

Weight Reduction Opportunities through Innovative Hydroforming Case of One Piece Frame Rails & Hollow Camshafts

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Introduction

Transportation of people and goods has always been a challenge facing humanity. Doing this has progressed through the years from the basic walking and carrying goods to our modern motorized modes that are so ubiquitous that we take them for granted. For many people the basics are still what they have to use most of the time, but everyone wants the ease of the faster options of using vehicles such as motorcycles, cars, trucks, planes and others.

With the already massive size and level of resource consumption of our collective transportation system, we are faced with the prospect of it only getting bigger. This is a trend that has been ongoing for many years and is recently accelerating because of the huge number of people in the developing world, most notably India & China (37% of total world population) with a pent-up demand for modern conveniences and transportation. Reducing this need/want seems unlikely. The most probable options are how we can best and most efficiently make our transportation system consume fewer resources. A key part of our strategy is and must continue to be making vehicles more efficient and consume fewer resources. This must include designing and devising ways to manufacture, maintain and operate, while attaining a reasonably long working life and disposing of them in an efficient manner that minimizes the required effort and cost at each stage.

The points of concentration to be examined more closely here are the manufacturing of automobile parts and their effect on the operating characteristics of such vehicles. The most important are:

- ◆ Bending and torsional rigidity
- ◆ Crash energy absorption
- ◆ Fuel economy
- ◆ Potential to reduce cost - Use less material ($\geq 60\%$ total cost) vs possible higher process cost

It has been recognized since people started using vehicles that a significant part of the energy required to propel a vehicle is due to its weight. This is the sum of the weight of the vehicle itself and what it is carrying. The first would be all parts of the vehicle, while the latter is people, luggage or any other cargo. The goal should be to minimize the first and maximize that the vehicle is capable of carrying safely. The neverending challenge is how to do so using the most effective and economical methods.

Lightweighting is used to describe a number of techniques aimed at reducing weight. Generally it is the activity of producing lightweight components for improved performance. Extremely clever and weight efficient (high strength/weight ratio) examples can be found in nature such as structures found in bones including notably the human spine. It's ability to move and bear large loads relative to its small structure weight is remarkable.

Lightweighting is a theme that has been prevalent in the automotive industry for decades and yet the commonly held perception is that a lot more remains to be done. Two reasons for this are the addition of equipment & features and a relaxing of weight reduction discipline. This leads to the need for a periodic renewal of the discipline of shedding mass by one or more of several different strategies. A third reason is the continual development of technology that provides new options that are difficult to synthesize with other elements like function requirements, material, design practices and meshing it with current design. This is a complex subject that is difficult to manage.

What Makes It So Difficult To Reduce Weight?

This situation seems comparable to personal weight loss in several respects. One is that there always seems to be a few more pounds to shed and it is easy to gain back weight that was previously shed. Vigilance to prevent or minimize future gains and recognizing new reduction opportunities are important, but challenging to maintain.

There are several factors that make the goal of designing the lightest weight structure to perform the required functions a moving target. These are:

- ◆ Changing requirements for vehicle function and expectations of consumers
- ◆ Expansion of the capabilities of current forming or assembly technologies
- ◆ Development of new technologies
- ◆ Materials
- ◆ Factors of safety (or uncertainty) that are built into the design
- ◆ How well informed were many design choices that were made; considering how many options
- ◆ Design decisions made for other reasons without
- ◆ If the potentially synergistic effect of losing weight in some parts are then taken into account in the design of the parts that must carry it

Each of these categories has more detailed areas that will be discussed with a focus on how they relate to hydroforming.

How To Reduce Weight

Lightweighting is a collection of strategies that make sense to a particular company or industry. They should also be open to new strategies or technology that may offer additional advantages. These strategies should be co-ordinated to achieve the lightest overall part. It is often not highlighted, but is an important point to make that part weight reduction is conditional on the parts functional requirements still being met.

Manufacturing options should be explored for their weight reduction potential. Relative cost should not be a concern initially, because lightweighting and cost can be at cross purposes. Too often cost is the first and by far the largest consideration. However if the weight reduction benefits are quantified first, more rational decisions can be made concerning benefit vs. cost, particularly if the total includes some components requiring the combined effect of 2 or more factors. They include:

1. Eliminating joints.
2. Eliminating welding
3. Reducing material added to make joints
4. Improve joint design for rigidity
5. Secondary stress analysis - deflection, stress reassessment
6. Using high strength steel or other lightweight materials - Aluminum, magnesium, plastics
7. Maximize section size, minimize wall thickness
8. Cross section shaping to minimize material use - expansion, wall thinning, loads
9. Wall thickness control - tailor welded or tailor rolled blanks
 - even more during hydroforming
10. Reconsider options for parts where different processes may reduce weight
11. Selecting the most effective processing steps - ie LPH, HPH, HDF, combination
12. Effectively coordinating use of the applicable strategies to maximize the benefits
13. Wholistic design strategy - The whole structure should be considered
 - Design can be handicapped by several factors
 - Focus is on many separate efforts focused on different parts and assemblies, while the whole structure is given less attention
 - Jumping to conclusions with insufficient information as a guide
14. Reconsider the whole structural system
 - Make 2 parts into 1; reduce part count
 - Part function multitasking
 - Overview - ensure right technology for each part
 - Allow structure to be effectively filled out
 - Reassess design choices to avoid structural degradation

Once the potential weight loss ideas are understood, cost can be considered to decide how to most effectively to implement them. The decision may be that the cost is unjustified for some components, but it will be more informed and better.

Hydroforming's Role in Weight Reduction

Hydroforming is a relatively new technology that has and will continue to play an important role in creating lightweight, efficient and effective parts for vehicles. The potential for further development is greater as well due to its 15-20 year history versus 100+years for stampings. Hydroforming makes parts that gain advantage from being tubular with similar features, capabilities and economics to other techniques like stamping and welding. Weight loss opportunities are one of the fundamental reasons for its rise from no structural part production 20 years ago to its status as a normal manufacturing option today.

We focus on 2 examples of how new tube hydroforming techniques can be used to make parts to achieve greater strength to weight levels of performance and how high strength steels can be used for even greater gains.

Automotive Structural Part Example: Frame Rails

The advantages of hydroformed frame rails compared to making a number of stampings and welding them together into a tube-like structure have been reasonably well documented and are at the root of why hydroforming has developed and grown to be used as much as it is today.

Frame rails for SUV's and small trucks are large parts that have the greatest potential for weight reduction. Some of these applications have used hydroformed frame rails, such as:

- ◆ Dodge Ram, Dakota, Durango
- ◆ Ford F-150,
- ◆ General Motors - Sierra, Envoy, Trailblazer, Tahoe
- ◆ Rover - Discovery 3

It has been common for a frame rail extending from front to rear bumpers to be split into 2 or 3 pieces. Two reasons for this are:

- ◆ Accommodating different vehicles that will use similar rails of differing lengths
- ◆ The manufacturing challenges to make the part design features in a one piece rail are too great or expensive

A high profile bumper to bumper frame rail is actually a car, the Chevrolet Corvette, although cars are almost solely constructed with unibody architecture.

However, many vehicles do not share frame rails with other vehicles of different length, particularly outside North America. In these situations, the manufacturing challenges are the sole limitation. SUV's in India, such as the Scorpio, Safari and utility vehicles like the Ace are examples. These manufacturing challenges are based on conventional or high pressure hydroforming (HPH), some of which are:

1. Material formability - big consideration
 - a. Wall thinning in the corners
 - b. End feeding - reduces wall thinning, but only effective 0.5-1.0 meters from the end
 - c. Lubrication & cleaning
 - d. High formability material required for process may not align with part design needs
 - e. Special 'hydroform' tube making
2. High strength steel & aluminum use substantially limits part design flexibility - desirable materials for lightweighting, but limited formability is a constraint
3. Die size, press size and expense
4. These and other economic factors can increase the cost to a level that is not justifiable

Material formability and end feeding not being effective in the middle of the part limits expansion where it is needed most in a long structural part, like a frame rail. Any one of these factors or several can combine to make hydroforming technically or economically unfeasible. However the advantages of full length rails are desirable to reduce weight as well as other reasons.

- ◆ No joints & accompanying overlaps - **weight reduction opportunity**
- ◆ Improved rigidity - **weight reduction opportunity**
- ◆ Lower assembly cost
- ◆ Dramatic welding reduction - **weight reduction opportunity**

- Accompanying distortion
- Local annealing
- Frame construction - hydroformed parts are more accurate & repeatable
- Stress concentrations reduction
- Improved durability

These factors make it desirable to find a way around the current limitations.

- Opportunities to Build A Better Frame Rail

Whenever development is able to eliminate or significantly push back previously imposed limitations, it provides an opportunity to extend the use and usefulness of hydroforming dramatically for frame rails and other parts. Being able to make frame rails without many of the limitations that were accepted in the past is very useful for vehicle structure designers.

Several unique strategies have been recently developed to substantially reduce or eliminate the limitations listed above in addition to providing the advantages of full length frame rails listed above. These capabilities improve the range of part features available to designers and the cost of producing them. They include:

1. Being able to make a more complex tubular bumper to bumper rail in one piece

These are some examples of achievable tubular cross sections, which is one aspect of desirable design features.

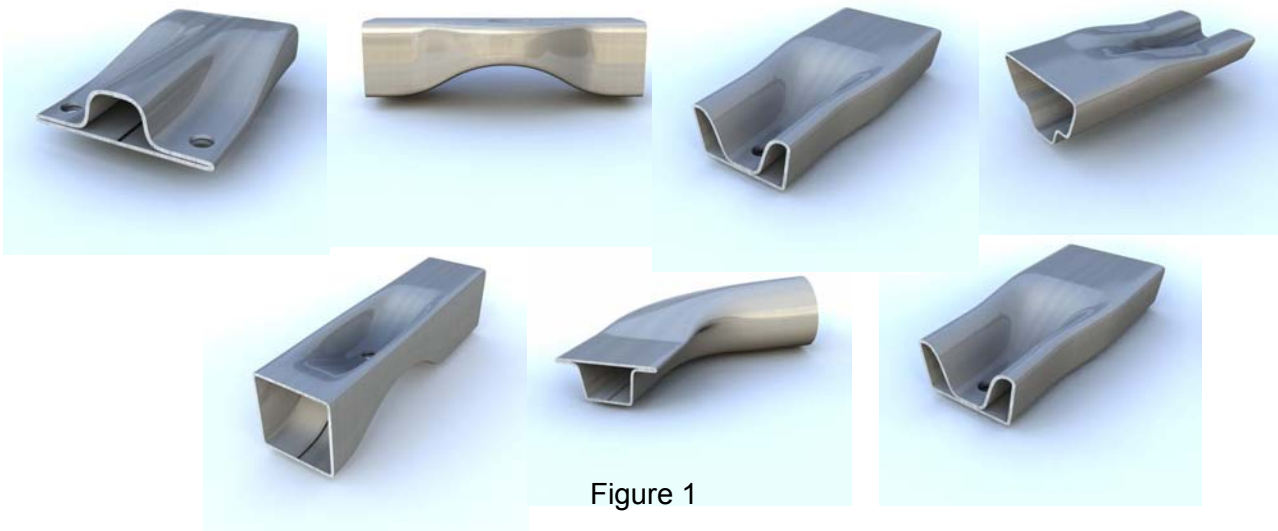


Figure 1

Others include placement and bend sharpness, as well as many of those listed below.

2. Creating large expanded section in the part center - *weight reduction opportunity*

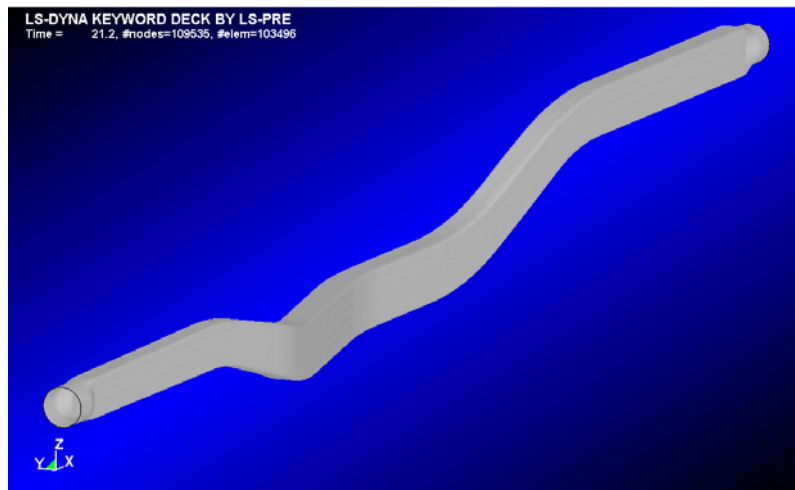


Figure 2

This frame rail design has 40% expansion in the center of the part, uses 125 mm diameter, 3 mm wall thickness & is 4.5 meters long. Material strength increases a small (5-10%) amount where expansion does not occur & substantially more where it does.

3. Wall thickness control - all subpoints are *weight reduction opportunities*

- a. **Prevent thin cross section corners** (Figure 3), maintain an even material thickness distribution around the cross section (Figure 4)

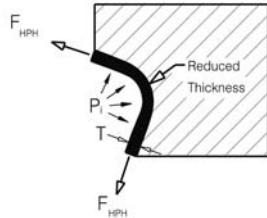


Figure 3

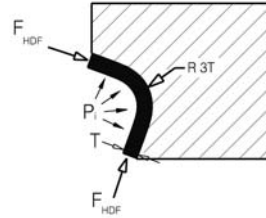


Figure 4

This effect can be prevented throughout the whole part length by using the HydroDieForming (HDF) method

- b. **Thinning in the expanded area can be mostly prevented** if desired by forcing additional material into the expanded area. The part in Figure 5 would have consistent thickness throughout the length and cross sections.
- c. **Thinning can be allowed to occur in proportion to expansion** to reduce weight.

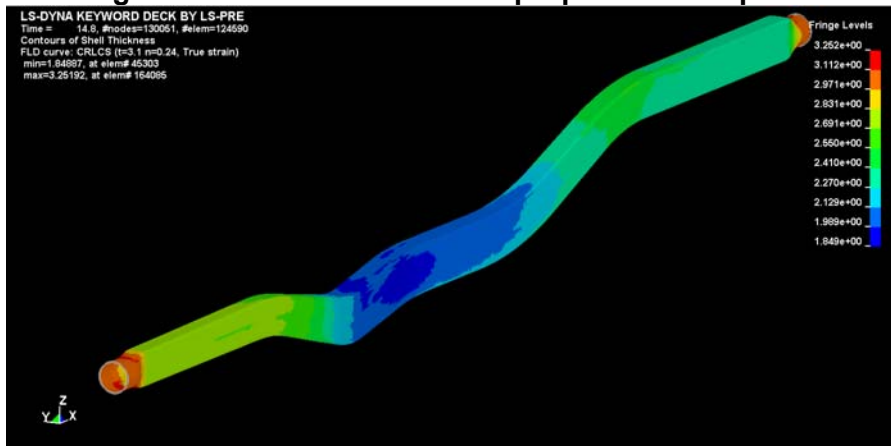


Figure 5

Reduction will be even, without corner thinning and be limited by the formability of the material being used. Larger cross sections can be more rigid, despite having a thinner wall. The part designer determines what is desirable, while simulation and experience must be applied to establish what is feasible for a stable process. Weight reduction and a material strength increase can be substantial.

- d. **Thinning can be controlled to be somewhere between b) & c).** This is likely a more common situation where some supplementary material is provided so the final wall thickness less than what it started at. The weight reduction opportunity is less, but still significant. Larger expansions are achievable than with c).
- e. **Controlled distribution of material** - thicker material where it is more beneficial, thinner where it is less needed
 - i. **Tailor welded tubes** - tube is purchased with different thicknesses and is useful for applications where the added cost for the tube blank is justified by the lesser weight and other benefits. Welded joints can be a challenge.

- ii. **Tailor rolled tubes** - tube is purchased with different thicknesses and is useful for applications where the added cost for the tube blank is justified by the lesser weight and other benefits. Work hardening can be an issue for larger thickness reductions.
 - iii. **Hydroform generated thickness variation** - material can be locally made thicker or thinner during hydroforming. The top & bottom of a frame rail can be thicker with the sides being thinner. This is a new design option that is cost effective
4. **Close tolerance tube wall thickness** reduces average weight. Technology can be added to any tube mill to make tubing with a much closer than normal tolerance with an added bonus of decreased process variation.
 5. **Some parallel ability to vary material properties locally**
 6. **Different materials - aluminum or high strength steels - *weight reduction opportunity***
This is a very important ability with stamping and by extension should be for hydroforming, wider use of these material is limited
 7. **Use smaller tonnage presses; faster cycle times** - production cost is perceived as being too high in a many parts where it technically should be used. Using the HDF approach reduces many cost factors, making previously uneconomical parts sensible to make now.
 8. **Punch all holes during hydroforming.** Using HDF provides the ability to punch many holes during hydroforming. It predominantly affects capital and piece cost, as well as position accuracy.
 9. **Making sharper cross section corners** where needed without increasing process cost

Having more control over putting material where it is needed and less where it is not is a big advancement in hydroforming technology. Being able to do so with the other options listed only adds to advantages that hydroforming provides. These

All options listed are achievable with low forming pressures allowing use of lower cost hydroforming. The greater value provided combined with the more favourable cost changes what makes technical and economic sense to hydroform.

The same principles explained relative to frame rails can be applied to other structural parts in any vehicle and for other purposes as well.

- Weight Loss Limitations (& How to Address Them)

There are a number of process and part performance factors that have been viewed by designers as limitations of the hydroforming process and structural part design in general. It now seems apparent that rather than assume the limits are irrefutable, there are strategies to avoid or at least reduce the potential limitations imposed by some of these factors. It is best to address these issues with an approach of how to do it rather than why it cannot be done. This list is not exhaustive, but provides a number of examples.

Welding Burnthroughs

This essentially means the material must have a minimum thickness, below which burnthrough defects occur creating an unacceptably high scrap rate. Another way to deal with this factor limiting wall thinness is better welding parameter control to reduce the tendency to burnthrough.

Weld Annealing Effect

This is a closely related effect that is part of the nature of welding since the heat used is sufficiently high to locally anneal the material. However, introducing less heat can also reduce this effect, such as laser welding as well as using a material that retains higher yield strength.

Attachment Point Stress Concentrations

It is common that transfer of stress from one part to another through a mechanical or welded joint with their relatively small joint cross section leads to high local loads. The coincidence of this high stress level with local annealing from welding heat means that material must be thick enough to prevent yield in an annealed state. Another option is using material whose annealed yield strength is higher thus allowing significant thickness reduction.

Insufficient Stripout Torque For Self Threading Holes

When punching holes in the part during the hydroforming operation for use with self threading fasteners a key characteristic is the material thickness. Other factors such as hole diameter and material strength have a smaller effect.

While this is a consideration, there may be options like using a lower tightening torque, a different male fastener, add a female fastener or another suitable measure. It is a matter of judging tradeoffs and picking the option with lower weight for a reasonable cost.

Oil Canning Effect

Attachment in middle of the flat applies force to bend the wall. Thicker walled material is one way to address this, but not an efficient one. Several alternatives are:

- Forming opposing walls together for the strength of 2 material thicknesses
- A connecting element to allow the load to be carried by 2 walls of a tube spaced apart
- To locate the mounting hole closer to a cross section corner

Tube Making Feasibility

This is a big consideration, because if you cannot get good quality, consistent tubing the number of problems that follow can be considerable. High diameter to wall thickness ratio (D/t) is highly desirable from a structural design perspective, providing a higher strength to weight ratio. A number of issues can arise that adversely affect tube weld seam quality. It is becoming more common that high strength steel tube is also a requirement, which presents larger challenges as the strength increases. Combining both can make the tube making process unsustainable. This must be addressed with a good tube maker to minimize weight.

Denting And Other Incidental Damage

This is chiefly a material handling issue, which happens more as the material gets thinner. Use of high strength material reduces the issue since it takes a larger force. Even a subtle dent in the tube can make it impossible to get the tube on the bending mandrel, which is a constant requirement for high D/t tubing. This normally means the tube is scrapped. Hydroforming will reduce an early dent. When it happens after hydroforming it is unlikely to cause further processing problems. However, denting at any point in the process can also be a cosmetic or visual concern and cause it to be scrapped at the customer's site. Commonly wall of 1.5 mm thick or greater has fewer problems, but 1 mm or less is quite prone to denting. More careful handling prevents occurrence, but in many industrial settings can be easier said than done.

Wall Thinning

In most hydroformed structural parts there are several reasons for wall thinning. These are bending, cross section expansion and hydroform wall thinning. The amount can be quite substantial and the pattern differs for each of these causes. The question is if the final wall thickness is less than the specified minimum and if this means that it is necessary to start thicker. Finite element analysis and process simulation can be used to determine the answers.

Automotive Structural Part Example: Hollow Camshaft

Hollow camshafts are produced by assembling aggregate parts, i.e., lobes, journals, sprockets etc on a tubular shaft. Compared to conventional solid cast or forge camshafts, hollow camshafts provide opportunities for:

- ◆ Weight reduction exceeding 50%
- ◆ Design flexibility to improve performance of engine and valve trains
- ◆ Reduction in cost.



Figure 6



Figure 7

The automotive industry in North America adopted hollow camshafts in 1990 and since then it has found widespread use in matured markets. Over a period of time, various car and engine makers or their suppliers have developed, and typically patented, their own method of camshaft assembly. All the prevailing assembly technologies have advantages and disadvantages.

Mainly the joint strength between cam lobe and shaft seems to be “adequate” for light duty passenger vehicles but not so for heavy duty commercial vehicles. As a result, presently, use of hollow camshaft is limited to passenger cars alone.

Recent development of a new method of making hollow camshafts, based on application of hydraulic pressure, offers the opportunity which we believe provides for much higher joint strength and consistent quality for both finished and semi-finished camshafts which is suitable for both passenger and commercial vehicles.

- Development

This technology is the result of close to 12 months of:

1. Detailed review of global technologies
2. Assessment of merits & demerits of current technologies. Study of more than 30 patents
3. Assessment of specifications for a versatile assembly technology
 - a. Lobe spacing
 - b. Passenger vs commercial vehicles
 - c. Net shape processes
 - d. Superior precision
4. Innovations evolved after detailed numerical evaluation of more than 20 assembly options
5. Prototypes have been made
6. Currently under patent processing

- Cam Lobes

The main task of the lobe are to provide the proper path to open and close the valves and withstand the pressure on its surface during millions of cycles without significant wear for its expected life. Lightweighting dictates having the largest hole for the lareset thinnest wall tube, but strength requirements and durability limit how far this design direction can go. The lobe must be thick enough maintain it integrity and that of the joint with th shaft.

Lobes can be made with casting, forging and powdered metal of various formulations. There are other options that seem to offer benefits additional to these 3 techniques. Properties and characteristics can be tailored to the engine manufacturers requirements.



Figure 8 - Solid Camshaft

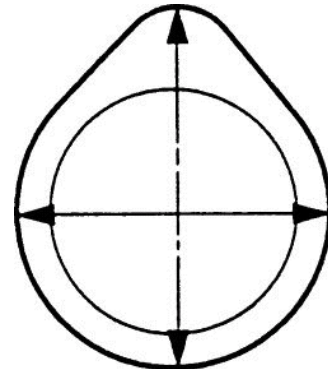


Figure 9 - Lobe for Assembly



Figure 10 - Assembled Section

- Tubular Shaft

The main function of the shaft is to be strong enough to withstand the stresses that are likely to be applied to it and maintain a durable joint with the lobes. Thinner walls desirable for lower weight must be balanced by ensuring it is strong enough. The materials most suited to this purpose are fairly well understood and determined based on real world experience.

- Assembly Process

The key part of this technology uses a unique approach to provide the opportunity to reduce or eliminate commonly accepted 'needed' operations such as lobe surface grinding and heat treating. The lobes are formed first and are locked on the tube using hydraulic pressure and developed fitting techniques. Doing this represents a substantial advance in camshaft manufacturing technology and potential improvements in engine performance that are very attractive.

This technique offers an optimum solution compared to other proven techniques. Some key factors relative to other previously techniques are:

1. Higher torque strength (applicable for both passenger and commercial vehicles).
2. Hydraulic process based on low assembly pressure (approx 10,000 psi). More accurate assembly tolerances and repeatability.
3. "Tolerant Process": Tolerances on aggregates and material "springback" are "absorbed" during assembly process.
4. No "Stress Raisers" ; better torsional fatigue strength
5. Closely spaced lobes\journals are an option

- Potential Functional Advantages

These are:

1. Weight reduction can exceed 60%
2. Less rotational inertia
3. Lower noise & vibration
4. Extra horse power
5. Improved fuel economy
6. Lower CG
7. Lower cost
8. Net shape forming and assembly - reduce/ eliminate grinding & several related problems
9. The lobe profile can be more aggressive than grinding allows - optimize valve opening/closing
10. Reduce or eliminate need for heat treating
11. Choice of roller or sliding follower
12. Improved engine dynamics and performance
13. Compromises with respect to material selection and design are reduced or eliminated
14. Suitable material properties for a sturdy assembly and to withstand high lobe contact stresses

Conclusions

Hydroforming offers many opportunities to reduce weight. Performance and cost improvements are possible depending on the specifics of the part design situation and how they are handled. It also offers significant weight reduction opportunities. These can range from no cost impact to a substantial increase. Designing and making the most efficient part is not automatic, easy or obvious. As with any other technology, there are many ways to misapply it and few ways to do it best. The best way to ensure proper application is to learn as much as possible about different methods to allow logical judgment of the merits of each approach and/or work with experts in the field to decrease learning time and increase confidence and probability of success.

Important principles to bear in mind when designing structures are:

1. Design for structure effectivity first.
2. Make structure design firmer; limit compromises that weaken or add compensating material. Even though hydroforming has good capability to accommodate such design features it is not a structurally good idea.
3. Reducing the number of joints is very important & can be worth some extra cost.
4. Use most advantageous cross section shapes for rigidity or stress levels where best suited.
5. Some compromises will be necessary to fit in the rest of the structure.

Losing weight is a tough, ongoing effort from which relaxing often leads to a relapse. A disciplined approach combined with determination, the most knowledgeable & innovative hydroforming and structural design engineers are the keys to success. Like personal weight loss it is not easy, but it is necessary.

Camshafts offer many advantages including the opportunity to reduce weight, but as part of the rotating mass of the engine the benefits of this weight reduction is multiplied. The assembly opens the options for selection of material suited for the multiple tasks required. The methodology used produces a strong joint between the parts and component size can be varied widely to satisfy strength requirements, weight reduction, durability and a number of other factors that designers may require. The bottom line is a better performing, more efficient engine and a better technology to make a very important part.