Tribology in Cold Pilgingering

Jens Hardell
Preface
This work has been carried out as a Master of Science thesis at Luleå University of Technology during the period 040901 - 050218. This work was assigned by Sandvik Materials Technology, Sandviken and was mainly performed at Tribolab at the Division of Machine Elements, Luleå University of Technology under the supervision of Professor Braham Prakash (LTU) and Dr. Åsa Lauenstein (SMT).
Acknowledgement
I would like to thank my supervisors Prof. Braham Prakash and Dr. Åsa Lauenstein for their guidance and devoted participation in this project. This work would not have been possible without their help and contributions. Other persons who deserve my gratitude are Albert Lauenstein at Sandvik tube mill 98 and Jonas Tömblom as well as his co-workers at Sandvik tube mill 60 who explained to me the working of cold pilgering and answered my questions.

Last but not the least I would like to thank my girlfriend Jessica for her tremendous support and patience. I could not have done it without you.

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Jens Hardell
Abstract

The lubricants that are used today by Sandvik Materials Technology AB in the cold pilger process contain chlorinated paraffins. Due to environmental, economic and health reasons, these lubricants have to be replaced. The method for trying out new pilger lubricants today is full scale trials in cold pilger mills.

The main aim of this thesis has been to investigate whether it is possible to evaluate pilger lubricants by using some standard laboratory tribological test methods. In addition to this, a review of published literature and a description of the cold pilger process in tribological terms have also been conducted.

The literature review included the published work pertaining to cold pilgering in tribology related scientific journals and books. This review indicated that only very limited information is available in open literature and the survey was therefore broadened to include other similar metal working processes.

The test methods that have been used are the sliding four ball test machine and the SRV (Schwingung Reibung Verschleiß) reciprocating friction and wear tester. The test specimens for the four ball machine were standard bearing steel balls. In the SRV tests, cylinder on disc and a ball on disc test specimen configurations were used. The cylinder specimens were manufactured from the tube material and the disc specimens were made of mandrel material. The balls for the SRV were made of standard stainless steel.

In the four ball machine, both the wear preventive characteristics and extreme pressure properties have been evaluated. In the SRV Optimol machine, seizure and wear tests have been performed.

To analyse the surfaces, Wyko 1100 NT optical surface profiler has been used. A more thorough analysis of test specimen surfaces was also carried out by using SEM/EDS at SMT.

The results show that the SRV cylinder on disc and ball on disc seizure tests are very representative of the cold pilger process. The ranking of various lubricant formulations from these tests correlate very well to the ranking from the full scale cold pilger trials. The surface damage modes and material transfer in the tests correspond well with those observed in the actual process. The SRV wear test corresponds only to a limited extent and the reason for this is that the ranking of cold pilger lubricants is not based on wear.

The four ball EP tests do not correlate that well with the real ranking. This is attributed to the use of different test specimen material in four ball tests as compared to that actual tube/mandrel materials and the test method may not reproduce the conditions prevalent in the cold pilger process. The four ball wear tests do not correlate at all to the actual ranking of lubricant formulations owing to the same reasons and also in view of the fact that the ranking is not based on wear.
## Contents

1. Introduction ........................................................................................................... 5  
   1.1 Main objectives .................................................................................................. 5  
   1.2 Process description .......................................................................................... 5  
   1.3 Tribology in cold pilgering .............................................................................. 6  
   1.4 Extreme Pressure additives ........................................................................... 9  

2. Literature review ................................................................................................. 10  
   2.1 Cold pilgering ................................................................................................... 10  
   2.2 Related research ............................................................................................. 10  

3. Lubricants ........................................................................................................... 14  
   3.1 Lubricant description ...................................................................................... 14  
   3.2 Lubricant ranking from full scale tests ........................................................... 15  
   3.3 Lubricant table ................................................................................................. 16  

4. Experimental work .............................................................................................. 17  
   4.1 Test methods ................................................................................................... 17  
   4.2 Test procedures ............................................................................................... 23  

5. Results and discussion ....................................................................................... 24  
   5.1 Four ball wear tests ....................................................................................... 24  
   5.2 Four ball EP tests ........................................................................................... 26  
   5.3 SRV cylinder on disc seizure tests ................................................................. 29  
   5.4 SRV ball on disc seizure tests ....................................................................... 31  
   5.5 SRV ball on disc wear tests .......................................................................... 33  
   5.6 Surface damage .............................................................................................. 36  
   5.7 Overall ranking .............................................................................................. 50  

6. Conclusions .......................................................................................................... 52  

7. Scope for further work ........................................................................................ 54  

8. References ........................................................................................................... 55  

9. Appendices .......................................................................................................... 56
1. Introduction
In cold metal forming processes it is often necessary to use a lubricant with Extreme Pressure (EP) additives in order to prevent seizure and minimize wear. Sandvik Materials Technology produces seamless stainless steel tubes in a process called cold pilgering. The lubricant that is used today contains chlorinated paraffins which are hazardous to the environment since they are not biodegradable. In addition to the environmental perspective these lubricants may also be carcinogenic and are very expensive to dispose. In order to minimize the number of full scale trials when trying out new lubricants, Sandvik Materials Technology (SMT) are interested to find a lab scale test method in which it is possible to sort out the bad test lubricants and only send the good ones to full scale trials.

1.1 Main objectives
The main objectives of this work are:
• To conduct a review of published literature related to cold pilgering and tribology
• To describe the cold pilger process in tribological terms
• To carry out tests on different lubricant formulations by using standard laboratory tribological test methods and to find if any one or more test methods can satisfactorily predict the behaviour of cold pilger lubricants

1.2 Process description
The pilger process was invented by the Mannesman brothers in 1880 and they produced tubes under heated conditions. The word “pilger” comes from the European pilgrims who had a progress that was considered to take two steps forward and one step back. In the heated pilger process, a double feed increment motion was used and when the rolls were forced over the tubes it would lose one increment of feed and therefore it was compared to the progress of the pilgrims. One of the first cold pilger processes was utilized in America in the late 1890`s and from there it has developed through numerous patents to what it has become today.
The basic principle of the process is that an extruded tube is fed towards a pair of rollers and an internal tool, called a mandrel is placed inside the extruded tube. When the tube is fed between the rollers the outer diameter is reduced and so is the wall thickness (see Fig.1 and 2). The latter is reduced due to the mandrel and its tapered shape. The rollers with tapered grooves are subjected to oscillating motion. The grooves enable feeding and rotating the tube after each stroke. A stroke is the back and forth motion of the rollers. The tube is also turned in order to get an even reduction. The total area reduction normally lies between 60-85%. This large plastic deformation generates a lot of heat. During pilgering, the inside and outside surfaces of the tube are lubricated. The ability of the lubricant to reduce wear and friction is decreased with increased heat which makes it necessary to cool the process. This is achieved by increasing the external oil flow and the oil is utilized to remove the heat and to lubricate the roller-tube interface. The internal lubrication is used for friction
and wear reduction between tube and mandrel, and it also plays a very important role in ensuring a good surface finish of the tube. It also has a large effect on the feed rate and amount of reduction.

Fig. 1. A schematic of the process at its starting position of the stroke

Fig. 2. A schematic at the end position of the stroke

There are several reasons for choosing cold pilgering over other metal forming processes. For example, tubes with an outer diameter <30mm can not be extruded and the same goes for tubes with a wall thickness <3mm. Cold pilgering also enables close tolerances regarding diameter and wall thickness, longer tubes and a very good surface finish. The uniform reduction achieved in cold pilgering process results in excellent mechanical properties of the final product. Cold pilgering is a process that is very suitable for production of large quantities in view of its speed and the high reduction rates. The reliability of the pilger mills is quite high. The mills are often very large and robust which make them very reliable. The most common problems are failure of shafts and bearings. The major disadvantages of this process are its expensive and complicated machinery. It demands knowledge and experience in order to obtain a high quality product to justify the investments.

1.3 Tribology in cold pilgering

In order to get a deeper understanding of the tribology involved in the cold pilger process, some work has been done towards analyzing a semi-pilgered tube in the 3D surface profiler. Some additional observations pertaining to wear and tribological contacts are also included in this section.

1.3.1 Surface damage

The examination of the inner surfaces of the tubes before and after pilgering indicates that the surfaces have undergone significant changes during the process. The inner surface of the extruded tube is rough and has an irregular surface pattern from the extrusion process (Fig. 3.). The surface roughness is about 2 µm. The surface roughness is the $S_a$ value which is the roughness for the surface area
compared to the \( R_a \) value which is the roughness along a line. When the tube enters the working section, it suffers severe surface damage and all the asperities are flattened out due to the high pressure exerted by the rollers (Fig. 4.). The surface roughness decreases to about 1 \( \mu m \). As the tube proceeds towards its final size, the surface roughness continues to decrease and the final tube has a surface roughness of about 0.2-0.4 \( \mu m \). There are other signs on the inner surface that can be traced to the contact between the tube and the mandrel. The tube has a radial surface pattern consisting of peaks and valleys. This is an “impression” from the mandrel which has the same pattern from the machining process. There are also some axial grooves on the inner surface of the tube which can be due to scratching against the mandrel (Fig. 5.).
1.3.2 Wear

There are several wear mechanisms involved in a cold working process like this. Two body abrasive wear would be the major mechanism based on the description in the previous section. Three body abrasive wear may also occur to some extent due to the presence of third body wear debris and hard carbonaceous particles resulting from degradation of the lubricant. There may also be some adhesive wear when the temperature is high and the contacting surfaces are not adequately lubricated owing to starved lubrication conditions. When a lubricant with lime stone fillers is used the surfaces are prone to fine three body abrasive wear damage. In some cases, this may be desirable as it has some polishing effect on the inner surface of the tube. However, on the other hand too much wear will damage the tube surface. In order to control the wear one has to select the lubricant, pressure, feed and strokes that will provide the desired results.

1.3.3 Tribological contact

From a tribological point of view, the contact between the mandrel and the tube is most significant. This can be described as a tube that is supported by an internal cylinder of relatively smaller diameter (see Fig.6). The contact would then be approximated roughly to a line contact and this is the case before and after the working section of cold pilgering. However, in the working section it will be an area contact since the tube is pressed against the mandrel by the rollers and it is plastically deformed.
1.4 Extreme Pressure additives

In order to withstand the severe operating conditions during cold pilgering of tubes, lubricant formulations containing extreme pressure (EP) additives are used to prevent seizure, reduce friction and wear and minimise severe surface damage to the tube surface. The most commonly used EP additives are sulphur, chlorine and phosphorus based compounds, either singly or a combination of these compounds. These additives work by reacting chemically with the interacting surfaces and form a tribochemical layers/films on the interacting surfaces. These films consist of a metal salt made from the bulk material, e.g. Fe, and the additive compound. The reaction is controlled by the temperature in the contact and the rate of the reaction increases with an increase in temperature. The interfacial temperature rise is strongly influenced by operating friction, sliding velocity and load and it activates the EP additives. The formation of protective surface layers/films requires fresh and chemically reactive surfaces, temperature and adequate time. As soon as the protective surface layers are formed, the sliding occurs between these tribochemical layers instead of the clean metal surfaces. During the sliding process, these layers are continuously worn and regenerated. In this process, the mating surfaces suffer wear/surface damage and the lubricant undergoes a process known as additive depletion. The reactivity of the EP additives is governed by the severity of the contact and operating conditions. The optimal lubricant formulation containing EP additives must aim at minimising adhesive and abrasive wear without resulting in excessive tribochemical wear. Another important point that must be kept in mind is the compatibility of different additives mating surfaces. For instance, one additive that works excellent in a steel-steel contact may not work in a bronze-steel contact and so on. It is therefore important to select an additive that will work best with materials of the contacting surfaces.
2. Literature review
This section reviews and summarises the published literature concerning cold pilgering and pertinent work in the field of tribology. This review indicated that so far only very limited work pertaining to tribological aspects of cold pilgering have been carried out as can be seen from the papers published in open literature. To broaden the literature search, the work pertaining to other similar metalworking processes and related research was also reviewed. The summary of reviewed papers and books is presented in Table I.

2.1 Cold pilgering
As mentioned above there are not that many publications on cold pilgering and tribology. The main focus of the research so far has been on material and mechanical behaviour of the process. Among the few papers concerning tribology within this area, Montmitonn, Farrugia, Aubin and Delamare [1] investigated the relationship between surface defects and the concentration of plateaus and whether a high concentration of surface defects comes from high contact pressure. The surface was considered to consist of valleys and plateaus and the concentration of plateaus is the amount of plateaus compared to amount of valleys on the surface area. The first statement was proved and a limit of about 90% plateaus was set when damage starts to occur. The second assumption was only partly true since the number of plateaus only increase with higher contact pressure as a secondary factor. In [2] Baensch gives an introduction to cold pilgering with its advantages, disadvantages and limitations. He also includes a discussion about costs and efficiency of the process. Stapleton [3] covers almost all aspects of the process in his book. Everything from history to start-up procedures and troubleshooting is brought up. The part on lubrication is very short and not so profound.

2.2 Related research
Andreasen et al have compared the performance of different lubricants in ironing of stainless steel using a strip reduction test. They studied the lubrication film breakdown, scratching, galling and pick up [4]. They found that lubricants containing chlorine additives perform best and that the tested emulsions were the worst. Lazzarotto et al presented a methodology for selection of lubricants for cold metal forming processes [5]. They looked at three criterions for ranking the lubricants, mean Coulomb’s frictions coefficient, sliding length before the damage occurs and the resulting surface roughness. Based on this, they also found that lubricants containing EP additives perform the best. Huart et al used an upsetting rolling test and FEM simulations to predict local behaviour of asperities during cold rolling [6]. They found that a rising forward slip increases the formation of iron fines and that trapped lubricant in surface pockets prevent the surface from being flattened out. Trapped lubricant in surface pockets has also been studied by Bech et al [7] and Sorensen et al [8]. They studied the escape of lubricant by micro-plasto hydrodynamic lubrication and micro-plasto hydrostatic lubrication and how different parameters affect these phenomena.
<table>
<thead>
<tr>
<th>No.</th>
<th>Title</th>
<th>Authors</th>
<th>Ref No</th>
<th>Process</th>
<th>Lubricants</th>
<th>Test Method</th>
<th>Summary and Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Internal surface roughness of cold pilgered zircaloy tubes</td>
<td>Montmiton et al</td>
<td>1</td>
<td>Cold pilger</td>
<td>Emulsion</td>
<td>SEM PSCT</td>
<td>Investigates two hypotheses: 1. Surface defects appear when the concentration of plateaus is high. 2. High concentration of plateaus comes from high contact pressure. To confirm 1., different surfaces pilgered under various conditions were examined. The assumption was confirmed and a limit of approx. 90% plateaus was set when damage starts to occur. For 2., a mechanical model was used. The assumption was only partly true. The number of plateaus does increase with higher contact pressure but in most cases only as a secondary factor. The lubricant itself remains a target for optimization.</td>
</tr>
<tr>
<td>2</td>
<td>Pilgering fundamentals</td>
<td>Baensch</td>
<td>2</td>
<td>Cold pilger</td>
<td>-</td>
<td>-</td>
<td>An introduction to cold pilgering, its advantages, disadvantages and limitations. Discusses efficiency and costs. Conclusions: To maximize output you have to maximize the product of finished tube length per stroke x annual number of strokes.</td>
</tr>
<tr>
<td>3</td>
<td>Cold pilger technology</td>
<td>Stapleton</td>
<td>3</td>
<td>Cold pilger</td>
<td>-</td>
<td>-</td>
<td>A very through book on cold pilgering which presents the technology from a historical perspective and continues with start-up procedures, tooling, maintenance, troubleshooting and much more.</td>
</tr>
<tr>
<td>4</td>
<td>Screening the performance of lubricants for the ironing of stainless steel with a strip reduction test</td>
<td>Andreasen et al</td>
<td>4</td>
<td>Ironing</td>
<td>Mineral oils with Cl, mineral oils without Cl, emulsions &amp; exptl oils</td>
<td>Strip reduction test</td>
<td>The test method simulates tribological conditions in an ironing process. Compares different oils regarding parameters like lubrication film breakdown, scratching, galling and pickup. The conclusions are that chlorinated paraffin oils are the best, emulsions are the worst and the others are equal. The tool rest temperature and the amount of reduction influence the threshold sliding length for galling significantly.</td>
</tr>
<tr>
<td>5</td>
<td>A selection methodology for lubricating oils in cold metal forming processes</td>
<td>Lazzarotto et al</td>
<td>5</td>
<td>Extrusion</td>
<td>Cutting oil Oils containing fats and EP additives Vegetable oil</td>
<td>Upsetting sliding test</td>
<td>An analysis of the process is made and the tests are performed with as realistic conditions as possible regarding physical and mechanical properties. Conclusions: Three parameters are used to determine which oil is the best. These are the mean Coulomb's friction coefficient, the sliding length before damage occurs and the resulting roughness. Based on these criterions the oils containing EP additives were the best.</td>
</tr>
<tr>
<td>6</td>
<td>Asperity deformation, lubricant trapping and iron fines formation mechanism in cold rolling processes</td>
<td>Huart et al</td>
<td>6</td>
<td>Cold rolling</td>
<td>URT FEM</td>
<td>The upsetting rolling test (URT) is used to simulate contact conditions for cold rolling. FEM simulations are used to predict local behavior of asperities during cold rolling. Conclusions: A rising forward slip increases the production of iron fines. Trapped lubricant prevents the surfaces from being flattened out. Trapping is possible during the first pass but negligible in the following passes. The initial roughness must be sufficient to permit trapping of lubricant.</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>A study of mechanisms of liquid lubrication in metal forming</td>
<td>Bech et al</td>
<td>7</td>
<td>-</td>
<td>Ester oil, paraffin oil, and mineral oil</td>
<td>Plane strip drawing with transparent die</td>
<td>Studies lubricant escape from surface pockets and the influence of material and process parameters. Backward escape by Micro Plasto Hydro Dynamic Lubrication and forward escape by Micro Plasto Hydro Static Lubrication. Mathematical models are compared with test results. Oscillations in drawing force due to escape of lubricant resulting in local drop in friction stresses.</td>
</tr>
<tr>
<td>8</td>
<td>A basic study of the influence of surface topography on mechanisms of liquid lubrication in metal forming</td>
<td>Sorensen et al</td>
<td>8</td>
<td>-</td>
<td>Base oils</td>
<td>Plane strip drawing with transparent die</td>
<td>Studying MPHDL and MPHSL and the influence of volume, shape and angle of lubricant pockets on these mechanisms. Conclusions are: Hydro static pressure increases in the beginning and after that the obtained pressure stops the pocket from further deformation. The level where the pressure is stabilized is independent of pocket volume. For MPHDL there is proportionality between the volume of emerged lubricant and pocket volume. This is due to the rate of pressure decrease in the pocket, a small pocket reaches the die pressure faster and therefore a smaller volume is emerged. The smaller the edge angle is the earlier the MPHDL starts and the larger the emerged volume. Pockets that are closer to each other allows MPHDL to interfere =&gt; thicker film.</td>
</tr>
<tr>
<td>9</td>
<td>The friction, mobility and transfer of tribological films: potassium chloride and ferrous chloride on iron</td>
<td>Gao et al</td>
<td>9</td>
<td>-</td>
<td>-</td>
<td>Ultra high vacuum chamber</td>
<td>FeCl$_2$ deposited onto iron causes friction to drop to a limiting value of approx. 0.08. Friction variations with film thickness suggests that it is due to formation of a monolayer approx. 10 Å thick. Friction drops to about 0.015 after about 30 rubbing cycles probably due formation of a transfer film. Conclusions are: EP film for reducing friction (not wear) only needs to be a few Å thick. Meanwhile an anti-wear film must be much thicker.</td>
</tr>
<tr>
<td>10</td>
<td>Tribological studies of thermally and chemically modified (TM and CM) vegetable oils for use as environmentally friendly lubricants</td>
<td>Adhvaruy et al</td>
<td>Soybean oil, TM, CM and unmodified</td>
<td>Ball on disc</td>
<td>TM and CM can influence wear and load carrying properties during boundary lubrication regimes. Chemical modification through increased polarity of triacylglycerol structures makes it possible to achieve a broad temp. range stability as well as great wear/friction characteristics.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Design and validation of laboratory-scale simulations for selecting tribomaterials and surface treatments</td>
<td>P. J. Blau</td>
<td>-</td>
<td>-</td>
<td>A thorough guide on how to select or build a suitable tribological test method. The process should be done in five steps: 1. A clear understanding of the tribosystem involved 2. Developing metrics to quantify the problem 3. Selecting necessary conditions for the simulation 4. Selecting or developing a test method 5. Validating the test results.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Optimization of cold rolling of precision tubes</td>
<td>Huml</td>
<td>Cold pilger</td>
<td>Computer model</td>
<td>Describes a computer model that has been developed in order to optimize process parameters. The model is based on material behavior such as characteristics and temperature influence.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3. Lubricants

This section provides a brief description of each lubricant. Various lubricant formulations studied during the course of this project and some of their properties are given in Table II-III. It may be pertinent to point out here that complete information about these lubricant formulations was not available. Some of the information given in Table III is from data sheets provided by the lubricant manufacturers but the remaining information is based on personal observations such as the smell of the fumes that are emitted during certain tests e.g., sulphur smells like rotten eggs and chlorine additives forms HCl.

3.1 Lubricant description

**L1:** This lubricant is presently used by Sandvik as an internal pilger lubricant. It is the best lubricant in terms of performance from Sandvik’s point of view. Its colour is light brown and it is quite thick due to lime stone filler particles. The size of the particles is 1-5 µm.

**L2:** This is presently used as an external pilger lubricant by Sandvik. Its viscosity is not so high and the colour is yellow.

**L3:** This sample is a mix of L1 and L2. The two lubricants get mixed during cold pilgering since the external lubricant is flushed over the working section and there is a leakage of the internal lubricant. They are then drained to a tank and recirculated. The colour is black and the viscosity is some where between the viscosity of L1 and L2. If the lubricant is left untouched for a longer period of time, the particles will separate by sedimentation. A thick black part will be found at the bottom and a clear fluid with low viscosity is found on the top.

**L4:** This has been tried as an internal lubricant with average results. The colour is red brown and it is quite thick.

**L5:** This lubricant has not been tested yet in full scale trials. Its colour is golden and it is very thick and sticky.

**L6:** This is presently used as an internal lubricant in cold pilgering. It is red brown in colour and the viscosity is not so high.

**L7:** This is presently used as an external lubricant in cold pilgering. Its colour is red brown and has a lower viscosity than that of L6.

**L8:** This lubricant is presently used for strip rolling operations by Sandvik. Its colour is light yellow and it has a very low viscosity.

**L9 and L10:** These two lubricants have been tried as internal lubricants with average results. Their colour is brown and they are extremely thick and sticky. Unfortunately, due to some chemical reaction they polymerize and became completely solid. They were kept in plastic containers at room temperature when this occurred. Figure 7 shows a picture of the rotating shaft in the four ball machine where L9 has stuck to the spindle and got drawn out of the cup.
3.2 Lubricant ranking from full scale tests

A ranking of some of the lubricant formulations has been done by SMT based on their performance in full scale cold pilgering tests. The criterions that they use to rank different lubricants in the pilger mills are:

- Maximum tube length that can be pilgered before material transfer occurs from the tube to the mandrel
- Maximum allowable stroke and feed limits before damage occurs on the tools and the tubes
- Maximum reduction possible before damage occurs

The grading of different lubricants is done on scale ranging from 1 to 5 where 1 is the lowest and 5 is the highest grade. Two lubricants with unknown ranking where also tested and they are listed at the bottom of the table.

<table>
<thead>
<tr>
<th>Lubricant</th>
<th>Grade</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>5</td>
<td>The top performance of all the lubricants</td>
</tr>
<tr>
<td>L2</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>L3</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>L6</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>L10</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>L9</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>L4</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>L8</td>
<td>1</td>
<td>This was chosen as a bad lubricant</td>
</tr>
<tr>
<td>L7</td>
<td>-</td>
<td>Not ranked</td>
</tr>
<tr>
<td>L5</td>
<td>-</td>
<td>Not tested</td>
</tr>
</tbody>
</table>
### 3.3 Lubricant table

<table>
<thead>
<tr>
<th>Lubricant</th>
<th>Density</th>
<th>Viscosity</th>
<th>EP additive</th>
<th>Filler</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>-</td>
<td>-</td>
<td>Chlorinated paraffin</td>
<td>Ca(OH)(_2)</td>
<td>Internal pilger oil</td>
</tr>
<tr>
<td>L2</td>
<td>-</td>
<td>75 cSt at 40(^\circ)C</td>
<td>Chlorinated paraffin</td>
<td>-</td>
<td>External pilger oil</td>
</tr>
<tr>
<td>L3</td>
<td>-</td>
<td>-</td>
<td>Chlorinated paraffin</td>
<td>Ca(OH)(_2)</td>
<td>Mix of the two above</td>
</tr>
<tr>
<td>L4</td>
<td>-</td>
<td>-</td>
<td>Sulphur</td>
<td>-</td>
<td>Experimental internal lubricant</td>
</tr>
<tr>
<td>L5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Experimental internal lubricant</td>
</tr>
<tr>
<td>L6</td>
<td>0.92 g/cm(^3) at 15(^\circ)C</td>
<td>470 mm(^2)/s at 40(^\circ)C</td>
<td>Sulphur</td>
<td>-</td>
<td>Internal pilger oil</td>
</tr>
<tr>
<td>L7</td>
<td>0.90 g/cm(^3) at 15(^\circ)C</td>
<td>90 mm(^2)/s at 40(^\circ)C</td>
<td>Sulphur</td>
<td>-</td>
<td>External pilger oil</td>
</tr>
<tr>
<td>L8 (strip rolling oil)</td>
<td>0.865 g/cm(^3) at 15(^\circ)C</td>
<td>19 mm(^2)/s at 40(^\circ)C</td>
<td>No EP additives</td>
<td>-</td>
<td>Contains lauric acid</td>
</tr>
<tr>
<td>L9</td>
<td>-</td>
<td>-</td>
<td>Sulphur</td>
<td>Ca(OH)(_2)</td>
<td></td>
</tr>
<tr>
<td>L10</td>
<td>-</td>
<td>-</td>
<td>Sulphur</td>
<td>Ca(OH)(_2)</td>
<td></td>
</tr>
</tbody>
</table>
4. Experimental work

As mentioned earlier, the main objective of this thesis has been to investigate whether it is possible to use one or more standard tribological test methods to predict the behaviour of cold pilger lubricants. There are extensive tribological test facilities at Tribolab, a newly established tribology laboratory at the Division of Machine Elements of Luleå University of Technology and all the tribological studies on various lubricant samples have been performed at this laboratory. The SEM/EDS analysis was performed at SMT in Sandviken.

4.1 Test methods

The tubes and tools during cold pilgering suffer damage due to galling (or seizure) and wear. Therefore, the most relevant methods for evaluating the performance of cold pilger lubricants are the EP property and the wear preventive characteristics tests.

A four ball test machine has been extensively used for evaluating the EP and wear preventive characteristics of lubricants by researchers and lubricant manufacturers. Keeping this in view as well as the possibility of applying high contact pressures and temperatures, the sliding four ball test machine was chosen for quick evaluation of cold pilger lubricants. However, the tribological contact in a four ball machine is three point contact and it is quite different from that encountered in cold pilgering. In actual cold pilgering, the contact between the tube and mandrel is line or area during the deformation process. In order to have a closer simulation, a second test machine, SRV Optimol tester was also chosen for evaluating the EP and wear performance of cold pilger lubricants. In SRV Optimol tester, it is possible to simulate various test configurations such as point, line and area contacts.
4.1.1 Four ball rotary tribometer
This test method is a well known way of comparing wear and EP properties of different lubricants. An overview of the machine is shown in Fig.8.

The basic principle is that a cup (Fig.9.) holding the three stationary balls is filled with the test lubricant and placed on a thrust bearing mounted on pneumatic bellows. The cup assembly is then raised until the stationary balls come into contact with the fourth rotating ball. The vertical load is controlled by the pneumatic loading arrangement. It is possible to raise the temperature in the cup containing the test lubricant. The test balls are standard bearing steel balls with a diameter of ½ inch (12.7 mm).

The machine is fully instrumented to enable measurement of lubricant temperature, surrounding temperature, frictional torque, vertical force, number of revolutions and
the rotational speed of the motor. The machine is also equipped with a computerised
data acquisition and control system.
During this work, three different test sequences was used for the tests, one according
to ASTM D4172 wear test and the other two sequences for evaluating the EP
properties. The EP test programs was partly based on the ASTM D2783 standard but
slightly modified. In both EP test methods, the specimens are loaded under
stationary conditions and the motor is allowed to reach its set rpm without rotating the
shaft. Once the right rpm is reached the clutch is released and the shaft starts
rotating. Sequence no. 1 utilized step-less increase of the load from the stationary
preload until welding occurred with a loading rate of approximately 30 N/s. The other
one increased the load in steps from the preload and according to the loads
described in the ASTM standard. Each load was held for 10 seconds before
increasing it to the next level. The reason for the second sequence was to see
weather there was a possibility of EP film formation during this some extra time
before the load was increased. The test parameters were set as follows:

| Wear test: | Speed   | 1200 rpm |
|           | Load    | 392 N    |
|           | Temperature | 70 °C   |
|           | Duration | 60 min   |

| EP test:  | Speed   | 1770 rpm |
|          | Preload | 785 N    |
|          | Load    | Step or step-less increase until welding occurs |
|          | Temperature | Initially ambient |

The contact pressure in the four ball machine is very high. At a vertical force of 3 kN
the contact pressure at each point contact was 6.70 GPa (See Appendix 1). The
maximum force that can be applied is 10 kN.
4.1.2 SRV Optimol test machine

This test machine has an electromagnetic drive that oscillates an upper test specimen with a certain frequency and stroke length against a lower stationary test specimen (Fig. 10).

![Image of SRV reciprocating wear tester](image1)

**Fig. 10. SRV reciprocating wear tester**

The upper specimen is loaded against the lower by a vertical loading arm. The lubricant is applied at the contact between the specimens. In these tests 5-6 drops of test lubricant were applied. The desired test temperature is attained by a heater that heats the lower test specimen. The lower specimen test block is mounted on a pair of piezoelectric force transducers so as to measure friction during the tests. The SRV machine is equipped with a computerised data acquisition and control system that enables measurement friction, applied load, temperature, frequency and stroke during the tests. As mentioned earlier, the contact in cold pilgering is a line/area contact and therefore a cylinder on disc configuration, as shown in Fig. 11, was chosen for evaluating the various lubricant samples.

![Image of cylinder on disc configuration](image2)

**Fig. 11. Cylinder on disc configuration**

The cylinder was made of duplex steel tube material and the disc from the mandrel material which was mar ageing steel. Since it was not possible to attain the desired
contact pressures with cylinder/flat contact even with the maximum permissible load in SRV tester, a ball on disc contact configuration as shown in Fig.12 was also chosen.

![Fig.12. Ball on disc configuration](image)

The ball of 10 mm diameter was made of austenitic stainless steel (X6CrNiMoTi17 12 2). The contact pressures in the pilger process lies somewhere between 2.5 – 3.5 GPa. In the SRV test with the cylinder on disc setup, the maximum contact pressure was 0.66 GPa (see Appendix 2). With the ball on disc configuration, it is possible to apply a contact pressure of 3.41 GPa with a normal load of 400 N (See Appendix 3). Since the maximum normal load that can be applied in SRV tester is 2 kN , it was more than adequate. The test parameters during SRV tests were set as follows:

**Cylinder on disc seizure:**
- **Preload**: 50 N
- **Load**: Incrementally increasing up to 2 kN
- **Temperature**: 70°C and 150°C
- **Stroke**: 1 mm
- **Frequency**: 15 Hz
- **Duration**: 20 min

**Ball on disc seizure:** Same as above

**Ball on disc wear:**
- **Preload**: 50 N
- **Load**: 200 N
- **Temperature**: 70°C and 150°C
- **Stroke**: 1 mm
- **Frequency**: 15 Hz
- **Duration**: 60 min

For the cold pilgering process, the sliding velocity of the tube was calculated as follows

\[
v_{slide} = \text{feed} \left[ \frac{mm}{stroke} \right] \cdot \text{average elongation} \cdot \text{strokes} \left[ \frac{strokes}{min} \right] \tag{1}\]
The values of feed, elongation and stroke in a typical cold pilger mill are as follows:

*Feed* = 7 mm/stroke  
*Average elongation* = 2  
*Strokes* = 130 strokes/min  
This yields \( v_{\text{slide}} = 30, 33 \text{ mm/s} \).

To obtain this sliding velocity in the SRV tests, the following stroke and frequency were chosen:

Stroke: 1mm  
Frequency: 15 Hz

This results in a sliding velocity, \( v_{\text{slide}} = 2 \cdot f \cdot s = 2 \cdot 15 \cdot 1 = 30 \text{ mm/s} \).

Two test temperatures were chosen, one moderate temperature (70°C) and another relatively higher with a view to study the action of EP additives during the tests.

### 4.1.3 Wyko 1100 NT 3-D optical profiler

The Wyko 1100 NT (Fig.13) is an optical surface profiler that combines light reflected from a reference surface combined with light reflected from the specimen surface to form interference fringes. The reference surface is moved by a piezoelectric transducer to cause a phase shift between the specimen and reference beam. This is then used to calculate the height of each point on the specimen surface. Using this data, a 3D image of the surface is generated. The analysis software enables calculations of various surface parameters and image processing.

The optical profiler has been used for analysis of the surface damage and quantification of wear of test specimens from different tribological tests.

*Fig.13. The Wyko 1100 NT optical surface profiler*
4.1.4 SEM/EDS
In scanning electron microscopy (SEM), an electron beam is focussed on the surface on the specimen surface. The secondary electrons emitted from the surface are utilised for producing an image of the surface.

Energy dispersive spectroscopy (EDS) uses the emitted x-rays from the surface of the specimen surface to analyse the surface chemical constituents.

These two methods were utilized in analysing the test specimen worn surfaces.

The main focus of SEM/EDS analysis was to examine the nature of surface damage, lubricant residues on specimen surfaces and material transfer, if any.

4.2 Test procedures
This section describes in detail the procedure for cleaning the test specimens and the method of conducting tribological tests.

4.2.1 Four ball tests
The balls and all the parts of the assembly are cleaned with acetone before the test. The balls are cleaned in an ultrasonic cleaner. The balls are then weighed and mounted in the test cup and collet. On completion of the test, the cup is cleaned and put under a microscope for measurement of wear scars. The measurements are made in both the directions, i.e. parallel and perpendicular directions to the wear marks. An average value of the six measurements is then reported as the average wear scar. The balls are then dismounted from the cup and collet and all the parts were cleaned by using industrial petrol and acetone. When the balls have been cleaned, a 3D image of the surface is obtained in the Wyko 3D-topometer. After this, all the balls were weighed and the weight loss was calculated. For the EP test specimens, the weight loss and 3D picture were not taken since most of the samples got welded together.

4.2.3 SRV tests
The test specimens were cleaned with industrial petrol and acetone in an ultrasonic cleaner before the test. They were then weighed and mounted in their holders. On completion of tests, the specimens were removed and again cleaned by using industrial petrol and acetone in an ultrasonic cleaner. They were weighed again and in order to obtain the weight loss. The 3D images of the wear scars were taken for quantification of wear.
5. Results and discussion

5.1 Four ball wear tests

All of the tests have been repeated twice since the ASTM standard suggests a maximum deviation of 0.12 mm between two tests. Some of the tests have been repeated several times to ensure reproducible results. Some lubricants have large differences in the results that could be due to misalignment of the balls or contamination of the test lubricant. L1 has two lower and two higher values. Based on results from other tests, the lower values are the correct ones since they correlate with the results from the used lubricant in this case as well as in all the other tests. The higher values could be a result of the filler particles or some of the previously mentioned reasons.

A lubricant having good wear characteristics produces a small wear scar that is circular with smooth edges and grooves. In addition to this, the weight loss should also be low if the lubricant has good wear preventive characteristics.

The four ball wear test results pertaining to different lubricants are given in Fig. 14. These results do not correspond that well with SMT’s ranking of different lubricants. If the average wear scar is considered, L8 has the best anti wear properties followed by L6 and L7.

![Fig. 14. Diagram of average wear scar from ASTM 2578 wear test. Lubricants are organized with the best lubricant to the left. The test is performed at 70°C, 1200rpm, 392N for 60min.](image-url)
The weight loss results are similar to the wear scar results as expected (Fig. 15). The wear of the fourth ball also indicated similar behaviour (Fig. 16). The small differences in the results could be caused due to the same reasons as for the wear scars. The filler particles in L1 seem to influence the results here as well. Note that a negative weight loss is due to material transfer and should be interpreted as a weight gain.

**Fig. 15.** The combined weight loss for the three stationary balls. The test is performed at 70°C, 1200rpm, 392N for 60m

**Fig. 16.** The weight loss in grams for the fourth ball. The test is performed at 70°C, 1200rpm, 392N for 60min.
These results differ considerably vis a vis the SMT’s ranking of different lubricants and this may be due to several reasons including the test specimen material (which in this case is bearing steel and not stainless steel), moderate load and temperature at which the EP additives may not get activated and so on. Further the wear test method itself may not an appropriate method for ranking lubricants for cold pilgering application. However, tests with ball specimens made of the actual tube/mandrel materials may yield better results.

5.2 Four ball EP tests
When ranking the lubricants based on the results from the EP tests it was evident that these too did not correspond to SMT’s ranking. L1, which was ranked as number one by SMT, finished among the three last in the weld load test. On the other hand, L2 that SMT ranked as number two finished at number two or three depending on the type of loading. The reasons could be the same as those mentioned earlier in case of the wear tests i.e., different material pair and contact configurations vis a vis the actual cold pilgering process.
These tests have not been repeated as the correlation results between the step and step-less loading cases correlate was a sufficient proof that the tests are reproducible. However, in some cases, additional tests were performed to establish repeatability of results.

Description and observations
A general observation regarding the lubricants containing sulphur and chlorine additives is that the fumes emitted during the EP tests at high temperature may cause headache, nausea and shortness of breath if one is exposed to it for a long duration. This fact makes it necessary to provide for very good ventilation if such lubricants are to be utilized. Another effect is the occurrence of discoloration/ corrosion of some steel parts in the test machine. When tests have been performed at high loads which yields high temperatures, the previous mentioned fumes seems to create an oxide layer on certain steel parts. This layer is difficult to remove without polishing. The parts made from aluminium are not affected by this.

L1: As seen in Fig. 17 and Fig. 18, the performance is not what would be expected. As mentioned earlier the material in the test specimens or the test configuration could be the reason for this.

L2: Performance is expected and the reason that it performs better in the step loading case is probably due to the fact that there is more time to form an EP film since it is held at each load for a certain time. The colour of the lubricant changes to dark purple during the test. A lot of fumes are emitted when the temperature is raised. One test was performed using a low preload of 250 N to see if the EP film was affected by this. The result was a slightly higher weld load, as can be seen from Fig.18, but it is not a significant difference.

L3: The performance is very similar to L1 even though it probably contains more L2. This would imply that the filler particles affect the EP film.

L4: The average performance of this lubricant was expected since it had average results from the full scale tests. Some fumes are emitted during the tests and the colour changes to dark brown.
L5: This lubricant has not been tried so far and as such it was considered as a wild card. It turned out to have the best performance of all the lubricants as far as their weld load rating is concerned. The colour changes to dark brown during the tests.

L6: The result was unexpected since it was ranked as an average lubricant by SMT. It ended up among the top three in both weld load and frictional torque. The colour changes to almost black and a lot of fumes are emitted during the tests.

L7: These results were on expected lines since it is an external lubricant and contains less EP additives than L6. It becomes darker in colour after the tests.

L8: The bad performance was expected since it contains no EP additives. As soon as the test starts, a sharp squeaking sound is heard and the balls seize. There is no welding since the load and temperature are low initially. A test was also performed using a lower preload of 250 N to see if that affected the results. But as can be seen from Fig. 17, it did not have any effect

L9 and L10: When performing tests on these lubricants, it was noticed that the lubricant stuck on to the spindle and were drawn out of the cup. The consequence of this was that very little or no lubricant was present at the sliding contacts between the balls. Another observation on these lubricants is that these lubricants become like rubber when exposed to heat, in this case 70-80°C. This would lead to problem of lubricating the contact area. In view of these facts, these tests may not be reliable since it is difficult to know if the contact was lubricated or not. As such, not further studies were conducted on these lubricants.
Fig. 17. Weld loads for the step-less loading test. The test was performed at 1770rpm, initial ambient temperature and until welding occurred.

Fig. 18. Weld loads for the step loading test. The test was performed at 1770rpm, initial ambient temperature and until welding occurred.
5.3 SRV cylinder on disc seizure tests

In these tests, the maximum contact pressure was 0.65 GPa at the final load of 2000N and the motion of the cylinder was perpendicular to the grinding direction of the cylinder. The reason for this is to retain the lubricant in the sliding contact between the mating specimens.

The frictional characteristics of different lubricants as a function of time at 70°C and 150°C are shown in Fig 19 and Fig. 20 respectively. These tests have shown great resemblance to the actual cold pilgering process regarding the performance of the lubricant. There is also an occurrence of material transfer from the upper specimen (cylinder) to the lower specimen (disc) and this behaviour has also been experienced in the actual process as material transfer from the tube to the mandrel has been observed. This has been shown later in the surface damage section of the report.

L1: As shown in the graph for tests at 70°C, an increase in friction is detected halfway through the test. The same thing occurs in tests at 150°C also but much earlier and at 1500 N, indicating the occurrence of seizure.

L2: The 150°C test starts off with a high initial friction which decreases quite fast. The friction starts to increase again after halfway through the test and some initial signs of seizure are observed at 1500 N. In the 70°C test, a high initial friction occurs but decreases quite rapidly and remains steady throughout the test. The initial high friction is due to the higher contact pressures that occur in the beginning.

L3: The results are very similar to the L1 results. A friction increase half way through the 70°C test is seen here as well. Similar behaviour has been seen in tests at 150°C test but slightly earlier. L3 also shows a very stable friction in both tests without any tendencies to seize.

L4: Has a low initial friction in the 70°C test but some frictional instability has been seen after ¼ of the test. Seizure occurs at 1900 N. The 150°C test has a low friction in the beginning but initial seizure occurs at 400 N and final seizure at 1100 N.

L5: The friction is initially high but starts to decrease after 1/3 of the 70°C test and continues to do so until the completion of the test. In the 150°C test, the friction is initially lower but the final value is the same as for the other test.

L6: The friction increases immediately when the test starts in both cases. The 70°C test suffers initial seizure at 500 N and final seizure at 900 N. The 150°C test shows similar result with initial seizure at 400 N and final seizure at 1000 N.

L7: A high initial friction in both tests. The 70°C test has initial seizure at 1000 N and final seizure at 1600 N. The 150°C test has a bit lower loads, as expected, with initial seizure load of 500 N and final seizure load of 1300 N.

L8: As expected, it has a very high initial friction and seizure tendencies are observed right from the start in both the tests. Final seizure occurs at 1500 N for the 70°C test and at 800 N for the 150°C test.

L9 and L10: No tests where performed owing to reasons explained earlier.
Fig. 19. Friction graph from 70°C test. Test was performed with 1mm stroke, 15Hz, 20min under step loading.

Fig. 20. Friction graph from 150°C test. Test was performed with 1mm stroke, 15Hz, 20min under step loading.
5.4 SRV ball on disc seizure tests

The contact pressure in these tests is much higher, above 5.5 GPa at 2000N, than in the previous tests conducted with cylinder in disc contact configuration. At 100N, the ball on disc configuration has a P=2.15 GPa while in the cylinder on disc case the contact pressure was only 0.65 GPa at 2000N. This should be kept in mind while comparing these two tests.

The frictional characteristics of different lubricants as a function of time at 70°C and 150°C are shown in Fig. 21 and Fig. 22 respectively. As mentioned earlier, stainless steel balls were used in these tests. Although the ball material was not exactly the same material as that of the tubes, yet the results correspond very well with SMT’s ranking.

L1: It has shown an extremely low and steady friction throughout both the tests. There are some small seizure tendencies at the end of the 150°C test but no real seizure occurred. This really shows that this lubricant is outstanding when the operating conditions are severe.

L2: Initial seizure occurs at 600 N and then the friction drops and it is quite steady until final seizure occurs at 1600 N in the 70°C test. In the 150°C test the friction varies a lot and seizure occurred at 1200 N.

L3: Has the lowest friction of all lubricants in these tests. It also shows a steady friction without tendencies to seize. Again it is shown what a difference the chlorinated paraffins make as compared to the other lubricants.

L4: The 70°C test has low initial friction and initial seizure occurs at 800 N and final seizure at 1200 N. The 150°C test also has a low initial friction and initial seizure occurs at 600 N and final seizure at 800 N. In both the tests, recovery from initial seizure has been observed indicating the action of EP additive.

L5: Have similar results in both the tests. The friction is low initially and increases steady until seizure occurred at 1100 N in the 70°C test and at 1200 N in the 150°C test.

L6: The friction is quite low in the beginning and decreases slightly until seizure occurs. In the 70°C test, initial seizure occurred at 600 N and final at 1100 N whereas in the 150°C test initial/ final seizure occurred at 800 N and 1400 N respectively.

L7: In the 70°C test, the initial friction was low and seizure occurred at 400 N. The test at 150°C test indicated somewhat higher initial friction and seizure occurred at 500 N.

L8: Very high initial friction in both the tests. Seizure occurred at 500 N in the 70°C test and the 150°C test lasted for 45 seconds only.

L9 and L10: No tests where performed in view of reasons explained earlier.
Fig. 21. Friction graph from 70°C test. Test was performed with 1mm stroke, 15Hz, 20min under step loading.

Fig. 22. Friction graph from the 150°C test. Test was performed with 1mm stroke, 15Hz, 20min under step loading.
5.5 **SRV ball on disc wear tests**

The friction characteristics obtained from SRV ball on disc tests are given in Fig. 23-24 and the wear results have been illustrated in Fig. 25. These results correspond quite well to SMT’s ranking. A clear difference is seen between the 70\(^0\)C and the 150\(^0\)C tests both regarding friction and wear (measured through weight loss). The chlorinated paraffin lubricant shows a lower friction and wear in the test at high temperature possibly owing to the formation of a protective EP film.

**L1:** An increase in friction occurs in the 70\(^0\)C test as in the previous tests. The friction is stable but the weight loss is rather high on both specimens. In the test at 150\(^0\)C, the friction increases in the beginning but decreases after 2/3 of the test most likely due to the formation of an EP film and has the lowest final value. The weight loss is also considerably reduced owing to the same reason.

**L2:** The friction shows average values without any spikes. A bit high initial friction but it decreases quite rapidly. The weight loss in the 70\(^0\)C test is among the lowest and in the 150\(^0\)C test it has the lowest weight loss.

**L3:** The friction is very similar to L1 but perhaps a bit lower. In both tests, a decrease in friction is detected at the end of the test. In the low temperature test the weight loss is average but at the higher temperature, the disc suffers very high weight loss and the wear of the ball is very low.

**L4:** Has the lowest friction of all in the 70\(^0\)C test with average weight loss. At the higher temperature it finishes among the lowest in friction and weight loss.

**L5:** Some high initial friction at the lower temperature and high weight loss on the disc and low on the ball. At the higher temperature the friction is equally high but a bit steadier and the weight loss is average.

**L6:** In the 70\(^0\)C test, the friction is a bit high in the beginning but decreases and ends second lowest. The weight loss at this temperature is quite high. In the 150\(^0\)C test some spikes are detected in the friction which indicates seizure and the weight loss is average.

**L7:** Quite high initial friction which decreases to an average value. Weight loss is below average. At the higher temperature it has the highest friction with some small spikes. The weight loss for the ball is very high at that temperature.

**L8:** Extremely high friction in both the tests. The test duration was very short, only a few seconds before seizure occurred and therefore no weight loss has been calculated.

**L9 and L10:** No tests where performed owing to reasons explained earlier.
Fig. 23. Friction graph from the 70° C test. Test was performed at 1mm stroke, 15Hz, 200N for 60min.

Fig. 24. Friction graph from the 150° C test. Test was performed at 1mm stroke, 15Hz, 200N for 60min.
Fig. 25. Left column shows the weight loss of the ball (above) and disc (below) for the 70°C test. The right column shows the 150°C test.
5.6 Surface damage
The section describes the work pertaining to examination of test specimen surfaces by employing Wyko 3D optical surface profiler and scanning electron microscope incorporating energy dispersive spectroscopy (SEM/EDS).

3D optical surface profiler examination of worn surfaces
The 3D topometer images of worn surfaces from the different tribological tests are presented below. The magnification values of the 3D optical profiler images are indicated on the left side of the images. The magnification values were chosen based on the size of the wear scar and the typical values were 2.5x, 5x and 10x.

5.6.1 Four ball wear test
A lubricant having good wear preventive characteristics produces a wear scar that is circular with smooth edges and fine grooves. The 3D pictures below shows the wear scar and the pertinent comments are given on the right side of the images.

<table>
<thead>
<tr>
<th>Lubricant</th>
<th>Wear scar</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>L8</td>
<td><img src="image1" alt="Image" /></td>
<td>Slightly elliptical</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fine grooves</td>
</tr>
<tr>
<td>L6</td>
<td><img src="image2" alt="Image" /></td>
<td>Circular</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Smooth edges</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fine grooves</td>
</tr>
<tr>
<td>L7</td>
<td><img src="image3" alt="Image" /></td>
<td>Circular</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Smooth edges</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fine grooves</td>
</tr>
</tbody>
</table>
L1
Elliptical
Rough edges
Blasted surface

L3
Rectangular
Rough edges
Deep grooves

L2
Elliptical
Fine edges
Some rough grooves

L4
Elliptical with flat ends
Fine grooves

L5
Circular
Smooth edges
Fine grooves
5.6.2 SRV cylinder on disc tests
A careful examination of 3D topometer images of test specimen surfaces from SRV tests has clearly shown transfer of material from the upper to the lower specimen. Instead of a wear groove on the disc, a ridge with transferred material is visible and the cylinder specimen surface is characterised by a wear groove. For some of the lubricants, e.g. L6, some abrading action is also evident as can be seen from the presence of deep grooves on both the disc and cylinder surfaces. A comparison of the images of the specimen surfaces from tests with L3 shows that the wear and material transfer is less in the test at 150°C indicating the effectiveness of EP additive as expected. A similar behaviour has been observed in case of L5.
SEM/EDS micrographs and X-ray dot maps
The SEM/EDS and X-ray dot mapping studies were carried out with a view to examine the nature of surface damage and material transfer during sliding and lubricant reaction products, if any on the test specimen surfaces. L1 and L4 have been chosen to display the results since L1 contains chlorine and L4 contains sulphur. The cylinder and disc specimens from SRV tests at 150°C were analysed by using SEM/EDS. These specimens were chosen as these were made from the actual tube and mandrel materials. The higher temperature tests were chosen because of the possibility of the formation of EP reaction layer.

L1: The EDS spectrum indicates the presence of chlorine on both specimens. Some Chromium can be found on the disc indicating that there is material transfer from the cylinder specimen since the disc material does not contain any chromium.

L4: Presence of some sulphur on specimen surfaces has been observed and it indicates the interaction of the lubricant additive with the test specimen surfaces. In this case, some chromium has also been detected on the disc which indicates material transfer from the upper to lower specimen.
<table>
<thead>
<tr>
<th>Lubricant</th>
<th>SEM micrographs</th>
<th>X-ray spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1 cyl. @600x</td>
<td><img src="image" alt="Image" /></td>
<td><img src="image" alt="Image" /></td>
</tr>
<tr>
<td>L1 disc @600x</td>
<td><img src="image" alt="Image" /></td>
<td><img src="image" alt="Image" /></td>
</tr>
<tr>
<td>L4 cyl.@300x</td>
<td><img src="image" alt="Image" /></td>
<td><img src="image" alt="Image" /></td>
</tr>
<tr>
<td>L4 disc@300x</td>
<td><img src="image" alt="Image" /></td>
<td><img src="image" alt="Image" /></td>
</tr>
</tbody>
</table>
5.6.3 SRV ball on disc tests
In these tests also some material transfer from the upper specimen to the lower specimen surfaces has been observed. Instead of a more uniform distribution as seen in case of the cylinder on disc contact, the material transfer is rather localised in the middle region of the wear scar. A large amount of wear debris was also found in the contact between the specimens while removing specimens after the completion of tests. This debris is likely to contribute towards occurrence of abrasive wear. Some abrasive wear grooves have also been seen in case of tests with L7 lubricant.
<table>
<thead>
<tr>
<th>Lubricant</th>
<th>Ball</th>
<th>Disc</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>L2@150°C</strong></td>
<td><img src="image1" alt="Ball Image" /></td>
<td><img src="image2" alt="Disc Image" /></td>
</tr>
<tr>
<td><strong>L5@70°C</strong></td>
<td><img src="image3" alt="Ball Image" /></td>
<td><img src="image4" alt="Disc Image" /></td>
</tr>
<tr>
<td><strong>L5@150°C</strong></td>
<td><img src="image5" alt="Ball Image" /></td>
<td><img src="image6" alt="Disc Image" /></td>
</tr>
<tr>
<td><strong>L4@70°C</strong></td>
<td><img src="image7" alt="Ball Image" /></td>
<td><img src="image8" alt="Disc Image" /></td>
</tr>
<tr>
<td><strong>L4@150°C</strong></td>
<td><img src="image9" alt="Ball Image" /></td>
<td><img src="image10" alt="Disc Image" /></td>
</tr>
<tr>
<td><strong>L6@70°C</strong></td>
<td><img src="image11" alt="Ball Image" /></td>
<td><img src="image12" alt="Disc Image" /></td>
</tr>
</tbody>
</table>
5.6.4 SRV wear tests
These tests have indicated a large difference in wear results at 70°C and 150°C. Here the results pertaining to L1 and L4 have been illustrated. The 3D images of worn surfaces from tests at 70°C are characterised by large wear scars containing deep grooves. At higher temperature (150°C), the wear scars are characterised by smaller and fine grooves. This difference is possibly due the formation of an EP film which protects the surfaces and reduces wear. Another thing that can be seen on the wear scars on the ball for L1 is that they are very smooth. This indicates that the filler particles have polished the surface during the test.
5.7 Overall ranking

The overall ranking is made for each test in order to see which test correlates well with the ranking of lubricants from the actual cold pilgering tests. The grades are from 1 to 5 where 5 is the highest and 1 is the lowest. The grade is based on all the results from the specific test. In the wear tests, the ranking is based on the wear scar diameter, weight loss, surface damage and friction (in SRV tests) whereas in the EP tests it is based on weld/seizure load, friction and surface damage.

The four ball wear ranking does not correspond well to the SMT’s ranking. The reasons for this lack of correlation may be attributed to the fact that SMT’s ranking is not based on wear. Further the differences in ranking may also be due to the use of different test specimen material during the laboratory test and the test method may not reproduce actual cold pilgering conditions.

The four ball EP tests correspond to some extent to the ranking done by SMT. The reasons for the lack of good correlation is mainly due to the use of different test specimen material and contact conditions in laboratory tests vis a vis the actual cold pilgering process.
The SRV cylinder on disc test results correlates very well with SMT’s ranking regarding the seizure preventive characteristics. In addition to this, these laboratory tests are able to reproduce the actual modes of surface damage and material transfer.

The SRV ball on disc results also has very good correlation to the real results even though the material combination is not exactly identical to the actual one.

The SRV wear results correlates to some extent to real results. As explained earlier, this is in view of the fact that actual ranking is not based on wear.
6. Conclusions

The following are the main conclusions of this work:

1. The cold pilgering process has been studied in detail and its salient tribological aspects have been studied.

2. A detailed review of the published literature pertaining to tribology of cold pilgering and other relevant literature has been carried out. This review of information available in open literature indicates that only a very limited work on tribological aspects of cold pilgering has been carried out so far.

3. Suitable tribological tests were selected for evaluation of lubricants for cold pilgering application. These test methods included:
   - Four ball tests: four ball wear and EP tests
   - SRV tests: cylinder on disc seizure tests, ball on disc seizure tests and ball on disc wear tests

4. Systematic tribological studies on 11 different lubricant formulations have been conducted by using the selected test methods. The main findings of these studies are as follows:

   **Four ball tests**

   The four ball test results do not correlate to the SMT’s ranking of different lubricants. The four ball wear tests also do not correlate well with the actual ranking. The reason for this lack of correlation is mainly in view of the fact that SMT’s ranking is not based on wear. Further the use of different test specimen material and test configuration vis a vis the actual cold pilgering may be the other reasons for this lack of correlation of results.

   The four ball EP tests also do not correlate well with the actual ranking and in this case the reasons for this lack of correlation may be due to the use of different test specimen material and test configuration vis a vis the actual cold pilgering process.

   **SRV tests**

   The SRV cylinder on disc as well as ball on disc seizure test results correlate well with the SMT’s ranking of different lubricant formulations. These tests are also able to reproduce the actual modes of damage observed on tube and mandrel surfaces.

   It appears that these tests can simulate the tribological contact encountered in cold pilgering process can be successfully employed in comparative evaluation of different lubricant formulations.
5. The ranking of the different lubricants from the SRV cylinder on disc and ball on disc tests are as follows:

<table>
<thead>
<tr>
<th>Cylinder on disc:</th>
<th>1. L3 (best)</th>
<th>Ball on disc:</th>
<th>1. L3 (best)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2. L1</td>
<td></td>
<td>2. L1</td>
</tr>
<tr>
<td></td>
<td>3. L5</td>
<td></td>
<td>3. L5</td>
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<td></td>
<td>4. L2</td>
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<td>4. L2</td>
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<tr>
<td></td>
<td>5. L7</td>
<td></td>
<td>5. L6</td>
</tr>
<tr>
<td></td>
<td>7. L4</td>
<td></td>
<td>7. L7</td>
</tr>
<tr>
<td></td>
<td>8. L8 (worst)</td>
<td></td>
<td>8. L8 (worst)</td>
</tr>
</tbody>
</table>
7. Scope for further work
The present work may be termed as a starting stage as far as cold pilgering tribology is concerned. There are several tribological aspects of cold pilgering that require in-depth and comprehensive research. Some of these R&D activities that can be taken up for further work are listed below.

1. Detailed analysis of cold pilgering process with a view to calculate various parameters that have relevance from a tribological point of view. These parameters include: contact pressures, sliding velocities, interfacial temperatures and plastic deformation of tube material etc.

2. Tribological studies on different tube/mandrel material pairs Ti and cold pilgering lubricants. The tube materials may include Ti, zircaloy, different grades of stainless steel etc. whereas different mandrel materials should be investigated.

3. Design and development of an improved tribological test method that enables tribological studies while the test specimens are plastically deformed

4. Development of new lubricant formulations. This work will be possible only through a close cooperation with some lubricant manufacturers
8. References


www.mpc-home.com/htmls/cps.htm 050213
9. Appendices

Appendix 1 Calculation of contact pressure in the four ball machine

Appendix 2 Calculation of contact pressure in the SRV with ball on disc configuration

Appendix 3 Calculation of contact pressure in the SRV with cylinder on disc configuration
Appendix 1

Calculation of contact pressure in the four ball machine

To calculate the contact pressure in the four ball machine the angle where the rotating ball is in contact with the stationary balls must be known. The balls can be seen as an equilateral tetrahedron.

![Diagram of tetrahedron with labeled points](image)

Point a is the centre of the fourth ball and b, c, d are the centers of the three stationary balls. The vertical force is applied on the fourth ball.

![Diagram of force applied](image)

The distance that is equal to 2r is equivalent to a-b, a-c, or a-d in the previous figure.

Calculating the angle $\alpha$

\[
4r^2 = y^2 + x^2
\]
\[
x = \frac{2r}{\sqrt{3}}
\]
\[
y = r \cdot \frac{8}{\sqrt{3}}
\]
\[
\alpha = \tan^{-1}\left(\frac{2 \cdot r \cdot \sqrt{3}}{\sqrt{3} \cdot \sqrt{8} \cdot r}\right) = 35.2644^\circ
\]
Point $z$ is the contact point between the fourth ball and one of the stationary balls.

Calculating the normal force to the contact point

$$\cos 35.2644 = \frac{F}{3w}$$

$$w = \frac{F}{3 \cdot \cos 35.2644} = 0.40825 \cdot F$$

The Hertzian point contact pressure is calculated as follows

$$v_1 = v_2 = 0.3$$
$$E_1 = E_2 = 2.06 \cdot 10^{-11} Pa$$
$$w = 0.40825 \cdot F$$
$$r = 0.00635m$$

Calculating $R_x$ and $R_y$

$$\frac{1}{R_x} = \frac{1}{r} + \frac{1}{r} = \frac{2}{r} \Rightarrow R_x = \frac{r}{2} = 0.003175m$$

$$\frac{1}{R_y} = \frac{1}{r} + \frac{1}{r} = \frac{2}{r} \Rightarrow R_y = 0.003175m$$

Calculating the equivalent radius

$$R = \left( \frac{1}{R_x} + \frac{1}{R_y} \right)^{-1} = 0.0015875m$$

Calculating the effective E-modulus

$$E' = 2 \left[ \frac{(1 - \nu_1^2)}{E_1} + \frac{(1 - \nu_2^2)}{E_2} \right]^{-1} = 2.2637 \cdot 10^{11}$$

$$\alpha_r = \frac{R_y}{R_x} = 1$$

$\alpha_r = 1$ yields the following

$$k = \left( \frac{R_y}{R_x} \right)^2 = 1$$
\[ \varepsilon = 1 + \left( \frac{\pi}{2} - 1 \right) \cdot \alpha, = 1.5708 \]

The size of the elastically deformed area

\[ D_x = 2 \left( \frac{6 \cdot \varepsilon \cdot w \cdot R}{\pi \cdot k \cdot E} \right)^{\frac{1}{3}} = 2.104 \cdot 10^{-14} \cdot 0.40825 \cdot F \]

\[ D_y = 2 \left( \frac{6 \cdot k^2 \cdot \varepsilon \cdot w \cdot R}{\pi \cdot E} \right)^{\frac{1}{3}} = 2.104 \cdot 10^{-14} \cdot 0.40825 \cdot F \]

The maximum contact pressure is calculated as follows

\[ P_m = \frac{6 \cdot w}{\pi \cdot D_x \cdot D_y} = \frac{6 \cdot 0.40825 \cdot F}{\pi \cdot 4 \left( 2.104 \cdot 10^{-14} \cdot 0.40825 \cdot F \right)^{\frac{1}{3}}} \]

\[ F = 3000N \Rightarrow P_m = 6.7029 GPa \]
Appendix 2
Calculation of contact pressure in the SRV with ball on disc configuration

The contact pressure for the Hertzian point contact in the SRV with the ball on disc configuration is calculated as follows

\[ F = 200 \text{ N} \]
\[ E_1 = E_2 = 2.06 \times 10^{11} \text{ Pa} \]
\[ \nu_1 = \nu_2 = 0.3 \]
\[ r = 0.005 \text{ m} \]

Calculating \( R_x \) and \( R_y \)

\[ \frac{1}{R_x} = \frac{1}{r} + 0 \quad \text{(Zero because the disc is flat)} \]
\[ \frac{1}{R_y} = \frac{1}{r} + 0 \]

Calculating equivalent radius

\[ \frac{1}{R} = \frac{1}{R_x} + \frac{1}{R_y} = \frac{1}{r} + \frac{1}{r} = \frac{2}{r} \Rightarrow R = 0.0025 \]

Calculating effective E-modulus

\[ E' = 2 \left[ \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \right]^{-1} \Rightarrow E' = 2.2637 \times 10^{11} \text{ Pa} \]

\[ \alpha_y = \frac{R_x}{R_y} = 1 \]

This yield
\[ \varepsilon = 1 + \left( \frac{\pi}{2} - 1 \right) \alpha_r = 1.5708 \]

\[ k = \left( \frac{R_y}{R_x} \right)^2 = 1 \]

Calculating the size of the elastically deformed area

\[ D_x = \left( \frac{6 \cdot \varepsilon \cdot w \cdot R}{\pi \cdot k \cdot E'} \right) = 0.0003757 \, m \]

\[ D_y = \left( \frac{6 \cdot k^2 \cdot \varepsilon \cdot w \cdot R}{\pi \cdot E'} \right) = 0.0003757 \, m \]

The maximum contact pressure becomes

\[ P_m = \frac{6 \cdot w}{\pi \cdot D_x \cdot D_y} = 2.706 \, \text{GPa} \]
Appendix 3

Calculation of contact pressure in the SRV with cylinder on disc configuration

The contact pressure for the Hertzian line contact in the SRV with the cylinder on disc configuration is calculated as follows

\[ F = 2000 N \]
\[ E_1 = E_2 = 2.06 \cdot 10^{11} Pa \]
\[ \nu_1 = \nu_2 = 0.3 \]
\[ r = 0.0075 m \quad (radius \ of \ cylinder) \]
\[ l = 0.022 m \quad (length \ of \ cylinder) \]

\[ \frac{1}{R_x} = \frac{1}{r} + 0 \Rightarrow R_x = 0.0075 m \]

Calculating effective E-modulus

\[ E' = 2 \left[ \frac{(1-v_1^2)}{E_1} + \frac{(1-v_2^2)}{E_2} \right]^{-1} = 2.2637 \cdot 10^{11} \]

Calculating load per unit length

\[ w' = \frac{F}{l} = 90909.091 N / m \]

The maximum contact pressure becomes

\[ P_m = \sqrt{\frac{w' \cdot E'}{2 \cdot \pi \cdot R_x}} = 0.661 GPa \]