Abstract: A system is provided for drilling a borehole into an earth formation, comprising a casing arranged in the borehole, a drill string extending through the interior of the casing to a lower end portion of the borehole, and a body of drilling fluid extending into the casing, the casing having an inner surface susceptible of wear due to frictional contact with an outer surface of the drill string during drilling of the borehole with the drill string. The system further comprises means for reducing wear of said inner surface of the casing, said means including at least one of a hardened layer at the inner surface of the casing, a friction-reducing layer at the outer surface of the drill string, and a lubricating compound contained in the body of drilling fluid.
Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPLO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MT, NL, NO, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Declaration under Rule 4.17:
- as to applicant’s entitlement to apply for and be granted a patent (Rule 4.17(U))

Published:
- without international search report and to be republished upon receipt of that report
The present invention relates to a system for drilling a borehole into an earth formation, comprising a casing arranged in the borehole, and a drill string extending through the interior of the casing to a lower end portion of the borehole, the casing having an inner surface susceptible of wear due to contact with an outer surface of the drill string during drilling of the borehole with the drill string.

During rotary drilling of the wellbore, the drill string is rotated from surface by a rotary table at the drilling rig to deepen the wellbore, whereby the rotating drill string normally is in frictional contact with the inner surface of the casing and the wellbore wall. Generally the accumulated friction force between drill string and casing/wellbore wall increases with increasing depth, tortuosity and inclination of the borehole, thus leading to increased torque at the rotary table. Furthermore, the frictional contact between the drill string and the casing potentially leads to wear of both the drill string and the casing. In conventional drilling applications, casing are installed at selected depth intervals of the wellbore, whereby generally the fracture pressure and the pore pressure of the surrounding formation are the determining factors for the length of each such depth interval. Except for the surface casing, each casing is lowered through a previously installed casing and extends from surface to near the lower end of the newly drilled depth interval. In view thereof subsequent casings necessarily are of stepwise decreasing diameter. The resulting nested casing arrangement implies
that each casing normally is in frictional contact with the rotating drill string only for the duration of drilling the next depth interval. Therefore, for such applications, casing wear is normally not a significant problem.

EP-1044316-B1 discloses a wellbore system whereby subsequent casings do not extend to surface. Instead, each new wellbore interval is provided with a casing that extends from the lower end of the previous casing to near the newly drilled wellbore interval. Furthermore, each casing is radially expanded in the wellbore after having been lowered to the desired depth so that the wellbore can be drilled at a substantially uniform diameter along the length thereof.

It is a problem of the known wellbore system that each casing is exposed to wear due to frictional contact with the rotating drill string, for prolonged periods of time. The present invention therefore sets out to provide an improved system for drilling a wellbore, which overcomes the problems of the prior art.

In accordance with the invention there is provided a system for drilling a borehole into an earth formation, comprising a casing arranged in the borehole, a drill string extending through the interior of the casing to a lower end portion of the borehole, and a body of drilling fluid extending into the casing, the casing having an inner surface susceptible of wear due to frictional contact with an outer surface of the drill string during drilling of the borehole with the drill string, wherein the system further comprises means for reducing wear of said inner surface of the casing, said means including at least one of a hardened layer at the inner surface of the casing, a friction-reducing layer at the outer surface of
the drill string, and a lubricating compound contained in the body of drilling fluid.

Tests have indicated that each said means are effective to protect the inner surface of the casing against wear, whereby the hardened inner layer of the casing protects the casing against the abrasive action of small particles contained in the drilling fluid, and the friction-reducing layer of the drill string and the lubricating compound in the drilling fluid protect the casing against high friction forces from direct contact with the drill string. For some applications, the best result is obtained if the system comprises each of the three wear reducing means, i.e. a hardened layer at the inner surface of the casing, a friction-reducing layer at the outer surface of the drill string, and a lubricating compound contained in the body of drilling fluid.

Suitably the hardened layer at the inner surface of the casing has a first hardness and the outer surface of the drill string has a second hardness, and wherein said first hardness is larger than said second hardness. For example, the ratio of the first hardness to the second hardness is between 1 and 5. Preferably the first hardness has a value of between 150 Hv and 600 Hv.

Suitably the friction-reducing layer of the drill string comprises poly-tetra-fluoro-ethylene (PTFE). The friction-reducing layer can be provided in the form of a coating applied to the outer surface of the drill string.

In an exemplary application, the lubricating compound includes between 64.25-90.89 wt% base oil, such as a natural triglyceride oil, fish oil, animal oil, vegetable triglyceride oil, sunflower seed oil, soybean oil, rapeseed oil canola oil, palm nut oil, palm oil, olive oil, rapeseed oil, canola oil, linseed oil, ground
nut oil, soybean oil, cottonseed oil, sunflower seed oil, pumpkin seed oil, coconut oil, corn oil, castor oil, walnut oil, natural or synthetic oil, or an ester.

Suitably the lubricating compound includes between 0.02-0.05 wt% metal deactivator, for example Triazol or benzotriazol derivatives, such as tolytriazol.

Advantageously the lubricating compound includes between 0.5-3.0 wt% antioxidant, for example aromatic amine antioxidant and/or hindered phenolic antioxidants antioxidants, such as for example, 2,6-bis (tert butyl-4-methylphenol, BHT). Example commercially available products are: Octylated, Butylated Diphenylamine Antioxidant from Ciba-Geigy Corp (lrganox L 57); 2,6-bis (1,1-dimethylethyl) -4-methyl-Phenol, from PMC, Inc (BHT); and Benzenepropanoic acid, 3,5-bis (1,1-demethylethyl )-4-hydroxy-, thiodi-2, 1-ethanediyl ester, from Ciba-Geigy Corp (lrganox 1035).

The lubricating compound preferably includes between 4-12 wt% sulfurized natural oils like sulfurized vegetable or animal fatty oils, with natural oils sulfur content 9%-21%, such as for example 13.5%-17.5%. Example commercially available products are: Sulfurized vegetable oils from Rhein Chemie Corporation (Additin RC-2515); and Sulfurized Lard Oil from Ferro Corporation (HSL).

The lubricating compound can include between 4-12 wt% phosphate ester, such as phosphoric acid esters with ethoxylated fatty ester (C)_{2-15} alcohols, preferably mixture of phosphoric acid ester with ethoxylated laurly alcohol and phosphoric acid ester with ethoxylated tridecyl alcohol. Example commercially available products are: Phosphoric acid ester with ethoxylated lauryl alcohol and phosphoric acid ester with
ethoxylated tridecyl alcohol from Houghton International (Houghton 5653).

The lubricating compound can include between 0.4-1.5 wt% phosphoric acid esters with ethoxylated fatty ester (C\textsubscript{12}-C\textsubscript{15}) alcohols, preferably mixture of phosphoric acid ester with ethoxylated lauryl alcohol and phosphoric acid ester with ethoxylated tridecyl alcohol. Example commercially available products are: Phosphoric acid ester with ethoxylated lauryl alcohol and phosphoric acid ester with ethoxylated tridecyl alcohol from Houghton International (Houghton 5653).

The lubricating compound suitably includes between 0.08-1.5 wt% viscosity modifier, such as polyacrylates, polymethacrylates, modifier inylpyrrolidone/methacrylate-copolymers, polyvinylpyrrolidones, polybutanes, olefin-copolymers, styrene/-acrylate-copolymers, polyethers, such as for example, styrene or butadiene-styrene polymer. An example commercially available product is Styrene Hydrocarbon Polymer from Lubrizol Corporation (Lubrizol® 7440S).

The lubricating compound suitably includes between 0.1-0.5 wt% pour-point depressant, for example polymethacrylates, alkylated naphthalene depressant derivatives, such as alkyl ester copolymers. An example commercially available product is Alkyl ester copolymer from Lubrizol Corporation (Lubrizol 6662).

The lubricating compound suitably includes between 0.01-0.2 wt% defoamer, such as silicon based antifoam agent. An example commercially available product is Silicon based antifoam agent from Ultra Additives (Foam Ban 103).
The lubricating compound can include between 0-5 wt% carboxylic acid soaps, for example alkali, alkanolamine, alkyl amine or alkoxylated acid soaps amine salts of mono- or dibasic fatty acids, or mixture thereof. An example commercially available product is Soap formed in situ as a product of reaction between Tall Oil Fatty Acids (Sylval® D3OLR from Arizona Chemical Co.) and triethanol amine (TEA 99 from Huntsman Corporation).

A number of drilling fluids were tested to determine the effect of various lubricating compounds on drill string wear, casing wear, and friction coefficient between drill string and casing. The tested drilling fluids were:

- fluid 1: water based drilling fluid containing 3 wt% bentonite;
- fluid 2: water based drilling fluid containing 3 wt% barite;
- fluid 3: water based drilling fluid containing 3 wt% Cosmolubric ETL manufactured by Houghton International Inc.;
- fluid 4: water based drilling fluid containing 3 wt% Torque Trim manufactured by Halliburton;
- fluid 5: water based drilling fluid containing 3 wt% Oleon manufactured by Oleon;
- fluid 6: water based drilling fluid containing 3 wt% Anderson manufactured by Leonard Andersen with Mobil Oil composition and PTFE particles;
- fluid 7: water based drilling fluid containing G-seal.

The drill string and casing were made of VM 50 steel.

The results of the tests are listed in table 1, whereby drill string wear and casing wear are indicated in mm/km which refers to wall thickness reduction (mm).
per km relative movement between the contact surfaces of the drill string and the casing.

Table 1

<table>
<thead>
<tr>
<th>fluid</th>
<th>drill string wear (mm/km)</th>
<th>casing wear (mm/km)</th>
<th>friction coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>fluid 1</td>
<td>0.035</td>
<td>0.47</td>
<td>0.45</td>
</tr>
<tr>
<td>fluid 2</td>
<td>0.009</td>
<td>0.09</td>
<td>0.21</td>
</tr>
<tr>
<td>fluid 3</td>
<td>0.004</td>
<td>0.03</td>
<td>0.16</td>
</tr>
<tr>
<td>fluid 4</td>
<td>0.003</td>
<td>0.05</td>
<td>0.16</td>
</tr>
<tr>
<td>fluid 5</td>
<td>0.006</td>
<td>0.06</td>
<td>0.27</td>
</tr>
<tr>
<td>fluid 6</td>
<td>0.002</td>
<td>0.03</td>
<td>0.16</td>
</tr>
<tr>
<td>fluid 7</td>
<td>0.057</td>
<td>0.41</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Also, tests were performed for various coatings applied to the outer surface of the drill string, to determine the effect of the coatings on drill string wear, casing wear, and friction coefficient between drill string and casing. The tested drill string coatings were:

coating 1: Victrex coat manufactured by Victrex Peek Coating (Houston TX, USA);
coating 2: Ruby Red manufactured by Kersten Kunstof coating (Netherlands);
coating 3: MC coat manufactured by Metal Coating Corp. (Coating (Houston TX, USA);
coating 4: Ceram coat manufactured by Freecom INC. (Coating (Houston TX, USA);
coating 5: Green coat manufactured by Endura Coating (Warren MI, USA);
coating 6: H329 coat manufactured by Hitemco Southwest (Coating (Houston TX, USA);
coating 7: T15 coat manufactured by Hitemco Southwest (Coating (Houston TX, USA);
coating 8: T90 green manufactured by Hitemco Southwest (Coating (Houston TX, USA).

The drill string was made of VM 50 steel, and the casing was made of VM 50 steel. The drilling fluid was water based and included Bentonite and barite as friction reducing compounds.

The results of the tests are listed in table 2, whereby drill string wear and casing wear are indicated in mm/km which refers to wall thickness reduction (mm) per km relative movement between the contact surfaces of the drill string and the casing.

Table 2

<table>
<thead>
<tr>
<th>Coating</th>
<th>Drill String Wear (mm/km)</th>
<th>Casing Wear (mm/km)</th>
<th>Friction Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coating 1</td>
<td>0.02</td>
<td>0.08</td>
<td>0.2</td>
</tr>
<tr>
<td>Coating 2</td>
<td>0.01</td>
<td>0.02</td>
<td>0.08</td>
</tr>
<tr>
<td>Coating 3</td>
<td>0.079</td>
<td>0.82</td>
<td>0.3</td>
</tr>
<tr>
<td>Coating 4</td>
<td>0.06</td>
<td>0.75</td>
<td>0.3</td>
</tr>
<tr>
<td>Coating 5</td>
<td>0.06</td>
<td>1.1</td>
<td>0.6</td>
</tr>
<tr>
<td>Coating 6</td>
<td>0.08</td>
<td>1.1</td>
<td>0.31</td>
</tr>
<tr>
<td>Coating 7</td>
<td>0.055</td>
<td>0.96</td>
<td>0.8</td>
</tr>
<tr>
<td>Coating 8</td>
<td>0.011</td>
<td>0.3</td>
<td>0.23</td>
</tr>
</tbody>
</table>

The invention will be described hereinafter by way of example in more detail with reference to the accompanying drawings, in which:

Fig. 1 schematically shows a wellbore drilled with an embodiment of the drilling system of the invention;

Fig. 2 schematically shows the wellbore of Fig. 1 during continued drilling of the wellbore; and

Fig. 3 schematically shows the wellbore of Figs. 1 and 2 after drilling is completed.
Referring to Fig. 1 there is shown a wellbore 1 formed into an earth formation 2 during drilling thereof using a drill string 4 provided with a drill bit 5. The drill string 4 extends from a drilling rig 6 at the earth surface 8 to the bottom 10 of the wellbore 1, and is provided with a flow passage (not shown) for pumping drilling fluid from the drilling rig 6 via the flow passage to the drill bit 5, and from there into the wellbore 1. An upper portion 12 of the wellbore 1 is provided with a first steel casing 14 having a lower end part 15 of increased diameter to receive a second casing (referred to hereinafter) therein. The first casing 14 is radially expandable and has a hardened inner surface 16, with hardness larger than the hardness of the outer surface of the drill string 4.

The drill string 4 is provided with an outer layer in the form of a poly-tetra-f luor-ethene (PTFE) coating 18. Suitably the PTFE coating 18 comprises Ruby Red Teflon marketed as Teflon® PFA Coating by Kersten Kunstof coating (Netherlands).

In Fig. 2 is shown the wellbore 1 after drilling of a further section thereof, whereby a second steel casing 20 is arranged below the first casing 14 in the wellbore 1. The second casing 20 extends a short distance into the lower end part 15 of the first casing 14 to provide a sealed connection between the two casings 14, 20. Similarly to the first casing 14, the second casing 20 is radially expandable and has a hardened inner surface 22, with hardness larger than the hardness of the outer surface of the drill string 4. Furthermore, the second casing 20 has a lower end part 24 of increased diameter to receive a third casing (referred to hereinafter) therein.
In Fig. 3 is shown the wellbore 1 after drilling is completed, whereby the drilling rig 6 has been replaced with a wellhead 26. A third casing 28 is arranged below the second casing 20 in the wellbore 1. The third casing 28 extends a short distance into the lower end part 24 of the second casing 20 to provide a sealed connection between the two casings 20, 28. Similarly to the first and second casings, the third casing 28 is radially expandable and has a hardened inner surface 30, with hardness larger than the hardness of the outer surface of the drill string 4.

During normal operation, the drill string is rotated by a rotary table (not shown) at the drilling rig 6 to drill an upper portion of the wellbore 1, whereafter the drill string is retrieved and the first casing 14 is installed in the upper wellbore portion.

Subsequently, the wellbore is drilled deeper whereby the drill string 4 passes through the first casing 14, and into the new wellbore portion being drilled. A drilling fluid is simultaneously pumped through the flow passage of the drill string 4 into the lower portion of the wellbore 1. The drilling fluid returns to surface through the annular space 32 formed between the wellbore wall and the casing 14 on one hand, and the drill string 4 on the other hand. The drilling fluid is provided with a lubricating compound in the form of vegetable oil to reduce frictional forces between the rotating drill string 4, and the casing 14 and wellbore wall.

After the new wellbore portion has been drilled to a selected depth, the drill string 4 is retrieved to surface and the second casing 20 is installed in the newly drilled wellbore portion. The second casing 20 extends a short distance into the lower end part 15 of
the first casing 14 to provide a sealed connection between the two casings 14, 20.

In a next step, a further wellbore portion is drilled whereby the drill string 4 passes through the first casing 14, the second casing 20, and into the further wellbore portion being drilled. Drilling fluid is simultaneously circulated downwardly through the drill string 4, and upwardly through the annular space 32 between the drill string 4 on one hand, and the wellbore wall and the casings 14, 20 on the other hand. The drilling fluid is provided with said vegetable oil to reduce frictional forces between the rotating drill string 4, and the casings 14, 20 and wellbore wall.

After the further wellbore portion has been drilled to a selected depth, the drill string 4 is retrieved to surface and the third casing 28 is installed below the second casing 20 in the wellbore 1. The third casing 28 extends a short distance into the lower end part 24 of the second casing 20 to provide a sealed connection between the two casings 20, 28.

The above steps are repeated as many times as required to drill the wellbore 1 to the desired depth.

By virtue of the hardened inner surfaces 16, 22, 30 of the respective casings 14, 20, 28, the PTFE coating on the outer surface of the drill string 4, and the lubricating compound in the drilling fluid, it is achieved that the frictional forces between the drill string 4 on one hand, and the inner surfaces 16, 22, 30 of the respective casings 14, 20, 28 is minimal.

Moreover, it is achieved that any wear of the inner surfaces 16, 22, 30 of the respective casings 14, 20, 28 due to contact with the rotating drill string 4, is limited to a minimum. The latter effect is of particular
importance since the major part of each casing section 14, 20, 28 does not overlap with any other casing section during drilling, so that each casing section 14, 20, 28 is exposed to frictional contact with the drill string 4 for prolonged periods of drilling. This is in contrast to conventional wellbore drilling whereby the casings are arranged in a nested arrangement with each subsequent casing extending to surface through a previous casing which thereby no longer is exposed to frictional forces from the drill string during further drilling of the wellbore.

Instead of using a conventional drill string which is retrieved to surface after drilling the respective wellbore portions, a drill string can be used that is transformed into a casing after a selected wellbore portion has been drilled. Such method is generally referred to as "casing drilling" or "liner drilling". For example, the drill string can be formed as an expandable tubular element that is radially expanded in the newly drilled wellbore portion to form a casing therein. It is envisaged that the method of the invention is of particular interest for these "casing drilling" or "liner drilling" applications since the drill string (which is to be transformed into casing) has no radial upsets like in a conventional drill string, which otherwise can be designed to minimise friction between the drill string and the borehole wall/casing, and wear of the casing. Furthermore, it is envisaged that friction reduction between drill string and borehole wall/casing is particularly important for "casing drilling" or "liner drilling" applications because it helps to reduce the rotational torque increase due to the relatively large
diameter of the rotating "casing" or "liner" relative to the borehole diameter.
CLAIMS

1. A system for drilling a borehole into an earth formation, comprising a casing arranged in the borehole, a drill string extending through the interior of the casing to a lower end portion of the borehole, and a body of drilling fluid extending into the casing, the casing having an inner surface susceptible of wear due to frictional contact with an outer surface of the drill string during drilling of the borehole with the drill string, wherein the system further comprises means for reducing wear of said inner surface of the casing, said means including at least one of a hardened layer at the inner surface of the casing, a friction-reducing layer at the outer surface of the drill string, and a lubricating compound contained in the body of drilling fluid.

2. The system of claim 1, wherein the hardened layer at the inner surface of the casing has a first hardness and the outer surface of the drill string has a second hardness, and wherein said first hardness is larger than said second hardness.

3. The system of claim 2, wherein the ratio of the first hardness to the second hardness is between 1 and 5.

4. The system of claim 2 or 3, wherein the first hardness has a value of between 150 Hv and 600 Hv.

5. The system of any one of claims 1-4, wherein said friction-reducing layer at the outer surface of the drill string comprises poly-tetra-fluor-ethene (PTFE).

6. The system of claim 5, wherein said outer layer forms a coating applied to the outer surface of the drill string.
7. The system of any one of claims 1-6, wherein the lubricating compound includes between 64.25-90.89 wt% base oil.

8. The system of claim 7, wherein said base oil is selected from a natural triglyceride oil, fish oil, animal oil, vegetable triglyceride oil, sunflower seed oil, soybean oil, rapeseed oil canola oil, palm nut oil, palm oil, olive oil, rapeseed oil, canola oil, linseed oil, ground nut oil, soybean oil, cottonseed oil, sunflower seed oil, pumpkin seed oil, coconut oil, corn oil, castor oil, walnut oil, a natural or synthetic oil, and an ester.

9. The system of any one of claims 1-8, wherein the lubricating compound includes between 0.02-0.05 wt% metal deactivator.

10. The system of any one of claims 1-9, wherein the lubricating compound includes between 0.5-3.0 wt% antioxidant.

11. The system of any one of claims 1-10, wherein the lubricating compound includes between 4-12 wt% sulfurized natural oils.

12. The system of any one of claims 1-11, wherein the lubricating compound includes between 4-12 wt% phosphate ester.

13. The system of any one of claims 1-12, wherein the lubricating compound includes between 0.4-1.5 wt% phosphoric acid.

14. The system of any one of claims 1-13, wherein the lubricating compound includes between 0.08-1.5 wt% viscosity modifier.

15. The system of any one of claims 1-14, wherein the lubricating compound includes between 0.1-0.5 wt% pour-point depressant.
16. The system of any one of claims 1-15, wherein the lubricating compound includes between 0.01-0.2 wt% defoamer.

17. The system of any one of claims 1-16, wherein the lubricating compound includes between 0-5 wt% carboxylic acid soaps.

18. The system of any one of claims 1-17, wherein the casing is formed of a plurality of casing sections, each casing section having at least a portion not overlapping with any other one of the casing sections.

19. The system of claim 18, wherein the casing is radially expandable, the system further comprising means for radially expanding a first one of said plurality of casing sections, and means for lowering a second one of said plurality of casing sections through said first casing section after radial expansion thereof.

20. The system substantially as described hereinbefore with reference to the drawings.