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Lubrication in tube hydroforming (THF) Part II. Performance evaluation of lubricants using LDH test and pear-shaped tube expansion test

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Abstract

Two model tests to evaluate lubricant performance under realistic tribological conditions occurring in the transition and expansion zones of a tube hydroforming (THF) process are presented. The model test for the transition zone is based on the limiting dome height (LDH) test principle. For the expansion zone, a pear-shaped tube expansion test (PET) developed by the authors is employed. Four lubricants were tested and ranked based on (a) dome wall thinning behavior (for LDH), (b) tube wall thinning, tube protrusion height (PH), tube bursting pressure (for PET), and (c) surface topography. Friction coefficients for the lubricants were estimated by matching the experimental and FE results.

Keywords: Limiting dome height; Pear-shaped tube expansion test; Tube hydroforming process

1. Introduction

Lubricants play a major role in tube hydroforming (THF) processes as they reduce the friction stresses/forces at the tool–tube wall interface, thus enhancing product quality. With good lubrication, problems associated with wrinkling, buckling, premature failure can be reduced or eliminated.

Due to lack of well-established tribo tests under THF conditions, most companies involved with THF resort to use lubricants for sheet metal forming [1,2]. This limits the optimum utilization of THF technology. These randomly selected lubricants that are meant for sheet metal forming may fail to perform in THF environment due to the difference in the mechanics of deformation between THF and sheet metal forming processes. Furthermore, these lubricants may be incompatible with secondary operations necessary in THF.

Process design and analysis of THF through FEM is also hindered by the lack of precise friction coefficients. It is common to find that most process designers prescribe a friction coefficient based on other metal forming processes. Depending on the THF part in consideration, the friction value randomly chosen may be far from reality.

In THF, one often encounters three friction zones: guiding, transition and expansion zones. Due to the difference in the mechanics of deformation in these zones, lubricants can perform differently. Thus, it may be necessary for process designer to prescribe different friction values from one zone to the other or resort to a different lubrication system or procedure.

In this paper, two model tests to evaluate lubricants for the transition and expansion zones are presented. These tests have been designed such that ranking of lubricants is easy and apparent. By combining experiments and FE simulation results, friction coefficients can be estimated. The evaluation of friction in the guiding zone is discussed elsewhere [3].

2. Evaluation of lubricant performance at the transition zone by the limiting dome height (LDH) test

The LDH test is used here to evaluate lubricant performance at the transition zone due to the similarities in the mode of material deformation encountered in the LDH test and that encountered in the transition zone of a THF process. In both, the LDH test and the transition zone of THF process, the blank is undergoing stretching and sliding along the die or punch surface.

We assume that the friction stress (τ_s) at the interface obeys Coulomb's law, i.e. $\tau_s = \mu P$, where μ is the coefficient of friction and P the interface pressure, good estimation of friction coefficient in THF (transition zone) using

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Table 1
Lubricants used for the tests

Lubricant	Properties/contents
Lub A	Polymeric film and blend of non-abrasive, dissimilar materials
Lub B	Solid lubricant, free from chlorine and sulfur
Lub C	Carbon black, graphite butoxyethanol and water
Lub D	Thermoplastic polymer, water and lithium stearate

LDH test will depend much on how close is the interface pressure induced by the LDH test to that encountered in the transition zone of THF process. The study conducted at Engineering Research Center for Net Shape Manufacturing (ERC/NSM-OSU) [2], has shown that by selecting appropriate thickness of a blank sheet, the interface pressure level encountered in THF operations can be emulated by the LDH test. In this study, results on performance evaluation of four lubricants (Table 1) are presented.

2.1. Approach

The experiments are conducted such that similar process conditions inherent in THF operations are induced. Major emphasis is put on generating interface pressure levels similar to the ones occurring in THF operations. Interface pressure is achieved by selecting appropriate blank thickness through FE simulations. As shown in a flow chart (Appendix A), the lubricant evaluation procedure is accomplished by (i) experimental measurement of the LDH test, (ii) FE simulations of the experimental setup for several friction coefficients, and (iii) comparison between experimental and FE simulation results.

The coefficient of friction for each of the lubricants is approximated by matching the FE simulations and experimental results. It should be noted that the ranking of lubricants by LDH test is mostly based on the fact that a good lubricant causes maximum wall thinning to occur near the apex of the dome [4,5].

2.2. Experimental setup

The experimental setup for the LDH test is as shown in Fig. 1. The main parts of the LDH tooling are upper die, lower die, lock bead, punch, and a load cell. The upper die is connected to the ram of a 160 ton hydraulic press while the lower die sits on cushion pins. The load cell is used to measure the punch force. A hemispherical punch of 152 mm (6 in.) diameter and an upper die of 50 mm (2 in.) radius were used. The average surface roughness for the punch was $R_{max} = 5\,\mu m$ ($R_a = 0.5\,\mu m$).

2.3. Test procedures

2.3.1. Determination of flow stress for hot rolled steel 1020

Hot rolled steel 1020 was used for the test. The flow stress for this material was determined using a tensile test machine.

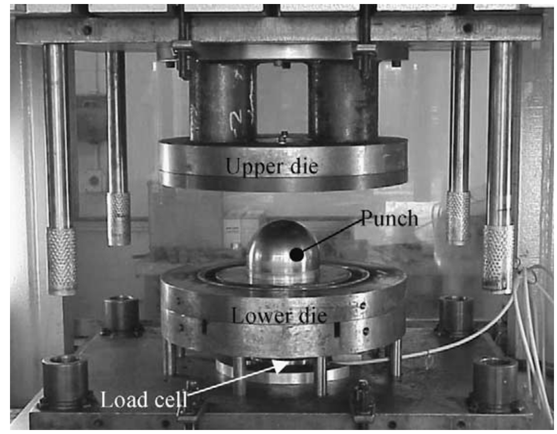


Fig. 1. LDH experimental setup.

This information was necessary for the FE simulations of the LDH test. The determined flow stress could be expressed by the power law as $\bar{\sigma} = 519\bar{\varepsilon}^{0.19}$, where $\bar{\varepsilon}$ is the effective strain.

2.3.2. Preparation of specimens and surface characterization

Round sheet specimens of 350 mm (14 in.) diameter and blank thickness of 3.5 mm (0.14 in.) were cut from a 1020 hot rolled sheet. This blank thickness was selected to achieve a realistic average interface (punch/blank) pressure of about 280 bar (estimated by FEM) which is an interface pressure that is present in the initial stages of THF. The surface roughness of the specimens was measured using stylus equipment. The average roughness was $R_{max} = 6\,\mu m$ ($R_a = 1\,\mu m$).

Four lubricants were used in the LDH test as shown in Table 1. All lubricants were applied by a brush. Lubricant A (Lub A) and lubricant B (Lub B) were left to dry at ambient temperature for 5 min, while lubricant C (Lub C) and lubricant D (Lub D) were heated to 50 °C for 15 min as recommended by the lubricant makers.

2.4. LDH tests

The LDH tests were conducted using a 160 ton hydraulic press at a ram speed of 60 mm/s. For each lubricant, six specimens were used. Three specimens were deformed until fracture so as to establish the limiting punch stroke below which fracture does not occur. After establishing the limiting punch stroke, the remaining three specimens were tested for each lubricant and the wall thickness distributions were measured using an ultrasonic measuring device. The wall thickness was measured from point A to B and A to C (Appendix B). The measurements were taken along two axes, i.e. X- and Y-axes. In each line, 20 measurement points were taken.

2.5. LDH test results and discussion

Fig. 2 shows the average wall thickness distribution (three specimens per lubricant) of the dome for the four lubricants

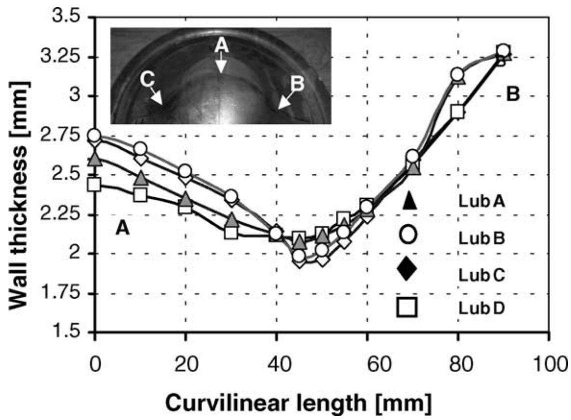


Fig. 2. Wall thickness distribution for Lub A, Lub B, Lub C and Lub D.

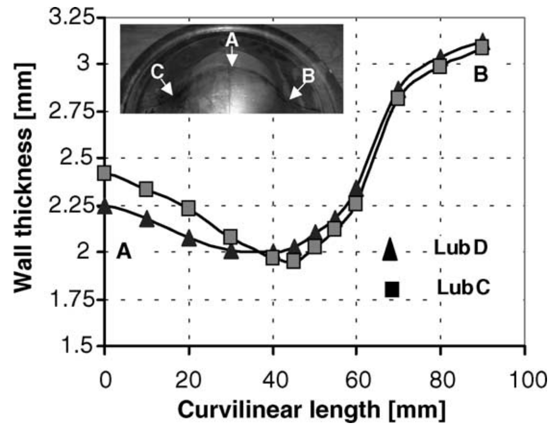


Fig. 3. Wall thickness distribution for Lub C and Lub D.

tested. The principle underlying the LDH test, as a friction test is that with a good lubricant the maximum thinning should occur near the apex while with a bad lubricant the maximum wall thinning should occur away from the apex. The LDH test results shown in Fig. 2 demonstrate that among four lubricants tested, Lub D is the best because the minimum wall thickness obtained with this lubricant is nearest the apex of the punch, namely about 30 mm, as seen in Fig. 2. Thus, the four tested lubricants can be ranked in order of their performance as shown below.

Rank	Lubricant
First	Lub D
Second	Lub A
Third	Lub B and Lub C

The punch load for the LDH tests were recorded and are shown in Appendix C. The change in the punch load with change in the type of lubricant is insignificant. Therefore, punch load cannot be used to rank lubricants with the LDH test.

To study the effect of material taken from a different batch lot, on the test results, the lubricants Lub C and Lub D were used and for each lubricant, four specimens were tested. As shown in Fig. 3, the wall thickness distribution trend is similar to that shown in Fig. 2.

The results also confirm that Lub D is better than Lub C. The distance from the apex of the dome to the location where maximum wall thinning occur is 30 mm for Lub D and 45 mm for Lub C. These are the same measurements that were obtained for the LDH test with specimens prepared from a different batch.

2.6. *Estimation of friction coefficient (LDH test)*

The friction coefficients for the lubricants were estimated by matching FE simulations with experiments. Table 2 gives the apparent friction coefficients for the four lubricants. The FE commercial code used in this study is DEFORM 2D.

Table 2
Estimated friction coefficients for the lubricants (LDH test)

Lubricant	Estimated friction coefficient, μ
Lub A	0.125
Lub B	0.15
Lub C	0.15
Lub D	0.075

The friction coefficient was varied in the FE simulations until the location of maximum thinning calculated through FE matched that observed in the experiments.

3. Evaluation of lubricant performance at the expansion zone (pear-shaped tube expansion test (PET))

The PET is developed to model THF condition at the expansion/calibration zone. Therefore, the tooling is primarily used here to test the performance of THF lubricants at the expansion zone. The details of the development of this tooling can be obtained in Part I of this paper series.

3.1. *Approach*

The pear-shaped expansion tooling developed at ERC/NSM-OSU is used (Fig. 4). The experiments are conducted such that similar process conditions inherent in THF operations are induced. Major emphasis is put on emulating the interface pressure levels similar to the ones occurring in THF operations.

The interface pressure is achieved by pressurizing hydraulic fluid inside a tubular specimen that is placed inside the die inserts until the required pressure is reached. After that, the pear-shaped geometry formed from the tubular blank is analyzed. The study done at ERC/NSM-OSU has shown that the pear-shaped die geometry is very sensitive to friction, and therefore, ranking of lubricants can easily be achieved based on:

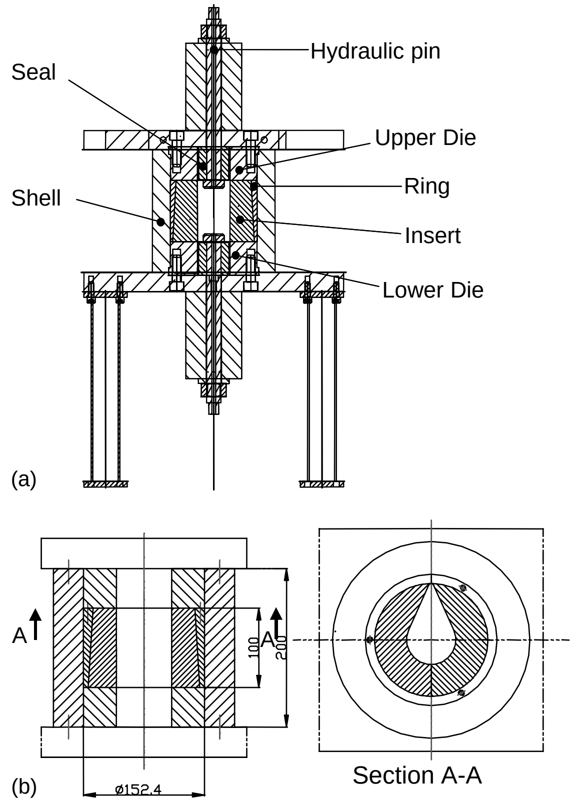


Fig. 4. (a) Pear-shaped expansion tooling. (b) Sub-assembly showing die inserts, ring and housing.

Wall thickness distribution: Change of maximum thinning of the tube wall near the apex of the pear-shaped formed tube as a function of lubricant.

(i) *Protrusion height* (PH): higher the PH the better the lubricant.
(ii) *Bursting pressure*: higher the bursting pressure the better the lubricant.

Similar to the LDH test, friction coefficient exhibited at the interface as a function of the lubricant used is estimated by matching experimental results and FE simulations of the test.

3.2. Experimental setup

The experimental setup for the PET is shown in Fig. 4. The main parts of the tooling are the lower and upper hydraulic cylinders, the main housing, the pear-shaped die inserts, and the hydraulic system. The die inserts are designed for testing a tube of 57 mm in diameter and 100 mm in effective length.

3.3. Test procedures

3.3.1. Preparation of specimens and surface characterization

Tubular specimens of 250 mm in length, 57 mm in diameter, and 1.6 mm wall thickness were cut from SS 304 and LCS 1008 materials. The surface roughness of the specimens was measured using stylus equipment. The average roughness was $R_{max} = 5.03\,\mu m$ ($R_a = 0.55\,\mu m$) for LCS and $R_{max} = 4.3\,\mu m$ ($R_a = 0.57\,\mu m$) for SS 304.

The procedures for applying the lubricants are the same as that used for the LDH tests. The difference is only that with the PETs, tubular specimens were used while with LDH, circular blanks were used.

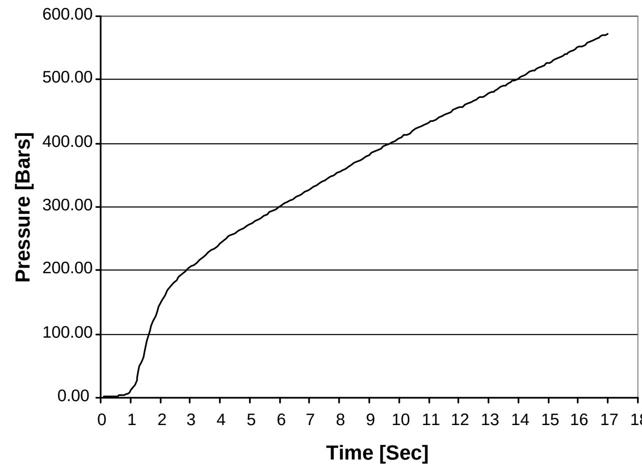


Fig. 5. Pressure-loading path used in the test for non-burst specimens.

3.4. Tube expansion tests

The tests were conducted using the pear-shaped tooling. A 700 bar hydraulic pump was used to pressurize the tubular specimens. Two kinds of tests were conducted.

(i) Pressurize the tube using the same pressure-loading for all lubricants so that the difference in wall thickness distribution and PH can be compared. Fig. 5 shows the pressure-loading path used in this case.
(ii) Pressurize the tube until it bursts.

The test matrix is given in Table 3. After the tests, the performance of the lubricants was evaluated by inspecting the wall thickness distribution, PH, bursting pressure level and surface topography.

Table 3
Test matrix

Material	Constant pressure (570 bar)	Number of specimens	Bursting pressure (bar)	Number of specimens
SS 304	Lub A	2	Lub B	2
	Lub B	2	Lub C	2
	Lub C	2	No lubricant	2
	Lub D	2		
	No lubricant	2		
LCS 1008			Lub B	2
			Lub D	2
			No lubricant	2

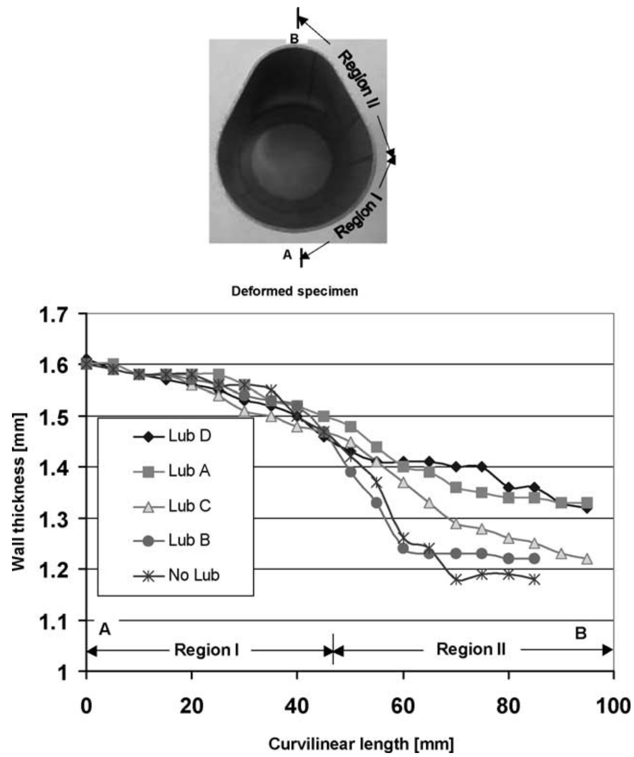


Fig. 6. Effect of lubricants on wall thickness distribution (pressure-loading path for these tests is shown in Fig. 5).

3.5. Results and discussion (PET)

Fig. 6 shows the variations of wall thickness distribution of the formed pear-shaped specimens. The wall thickness was measured by an ultrasonic measuring device. The wall thickness distribution profiles for Lub A and Lub D decrease linearly along regions I and II. At point A, a wall thickness of $t = 1.6$ mm is observed, while at point B a maximum thinning of $t = 1.32$ mm is observed for both Lub A and Lub D.

The wall thickness distribution for lubricants, Lub C, Lub B and No-Lub (non-lubricated) exhibit different thinning trends along regions I and II. In region I, the wall thickness decreases gradually, while in region II it decreased rapidly to a maximum thinning (at point B) of 1.25, 1.25 and 1.18 mm for Lub C, Lub B and No-Lub, respectively.

The linear decrease in wall thickness from region I to II for Lub A and Lub D implies that the tube material flows easily towards the apex of the pear-shaped die. This is attributed to the low friction stress at the tool–workpiece interface. Hence, Lub A and Lub D have lower friction coefficients.

On the contrary, the wall thickness distribution observed for specimens coated by Lub C, Lub B and No-Lub indicate that the friction at region I was so high that material hardly flows toward the apex of the pear-shaped die. Thus using the difference in the maximum wall thinning as one of the criteria to rank lubricants, we find that lubricants, Lub A and Lub D have the highest lubricity level. In the order of increasing performance, the four lubricants can be ranked as shown below.

Rank	Lubricant
First	Lub A and Lub D
Second	Lub C
Third	Lub B

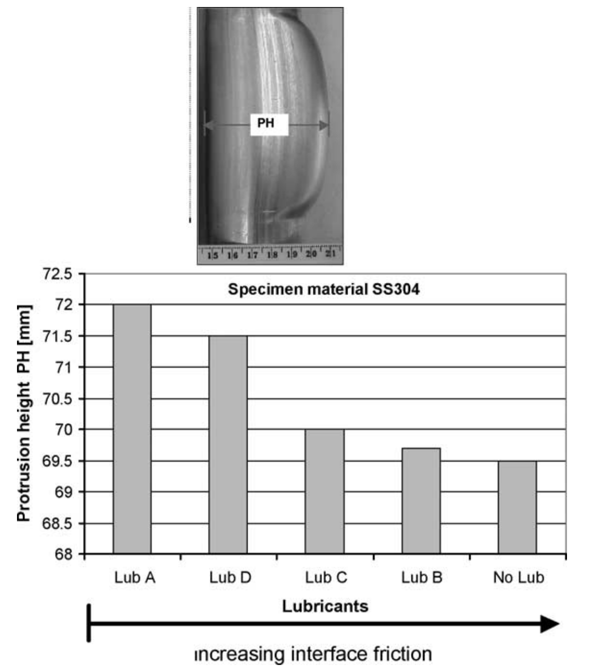


Fig. 7. Lubricant performance as a function of PH (pressure-loading path for these tests is shown in Fig. 5).

Another criterion used to rank the lubricants was the difference in the PHs attained, i.e. the higher the PH, the better the lubricant. Fig. 7 shows the PHs attained for all lubricants. All the tests were conducted using the pressure-loading path shown in Fig. 5, where a maximum pressure of 570 bar was attained. As can be observed in Fig. 7, Lub A resulted in a PH of 72 mm followed by Lub D with a PH of 71.5 mm. These results show a similar trend as that observed in wall thickness distribution (Fig. 6). Based on the PH, the lubricant performance can be ranked as shown below.

Rank	Lubricant
First	Lub A
Second	Lub D
Third	Lub C
Fourth	Lub B

A third criterion used to rank lubricant performance in this study was the bursting pressure. This criterion is based on the fact that the higher the bursting pressure, the better is the lubricant applied. Fig. 8 shows the bursting pressure

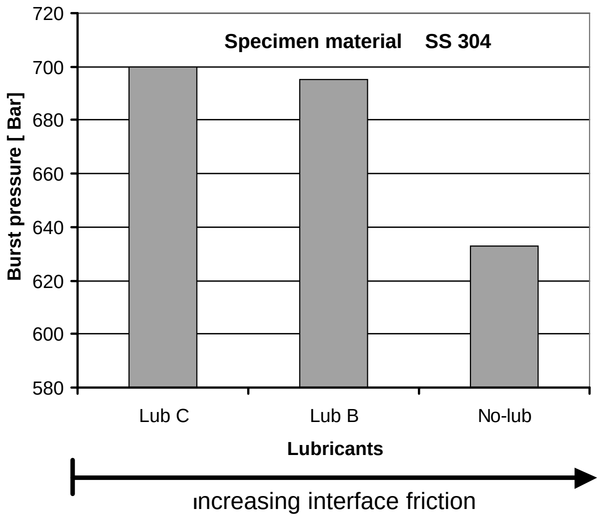


Fig. 8. Influence of lubricant on bursting pressure (specimen SS 304).

attained when lubricants, Lub C, Lub B and No-Lub were used. Only two lubricants were used in this test because the present expansion tooling setup cannot generate pressure of more than 700 bar. Thus, it was impossible to burst stainless tubes (SS 304, wall thickness of 1.6 mm) coated with Lub A and Lub D. This again implies that Lub A and Lub D are better than the other two lubricants (Lub C and Lub B). The burst pressure trend observed (Fig. 8) when Lub C, Lub B and No-Lub were used agrees well with the results obtained with other criteria.

Fig. 9 shows the burst pressures for LCS 1008 specimens when Lub D, Lub B and No-Lub were used. The results show a big difference in bursting pressure between Lub B and Lub D. This justifies that Lub D is far better than Lub B in the expansion zone.

3.5.1. Surface topography

In order to study the effect of lubricant on the surface quality of the deformed specimens, photographs and optical micrographs were taken (Appendices D–F). Visual observations on the micrographs indicate that with the exception of non-lubricated specimens, there is no remarkable difference in the surface quality of the tested specimens.

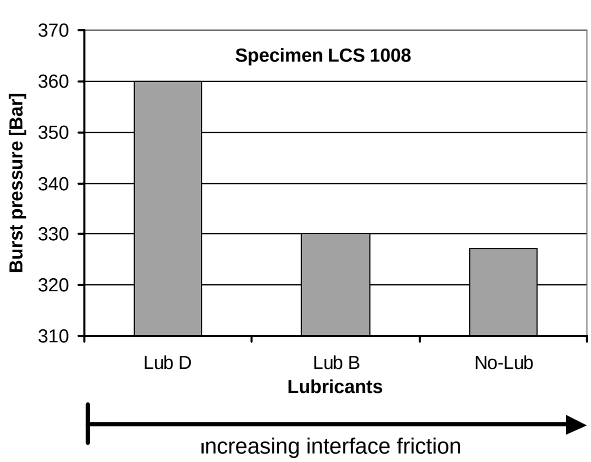


Fig. 9. Influence of lubricant on bursting pressure (specimen LCS 1008).

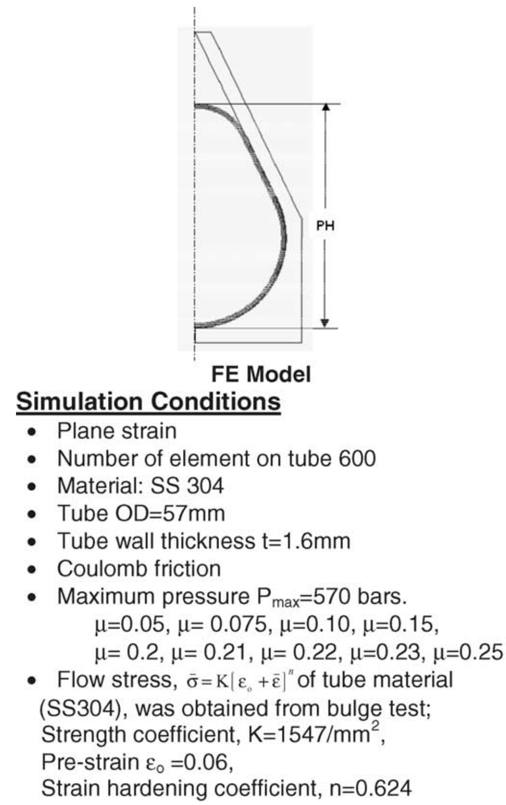


Fig. 10. FE model for PET.

3.6. Estimation of friction coefficient (PET)

Estimation of friction coefficient for the lubricants used was done by matching the PH, PH obtained from FE and experiments. The details of the sensitivity of the pear-shaped die geometry on friction as obtained through FE analyses are covered in Part I of this paper series and in [6].

The PHs obtained from experiments for the four tested lubricants can be seen in Fig. 7. To match these PHs, several FE simulations were conducted by varying friction coefficients as shown in Fig. 10. The estimated friction coefficients are shown in Table 4.

Table 4
Estimated friction coefficients for the lubricants (pear-shaped test)

Lubricant	Estimated friction coefficient, μ
Lub A	0.075
Lub B	0.22
Lub C	0.20
Lub D	0.10

4. Comparison of test results obtained from the LDH and the PETs

The lubricant performance results for the LDH (transition zone) and the PET (calibration zone) show similar trend. In both tests, Lub A and Lub D performed better than Lub B and Lub C. These results suggest that the tribological features displayed by the transition zone are very similar to the ones in the expansion zone. Furthermore, the results have demonstrated that tribological test results obtained from LDH test can be transferred to THF with great accuracy.

5. Summary and conclusions

The LDH test has been used in this study to evaluate lubricant performance for the transition zone while the PET has been used to evaluate lubricant performance for the expansion and calibration zones. Lubricants, Lub A, Lub B, Lub C, and Lub D were tested.

With the LDH test, the lubricants could be ranked in the order of performance by observing the location of maximum thinning. The friction coefficient for each lubricant was estimated by comparing FE simulations and the LDH test results.

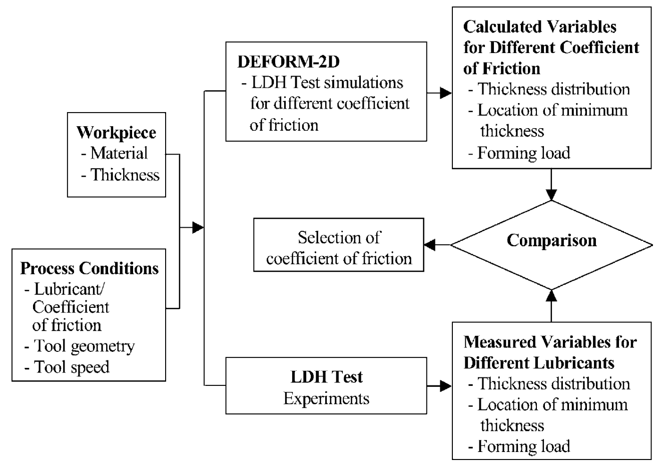
The PET was used to evaluate lubricant performance for the expansion zone. The ranking of the lubricants using the pear-shaped test was based on the difference in the maximum wall thickness, PH, and bursting pressure attained for each lubricant tested. By comparing FE and experimental results, friction coefficients for the four lubricants tested were estimated.

The following conclusions can be drawn from this study:

1. Lub D gave the best performance in the transition zone as evaluated by the LDH test. The second best was Lub A.
2. Lub B and C performed worse in the transition zone (LDH test).
3. Lub A gave the best performance in the expansion zone. Lub D also performed very good (second best) in the expansion zone (pear-shaped tooling).
4. Lub B and C performed worse in the expansion zone (pear-shaped test).
5. Among the four lubricants tested, Lub C is the most difficult to wash off the specimens.
6. The lubricant performance trends for both, the transition and expansion zones have been observed to be similar.
7. Tribological test results obtained by LDH test can be transferred to THF process.
8. Though the PET exhibited huge differences in material flow during deformation as a function of the lubricant used, the surface quality of the tested specimens remained almost the same.

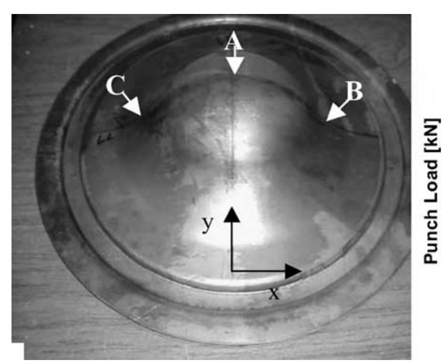
Appendix A

Flow chart describing the procedure used to determine the coefficient of friction using the LDH test



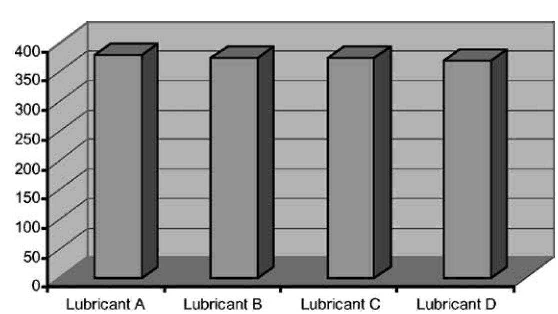
Appendix B

Directions of wall thickness measurement (LDH test)



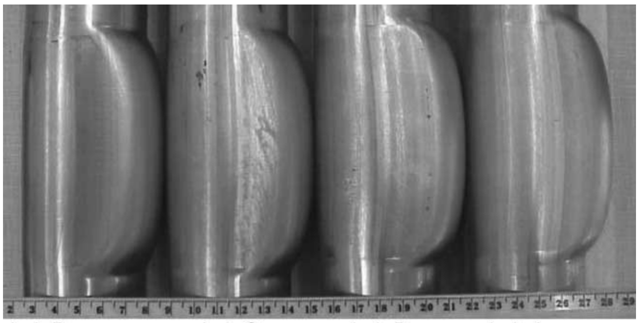
Appendix C

Variation of punch load for different lubricants (LDH test)



Appendix D

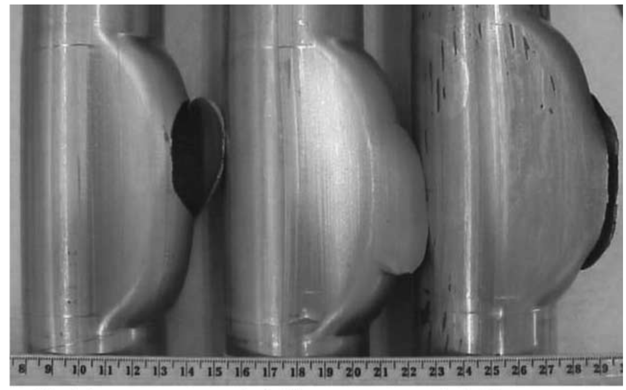
Specimen geometry after test (constant pressure, SS 304)



Lub B, Lub C, Lub D, Lub A,

Appendix E

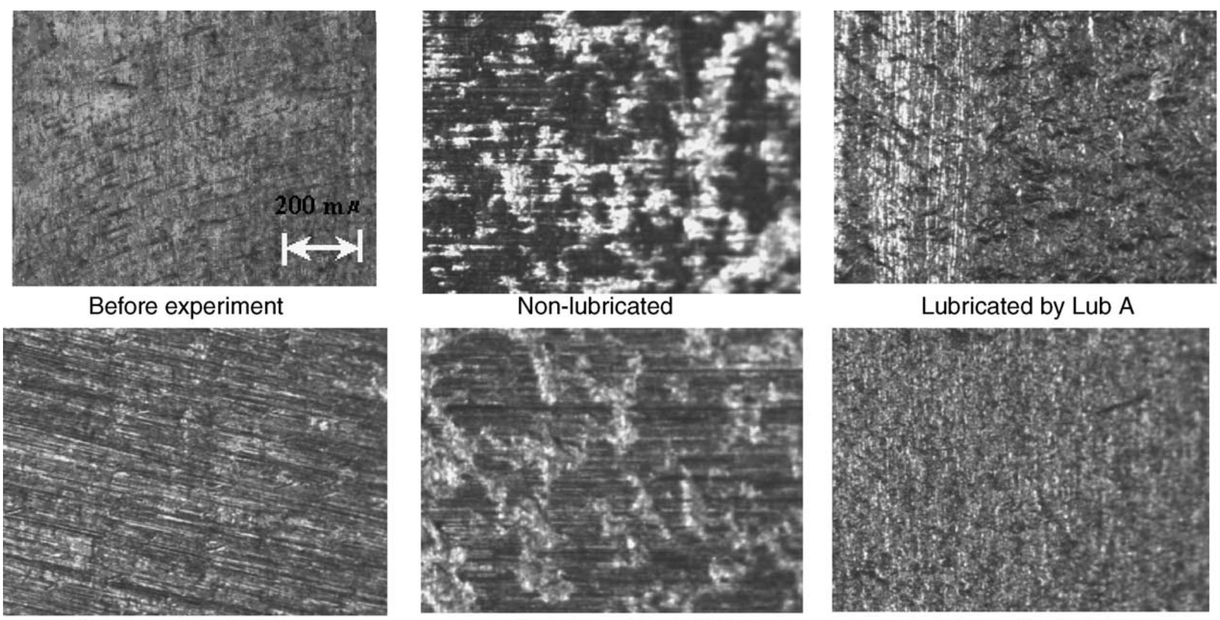
Specimen geometry after test (SS 304)



No-lub Lub B Lub D

Appendix F

Optical micrographs of tested specimens (SS 304-pear-shaped test)



Before experiment, Non-lubricated, Lubricated by Lub A

Lubricated by Lub B, Lubricated by Lub C, Lubricated by Lub D

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