TESTING NEW TRIBO-SYSTEMS FOR SHEET METAL FORMING OF ADVANCED HIGH STRENGTH STEELS AND STAINLESS STEELS[I]

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ABSTRACT

Testing of new tribo-systems in sheet metal forming has become an important issue due to new legislation, which forces industry to replace current, hazardous lubricants. The present paper summarizes the work done in a recent PhD project at the Technical University of Denmark on the development of a methodology for off-line testing of new tribo-systems for advanced high strength steels and stainless steels. The methodology is presented and applied to an industrial case, where different tribo-systems are tested. A universal sheet tribotester has been developed, which can run automatically repetitive Bending Under Tension tests. The overall results show that the methodology ensures satisfactory agreement between laboratory tests and production tests, although disagreement can occur, if tribological conditions are not the same in the two cases.

Keywords: Sheet metal forming, off-line testing of tribo-systems, galling.

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INTRODUCTION

New, stricter regulations on handling of chemical products, such as REACH [1], and the new “green” trend in some companies have forced sheet forming industry to replace hazardous lubricants, such as chlorinated paraffin oil, with more environmentally friendly ones [2]. This implies, however, some drawbacks, such as high costs in the production testing of new lubricant systems, and possible film breakdown due to poorer performance, which leads to pick-up and galling and requirement for demounting and repolishing of tools [3].

Introduction of new lubricants in industrial production is often based on rather few if any laboratory tests followed by production tests comparing the results with the old lubrication system. Realistic simulation of production conditions in the laboratory can be difficult to achieve, and custom built laboratory tests have been developed for the simulation of deep drawing and ironing operations [4]. If they show satisfactory results, the new tribo-system is tested in production. Although the tests may be able to control the main parameters such as normal pressure, sliding length and velocity, the procedure does not take into account long term temperature development in the tools and the gradual build-up of pick-up, which control the limits of lubrication [5]. They are lacking the possibility of automated, repetitive testing, which is essential for the quantification of the limits of lubrication. The present work shows a methodology for off-line testing applied to an industrial case, where Bending Under Tension test (BUT) is selected as the simulative test. A few new, environmentally friendly tribo-systems are investigated using the methodology.

METHODOLOGY FOR OFF-LINE TESTING

The proposed methodology takes its starting point in an existing production process, where a hazardous tribo-system is used, which has to be replaced with an environmentally benign one. The production platform defines the values of the main tribo-parameters, which are determined by numerical modelling. Then an appropriate laboratory test is selected and designed to simulate these conditions, again using numerical modelling in order to ensure similar parameter values. After this a new tribo-system is selected for investigation, at first screening its performance in a few tests. If poor results are obtained, the tests are stopped and two alternatives appear: 1) a new tribo-system is selected, 2) the component geometry and/or production platform may be modified in which case the procedure starts all over again. If, on the other hand, promising results are obtained, a complete laboratory test campaign is performed in order to determine an appropriate working window for the tribo-system. Again, the two earlier mentioned alternatives may appear, i.e., either poor results or good results. In the first case, the same procedure as mentioned above is carried out; in the second case, production testing is done. This may once again give poor results, in which case the procedure is as before, or good results, in which case the testing is successfully completed.

PRODUCTION PLATFORM

An industrial case study is selected to exemplify the methodology described in Chapter 2. It is a stainless steel tube with a flange manufactured at the Danish company Grundfos in a progressive stamping tool, see Fig. 1. After blanking 1 and 2, follows a deep drawing operation 3 and two redrawing operations 4 and 5, sharp pressing of the flange 6, and punching of the bottom hole 7. The last operation is cutting out the part from the sheet strip. The workpiece material is austenitic stainless steel EN 1.4301 fed as strip material from a coil with cross section of 1.0x62.5mm. The blank produced in operations 1 and 2 is Ø50mm. The drawing ratio in the deep drawing operation is: DR3 = 1.8, and in the two redrawing operations DR4 = 1.32 and DR5 = 1.28. Lubrication is done with chlorinated paraffin oil. The die tool material is PM Vanadis® 6, from Uddeholm, PVD coated with TiAlN and hardened and tempered to 62 HRC. The production rate is 40 strokes per minute. The tribologically most critical operation is the second redrawing operation 5, where galling occurs, if less efficient lubricants are used.

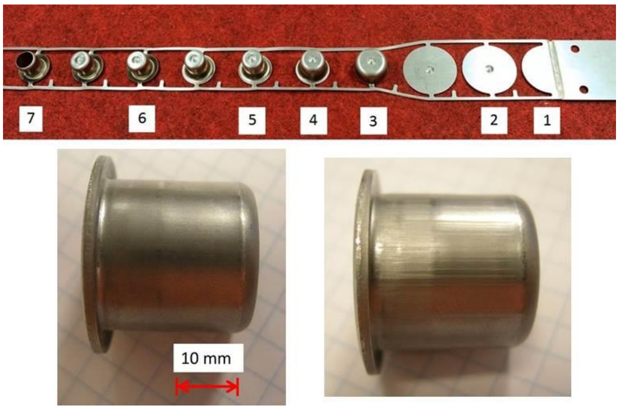

Figure 1. Top: production layout with successive operations in progressive tool, Bottom: finished specimens left successful, right after initiation of galling.

The study covers three different workpiece materials:

- Austenitic stainless steel EN 1.4301, surface 2B from Outokuumpu, Rp_{02} = 320 MPa
- Lean duplex stainless steel EN 1.4162 (LDX 2101®) surface 2E from Outokumpu, Rp_{02} = 530 MPa
- Dual phase high strength steel Docol® DP800 from SSAB EMEA, Rp_{02} = 620 MPa

It is emphasized that EN 1.4162 and DP 800 are not typical workpiece materials used in such a demanding sheet forming operation. The materials were selected in agreement with the partners in the project with the goal to validate the methodology besides finding new tribo-systems that could replace the old ones.

Two different tool materials are investigated:

- Powder metallurgical tool steel Vanadis® 4 Extra (V4E), hardened and tempered to 62 HRC
- Powder metallurgical tool steel Vancron® 40 (V40), 63 HRC.

The lubricants investigated are:

- Rhenus SU 166 A from Rhenus Lub, a mineral oil base with Ca- P- and S-additives. Viscosity ν = 150 mm^2/s at 40°C
- Anticorit PL 3802-39s from FUCHS Europe, a thixotropic, chlorine free oil with anticorrosive properties. Viscosity ν = 60 mm^2/s at 40°C
- Anticorit PLS 100 T from FUCHS Europe, a thixotropic, chlorine free oil with anticorrosive properties. Viscosity ν = 100mm^2/s at 40°C

Table 1 shows the experimental plan, indicating which combinations of workpiece materials, lubricants and tool materials are investigated.

Table 1. Tested tribo-system.

	Workpiece material					
Lubricants	EN 1.4301		EN 1.4162		DP 800	
Anticorit PL 3802-39s					V4E	V40
Anticorit PLS 100 T					V4E	V40
Rhenus SU 166 A	V4E	V40	V4E	V40		

NUMERICAL ANALYSIS

Following the methodology outlined in Chapter 2, FE analyses of the production platform are carried out for the three different workpiece materials: austenitic stainless steel EN 1.4301, lean duplex stainless steel EN 1.4162 and advanced high strength steel DP800.

<u>Production process</u>

The stress-strain curves for the materials are determined by plane-strain upsetting tests. A general friction model combining Coulomb friction at low normal pressures with constant friction at high normal pressures [6] is adopted. The coefficient of friction is calibrated by comparing the calculated and measured punch forces. Focusing on the critical, second redrawing operation, Fig. 2 shows the normal pressure in the radial direction with respect to the die radius of curvature for the material example DP 800 [7].

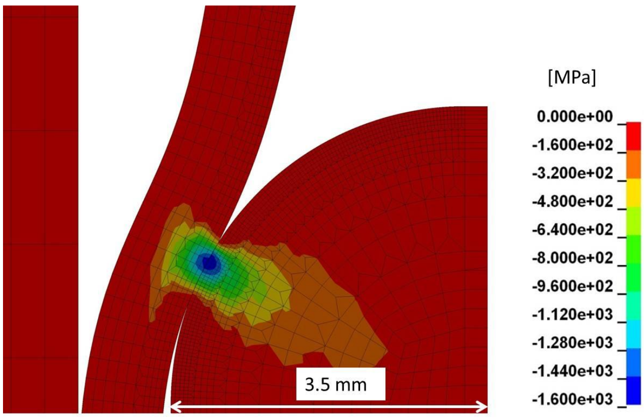

Figure 2. Radial pressure distribution in operation 5 (DP800).

The stress displayed at the die/workpiece interface is therefore the normal pressure on the interface, which is noted to be quite high with a peak value of about 1600 MPa. This is due to heavy strain hardening in the prior two drawing operations and the very small contact length between the workpiece and the die, approximately equal to the sheet thickness, leading to large pressure gradients in the peripheral as well as in the radial directions and to a stress pattern far from conventional sheet forming. Fig. 3 shows the peak normal pressure as a function of time for the three materials investigated.

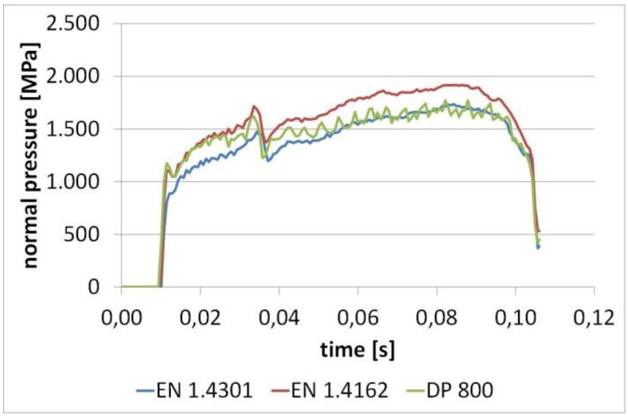

Figure 3. Peak normal pressure as a function of time.

It is noticed that EN 1.4301 and DP 800 reach the same maximum value 1750 MPa, whereas EN 1.4162 has a peak value of about 1900 MPa.

<u>Simulative test</u>

The production process including deep drawing followed by two redrawing operations intuitively points out Bending Under Tension to be selected as the simulating laboratory test. In the following, FE analyses of the pressure distributions for the three different workpiece materials are carried out in order to modify the test to emulate the production conditions.

The first analysis of a standard 90° BUT test with tool pin radius 3.5mm corresponding to the die radius of curvature was carried out for EN 1.4301 workpiece material [8]. At a back tension stress of 300 MPa, normal pressure in the tool/workpiece interface reached about 300 MPa. Such a high back tension stress is actually not recommended, since it is very close to the initial yield stress of 320 MPa. This means that the standard test is not suitable for the simulation of the production process, which reached about 1750 MPa as shown in Fig. 3. In order to reach a more realistic emulation of the production process, the pin tool was modified by limiting the contact zone to an angle of max. 45°, [8] see Fig. 4. The pin radius was kept equal to the die radius of 3.5mm. The radial normal stress distribution for DP 800 is shown for a back tension stress of 300 MPa in Fig. 4. Contact is not appearing on the entire 45° test surface of the pin tool. There is no contact on the first 8° and in a medium zone of 20-30°. At 42°, a maximum interface pressure of 1600 MPa is achieved, which is very close to the production value. As regards the workpiece material EN 1.4301, a lower back tension stress of 200 MPa is chosen to avoid strip failure. This back tension resulted in a lower peak pressure of about 1100 MPa. The coefficient of friction □ = 0.1 was set equal to the one applied for the production test analysis.

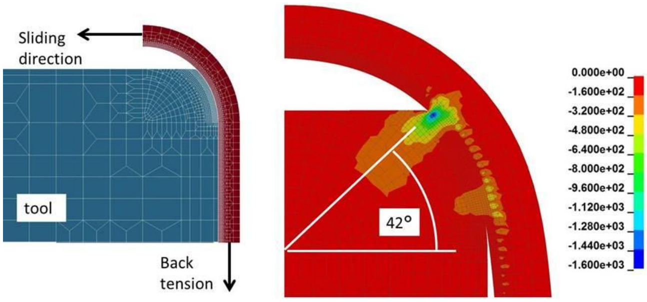

Figure 4. left: 2D model of BUT test. Right: radial pressure (DP800).

LABORATORY TESTS

After fixing the BUT test parameters by numerical analysis, the laboratory tests can be carried out. The application of Bending-Under-Tension tests to simulate the tribological conditions in the die shoulder during deep drawing has been utilized by a large number of authors starting with Littlewood and Wallace [9]. Later developments include Wilson et al. [10], Weinmann and Kernovsky [11], Wang et al. [12] and Vallance and Matlock [13], which give a good review on the different test variants. All of these tests are based on one or a very limited number of strokes leaving no possibilities for long term testing of slowly developing pick-up. The only test allowing this is to the best of the authors' knowledge the one developed by Hennig and Groche [14], where back tension is ensured by a draw bead located ahead of the BUT tool. The present work presents a more flexible solution introducing direct (feedback based) control of the back tension, which allows it to be varied during the stroke. A new, universal, automatic sheet-tribo-tester has been developed for the purpose [15]. Fig. 5 shows the equipment, which has three hydraulically powered movements controlled by a PLC and programmed on a PC provided with a customized LabView program, in which all main parameters are set.

Figure 5. New sheet tribotester.

The innovative feature of the machine is the possibility to run test from a coil, enabling repeated testing at a similar rate as in industrial production. This makes it possible to emulate the graduate but often slow build-up of pick-up of workpiece material on the tool surface occurring in production, which is impossible in the simple above mentioned laboratory tests [9-14], where the extended time between repetitions allows the tool to cool down [16]. The equipment is designed for all the main sheet tribo-tests [4], e.g. Plane-Strip-Testing (PST), Bending-Under-Tension (BUT) testing, Draw-Bead-Testing (DBT) and Strip-Reduction-Testing (SRT) with adjustable sliding length (0-250 mm), sliding speed (0 – 150 mm/s), cycle time (0-95 spm) and total number of strokes.

The back tension applied for each workpiece material was determined in the simulations. The laboratory tests were performed at the same rate of 40 strokes/min as used in the production. The sliding length was 20 mm, corresponding to the height of the produced cup, and the sliding speed was 50 mm/s, which is less than half of the production value. The reason to choose a lower value was that the high acceleration of the pulling axis generates a high initial peak load, which could break the strip. The tribo-systems were tested by performing 1500 strokes, which are expected to provide a good indication of the long term lubricant performance. The tribo-systems are evaluated by analyzing the torque and force values plotted as a function of the number of strokes. In case the lubricant film breaks down, the curves should rapidly increase [16]. However, in the preliminary tests it was realized that these two parameters may not be sensitive enough to evaluate the limits of lubrication. This is mainly due to the small contribution of a possible galling formation to friction, since high drawing and back tension forces are applied. The tool surface was therefore visually inspected after testing to identify possible pick-up formation. An alternative evaluation method could be roughness measurements of the workpiece surface after testing. This method has been used with success in Strip Reduction Tests (SRT) [17], but a few trials showed that it was not applicable in the present BUT tests.

In this paper only a small selection of the achieved results are presented. Fig. 6 shows the force and torque curves for the tribo-system DP800-V4E-PLS100T. The curves are noticed to fluctuate around an average value. This is due to a systematic error in the measurement system, which was present in every test. The reader should focus on the trend of the curve. In Fig. 6 both curves are fairly constant, which indicates that no critical lubricant film breakdown has occurred.

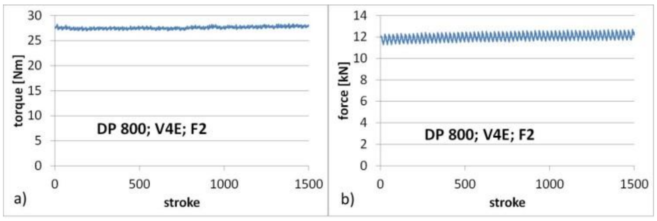

Figure 6. DP 800, Vanadis® 4 Extra (V4E), Fuchs PLS 100 T (F2): a) torque and b) drawing force.

Figs. 7a and b show the tool surface at about 42° (exit edge) and 10° (entrance edge), respectively. The pictures were taken using a Light Optical Microscope with 5x magnification. The white squares indicate where the contact with the strip occurred. In both photos some vertical scratches caused by sliding appear, which indicates where the contact has occurred. In Fig. 7a, a bright area caused by light reflection appears below the white square. In this area the horizontal texturing due to polishing is clearly visible. This verifies the numerical analysis, which indicated that there was no contact in the middle of the curvature.

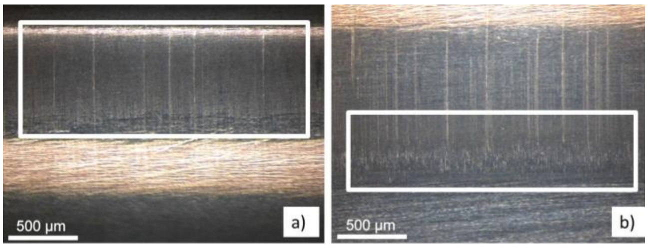

Figure 7. LOM pictures of BUT tool surface. DP 800-Vanadis® 4 Extra- FUCHS PLS 100 T: a) exit edge, b) entrance edge. Sliding direction from bottom to top. The frames indicate where the contact occurred.

All combinations shown in Table 1 were tested in the laboratory test. The results indicated that the tribo-systems with DP 800 material perform very well without any significant lubricant film breakdown or galling. Further testing was performed with increased sliding length (100 mm), sliding speed (100 mm/s) and tool rest temperature (about 60°C) without achieving lubricant film breakdown. The same good results were obtained with the tribo-systems for EN 1.4301, whereas EN 1.4162 showed galling to occur before reaching 1500 strokes. In all tests no significant difference was seen between the two tool materials, and the two Fuchs oils showed similar behavior.

PRODUCTION TESTS

Production tests of all combinations in Table 1 were performed. Although the tribo-systems with EN 1.4162 workpiece material failed to run 1500 strokes in the BUT tests, before galling occurred, it was decided to carry out the production test of these tribo-systems too, since the objective was to check the methodology, which implied that poor results in simulative testing should also be verified by production testing.

In the production tests the tribo-systems were evaluated by visual inspection of the outer surface of the formed component after producing of 1500 parts. In order to measure the temperature development a thermocouple was welded inside the die of operation 5 in a Ø2.2 mm bottom hole with a distance 2 mm from the die surface. Fig. 8a shows the temperature development for the tribo-system DP800-V4E-Fuchs3802. The temperature increases fast during the first 100 strokes, corresponding to about 2-3 minutes of production, after which the value goes asymptotically towards an average value of about 118°C.The behavior is similar for the stainless steel, but the average asymptotic value is about 100°C. Fig. 8b compares the temperature for the two Fuchs oils, where no significant difference is noticed.

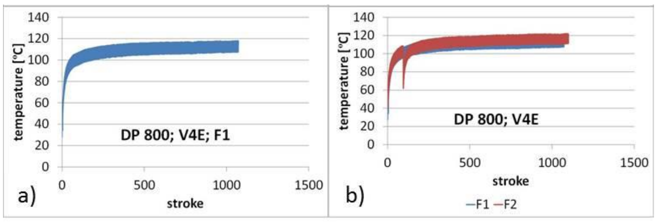

Figure 8. Temperature measurement in production tests: a) DP 800, Vanadis® 4 Extra (V4E) and Fuchs 3802-39S (F1); b) comparison between two Fuchs oils.

Fig. 9a shows a cup produced in EN 1.4301. The surface shows no sign of galling, and the parts were accepted according to the surface requirement. Fig. 9b shows a cup produced in DP 800 using the Fuchs PL 3802-39s. In this case the cup shows clear sign of galling and is rejected. This is the only case where the production and laboratory results did not match. The same result was obtained for both tool materials. Fig. 9c shows the pick-up formed on the tool curvature. Fig. 9d shows a cup produced in DP 800 using Fuchs PLS 100 T. The surface has very light galling and the cups were accepted. The tests with EN 1.4162 workpiece material resulted in immediate galling, as expected from the BUT test results.

Figure 9: Specimen results a) EN 1.4301; b) DP 800 with severe galling; c) pick-up on V4E die 3 tested with DP 800; d) DP 800 with no significant galling (the arrow indicates local, light galling).

CONCLUSIONS

A methodology for off-line testing of tribo-systems for sheet forming production is proposed. The methodology is based on numerical modelling of the production platform in question, after which an appropriate simulative test is selected and modified by using numerical modelling in order to ensure the same tribo-conditions as in the production process. Screening of new tribo-systems is carried out in laboratory before selecting the most promising ones for production testing. A custom built sheet tribo-tester was designed and constructed enabling repeated testing of strip from coil at a speed comparable to that in automatized deep drawing production. The methodology was tested on a specific production platform, which turned out to be tribologically very severe and maybe not be the best example for testing the methodology. It is concluded that special precautions need to be taken to ensure appropriate emulation of the conditions in the laboratory testing of new tribo-systems. With such precautions, good predictions of the performance can, however, be expected.

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