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Tribo-systems for Sheet Metal Forming

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NEW TRIBO-SYSTEMS FOR SHEET METAL FORMING

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Abstract

The present paper gives an overview of more than 10 years work by the author's research group through participation in national as well as international framework programmes on developing and testing environmentally friendly lubricants and tool materials and coatings inhibiting galling. Partners in the programmes come from Germany, United Kingdom, Finland, Poland, Slovenia, Spain and Denmark. They represent lubricant developers, testing experts and industrial end users as well as numerical modelling experts simulating fundamental lubrication mechanisms and computing basic process parameters. The author's research group has especially been involved in the development of a system of tribo-tests for sheet metal forming and in testing and modelling of friction and limits of lubrication of new, environmentally friendly lubricants and tool materials.

1. Introduction

Increasing focus on environmental issues in industrial production has urged a number of sheet metal forming companies to look for new tribo-systems in order to substitute hazardous lubricants such as chlorinated paraffin oils. These lubricants are expected to be prohibited in the Scandinavian countries as soon as efficient alternatives are found. The problems are especially pronounced, when forming tribologically difficult sheet materials such as high strength steels and stainless steels, and when the forming process itself due to high degree of deformation causes substantial temperature increase in the tool/work piece interface. Higher temperatures lead to thinner lubricant films and the risk of galling, i.e. breakdown of the lubricant film causing pick-up of work piece material on the tool surface and scoring of subsequent work piece surfaces and in such cases chlorinated paraffin oils have proved to be the only efficient lubricant.

These circumstances led to the establishment of a Danish industrial research program "Development and testing of environmentally friendly lubricants for sheet metal forming of stainless steel and other sheet metals" running through a 10 years period, 1994-2003, as well as a European framework programme, ENLUB: "Development of new, environmentally acceptable lubricants, tribological tests and models for European sheet forming industry", 2002-2006. The present paper describes the involvement of the author's research group in these programs testing a variety of work piece materials, lubricants and tool materials. The lubricants investigated includes the ones developed in the research programs as well other new, environmentally friendly lubricants.

2 Selected test methods

A major issue when testing has been to determine the limits of lubrication as a function of the most important process parameters influencing these, i.e. normal pressure, sliding length and tool temperature. Possibility of changing these parameters under close control is therefore important as well as determination of the actual onset of lubricant film break. An overview of sheet tribology tests found in literature is given in [1]. In the present work some of these tests have been selected and refined and supplemented with new ones in order to test the performance under the varied conditions appearing in sheet metal forming, [2]. The tests applied are:

Simulative tests

BUT: Bending Under Tension test

DBT: Draw Bead Test

SRT: Strip Reduction Test

Process tests

DDT: Deep Drawing Test

PUT: Punching Test

Production test

PTPT: Production Tests in Progressive Tool

3 Materials

The Danish research program was focussed on development of lubricants for stainless steel sheet whereas the European project also dealt with deep drawing steel. The material grades tested are listed in Table 1 together with the tool materials and coatings applied.

Table 1. Sheet materials and tool materials and tool coatings tested.

	Sheet material	Grade	Surface
	Stainless steel	Wn.1.4301	
	Stainless steel	Wn.1.4401	2B
	Mild steel DC04	Wn.1.1403	As
	Zn-coated mild steel	DX56 (Z100)	As
	Zn-coated mild steel	DX56 (Z100)	EDT rolled

Test	Tool material/coating	Hardness	Ra
BUT	BUT: AISI M3:2 PM (UHB-Vanadis 6)	62 HRC	0.1 μm
DBT	AISI M3:2 PM (UHB-Vanadis 6)	62-64 HRC	0.05 μm
SRT	SRT: AISI M3:2 (UHB-Vanadis 6) UHB-Vancron Balinit Lumena coating (TiAlN)	62 HRC 62-64 HRC 3400 HV	0.02 μm 0.03 μm 0.03 μm
PUT	AISI M3:2 PM (UHB-Vanadis 6)	62-64 HRC	0.15 μm
DDT	AISI M3:2 PM (UHB-ASP 23)	64 HRC	0.04 μm
PTPT	AISI M3:2 PM (UHB-Vanadis 6) Balinit Lumena coating (TiAlN)	3400 HV	0.06 μm

The lubricants tested are listed in Table 2. Lubricants No. 1 and 2 from Castrol are commercial, commonly applied, environmentally hazardous oils containing chlorinated paraffin oil. Lubricants No. 3 and 4 are refined oils developed from fir tree by the partner Pinifer in the EU project. Lubricant No. 5 from Chemetall is a water based polymeric dispersion, incl. water soluble waxes, defoamer and additives. Lubricant No. 6 from Houghton is a commercial, high viscosity mineral oil. Lubricants 7-10 are commercial, environmentally friendly lubricants developed as alternatives to the chlorinated paraffin oils by the companies Rhenus, Jokisch and Holifa. Lubricants No. 11 and 12 are dry-in lubricants developed in the Danish framework program. Lubricant No. 13 is commercial drawing grease.

Table 2. Lubricants tested.

No.	Lubricant manufacturer	Code	Description	Kinematic viscosity at 40˚C	Environm. hazardou s
L1	Castrol	TDN81	Highly chlorinated paraffin oil	165	Yes
L2	Castrol	PN226	Medium chlorinated paraffin oil	66	Yes
L3	Pinifer	P1	Vegetable oil based on fatty acid methylester	205	No
L4	Pinifer	P3	Vegetable oil based on trimethylol propan ester	17	No
L5	Chemetall	L6250	Water based polymeric dispersion, incl. water soluble waxes, defoamer and additives	-	No
L6	Houghton	CR5	Naphthenic mineral oil witout any EP additives	660	No
L7	Rhenus	SF135	Mineral oil with Ca-, P- and S-additives	135	No
L8	Rhenus	CXF125	Mineral oil with Ca-, P- and S-additives	125	No
L9	Jokisch	Type 2830	Water based with fatty acids, fatty acid esters, emulsifiers, corrosion inhibitors	420	No
L10	Holifa	VP1145 GD3-400	Mineral oil with additives	400	No
L11	DTU/Esti Chem	RaSeOPoES	Rapeseed oil + polyol ester + sulfur additive	-	No
L12	DTU/Esti Chem	AqEmPoES	Aqueous emulsion with polyol ester and sulfur additives	-	No
L13	International Compounds	IC345	Commercial drawing grease	5000	No

In the following the tests will be shortly described together with results on testing the performance of a number of different lubricants in forming of stainless steel sheet.

4 Bending under tension test

The Bending-Under-Tension test, also called the BUT test, is traditionally performed by differential measurements carrying out two tests after each other, one by drawing over a fixed, circular cylindrical tool-pin, the other over a freely rotating pin, implying that no sliding takes place, Figure 1. The difference in front tension measured in the two tests gives an estimate of the friction. A drawback of this method is stochastic variations, which may cause large scatter, and the fact that steady state conditions must be present when measuring. In order to solve this problem Andreasen et al. [3] have developed a new variant of the BUT test measuring not only front and back tension but also the torque on the tool-pin with a piezoelectric transducer.

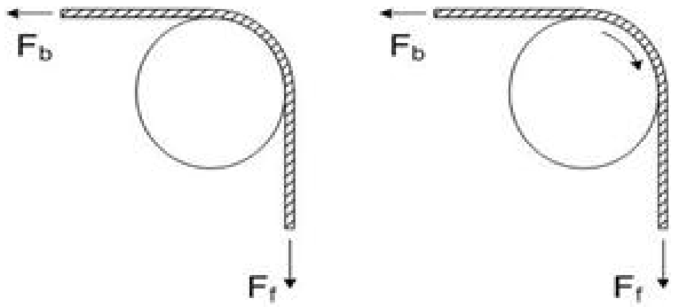


Figure 1. Schematic outline of BUT test.

The test is specially designed for studying the influence of a large number of parameters on friction and limits of lubrication. As such, tests can be performed with varying tool-pin materials and radii, drawing speed, back tension, lubricants, strip materials and dimensions. To simulate the influence of varying tool temperature in sheet metal forming, electric heaters can be inserted in the tool-pin holder heating up the tool-pin to maximum 100°C.

Figure 2 shows the development of front tension force and torque for two different tool preheat temperatures in testing 800×25×1.25 mm stainless steel strips of Wn. 1.4401 lubricated with CR5. The tool pin applied was ø 10 mm made of AISI M3:2 PM, hardened and tempered to 62 HRC and ground and polished to Ra = 0.1 µm. Drawing speed was 100 mm/s. In case of testing at tool temperature 20° C the torque is stable. At T = 55° C a steady increase in the torque is noticed and at 50 mm drawing length, the torque starts to fluctuate severely and a high frequent noise was heard, caused by severe stick-slip. The reason for breakdown of the lubricant at higher tool preheat temperature is, that increasing temperature decreases the lubricant viscosity implying smaller film thickness.

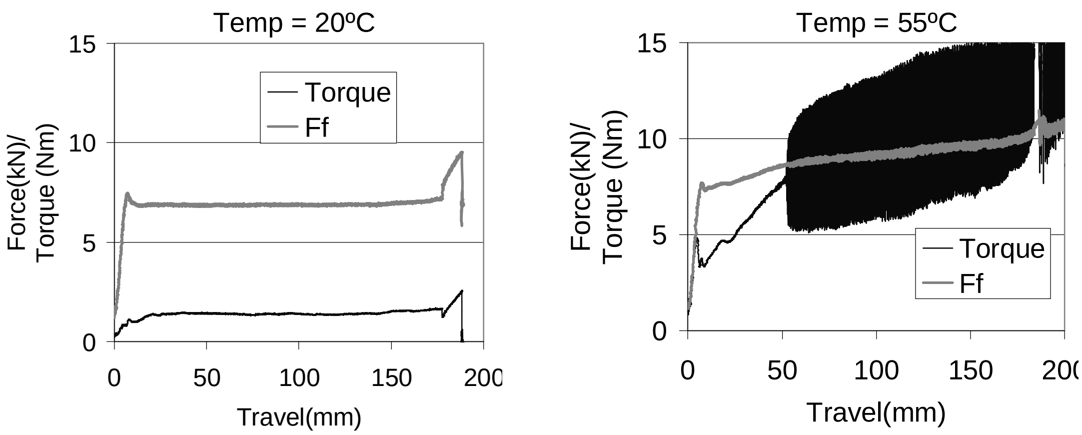


Figure 2. Force and torque history curves for two different tool preheat temperatures

Figure 3 shows the results from five different lubricants at a tool rest temperature of

70ºC. It is noticed that Pinifer 1 and the polymer coating L6250 perform similarly well as TDN81, whereas Pinifer 3 and mineral oil CR5 show very poor performance with much higher friction increasing with the sliding length. As regards the mineral oil, which was tested at 60ºC, since it broke down immediately at 70 ºC, the large oscillations at sliding lengths above 100 mm are due to stick-slip. Visual inspection of the strips and the tool surfaces showed severe galling when using Pinifer 3 and CR5 corresponding to these measurements, whereas slight galling was observed with Pinifer 1. No galling was observed with TDN81 and the polymer coating. The decreasing friction with increasing sliding length observed for TDN81 may be attributed to chemical reaction with the tool surface forming a boundary film at increasing temperature.

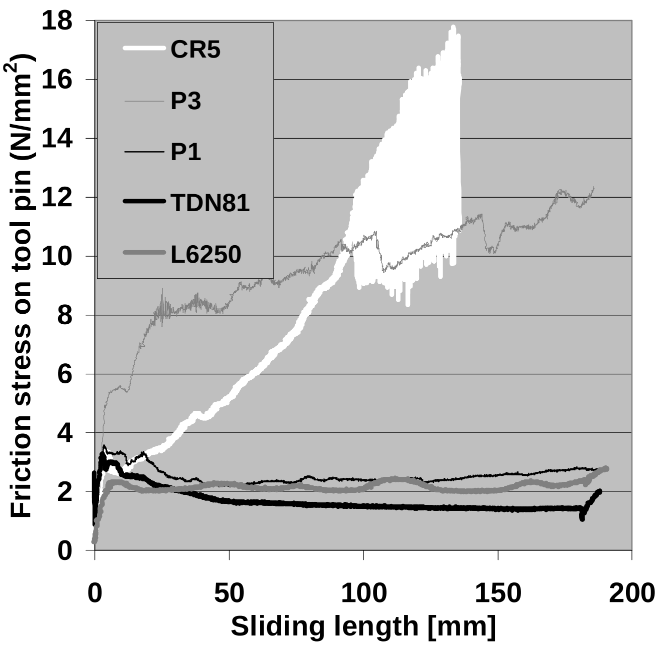


Figure 3. Friction versus sliding length in BUT testing of different lubricants specified in Table 1. Tools preheated to T=70ºC except for CR5, where T=60 ºC.

P1, L6250 and TDN81 showed similar good performance on mild steel and the Zn-coated steel as on stainless steel, whereas P3 again gave poor results. There were no indications that EDT texturing of the Zn-coated steel improved the lubrication performance.

5 Draw bead test

A schematic outline of the DBT is shown in Figure 4. Similar to the BUT test this test is normally carried out twice to determine friction as the difference between drawing force without and with rotating tool implying the same drawbacks as in the BUT test. In order to avoid this problem a new draw bead test has been proposed by Olsson et al. [4] measuring the friction force acting on the tool radius directly by a build-in, piezo-electric torque transducer. This technique results in a very sensitive measurement of friction, which furthermore enables recording of lubricant film breakdown as function of the drawing distance.

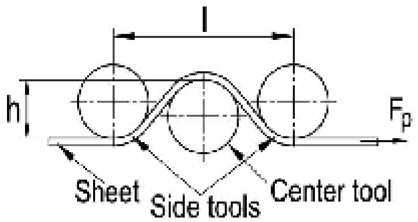


Figure 4. Schematic outline of DBT.

The tool pins made of AISI M3:2 PM had a diameter D = Ø 10 mm, surface roughness Ra = 0.05 µm, distance between outer tool pins l = 25.6 mm, penetration depth h = 3.7 mm (37%), drawing velocity v = 47 mm/s. The strip made of stainless steel Wn. 1.4401 had dimensions w×t = 25×1.0 mm. The back tension force was 0.85 kN corresponding to 11% of the yield stress of the strip material.

DBT tests were done on stainless steel Wn.1.4401 with lubricants: TDN81, P1, L6250, CR5, SF135 and CXF125, referring to Table 2. Two different tool temperatures were investigated, i.e. 20ºC and 80ºC. All lubricants performed well at room temperature, but the mineral oil CR5, which gave the lowest friction at room temperature, broke down at 80ºC resulting in severe galling and high friction. The other lubricants performed equally well at 80ºC as at room temperature although with somewhat increased friction.

6 Strip reduction test

A schematic outline of the SRT is shown in Figure 5. A round, non-rotating tool-pin is pressed towards the test strip supported by a thicker tool plate. Reduction in thickness may be varied, it was held at 20-30% in the present tests. The strip and the supporting tool plate are subsequently drawn in horizontal direction up to a maximum sliding length s=300mm under constant reduction. Drawing force is measured by a piezoelectric transducer. The tool-pin can be preheated to maximum 200˚C by electric heaters embedded in the shoe loading the tool-pin. Threshold sliding for the onset of galling is determined by visual inspection of the drawn strip and by roughness profile measurements of the strip surface perpendicular to the drawing direction with 30mm intervals. The set-up allows four tests with the same pin tool before repolishing, by turning the tool 90º after each test. Test specifications are: tool pin of AISI M3:2 PM with diameter D = Ø 15 mm, roughness Ra = 0.02 µm, strip reduction 0 < r <50%, punch travel 0-300 mm, drawing speed 25-150 mm/s. A detailed description of the test design is given in [5]. In the test results presented below, the stainless steel strip had dimensions l×w×t = 500×15×1.0.

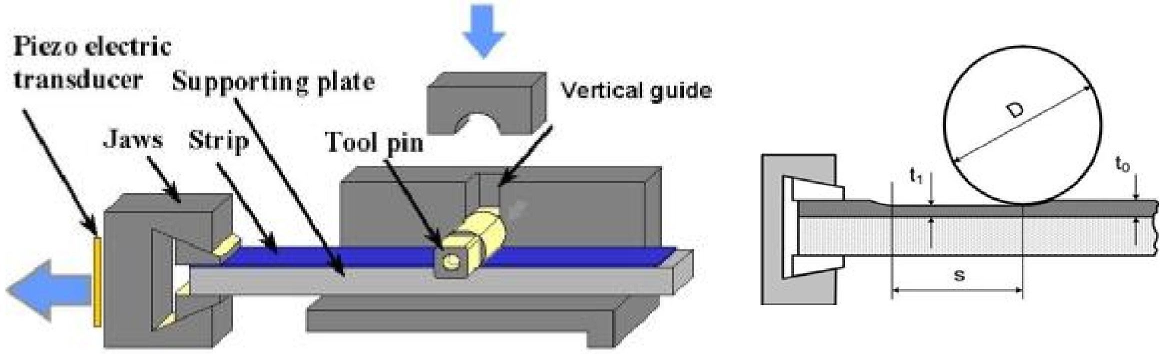
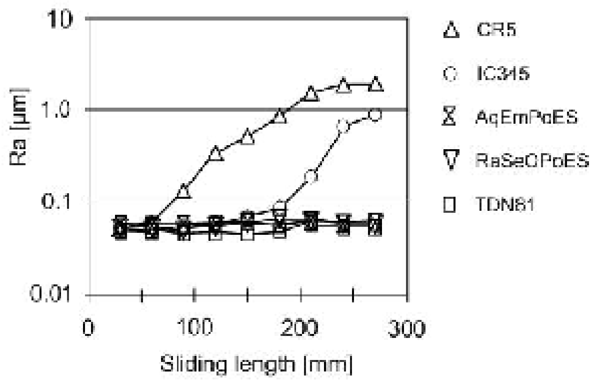


Figure 5. Schematic outline of SRT.



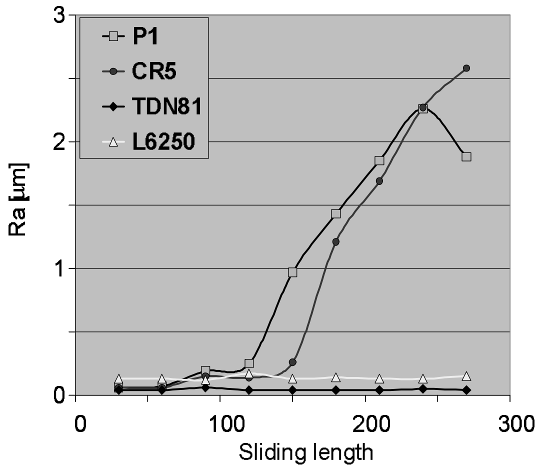


Figure 6. Ra versus sliding length in strip reduction testing of stainless steel, Wn. 1.4301 with different lubricants specified in Table 1, tool temperature 20 ºC, r = 32%.

Figure 7. Ra versus sliding length in strip reduction testing of stainless steel, Wn. 1.4401 with different lubricants specified in Table 1, tool temperature 20 ºC, r = 25%.

SRT tests were done on stainless steel Wn. 1.4301, Wn. 1.4401 and mild steel DC04. Tests on stainless steel were done with all the lubricants listed in Table 2. Figure 6 shows the surface roughness Ra across the test strip with increasing sliding length for Wn. 1.4301 lubricated with TDN81, RaSeOPoES, AqEmPoES, IC345 and CR5. Testing was done at room temperature with a reduction r = 32%. The two dry-in lubricants Rapeseed Oil + Polyol Ester and Sulphur and Aqueous emulsion with Polyol Ester and Sulphur performs as well as the chlorinated paraffin oil, whereas the drawing grease and the mineral oil both break down after a threshold sliding length due to increase of tool temperature implying decreasing viscosity and film thickness. The reason that CR5 breaks down even with no preheating of the tool in SRT, whereas it only breaks down at preheated tool temperature in case of DBT, is that the SRT is more severe than the DBT, since the heavy deformation leads to excessive heating..

Figure 7 shows similar results comparing the performance of Pinifer 1 and polymer coating with CR5 and TDN81 for stainless steel Wn. 1.4401 reduced 25% in thickness with non-preheated tools. It is seen that mineral oil and Pinifer 1 breaks down at approximately the same threshold sliding length of 125 mm after which heavy galling occurs, whereas the chlorinated paraffin oil and the polymer coating show no sign of breakdown after 300 mm sliding length. The galling of Pinifer 1 in the draw bead test performed with a tool rest temperature of 70ºC is significantly less pronounced than in the present strip reduction test performed at room temperature, again due to the fact that the latter is tribologically much more severe.

Testing of P1 and Jokisch 2830 on mild steel DC04 with non-preheated tools showed severe galling, whereas CR5 and Rhenus CXF125 both performed well. Best performance was obtained with TDN81.

In a more recent study new tool material and tool coating have been tested with SRT of Wn. 1.4401 at 30% reduction lubricated with the environmental friendly oils, CXF125 and SF135, which were compared with PN226 and CR5. The new tool material and tool coating investigated were Uddeholm's Vancron 40, a Cr-Mo-W-V-N alloyed PM tool steel with improved galling resistance and UHB-Vanadis 6 coated with Balinit Lumena. These two tool surfaces were compared with the reference tool material UHB-Vanadis 6. Figure 8 shows the threshold sliding length of the different tribo-systems for initial tool temperatures of 20ºC and 50ºC. When the threshold is reaching the maximum sliding length 300mm, it indicates that no lubricant breakdown has occurred. It is seen that the TiAlN coating is very efficient in preventing galling. A few tests made at 70 ºC showed the same results, i.e. no galling. At high tool temperatures, where the lubricant film is stressed, the new, galling resistant tool steel Vancron 40 is generally superior to Vanadis 6. At low initial tool temperature the effect is not pronounced, which is explained by large experimental errors found in this case. Comparing the different lubricants it is noted that CXF125 has significantly higher threshold sliding length than CR5 and SF135.

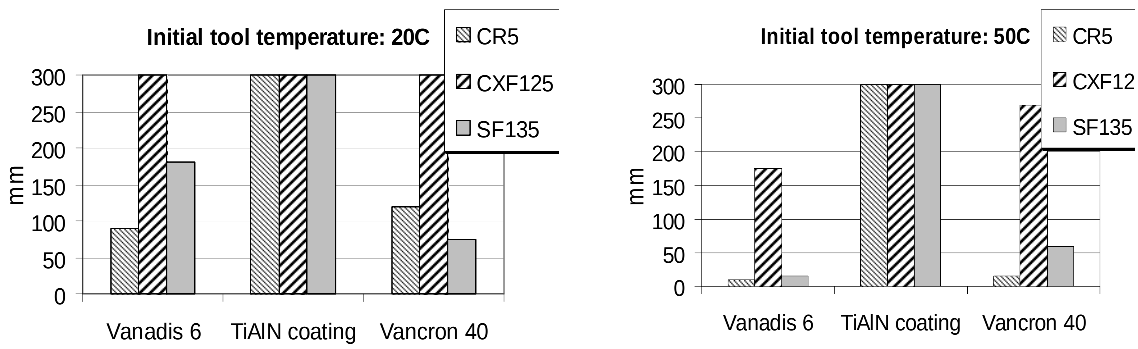


Figure 8. Threshold sliding length before galling in strip reduction testing of different tribo-systems, initial tool temperature, 20ºC and 50ºC.

7 Deep Drawing Test

The deep drawing test is developed for drawing cups with Ø 50 mm punch diameter and Ø 55 mm die diameter, in t_0 = 2 mm sheet. The die entry radius is rather small, r = 6 mm, in order to stress the lubricant. Separate transducers measure the deep drawing force and the backstroke force appearing, when the punch with the drawn cup reverses through the die. Using a rather small clearance $1.1xt_0$ between punch and die possible lubricant film breakdown is observed by measuring the backstroke force. Drawing speed is 40 mm/s. The tool can be preheated up to 160ºC by electric heaters embedded in the die. A detailed description of the test is given in [6].

DDT were carried out in 2 mm stainless steel Wn.1.4401 lubricated with TDN81, P1, P3 and CFX125. P1 gave acceptable results whereas P3 resulted in heavy galling. Polymer coating L6250 and the environmentally friendly oil CFX125 showed excellent performance almost comparable to the chlorinated paraffin oil TDN81. It is worth to note that the deep drawing test showed the same lubricant ranking as the BUT test, which was intended to simulate deep drawing. Figure 9a shows a plot of the measured maximum deep drawing force as a function of stroke number. Little difference is noted between the tested lubricants, TDN81, CR5 and the environmentally friendly lubricant VP1145GD3-400. This is, however, not the case as regards the maximum backstroke force, which is highly sensitive to galling occurring with CR5 but not the other two lubricants.

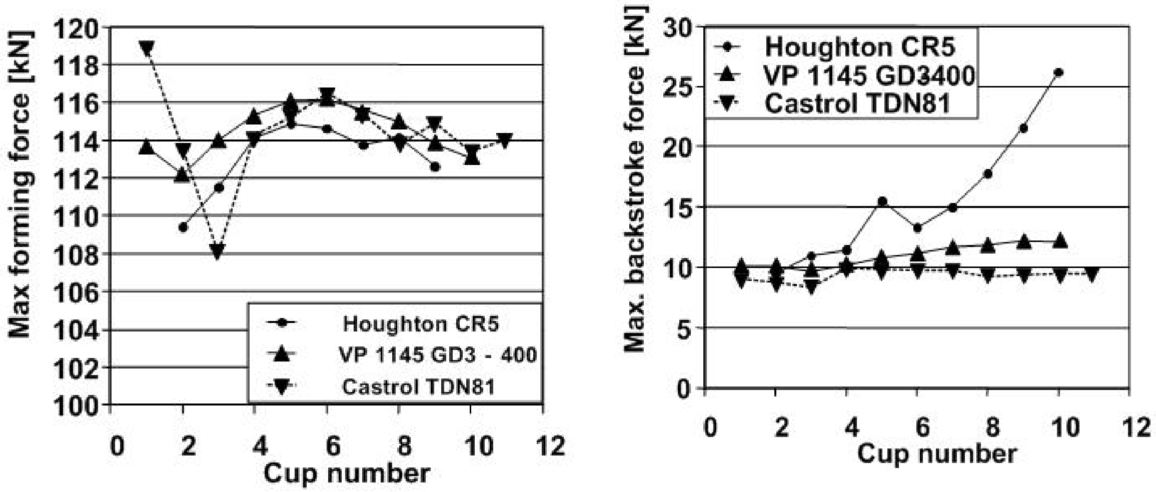


Figure 9. Deep drawing stainless steel Wn.1.4401 with different lubricants. a) Maximum deep drawing force, b) maximum backstroke force, tool temperature 20 ºC, [6].

8 Punching Test

Punching is one of the tribologically most severe sheet forming operations. Olsson et al. [7] have established a punching test on a 320 kN eccentric press with 150 spm. Punching of two holes at a time, Ø 2 mm in diameter, is carried out in 1mm sheet. In order to stress the lubricant the clearance is small, 10-15 µm. The test is running similar to real production with continuous lubrication and feed implying that preheating of the punches is unnecessary. The punch force as well as the backstroke force on each of the two punches is registered on a PC continuously during testing. The backstroke force is very sensitive to even the slightest pick-up on the punch stem implying that the test has proven very adequate for determining lubricant film breakdown and ranking lubricants. A detailed description of the test is given in [7].

PUT tests at the authors laboratory were done in 1mm stainless steel sheet Wn.1.4401. The following lubricants were tested: PN226, L6250, P1, CR5, CXF125. As an example the normalized, maximum backstroke force (i.e. the friction stress on the punch stem) versus the number of strokes is plotted for 1 mm Wn.1.4401 sheet lubricated with PN226, L6250, P1 and CR5 in Figure 10. The chlorinated paraffin oil PN226 and the Pinifer P1 oil works fine, whereas the polymer coating and the plain mineral oil results in heavy pickup and large increase of the backstroke force. The reason for the poor performance of the polymer coating L6250 is that it is solid implying no possibility to access the critical area between the punch stem and the cylindrical surface of the hole in the sheet. The better performance of PN226 and P1 than CR5 indicates that the boundary lubrication effects of P1 have reacted with the punch stem. This hypothesis is supported by DTA (differential thermal analysis) showing chemical reaction between the tool material UHB-Vanadis and PN226 even at moderate temperature increase, implying that a boundary layer has formed on the punch stem impeding pickup. Testing of the new, environmentally friendly lubricant CFX125 showed equally good performance as P1. When increasing to 1.5mm sheet, galling occurred when using P1 whereas CFX125 performed better.

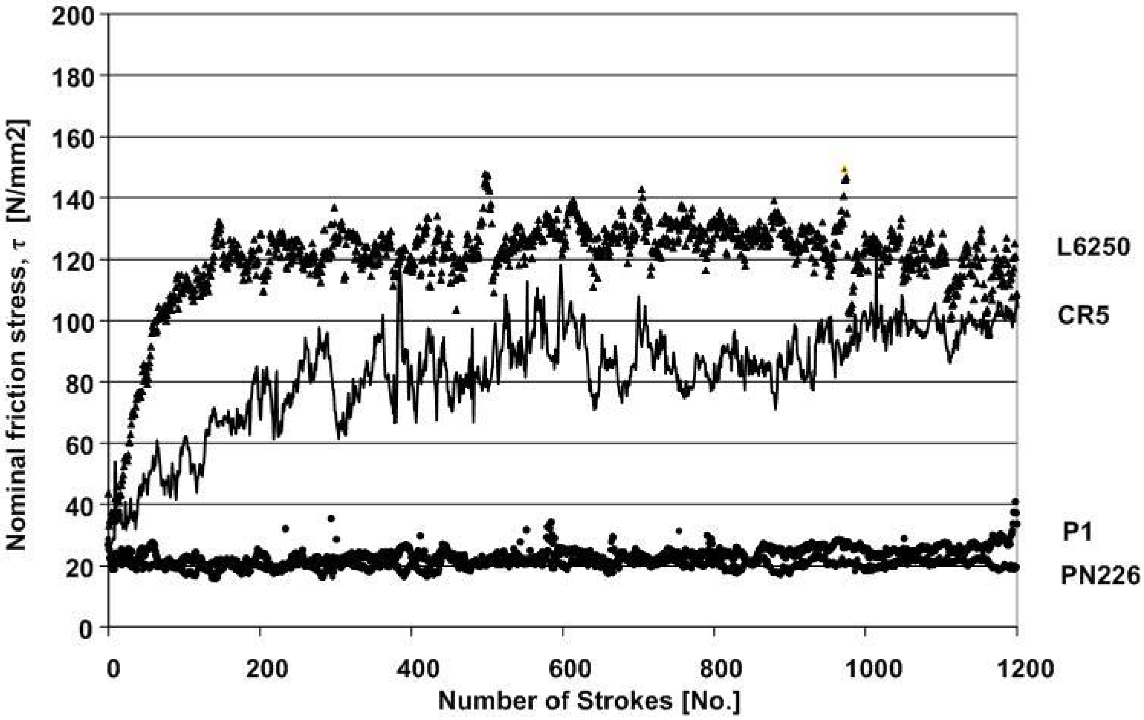


Figure 10. Maximum, nominal backstroke force versus number of strokes for different lubricants, [7].

9 Production Tests in Progressive Tool

A number of production tests were carried out in progressive tools, [8]. One of these, a tool at Grundfos A/S for production of the cap for a stainless pump, is here described in more details. Figure 11a shows a schematic outline of the five operations, Figure 11b shows a photo of a work piece strip taken out of the tool. The five operations are as follows: 1. punching, 2.

deep drawing, 3. punching, 4 collar drawing and ironing, 5. blanking of the finished component. The tool is equipped with force transducers in the two tribologically most critical operations, i.e. the punching operation 3 and the collar drawing and ironing operation 4. The transducers are preloaded piezoelectric ones located between the punch and the punch support. Preloading is required to keep compressive load on the transducers even during the backstroke, thereby enabling measurement of the backstroke force. Preliminary tests showed the ironing operation 4 illustrated in detail in Figure 11c to be the most critical, often leading to lubricant film breakdown and galling between punch and inner surface of the collar as seen in Figure 11d. In order to study this phenomenon more closely, thermocouples were embedded in the punch as well as in the die approximately 1mm from the tool surface by EDM-machining flat bottom holes in the tools from the back side, see Figure 12.

Production tests have been carried out with UHB-Vanadis 6 tool steel coated with Balinit Lumena coating and the lubricants CXF125, SF135 and PN226 at 50 and 100 spm (strokes per minute). Furthermore the process has been simulated in the commercial FE-program DeForm v9.1 as a continuous production run at 100 spm. A comparison between measured and simulated temperatures of the punch and die are shown as functions of time in Figures 13 and 14, respectively. It can be seen how the steady state tool temperature changes significantly with varying production speeds.

The tests showed that the temperature development in the tools and the steady state temperature during production are practically independent of the applied lubricant. The speed of production, however, has a large influence on the measured temperature, as observed in Figures 13 and 14. The calculated temperature development fits very well with the experimental one.

The experiments showed that initiation of galling in the process can easily be identified from the measured process parameters. The production experiments reported here and similar ones from other production tools at Grundfos show, that low production speed (50 spm) can prevent galling from initiating but if the speed is increased too much (100 spm), galling appears after a critical amount of strokes. This is mainly ascribed to the large increase in temperatures of the tool and the tool surface, which stresses the tribo-system. Galling is clearly visible both on the punch and work pieces. The force measurements have proven to indicate the onset of galling. Especially the backstroke force is very sensitive to any pickup on the punch, increasing significantly with the amount of pickup.

Experience from other production tools at Grundfos furthermore shows, that the steel grade can have influence on the initiation of galling. Comparison of similar production in Wn. 1.4401 and Wn. 1.4301 with the new, environmental friendly oil CFX125 have shown the former to cause galling if production speed is too high, while the latter runs without problems. This is ascribed to the fact that a higher yield stress of the workpiece material results in more heat generation and a higher temperature in the tool surface.

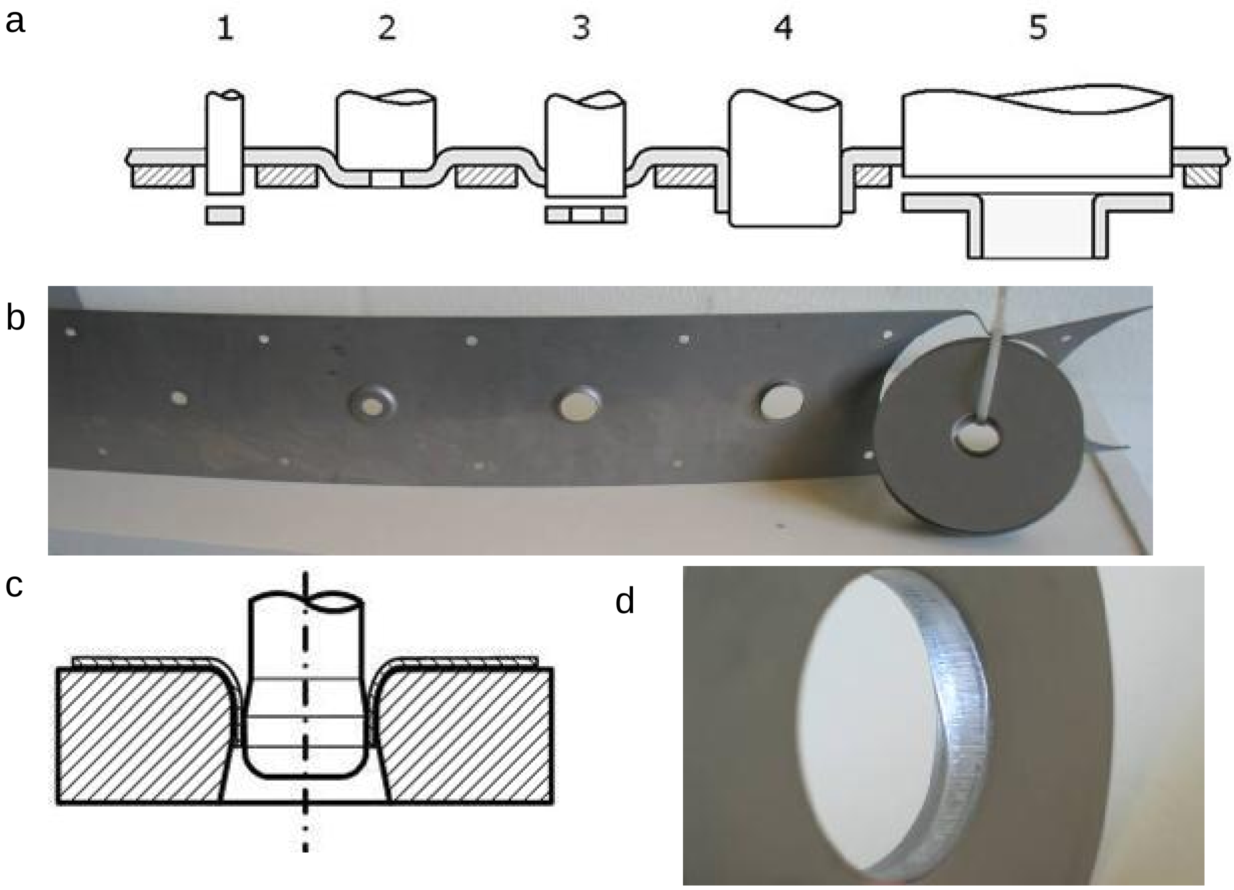


Figure 11. Production test in progressive tool. a) schematic outline of operations b) photo of deformed strip, c) outline of ironing operation d) photo of ironed collar with scoring marks .

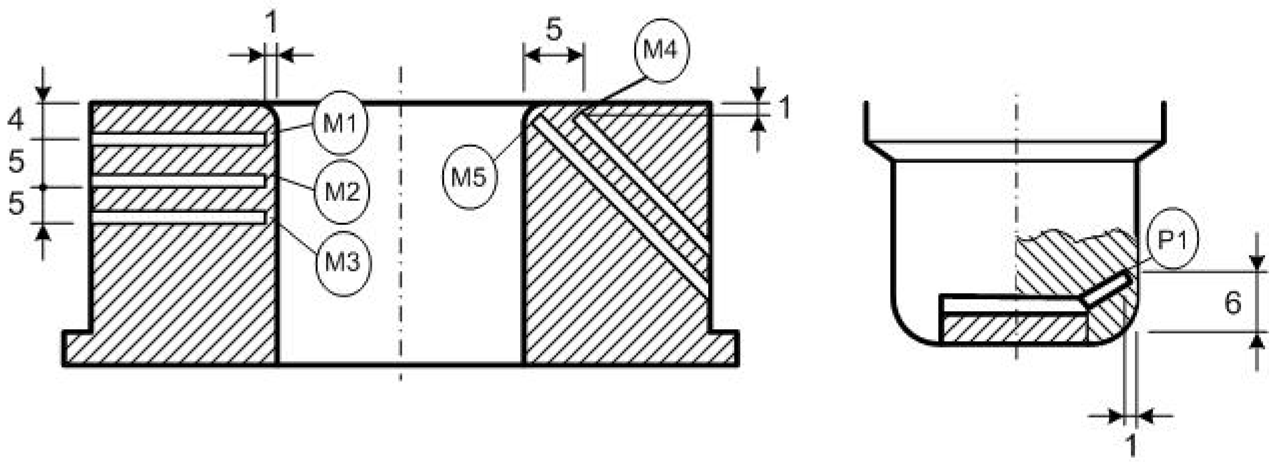


Figure 12. Location of embedded thermocouples in punch and die, step 4 in the production tool.

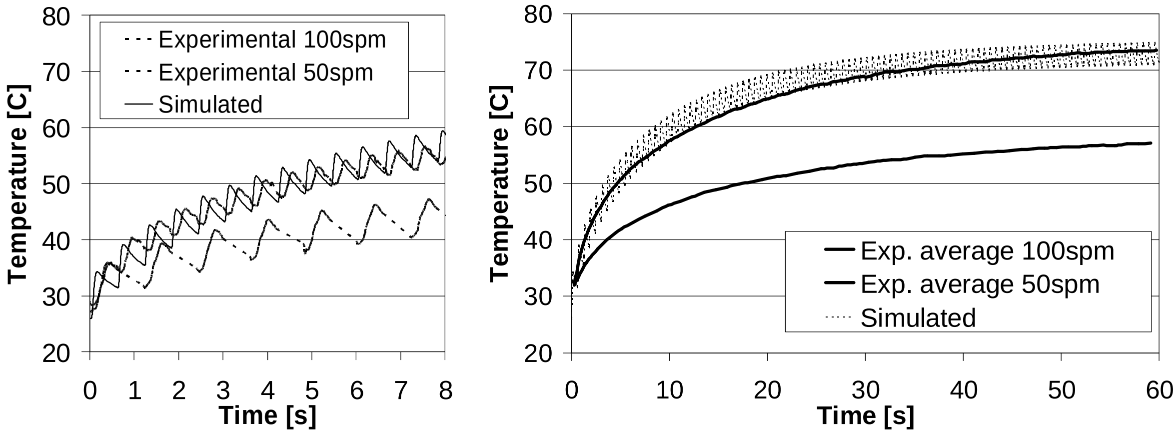


Figure 13:   Experimental and simulated punch temperatures

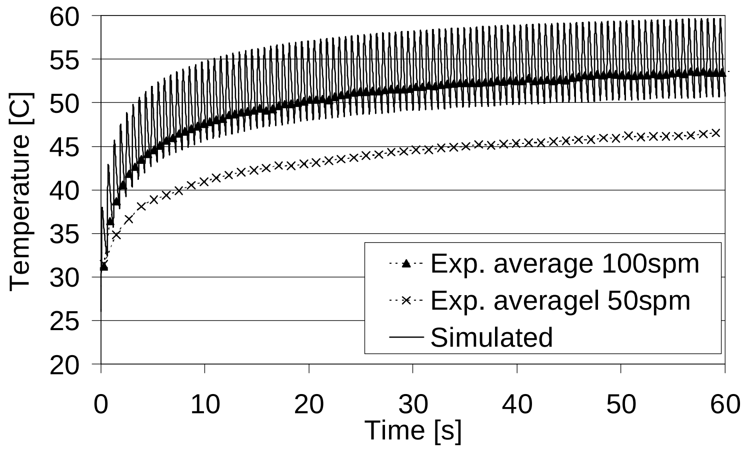


Figure 14:   Experimental and simulated die temperatures

10 Conclusions

The system of simulative tribo-tests developed by the authors research group for sheet metal forming has proven to efficiently cover the required variety of sheet forming operations applied in industry. Running the tests at elevated tool temperature has proven to be vital to reflect the conditions in real production, since the limits of lubrication for many lubricants vary considerably with tool temperature. Large advantages are obtained by testing off-line, since production breakdowns are avoided, which would otherwise be required to clean tools before providing new lubricant. Longer productions stops to demount tools for redressing, as occurring, when pickup occurs due to testing of a poor lubricant can be avoided by sorting out this in laboratory tests before production trials are done.

The environmentally friendly lubricants P1, RaSeOPoES and AqEmPoES proved to be good if not too severely stressed in the simulative tests, and they have been successfully tried out in light to medium severe deep drawing production, but not in very severe production tests.

Polymer coating L6250 proved very good in simulative tests as well as in production under severe conditions but it was not feasible for multistage operations in progressive tools and for punching. The commercial, environmentally friendly oils CFX125 proved very efficient even at severe conditions like punching and deep drawing + ironing in production on progressive tools as long as the production speed did not exceed 50 spm. The best lubricants are still the chlorinated paraffin oils.

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