utilization of aluminum amalgams and high quality steel is viewed as another method for accomplishing lighter parts.

Organizations and establishments are investigating each shot and chance to make savvy generation with lighter and more grounded items. For example, union of oil into cylinder making is viewed as one method for expanding generation rate. Use of different welding types, for example, gas metal circular segment welding, laser welding, electron shaft welding, is examined to look better material properties. Cylinder making (shaping) cells are in thought rather than ordinary cylinder moving factories in some legitimate cases.

Accordingly, all parts of hydroforming innovation require complete consideration of specialists for better comprehension of its subtle elements. By and large, incline in this innovation appear to pursue a similar improvement way of other metal framing forms.

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### Conflict of Interest

None of the authors have any conflicts of interest to declare.

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