Tribological Issues in the Tube Hydroforming Process—Selection of a Lubricant for Robust Process Conditions for an Automotive Structural Frame Part

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In this paper, an overall review of tribological issues in the tube hydroforming process is presented. Guidelines for the selection of lubricants under the hydroforming process conditions are summarized following a description of existing testing methods and apparatus. A methodology of combined experiments and FEA was presented to determine the coefficient of friction in the hydroforming process in addition to selecting a proper lubricant for a given part and process design. Experimental results showed that thickness of the final part at critical regions, amount of axial feeding and axial force are strong indicators of lubricant performance whereas effect of lubrication on the part flatness, corner radius formation and box dimensions are found to be negligible.
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1 Introduction

The tube hydroforming process (THF) has recently found a wide application opportunity in the automotive industry, and is of increasing interest to other industries as well. The increased interest stems in part from the fact that, through the THF process, manufacturers are able to produce complex shaped parts with lightweight and fewer welds, Fig. 1. Advantages of hydroforming include potentially reduced tooling costs, reduced finishing costs on formed parts, excellent material utilization, fewer operations, and improved part quality. In the tube hydroforming process, a blank tube, straight or preformed, is shaped in a die cavity through the application of hydraulic internal pressure and simultaneous axial compressive forces from both ends as depicted in Fig. 1. More details about the basics of hydroforming process can be obtained from [1–4].

In this paper, a general review of the tribological system in the tube hydroforming process is presented in Section 2. In Section 3, general industrial guidelines for the selection of an appropriate lubricant for a given hydroforming application are provided. Recently developed laboratory testing apparatus at various research institutes and their principles are explained in Section 3. Results of the experimental work for hydroforming of a structural automotive frame part using different lubricants are presented in Section 4. Finally, a methodology for determining the friction coefficient comparing FEA simulation results with experimental findings is described in Section 4.

2 Tribological System in Hydroforming

One of the various important part, process and tooling parameters of hydroforming process is the tribological system. Tribological system in hydroforming consists of the following elements or factors: (a) Surface conditions of tube and die, (b) contact area and associated state of stress, (c) pressure, (d) sliding velocity, (e) tube and die materials and their mechanical properties, (f) die coating, (g) positioning of the parting line, and (g) lubricant. Since most of the above factors are embedded and difficult to change once a hydroforming system (i.e., part, tooling and process) is designed and manufactured, the overall performance of the tribological system can be controlled and tailored to the desired conditions by selecting an appropriate lubricant for a given case. An appropriate lubricant can effectively (a) separate work-piece and die surfaces to protect die surfaces, (b) reduce interface friction, (c) help material flow to achieve complete cavity filling, (d) obtain parts with required thickness specifications (reduce thinning), (e) prolong die life by reducing wear and contact stresses [5–10].

Effect of friction and different lubricants on formability and extend of protrusion height of a hydroformed part was described in various studies beginning in the 1970's [11]. Limb and his team performed bulge forming of tubes of different materials with changing wall thickness. They reported that increasing the internal pressure gradually during the application of axial load gives the best results on thinning and complete filling. Thickening of tube wall at feeding zone was also mentioned due to the friction between tube and die surface. In addition, experimentation of different lubricants such as PTFE film, colloidal graphite and Rocol R.T.D. 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 flat area. With proper lubrication, it was reported that a flatter bulging of the Tee protrusion was obtained. Later, Limb et al. used oil as pressurizing medium in their experiments to investigate the forming of copper, aluminum, low carbon steel and brass Tee-shaped tubular parts [12]. Results of lubricant and material evaluations were reported in terms of protrusion height attainable. As reported by Ahmed et al., Hutchinson carried out experimental studies to investigate the effect of different lubricants on bulging of tubes [13].

In hydroforming, boundary lubrication governs the friction conditions. As the internal pressure increase, the area of contact at the interface also increases and sticking friction may become dominant. When the lubrication film is thick to separate asperities on the tool and workpiece, friction is low (thick film regime). But, this leads to rough surface conditions on the formed part as plastic deformation of the workpiece surface is limited. When, the lubrication film is thin, asperities on tool and workpiece have an increased contact. While this leads to formed parts with better sur-

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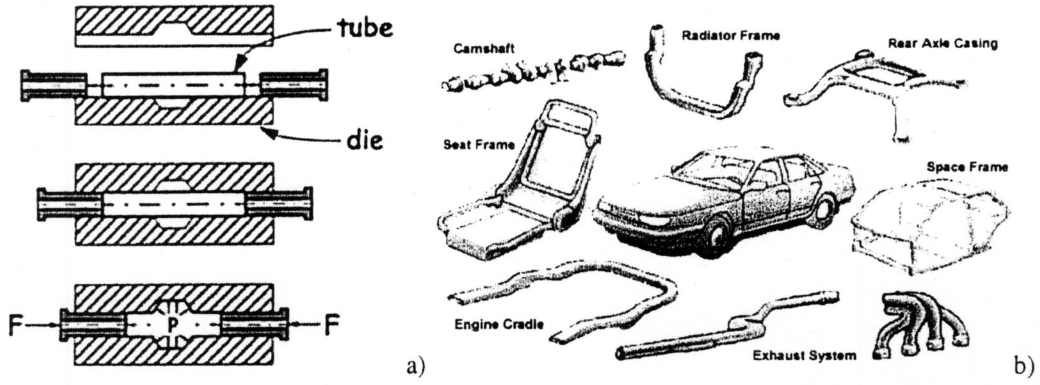

Fig. 1 Sequence of forming operations in a typical hydroforming process, (*b*) Some automotive parts candidate forming with hydroforming

face finish, it causes an increased friction that results in tool surface wear out, lower tool life, higher forming loads, and larger equipment requirements [8,9,14].

Even though, in reality, friction conditions vary with location and time during the forming process depending on surface pressure, sliding velocity, surface topography and temperature, in modeling of the forming processes constant friction models have been widely used. Coulomb friction model has been used to represent the friction conditions in sheet metal forming [15–22]. According to the Coulomb friction law, the tangential (frictional) stress (τ) is proportional to the normal stress (σ_n) at the interface as follows where the proportionality constant is called the friction coefficient (μ).

$$\mu = \frac{F_t}{F_n} = \frac{\tau}{\sigma_n} \tag{1}$$

Some researchers attempted to develop techniques to introduce varying or adaptive friction models into finite element modeling of several metal forming processes. Hsu and Wilson introduced such a technique to simulate an axisymmetric stretch forming process [23]. Hsu and Lee later extended the same technique for the simulation of a simple upsetting process [24] so did Guerin et al. [25] using a different method. Behren et al. implemented an adaptive friction model into the simulation of a multi-stage forging process [26].

Topography of tool and tube plays an important role in tribological mechanism of hydroforming process [14,27–29]. Especially, it is necessary to understand the effect of varying surface roughness of a part undergoing a heavy cold working with changing state of stress in hydroforming. At the early stages of the process, there are peaks and valleys at the contact surface. Hence, friction conditions are severe as lubricant is trapped in this rugged surface structure, and may not help separating the die and part surfaces. As pressure increases, part is deformed into given shape, and asperities begin to disappear. As a result, friction condition becomes less hostile in terms of surface, however since the surface pressure is increased an overall increase in the friction coefficient is observed. Friction coefficient at low-pressure levels is found to be higher than friction coefficients at high pressures [8,9].

Hydroforming of aluminum may bring additional challenges as surfaces of aluminum alloys are covered with a thin and hard oxide layer. Breakage of this layer die to heavy cold working during deformation of the part surface would expose additional and unexpected surfaces to the contact mechanism. Since these additional surfaces are not lubricated properly and sufficiently, they may cause harsh contact conditions resulting in excessive thinning and early fracture of the part. The build up of particles on the tool surface (i.e. galling) particularly of concern in the forming of aluminum alloys. Excessive galling results in scratching and tearing of the part in severely strained areas [1,8,9,30–32]. Structural frame parts with particularly long and varying cross-sections require substantial axial feeding in order to form into die cavities without much expense of excessive thinning at the expanded regions. 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 for the successful and defect-free forming of the parts. Selection of an appropriate lubricant and die coating is essential to overcome sliding friction, prevent sticking and galling to reduce tool wear, axial forces and excessive thinning [1–4,19–22].

Prier et al. identified different friction zones on a typical hydrofroming process depending on the effects of axial force, feeding and geometrical aspects [8]. These friction regimes and consequent friction coefficients continuously vary with location and time. The surface pressure, sliding velocity, and state of stress and strain were identified to be different in these zones as follows (Fig. 2): (*a*) Guide zone, (*b*) Transition zone, (*c*) Expansion zone. In these three zones, the following conditions prevail:

- Guided Zone: Friction in guided zone is high. Tube and die surfaces are in contact under pressure and straight axial compression. Axial movement of material is very rapid compared to expansion zone. Material movement rate may vary between 50–100 mm/sec. Very little expansion (<5%)
- Transition Zone: Deformed part and die surfaces are in contact under pressure and a tri-axial state of stress exists. Material movement rate is slow compared to guided zone. Sliding velocity smaller than that of the guide zone (10–30 mm/sec), but still appreciable,
- Expansion Zone: Substantial expansion under bi-axial stresses where axial feeding is negligible. Material movement in circumferencial direction is dominant compared to negligible axial movement. Tensile stresses are prevalent (axial and hoop direction), Sliding velocity is small (<10 mm/sec), Surface expansion is large (>20%).

3 Selection of Lubricants for Hydroforming Process and Testing Methods to Determine the Friction Coefficients

For a given set of die and tube materials, surface and loading conditions, selection of an appropriate lubricant is essential to overcome sliding friction, prevent sticking and galling, reduce tool wear, axial forces and excessive thinning to produce a sound and acceptable hydroform part. An effective hydroforming lubricant should be selected based on the following criteria [1–4,8,9,33–35]:

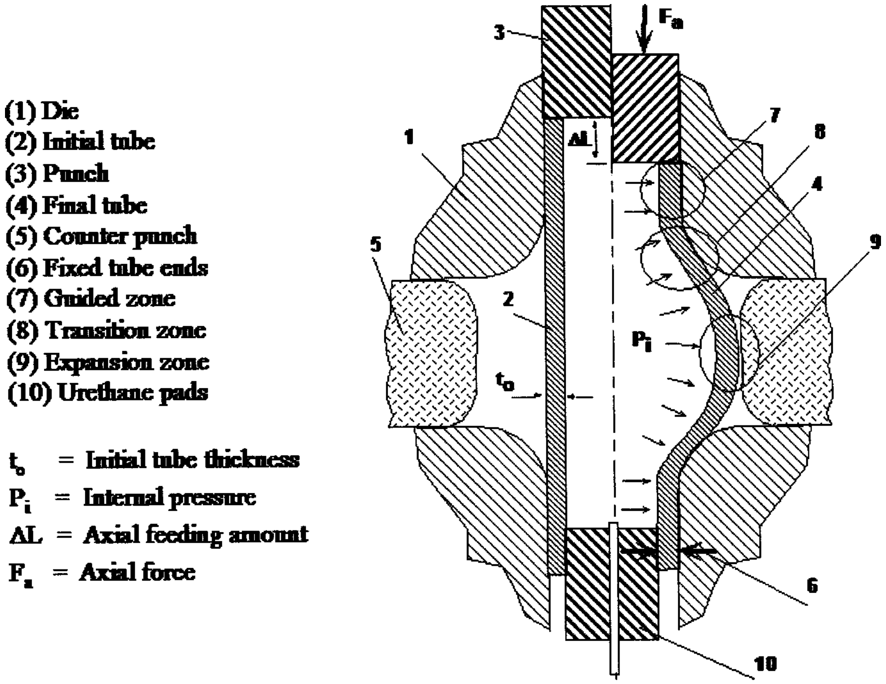

Fig. 2 Schematic of hydroforming of a simple bulge, and various friction zones in a typical hydroforming process

- Performance during bending, pre-forming and hydroforming stages: Lubricity to reduce sliding friction between tooling and tube surface
- Durability under high pressure values up to 6–15 ksi at the tube-to-tooling interface to prevent sticking and galling
- Minimum abrasivity to reduce tool wear
- Compatibility with hydroforming fluid, rust prevention medium, cutting fluids and other environmental requirements: Incompatible lubricants would increase the frequency and hence the cost of filtering of the forming fluid. It may damage the hydraulic system.
- Ease of application: Automation of the lubricant application is essential for reducing the cost per part and for a consistent use
- Ease of removal: Cleaning with washing fluids. There should not be any residues left on the part as these may adversely affect post-hydroform operations like welding and cutting
- Cost: Considering all aspects such as lubricant cost per part, application and removal system cost and cost of washing fluids, cost of filtering the forming medium, etc.

There are many lubricants that are used currently or thought to be suitable for hydroforming operations. These lubricants can be broadly classified as follows: (a) Dry lubricants: borax-based, soap based or polymer-based, (b) Wet lubricants: oil-based, water-based, (c) Paste lubricants. Dry lubricants are usually found to be more effective in terms of performance to reduce friction and increase tool life [30–32]. Their application can be automated to yield consistent lubrication thickness with proper instrumentation. Such an application system even can be installed just after tube rolling operation. This would result in a clean and cost effective lubrication practice as it could eliminate one of the steps in hydroforming shop floor. Savings in terms of shop floor space, cleaning, safety, process delays, compatibility with environmental regulations, and etc. should be considered as further advantages of dry lubricants [33–35]. Drying time is very crucial for dry lubricants as inappropriate dry time and environment may cause not only ineffective lubrication but also be harmful to the hydraulic system. Moreover, their removal requires special washing fluids. They are found to be more expensive than wet lubricants when drying time, application and removal process and their original costs are added. On the other hand, cost of wet lubricants is lower than dry lubricants. They are relatively easy to remove. But, application of wet lubricants requires care, and is not completely suitable for automation. Compatibility with forming fluids is another issue. Most importantly, they do not perform as well as dry lubricants do. Hence, a compromise must be made depending on the part complexity and quality requirements [8,9,33–35].

Until recent years, there have not any reported testing methods or equipment development to measure or evaluate friction in tube hydroforming process. In order to facilitate the modeling of the process, usually a friction coefficient (in case of hydoforming and sheet metal forming processes, Coulomb friction coefficient) has to be assumed in FEA. In order to determine reasonably acceptable friction coefficients, various testing methods and apparatus for each regime have been already developed or suggested by various institutes as of today. Schmoeckel demonstrated the use of friction testing in a guided zone where basically a tube is pushed at various sliding velocity through a round die cavity while pressurized internally [8,36]. Figure 3 depicts the basic schematic of this apparatus. Friction coefficients of different lubricants and materials under internal pressure levels could then be obtained with such a method. Dohmann suggested a Tee-shape tooling to measure friction coefficient at transition and expansion zones [9]. Other researchers conducted pin-on-disk or twist tests to rank the performance of different lubricants suggested for hydroforming applications [33,34]. As a result, all parameters affecting friction conditions should be improved for an overall success in hydroforming. Dalton proposed the use of a square die to rank lubricants according to their performance at calibration zone [33]. Altan and his group at OSU have been developing tooling and testing methods covering all friction regimes in the tube hydroforming process. Their first tooling is very similar to the one suggested and used by Schmoeckel. Their second tooling is a variation of Dohmann's method and tooling. In this one, they utilize a tooling with a pear shaped die cavity instead of a Tee protrusion [37]. Height and thickness variation along dome of the pear shape

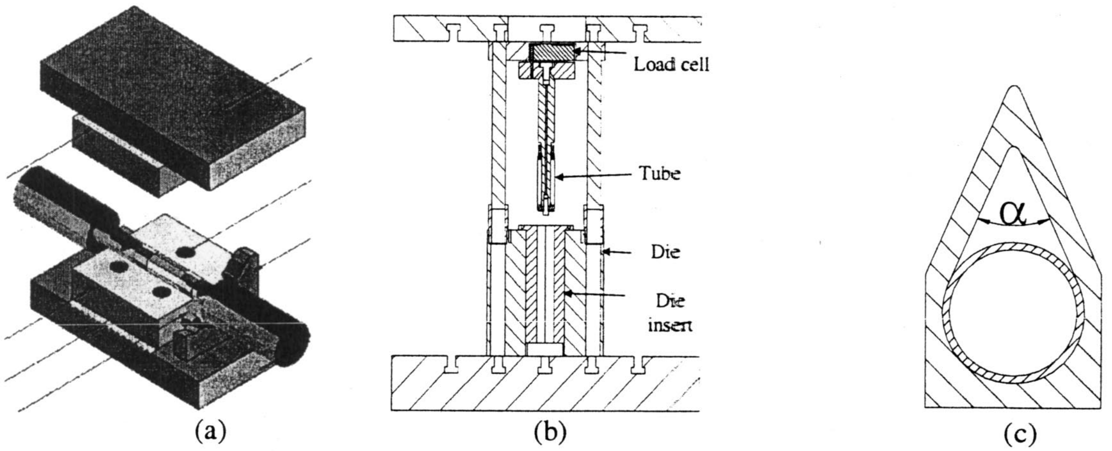

Fig. 3 Some of the existing friction testing apparatus for hydroforming. (*a*) University of Darmstadt's testing tooling for guiding zone friction measurements [8,36], (*b*) OSU's test tooling for guiding zone friction measurements [37], (*c*) OSU's test tooling for expansion zone friction measurements [37]

is used as an indication of lubrication's performance and to determine a coefficient of friction via FEA comparisons. Vollertsen suggested use of a tube upsetting test under hydraulic pressure for measurement of coefficient of friction under hydroforming conditions [38]

4 Experiments on a Structural Automotive Frame

Even though the methods and testing apparatus described in the previous section found to be useful in determining the friction coefficients and ranking lubricants, manufacturers of hydroformed parts (OEMs and suppliers) still hesitant to use these findings right away without further testing for particular parts under production conditions since selection of lubricants for mass production also requires cost (in terms of lubricant, application, removal, filtering), compatibility and environmental justifications as explained before. Manufacturers are required to perform in-house testing of several lubricants during prototyping for each particular part to ensure the required dimensional specifications of the actual parts under production conditions before they can start mass production. Wall thickness, flatness and radius specifications need to be verified with specified values determined for NVH and crash requirements of a vehicle. These tests cause delays in product lead times and increase the cost of development. In this paper, experiments and their results on an actual structural frame rail, as depicted in Fig. 4, are presented following an FEA study for comparison to determine the friction coefficients for each lubricant for future use. The structural frame part and tooling selected for this study possess various characteristics of any hydroformed part such as multiple bends, radical changes in cross sections, tight radii, etc. Hence, a systematical experimentation supported and compared with FEA simulations, as outlined in this paper, would help manufacturers to eliminate tedious, lengthy and costly testing of different lubricants for every part type. Instead, manufacturers can capture the knowledge of lubrication and friction through only a limited number of experimentation and exhaustive computational analysis saving time, money and other resources.

Four (4) lubricants of different types are tested in hydroforming of a structural part. While all the elements of the process, part and tooling were controlled to be the same, only lubricant type was changed in the experimental plan for this study. In order to investigate the effect of initial thickness on the performance of lubricants, tubes with two different initial thickness values were used (i.e. $t_o = 3$ mm and 4 mm). Table 1 tabulates these lubricants and their brief specifications. All tubes were of the same material (LCS 1008) with an initial diameter of 100 mm and initial thickness values of 3 and 4 mm. All tubes were cleaned before application of lubricants as bending, pre-forming and hydroforming dies were also cleaned before and after testing of each lubricant set. Lubricants of dry, wet and paste types were applied manually by the same technician on to tubes before bending process according to the specifications provided by the lubricant suppliers. Between testing of each set, extra tubes with the next lubricant type were formed in order to achieve steady state conditions of the hydroforming system. A sample size of three (3) was used in the analysis of the data.

The followings were measured on each part: (a) thickness at three different critical regions identified previously after experimental trials and FEA (these critical regions are depicted in Fig.

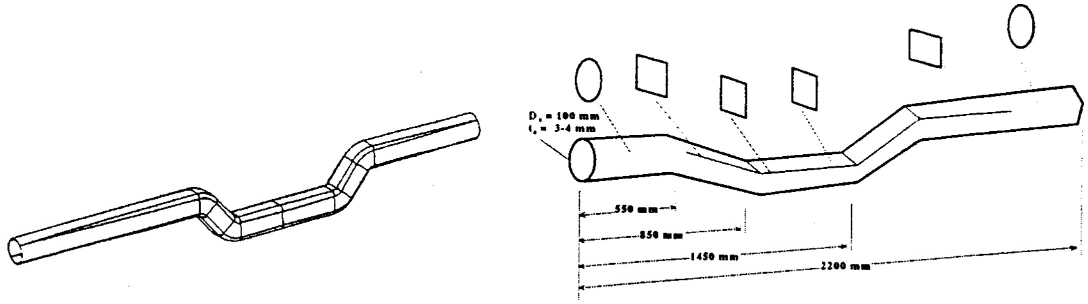

Fig. 4 Structural hydroform part used this experiment and overall dimensions

Table 1 List of lubricants used in the experiments

#	Type	Specifications
Lube 1	Wet	Water based, pre-emulsified, contains solid lubricant, chlorine & sulfur free
Lube 2	Dry	Water based, air dried, contains pressure resistant substances
Lube 3	Wet	Synthetic, water soluble, high viscosity
Lube 4	Paste	Off-white paste form, can be diluted with water

4), (b) difference between part and tube length, (c) flatness at various regions, (d) corner radii at various locations on the part, (e) box dimensions (height and width), and (f) amount of axial force. Thickness measurements were performed using an ultrasonic device. For verification, some parts were cut into sections, and measurements with a micrometer were conducted at the same regions. Both methods were found to give similar results within a deviation of 3–4%. Rest of the measurements was performed using the ultrasonic measurement method as it was found to be friendly and faster. Flatness, box height and width and radius measurements were performed on a CMM machine. The length of initial tube and final part were the easiest to measure. It was recorded to compare the amount of total axial feeding for each set. In addition to the above responses, the followings were also checked and recorded for comparison purposes: (a) application of lubricants and associated difficulties and problems, (b) cleaning of lubricant after hydroforming, and (c) die galling and residues on die surfaces.

Experimental Results. Figure 5 illustrates the thickness measurement comparison at Regions B, C, D for four (4) lubricants on parts with two different initial thickness values (i.e. $t_o = 3$ and 4 mm). Around 100 thickness measurements with ultrasound device were conducted on webs and tension flanges at each region. The average and the lowest values of these readings for each lubricant at each region were compared here. Dry lube (Lube 2) offered the least amount thinning compared to the rest of the lubricants at all regions. Water-based wet lubricant (Lube 1) comes after dry lube regarding the thinning performance. Effect of lubricant on the final part thickness becomes more visible on parts with larger initial thickness value (i.e., 4 mm) compared to parts with 3 mm of initial wall thickness. Lubricants 2 and 1 not only provided the least amount of thinning but also the least variation of thickness at all regions. Hence, they are more likely to provide a robust production process than other lubricant tested.

Figure 6 depicts the effect of lubricant performance on axial force requirement and feeding capability. As seen from this figure, parallel and in accordance with what observed on thickness comparison charts, Lube 2 (dry lube) offers the largest axial feeding capability (when total of right and left axial feeding values are compared) while requiring the least amount of axial force on both cylinders. This is exactly what should be expected from a good lubricant with low coefficient of friction. Similarly, Lube 2 would be the second best option in terms of feeding capability and force requirements. Similar to thickness comparisons, thicker tubes provides a better discrimination of lubricants as axial force measurements on parts with ($t_o = 3$ mm) are very close to each other regardless of cylinder, Fig. 6. Comparison of deviations in box width & height, flatness and corner radius with respect to designed or desired values at several regions did not reveal any indication of a superior lubricant over others, hence only overall average values of these responses are presented in Fig. 7.

Prediction of Coefficient of Friction (μ) Comparing the Experimental and FEA Results. FEA of the same experimental conditions (i.e., geometry, material, loading) were conducted for comparison purposes. Three-dimensional, explicit FEA code LS-DYNA was used for computer simulations. Shell elements were used in modeling of the structural part while dies and punches were assumed to be rigid. Figure 8 illustrates the FE model, a typical forming sequence (bending, preforming and calibration stages) as well as thinning and thickness distributions on a typical simulated final part. Table 2 presents the material and process conditions used in the simulations. All conditions were kept the same except friction coefficient. As seen in Fig. 8, critical expansion regions were verified with FEM simulations. After each simulation, minimum thickness values at three different critical regions (B, C, and D) were compared with experimental measurements in accordance with the flow diagram in Fig. 9. Comparison

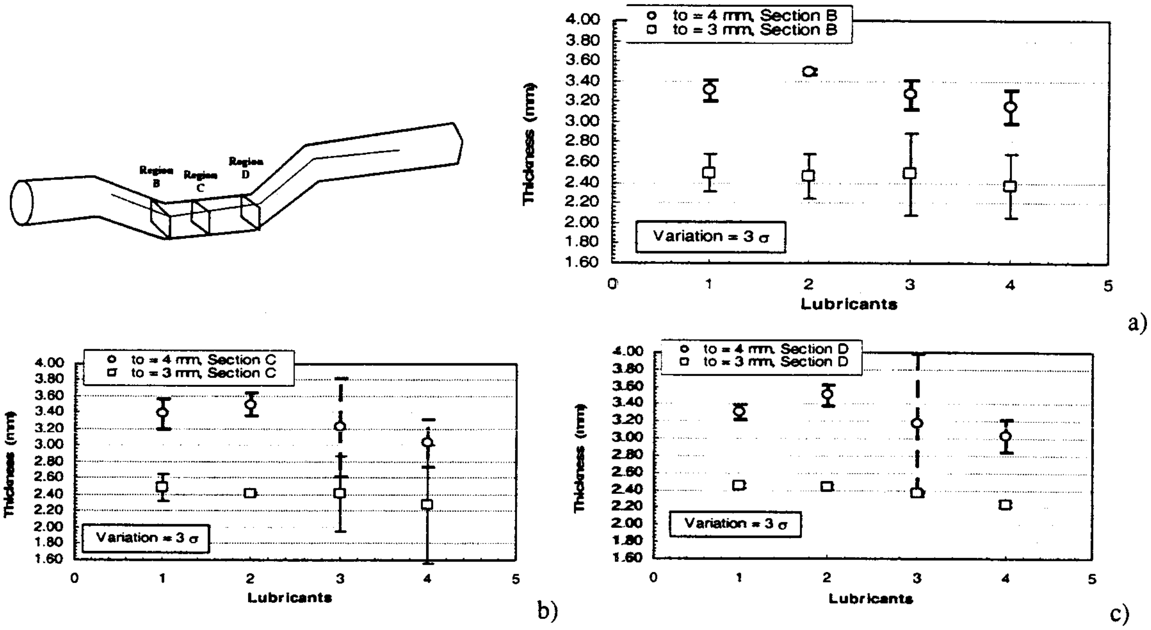

Fig. 5 Comparison of minimum thickness measurements in regions B, C, and D for respective lubricants. Tubes with two different initial thickness values (3 and 4 mm) were tested. Lubricant 2 offers the least amount of thinning when all regions and different initial tube thickness conditions are considered.

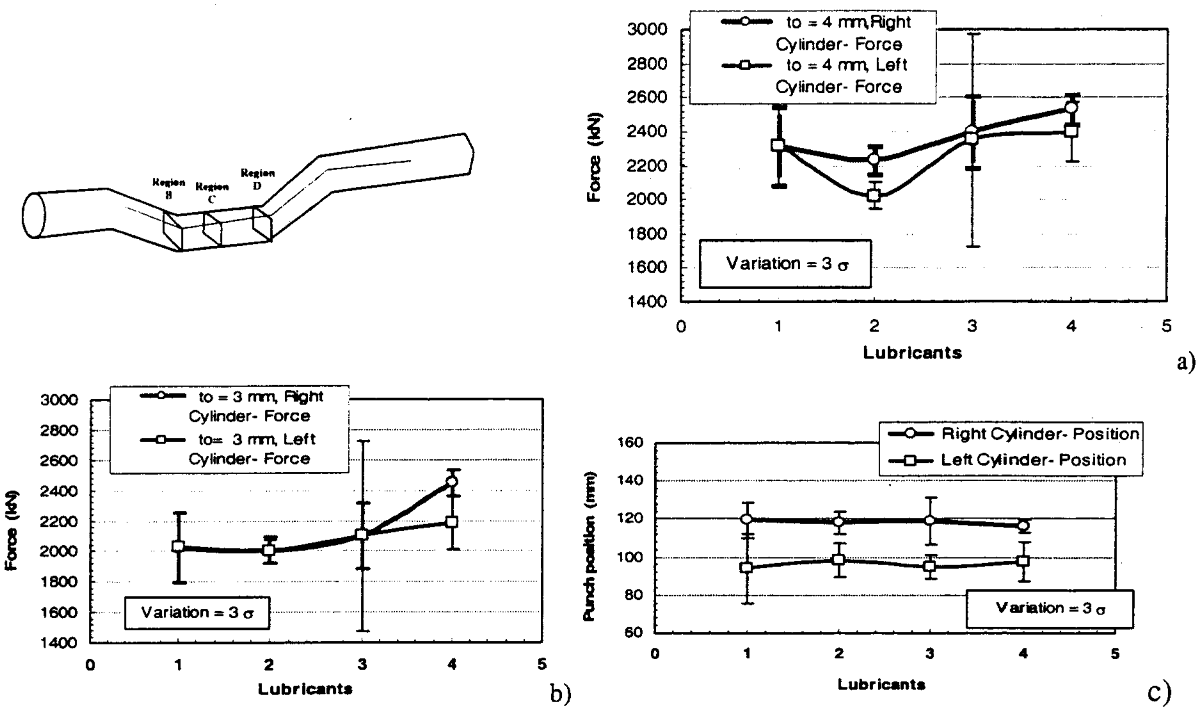

Fig. 6 (*a* & *b*) **Comparison of axial force readings for respective lubricants on parts with two different initial tube thickness values. (*c*) Comparison of punch positions (not real feeding) for parts with initial thickness of 4 mm. Lube 2 performs the best in terms of the smallest force requirements and largest total axial feeding capability.**

of the minimum predicted thickness (t_c) and minimum measured thickness (t_e) values at three different critical regions (B, C and D) was used to determine an appropriate coefficient of friction (μ) for the respective lubricant, Fig. 9. Comparisons at individual narrow zones and minimum of the overall regions were performed. Whenever a coefficient of friction (μ) in FEA resulted in thickness predictions within 5–10% error with respect to measured thickness values, respective (μ) was accepted as a representative value

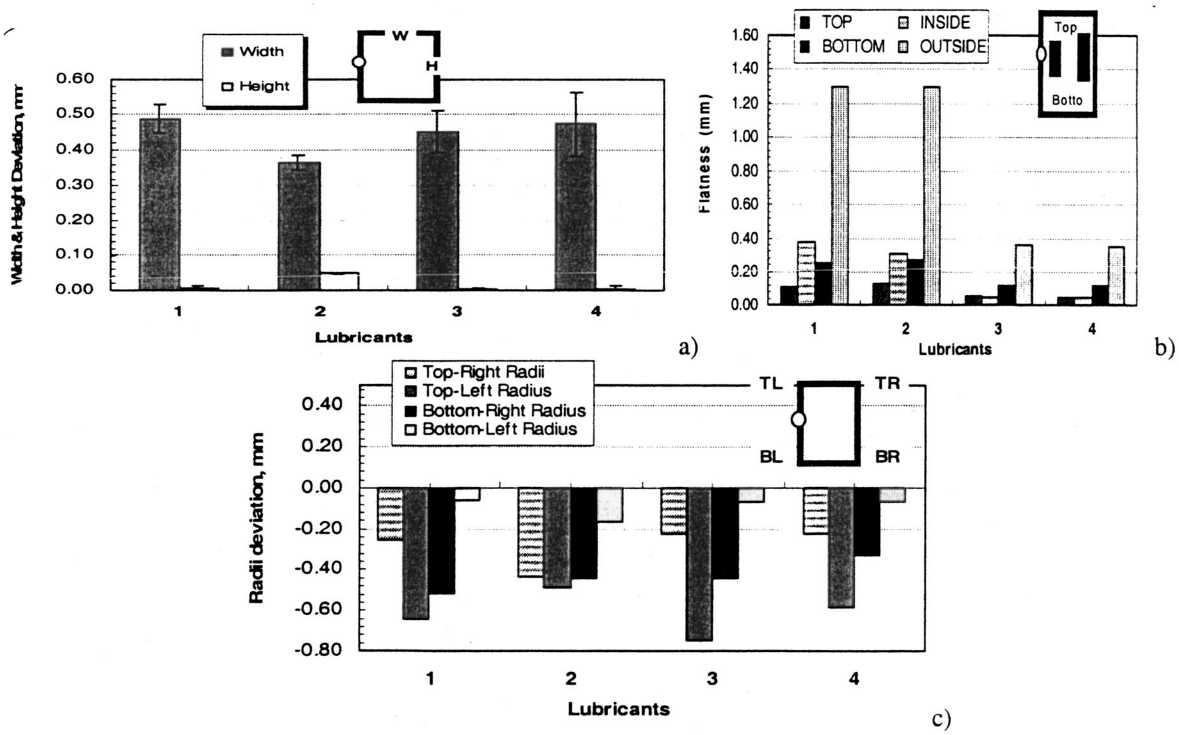

Fig. 7 Comparison of (*a*) **overall box dimension** (**height and width**) **deviation at all regions.** (*b*) **Comparison of flatness at Region B and Region C** (*c*) **Comparison of overall radius deviation at all regions. None of these measurements indicates a clear result.**

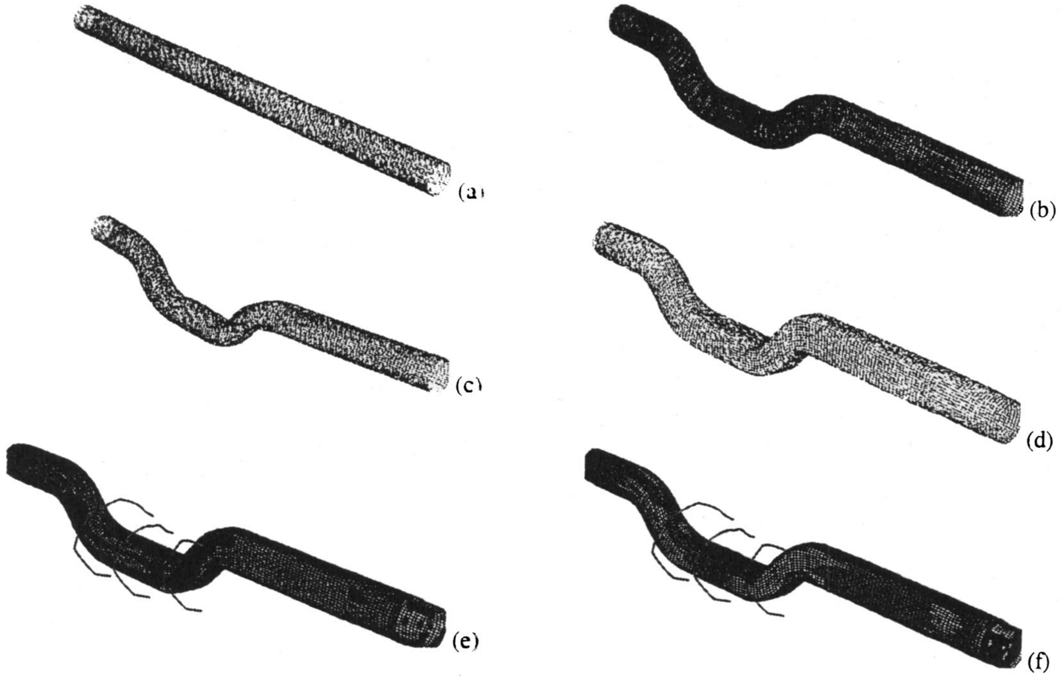

Fig. 8 (*a*) FE Model, (*b*, *c*, *d*) forming sequence, (*e*) thinning and (*f*) thickness distributions on a typical final part

for the lubricant used in that set of testing. Satisfactory matching of thickness predictions at these three different but critical regions was found to be reasonably and practically enough to estimate the value of (μ). Note that value of (μ) may slightly differ between different FEA codes depending on their element type, solution method and most importantly selected contact algorithm. Hence, a cross-check is required to see whether, under similar circumstances, predicted (μ) would result in the same thickness predictions using different FEA software.

Through this trial and error scheme, a narrow range for coefficient of friction (CoF) for each lubricant was estimated as tabulated in Table 3. Such predicted CoF ranges, then, can be used in

Table 2 Material and process conditions used in FEA of the hydroform part

Material Conditions		Process Conditions							
K	480 Mpa	*t*, sec	0	1	2	3	8	16	20
n	0.16	Pi, MPa	0	6	20	30	80	100	130
YS	200 Mpa	da_{left}, mm	0	5	11	35	64	75	82
Do	100 mm	da_{right}, mm	0	7	12	48	82	104	110
to	3 & 4 mm	Fa_{left}, kN							Max. 2800 kN
Lo	2200 mm	Fa_{right}, kN							Max. 2800 kN

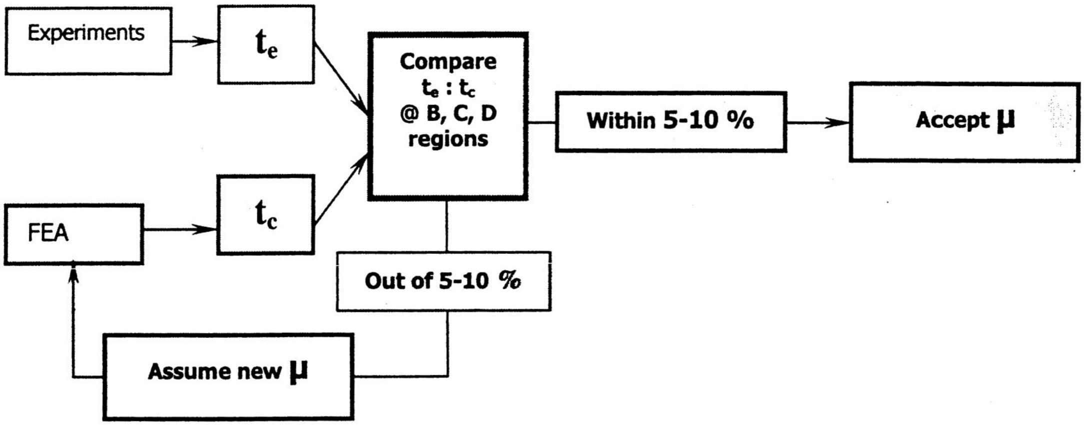

Fig. 9 Methodology used to predict coefficient of friction based on measurement values and FEA results

Table 3 Predicted coefficient of friction after comparison of experimental measurements and FE simulations planned in accordance with scheme outlined in Fig. 8

#	Type	Predicted Coefficient of Friction
Lube 1	Wet	0.08–0.09
Lube 2	Dry	0.04–0.05
Lube 3	Wet	0.12–0.14
Lube 4	Paste	0.19–0.22

future hydroforming simulations involving that particular lubricant or a similar one as almost no quantitative tribological data is available for hydroforming process.

5 Discussion and Conclusions

Before, stating the conclusions for this study, it is necessary to indicate that thickness predictions with FEA are usually lower than actual measurements as FEA gives a lower bound solution. Such an observance was also made in other studies as reported in [18–22]. As a result, the followings can be concluded from this study: (a) Deviations in flatness, box dimensions and radius with respect to designed values were not found to be a good indication of lubricant performance in hydroforming of this particular part. (b) Thickness comparison of critical expansion regions and amount of total axial feed are discriminative and good indications of lubricant performance (c) Dry lube was found to result in least thinning amount for the structural part used as an example in this study. Wet and paste lubes almost lead to similar thinning values to each other. Only Lube 1 of wet lubes slightly performed better than others. (d) When all aspects of lubrication including cost, application, removal, compatibility, overall die life, hydraulic system life, etc. as explained in section 2, dry lubricant would be the choice of application for this case, and may be for many other similar parts. (e) Wet Lube 1 could be the second choice as it provides ease of application and removal as well as compatibility with other working fluids in the hydroforming system. (f) As such a structural part shape, cross-sections and dimensions are very common in the automotive applications, selection of lubricant and other aspects explained above can be also applied to other cases when other specific information is not available. (g) Use of FEA along with experimental findings not only offer determination of friction coefficients, which is difficult to predict otherwise, but also would eliminate experimental try outs in the future for parts of the similar material, lubricant and geometry.

On the other hand, it has to be remembered that friction conditions in metal forming processes vary with location and time during the forming of a part as a function of contact pressure, sliding velocity, surface roughness and temperature. Therefore it is very difficult to model and introduce such a model into the FE analysis or other numerical solutions. As indicated before, some researchers attempted to implement such variable or adaptive friction models into computer simulations of simple metal forming processes such as upsetting, axisymmetric forming and rolling [23–26]. Finally, development and use of environmentally-friendly lubricants should be another vital aspect during selection of lubricant [31,39–41] in addition to other factors mentioned in this manuscript.

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