New tribo-systems for sheet metal forming of advanced high strength steels and stainless steels

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New tribo-systems for sheet metal forming of advanced high strength steels and stainless steels

by

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For fulfillment of the degree

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</tbody>
</table>

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With great knowledge comes a great responsibility.
Preface

This PhD thesis is submitted in partial fulfillment of the PhD degree at the Technical University of Denmark. The PhD work was carried out from the 1st August 2010 until the 31st July 2013. The project was supervised by prof. Niels Bay (main supervisor) from the Technical University of Denmark, M.Sc. Fredric Bergström from Uddeholms AB, Ph.D. Sven Erik Hörnström from SSAB AB, senior engineer Erik Madsen from Grundfos A/S and Ph.D. Erik Schedin from Outokumpu Stainless AB. A short external stay of two weeks was done at the Sheet Metal Forming Group at Aalborg University. The project was funded by Grundfos A/S, Outokumpu Stainless AB, Outokumpu Stainless Research Foundation, SSAB AB, Technical University of Denmark and Uddeholms AB. IPU is acknowledged for partially funding the design and construction of the Universal Sheet Tribotester.

First of all I would like to thank prof. Niels Bay for giving me the opportunity to work in his group. Not only has he been a mentor throughout the PhD but he also shared a contagious passion for metal forming and manufacturing technology. Special thanks to all co-supervisors Fredric Bergström (Odd Sandberg), Erik Madsen, Sven Erik Hörnström and Erik Schedin for supporting me throughout the PhD, especially Erik Madsen for helping and guiding me during my time at Grundfos.

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Let’s move to another country: Italy. Many thanks to Matteo Varotto who, in good and bad time, has always been a close friend. Thanks to all friends from Murelle who always welcome me when I am there. Thanks to my family who encouraged and supported me to jump into the Danish experience.
31st July 2013, Kgs Lyngby

Ermanno Ceron
Abstract

The environmental issue, concerning the lubrication in sheet metal forming, has become considerably important in the past 10 years. Besides the fact that legislation is becoming more restrictive on the type of lubricant industry is allowed to use, many companies are embracing the path of social responsibility and sustainability, which implies a careful application of environmentally friendly technology. On the other hand the global market requires more and more complex products, which ignites a chain reaction that affects the whole life cycle of the product. Regarding sheet metal forming, this means that the performance of the workpiece materials have to improve in order to satisfy higher strength and lower weight requirements. This however leads to challenges in the forming operation, especially when high surface expansion and elevated strain are involved. The challenge is to achieve long production run and fulfilling the product specification. This means that galling is one of the first problems occurring in sheet metal forming. The remedy has been so far the application of hazardous lubricant such as chlorinated paraffin oils. The technology in environmentally friendly lubrication is advancing but it faces the reluctance of industry in the application of new solutions, due to the high trial costs. This project presents a new methodology for testing new environmentally friendly tribo-systems for sheet metal forming of advanced high strength steels and stainless steels. For the purpose, a new Universal Sheet Tribotester was developed. A production process was selected at Grundfos, which is currently running with chlorinated paraffin oil. The process includes a deep drawing and two subsequent re-drawings in a progressive tool. The process was numerically analyzed to investigate the tribological conditions. A suitable laboratory test (BUT test) was selected to simulate the production process. The BUT test was numerically analyzed to verify that the tribological conditions are close to the production process ones. A few interesting new tribo-systems were selected to be investigated in the BUT test. Some of them showed promising results and were further tested in production. Besides the analysis of the lubrication performance, thermal investigation of the limit of lubrication was performed by means of numerical simulation. The results showed that there is a correlation between laboratory and production tests, but also that improvements are needed to emulate tribological conditions in production. This may allow a better characterization of the tribological conditions by means of numerical methods, when testing new solutions in production, therefore reducing the related costs.
Resumé (Dansk)

Contents

Chapter 1  Introduction ................................................................................................ 1
  1.1 Project motivation .................................................................................................. 2
  1.2 Project vision and goals ..................................................................................... 3
  1.3 Outline of the remaining chapters ...................................................................... 3

Chapter 2  State of the art in sheet metal forming tribology ........................................ 5
  2.1 Simulative tests .................................................................................................. 5
    2.1.1 Bending Under Tension test ....................................................................... 6
    2.1.2 Draw Bead test ........................................................................................... 7
    2.1.3 Strip Reduction test .................................................................................... 8
  2.2 Environmentally benign tribo-systems in sheet metal forming ......................... 9

Chapter 3  Industrial motivation ................................................................................ 15
  3.1 Industrial case study ......................................................................................... 15
  3.2 Identification of potential tribo-systems .......................................................... 20
  3.3 Conclusion ....................................................................................................... 23

Chapter 4  A methodology for off-line testing of tribo-systems in sheet metal forming .................................................................................................................. 25
  4.1 The methodology ............................................................................................. 25
  4.2 Discussion ........................................................................................................ 27

Chapter 5  A new universal sheet tribotest rig ........................................................... 31
  5.1 Concept ............................................................................................................ 31
  5.2 Design and construction of the UST2 .............................................................. 32
    5.2.1 Axis 1 ........................................................................................................ 33
    5.2.2 Axis 2 ........................................................................................................ 34
    5.2.3 Axis 3 ........................................................................................................ 35
    5.2.4 Pumping station ........................................................................................ 35
    5.2.5 Electronic system ...................................................................................... 36
    5.2.6 Coil reel .................................................................................................... 37
    5.2.7 Lubrication system ................................................................................... 38
    5.2.8 PID controller ........................................................................................... 38
    5.2.9 LabVIEW® program ................................................................................ 42
  5.3 Simulative tests in the UST2 ............................................................................ 42
    5.3.1 Bending under tension test (BUT) ............................................................ 42
Nomenclature

\( a_1 \) [ms] acceleration time axis 1
\( b \) [mm] position axis 2
\( \mathbf{b}_{n+1} \) [mm] nodal displacement vector
\( \dot{\mathbf{b}}_{n+1} \) [mm/s] nodal point velocities at time n+1
\( \ddot{\mathbf{b}}_{n+1} \) [mm/s²] nodal point accelerations at time n+1
\( c \) [W/mK] thermal conductivity
\( CV \) [] HACD command value
\( D \) [mm/s] damping matrix
\( d_1 \) [ms] deceleration time axis 1
\( DR \) [] drawing ratio
\( E \) [MPa] elastic modulus
\( \varepsilon \) [] effective plastic strain
\( F \) [N] internal force
\( F_b \) [N] back tension force
\( g \) [] variable of integration
\( HTC \) [kW/m²K] heat transfer coefficient
\( I \) [mm⁴] second moment of area
\( IT \) [°C] initial temperature
\( K_d \) [] derivative coefficient PID
\( K_i \) [] integrative coefficient PID
\( K_p \) [] proportional coefficient PID
\( l \) [mm] sliding length
\( L \) [mm] beam length
\( m \) [] friction factor
\( M \) [kg] lumped mass matrix
\( \mu \) [] coulomb coefficient of friction

\( p \) [] penalty factor

\( P \) [N] body force and external load vector

\( P_1 \) [bar] bottom chamber pressure of axis 2

\( P_2 \) [bar] upper chamber pressure of axis 2

\( q \) [MPa] normal pressure

\( q^* \) [MPa] normal pressure at limit of proportionality in the friction model

\( R \) [mm] radius of curvature BUT tool

\( R_a \) [\( \mu \)m] roughness

\( R_d \) [mm] radius of curvature in deep drawing

\( R_{\rho 02} \) [MPa] yield stress

\( R_t \) [\( \mu \)m] roughness

\( R_1 \) [mm] radius of curvature die operation 1

\( R_2 \) [mm] radius of curvature die operation 2

\( R_3 \) [mm] radius of curvature die operation 3

\( s \) [mm/s] sliding speed

\( \sigma_b \) [MPa] back tension

\( t \) [s] time or instantaneous time

\( t_s \) [s] time step

\( \tau \) [MPa] friction stress

\( \tau_{max} \) [MPa] maximum friction stress

\( u \) [mA] HACD card output

\( v \) [mm2/s] kinematic viscosity

\( w \) [mm] beam deflection

\( x^0 \) [mm] nodal position at time 0

\( x^{n+1} \) [mm] nodal position at time \( n+1 \)

\( X \) [mm] abscissa Cartesian coordinate
$Y$ [mm] ordinate Cartesian coordinate
Chapter 1  Introduction

The introduction of new technologically advanced materials in sheet metal forming such as stainless steels, Advanced High Strength Steels (AHSS), Transformation Induced Plasticity (TRIP) steels and Twinning Induced Plasticity (TWIP) as well as the application of Aluminum alloys, and Titanium alloys implies severe tribological conditions. This is mainly due to higher normal pressure and temperature at the workpiece/tool interface. All these materials are prone to galling leading to poor surface quality of the produced parts as shown in Figure 1.1. Industry has solved the problem by using chlorinated paraffin oils, which establish efficient boundary lubrication and allows long production runs [1, 2].

![Part with no sign of galling](image1.png) ![Part with severe galling](image2.png)

**Figure 1.1.** Production example with and without galling.

It is well known that legislations regarding application of chemicals in industry are becoming more restrictive especially in Europe and Japan. European Union introduced in 2007-2008 a new law REACH [3], which aims at a high level of protection of human health and the environment from the risk posed by chemicals. This law compels industry to manage the risk and provide appropriate safety information for the users. Besides the normative restriction, some manufacturers have to fulfill higher quality standards imposed by customers as regards the residuals of hazardous lubrications on the product surface. Cleaning operations have become fairly efficient but it is not always possible to guarantee 100% removal of all chemicals. Moreover the cleaning operation is considered as a cost that does not add value to the product. Therefore industry is eager to find a solution in order to produce “clean” parts without the use of washing station. In some cases, like equipment for food industry, the demand of completely hazardous free lubrication from any component of the machine is increasing.
This becomes a challenge for industry as well as lubricant manufacturers because the development of new environmentally benign lubricants implies thorough production tests in order to investigate the limit of lubrication. In most cases there is reluctance toward production tests; especially the risk of damaging expensive tools is a primary drawback. For this reason, off-line testing of tribo-systems is preferred.

1.1 Project motivation

As mentioned before, the environmental issues posed by the application of hazardous lubricants are putting pressure to industry to replace them. The European Union funded the framework project ENLUB in 2002-2006, in which a number of European partners investigated different, alternative environmentally friendly lubricants for sheet metal forming. Unfortunately, the results showed that chlorinated paraffin oils still had outstanding tribological performance as discussed in [4]. Therefore it is used in stamping processes, where severe tribological conditions occur. However encouraging results were achieved with some more environmentally benign lubricants, giving hope to researchers and industry and increasing the knowledge about the lubrication mechanisms and the critical parameters that affect the limit of lubrication.

Many researchers have shown that improvement of tribological performance should not be limited to the lubricant but other factors play an important role such as workpiece surface topography [5-12], tool material [13-16], tool surface topography [17-20] and tool coating [21-27]. In this project, focus is directed on the combination workpiece material/tool material/lubricant and it will be referred as tribo-system.

The road toward the “chlorine free production” is still long and difficult but the direction seems to be the right one. The metal forming group at MEK-DTU is focused on increasing the knowledge about limit of lubrication in sheet metal forming and strengthen the role of off-line testing. One of the main issues of all simulative test machines is the problem to run repeated experiment at a test rate similar to production. A survey of the main tribology laboratories around the world has confirmed this lack [5, 28, 29]. The only two machines, to the knowledge of the author that can run automatically repeated tests are located at the Institute of Production Engineering and Forming Machines at the University of Darmstadt [30, 31].

Previous researches have shown that pick up builds up slowly and the exact initiation of galling is difficult to assess [32]. Concluding from the above the following requirements are identified:

- Replacement of hazardous lubrication with new more environmentally benign one
- Off-line test method for new tribo-systems able to simulate production conditions.

So far the Bending Under Tension (BUT) and Draw Bead Test (DBT) have been performed at MEK-DTU in a Universal Sheet Tribotester machine (UST1) [33]. The
UST1 was built in 1991 and it consists of two 50 kN hydraulic cylinders controlled by electromechanical valves. The machine can run a sliding length of 0-300 mm at a sliding speed of 0-150 mm/s but each test runs on a single piece of strip cut from a coil. Therefore it was decided to upgrade the laboratory with a new tribotester, which can allow running from a coil to improve simulation of production conditions, thereby increasing the confidence of industry in running production tests of successfully laboratory tested tribo-systems.

This project was born from the expert minds of five tribologists, who gather every year at the Galling seminar. This private club of galling experts takes place in Scandinavia. About thirty people from industry and academia meet for two days and discuss about challenges, possible solutions and new developments. The partners in the project represent four companies and one university: GRUNDFOS A/S (Mr. Erik Madsen), OUTOKUMPU Stainless AB (Ph.D. Erik Schedin), SSAB AB (Ph.D. Sven Erik Hörnström), UDDEHOLMS AB (M.Sc. Odd Sandberg/M.Sc. Fredric Bergström) and the Technical University of Denmark (Prof. Niels Bay). GRUNDFOS is a Danish water pump systems manufacturer, OUTOKUMPU is a global stainless steels producer, SSAB is a leading high strength steels producer and Uddeholm is a Swedish tool steels producer.

1.2 Project vision and goals

Hereafter the objectives of the present project are defined:

1. To develop a methodology for off-line evaluation of performance of existing as well as new tribo-systems in sheet metal forming.
2. To find new, environmentally benign tribo-systems for sheet metal forming of advanced high strength steels and stainless steels.

How can this be achieved? The first goal requires first of all brainstorming and collection of information on the state of the art of laboratory test methods.

The second goal follows naturally after the first one. When the methodology is developed, new, environmentally benign tribo-systems can be tested. The tribo-systems will be chosen from the available ones in the market, i.e. with no development of new tool material, tool coating, workpiece material, lubricants, etc. in the present project.

1.3 Outline of the remaining chapters

The following Chapter 2 gives a state of the art of tribology in sheet metal forming. Some simulative tests and environmentally friendly tribo-systems will be presented. Chapter 3 introduces the industrial case that was investigated during the present project. A general description of the production process as well as the progressive tool is given. The chapter introduces the reader to the industrial motivation of the project. Chapter 4 describes the new Universal Sheet Tribotester developed at DTU-MEK. A detailed description of all the features is given together with a description of the simulative tests,
Chapter 1 - Introduction

which can be performed on the rig. Chapter 5 introduces the methodology for off-line evaluation of new environmentally friendly tribo-systems in sheet metal forming that has been formulated and applied in this project. Chapter 6 describes the numerical analysis of the production process as regards the tribological conditions. The results are presented and discussed. Chapter 7 deals with the numerical analysis of BUT test and the experimental tests. The laboratory test results are presented in details and discussed. Further, a thermal analysis is presented. Chapter 9 describes the production tests. A thermal analysis and comparison with experimental results will close the chapter. Chapter 10 presents conclusions and proposal for future work.
Chapter 2  State of the art in sheet metal forming tribology

This chapter deals with the state of the art in sheet metal forming tribology. First an introduction on the simulative tests in sheet metal forming is presented. The focus is then directed toward the main laboratory tests developed at DTU-MEK. A general description of the selected tests is following reported. After that a brief description of the main advances in new tribo-systems for sheet metal forming is presented.

2.1  Simulative tests

Whenever a new technology, for example a new lubricant or new tool material is developed, the performance can be investigated running a laboratory test where the production conditions are simulated. In metal forming, comprehensive reviews of tribological tests have been given by refs [34-39]. Bay et al. proposed to organize tribological test methods in the following two categories:

- process tests
- simulative tests

where process tests are characterized as tests applying typical metal forming operations without changing the basic of process kinematics, whereas simulative tests are tests modeling the tribological conditions in metal forming processes with the attempt to study friction and/or lubrication in a specially controlled way.

Figure 2.1 shows how a sheet metal forming process can be simulated with different tests. In fact, a sheet forming production process like cup drawing has different contact condition due to different: sliding velocity, contact pressure, interface temperature and surface expansion.

At the Department of Mechanical Engineering (MEK), Technical University of Denmark (DTU), Bay et al. have developed tests Nos. 1-6 [33, 40-42]. Besides these simulative tests, the Danish laboratory has developed three process tests: Deep Drawing Test (DDT), PUnching Test (PUT) and IRoning Test (IRT) [43-46].

After a thorough investigation of the 6 simulative tests, DTU-MEK has decided to focus on three of them:

- Bending Under Tension test (BUT) simulating the condition at the die curvature. It represents mild tribological conditions with medium normal pressure, small surface expansion and low interface temperature.
- Draw Bead test (DBT) representing medium tribological conditions with medium-to-high normal pressure, small surface expansion, and medium interface temperature.
• Strip Reduction test (SRT) simulating the ironing process. It represents severe tribological conditions with high normal pressure, medium surface expansion, and high interface temperature.

![Diagram of simulative tests for sheet metal forming](image)

**Figure 2.1.** Schematic illustration of simulative tests for sheet metal forming [4].

### 2.1.1 Bending Under Tension test

The BUT test is a simulative test, where a strip is bended and slid around a tool pin. Figure 2.2 shows an outline of the test. Back tension is applied at the end of the strip in order to increase the normal pressure at the interface tool/workpiece. The BUT test has a long story of contributions from many research laboratory around the world [47-62]. The first devices were simple machines, where the drawback was that two subsequent tests were needed in order to calculate the friction. The first test was run with a fixed tool pin and the second with a freely rotating pin. Then the pulling forces were subtracted in order to extract the friction force. Weinmann [62] developed a special design where front and back tension forces can be acquired directly, but due to the contributions from bending and unbending friction could still not be measured directly.

Andreasen et al. [40] developed an improved design, measuring front and back tension as in the Weinmann test, but further allowing measurement of the torque directly on the tool pin. They showed how an increase in torque trend can be related to galling. When the limit of lubrication is reached, pick-up builds up quickly on the tool surface resulting in an increasing torque. The test is specially designed for studying the influence of critical parameters on friction and limits of lubrication such as tool
material, radii and surface topography, tool rest temperature, drawing speed, back tension, lubricants, strip material and dimensions.

![Schematic view of the BUT test.](image)

Figure 2.2. Schematic view of the BUT test.

### 2.1.2 Draw Bead test

The DBT test (see Figure 2.3) is a simulative test where a strip is bent around three tool pins. A back tension can be applied. The DBT test has been used to investigate friction conditions of the draw bead in deep drawing. DBT test devices have been built in different laboratories and evaluations of lubricants in sheet metal forming have been done [35, 49, 55, 63-69]. Similarly to the BUT test, a major drawback in all these studies is that determination of friction is not direct but requires repeated measurements of the drawing force, with and without relative sliding between the draw beads and the sheet material in order to compensate for bending and unbending forces. This implies the requirements for two tests, one with a fixed draw bead tool and the other with a freely rotating one. This approach has unfortunately large uncertainty due to scatter [69].

Olsson et al. [41] have developed a new design, which measures the friction force acting on the tool radius directly by a built in, piezoelectric torque transducer. This technique results in a very sensitive measurement of friction, which furthermore enables recording of lubricant film breakdown as a function of the drawing distance.
2.1.3 Strip Reduction test

The SRT test is used to simulate the ironing process. The thickness of a strip, usually around 1-2 mm, is reduced by a tool as illustrated in Figure 2.4. A number of researchers have investigated the limit of lubrication in ironing process applying this test [34, 35, 70-75]. Generally the SRT tool geometry resembles the production one or at least it has wedge shape with an attacking angle similar to the production die. This design has the drawback, that the polishing operation is time consuming and skilled personnel are required.

Bay et al. [4] have developed a new design, where the tool is a cylinder with squared ends. These impede the rotation of the pin during the test and allow using four test surfaces with the same tool. Moreover the cylindrical shape makes polishing operation easier. The disadvantage is that the polishing texture has the same direction as the sliding length and this could affect the hydrodynamic lubrication effects [76].
2.2 Environmentally benign tribo-systems in sheet metal forming

The tribological severe conditions at the tool/workpiece surface lead often to the formation of localized cold welded workpiece material, pick-up, on the tool surface [77]. Depending on the amount of pick-up, galling occurs generating the typical scratched workpiece surface, which is considered of a poor quality. The review in [78] describes the development and ongoing research on new environmentally benign tribo-systems in metal forming. As mentioned before the application of workpiece materials prone to galling pose a challenge for the industry.

In many cases, focus is directed on replacing the hazardous lubricants, which is typically oil based chloroparaffin. These types of hazardous lubricants are mainly used in stamping of stainless steels and other tribologically difficult materials. One solution is the application of dry film lubrication. Dry film lubricants are solid film, which are deposited on the sheet surface. They are divided in two categories:

- water-soluble dry film lubricants
- water-free dry film lubricants.

Water-soluble dry film lubricants are applied at the rolling mill in the amount of 0.5-1.5 g/m². They form a uniform film on the sheet protecting the material from corrosion. The main disadvantage is the incompatibility with most adhesives used in automotive industry [79]. The water-free dry film lubricants are also applied at the rolling mill and they have shown better drawing performance compared with oil-based lubricants [80, 81]. They are preferred to water-soluble types because they are compatible with almost all commonly used adhesives applied in the automotive industry. The overall advantages of dry film lubricants can be summarize in the following points:

1. reduced requirements for recycling and disposal
2. uniform coating thickness
3. reduced amount of lubricant compared with oil-based lubricants
4. may eliminate washing operations
5. compatibility with assembly operations
6. more environmentally benign than the petroleum based

Chandrasekharan et al. [81] have performed several deep drawing tests on dry film lubricants on mild steel AKDQ 1008. The results showed that dry film was one of the best compared with phosphate coating lubrications, two types of emulsions and a solid lubricant. Pfestorf et al. [82] have tested polymer dry film lubricants on aluminum sheets. The results showed good performance of water-free lubricants compared with mineral oil. Lubrication seems to be independent on the surface roughness and amount of lubricant. Jaworsky et al. [83] have tested polymer dry film on steel sheet using ironing test. They found that increasing the die angle the film tends to be shaved off. A maximum angle of 6 degree is suggested. On the other hand, it was seen that increasing the angle the friction force decreases. The friction was also found to be dependent from
the reduction. Selles et al. [84] have tested a three layered polymer film in ironing process. Such a layer consists of a “tie” layer bonded to the steel sheet, a “top” layer at the exterior and a “bulk” layer between these two polymers. This system allows improving performance of each layer as regards bonding, friction and ironability. In Japan, Imazu et al. [85] have successfully introduced polyester film in ironing process of aluminum cans production.

The main disadvantage of dry film lubricants is the poor performance in multistage deep drawing and ironing operations. This is due to the fact that the layer is removed in the first operation. In this case the research has gone toward the development of chlorine-free oil based lubricants. Bay et al [4] have tested different oils using Bending Under Tension test. The results show that vegetable oil based on fatty acid methyl ester from Pinifer gives constant, low friction on a sliding length of 300 mm. This type of lubricant is biodegradable and environmentally benign. In the same work, a water based polymer coating was tested, which also gave good results. In ironing process, combined laboratory and production tests showed that mineral oil CXF125 from Rhenus Lub can prevent galling when the punch is coated with TiAlN. The results showed that the production speed had a significant influence on the limit of lubrication. This is due to the fast increase of the temperature at the tool/workpiece interface [32].

Rao et al. [86] have tested boric acid H$_2$BO$_3$ as lubricant for aluminum. The acid forms a strong, chemically bonded film on the sheet surface. This was proved to be more environmentally benign and easy to remove. Mori et al. [87] have developed an electrochemical coating technique, where an artificial layer of oxide is created on titanium sheet. Tests in a multistage progressive tool were successfully performed.

Besides the recent developments on new lubricants the tribological performances can be increased applying the following technologies:

- anti-seize tool materials
- anti-seize tool surface treatments
- structured workpiece surfaces
- structured tool surfaces.

Azushima et al. [88] have tested different tool materials in cold rolling. The investigation showed that a finer distribution of carbides in the tool matrix gives higher reduction of the sheet without galling occurrence. The technological development around tool materials has enlightened the great tribological properties of powder metallurgical nitrogen alloyed tool steel. Uddeholm has recently introduced a nitrogen alloyed powder metallurgy tool steel Vancron® 40 (hereafter called V40), which has shown superior anti-galling properties compared with conventional tool steels [89, 90]. Figure 2.5 shows the microstructures of four different cold work tool steels. Laboratory tests showed that the V40 fine structure enhances the lubrication mechanisms resulting in a longer production run [91, 92]. There are two hypotheses, which could explain the better performances of V40 respect to the other steels. The first one is proposed by Bay
et al. [78] and is based on mechanical mechanism activated by the special surface
topography. When the tool surface is polished down to about $Ra = 0.05 \mu m$ the nitrides
sticks out like rounded iceberg tips. The hard phase has no affinity to the workpiece
material thus preventing adhesion and the intermediate matrix material is slightly
lowered from the hard phase asperities (see Figure 2.6) enabling pockets of lubricants to
be trapped in the surface. The second hypothesis, proposed by Hatami et al. [14],
explains the excellent lubricious properties thanks to a chemical mechanism that take
place on the tool surface. The Vanadium Nitrides (VN) can generate Magnéli types of
oxides $V_2O_5$ when heated up. These oxides protect the matrix surface and have low
friction [93-95]. When the oxides are removed the VN come in contact with the
workpiece material generating heat and producing more Magnéli oxides. This self-
sustaining mechanism seems to be the key point to why the V40 may run longer
production than other tool steels.

Kataoka et al. [15] have tested ceramic tool materials in deep drawing of Ti, Al, mild
steel and Cu in dry conditions and they found interesting results. The ceramic seems to
perform as good as conventional tool steel when lubrication is applied in the latter. The
drawback is the challenging polishing operation of these materials [96].

![Figure 2.5. SEM pictures (back scattered electron mode, atomic number contrast) of microstructure in hardened and tempered conditions from Uddeholm, 60-62 HRC, for a) Vancron® 40, b) Vanadis® 6, c) Vanadis® 23 and d) AISI D2 [91].](image1)

![Figure 2.6. SEM picture (secondary electron mode) of Vancron® 40 showing the nitrides on the surface [78].](image2)
In sheet metal forming anti-seizure tool surface treatments are mainly extra layers of hard materials deposited on the working tool surface. They are becoming popular mainly due to the combination of excellent tribological performances, fast coating process and relatively low price. Some of the most common coatings are single layer PVD or CVD coated [97]. The thickness is in the order of microns, which does not affect dimensions of the tool. This means that it is not necessary to remove extra material on the tool surface. Kim et al [16] have tested PVD coatings with CrN, XNP and TiCN in a combined strip drawing and ironing test of uncoated as well as galvanized AHSS and found that TiCN showed the best efficiency to prevent galling. Klocke et al. [24] have replaced chlorinated paraffin oil using a new graded Zirconium Carbide ZrC₈ coating with a biodegradable rape oil testing stainless steel EN 1.4301. Nakamura et al [98] have tested Diamond Like Carbon (DLC) coating on high speed tool steel AISI M2 in lubricated forming of titanium sheets. The results showed low friction and no galling using a simulative tribo test. DLC and WC/C coatings have been also tested in production and interesting results were achieved [27, 99, 100]. The main drawback of DLC coating is the fragility of the bonding between coating and tool material. A possible solution to this problem can be increasing the substrate surface roughness and introduction of interface layers [101].

The advantages of structured workpiece surfaces have been known for years [102-106]. The main mechanism activated by these surfaces is the entrapment of lubricant in small pockets, which lowers the friction and separates the tool from the workpiece. This means that in order to activate the mechanism a liquid lubricant is required. Another drawback is the decreased efficiency of the mechanism when this technology is applied to multistage processes, since the workpiece surface is leveled in the first operations. The pockets are eventually vanishing. The degree of pocket-shrinking depends on the amount of deformation and normal pressure the surface undergoes.

Structured tool surfaces in sheet metal forming have been applied mainly to rolling operations. Usually the surface is prepared using one of the following methods: Electro Discharged Texture (EDT) [107], Shot Blasting Texture (SBT) and Electron Beam Texture (EBT) [108]. One promising innovative method is the Electro Chromium Depositing (EDC). A chromium coating is deposited on the rolls surface, which acquires a special topography consisting of small, hard, hemispherical particles [109-111]. This structure produces a uniform distribution of lubricant pockets on the sheet. A new interesting development on multifunctional surfaces has emerged in the past few years. Multifunctional surfaces are tailored, structured tool surfaces, which facilitate the entrapment and escape of lubricant. Costa et al. [112] performed strip drawing tests using stationary dies, where three different types of structured surface were investigated: circular pockets, grooves parallel to the sliding direction and grooves perpendicular to the sliding direction. The perpendicular grooves generated a drawing force half in magnitude compared with the others. Tests on polished, non-textured dies were also compared showing higher force. Godi [113] has characterized and tested a new type of multifunctional surfaces in laboratory as well as production tests. BUT
laboratory tests on stainless steel showed promising results. Figure 2.7 shows how the MUFU surface tested in BUT test appears. Production tests on deep drawing of stainless steel cups resulted on lower force compared with TiAlN PVD coated die.

**Figure 2.7.** MUFU profile and areal topographies on the radii of BUT tool [113].
Chapter 3  Industrial motivation

This chapter deals with the presentation of the production process, which has been chosen for the investigation. The tool and the product are described as “state of the art” of the process at Grundfos. At the time the PhD project started in 2010, the production runs with chlorinated paraffin oil as lubricant. Grundfos expressed the goal of substituting the hazardous lubricant with a more environmentally friendly one limiting the number of production tests as much as possible. The main parameters of the process are then presented. In the last part of the chapter new tribo-systems are proposed for testing.

3.1  Industrial case study

In agreement with all the partners in the project, a product was selected at Grundfos production. It is a small cup (code name EL-TUBE) produced in a progressive tool. Figure 3.1 shows the sequence of operations the part undergoes together with the final component. The workpiece material is austenitic stainless steel EN 1.4301. The strip section is 1x62.5 mm. The cup is formed starting from a blank of ø50 mm as shown in operation 0. The main shape of the cup is formed in three consecutive steps: first deep drawing and then two subsequent redrawing operations. The first operation 1, is performed with a drawing ratio $DR = 1.8$. Operation 2 has a $DR = 1.32$ and operation 3 has $DR = 1.28$.

Figure 3.1. Progressive steps of EL-TUBE component and final product.
Figure 3.2 shows the cross sections of the blank and the three consecutive operations. Figure 3.3 shows an outline of the forming operations. The progressive tool has a bottom plate, a medium plate and a top plate. The bottom plate is mounted on press the table and top plate on the upper ram, whereas the medium plate is connected to the top one through gas springs. When the ram moves, the top and medium plate move downwards until operation 2 and 3 are completed. At this point the medium plate has reached its bottom position and the top plate continues to move downwards performing operation 1. The dies and punches of operation 1, 2 and 3 are made of powder metallurgical tool steel Vanadis® 6 from Uddeholm and coated with TiAlN.

![Figure 3.2](image1)

**Figure 3.2.** Overlying sections of EL-TUBE component. The four sections represent the starting blank and the three consecutive forming operations [114].

![Figure 3.3](image2)

**Figure 3.3.** EL-TUBE tool scheme of the three operations: a) tool open, b) the medium plate closes forming the workpiece in operation 2 and 3, c) the top plate closes forming operation 1 [114].

The bottom plate of the progressive tool is shown in Figure 3.4, whereas the top and medium plates are shown in Figure 3.5. The tools for the three operations are indicated by the arrows. Punch 1 is not visible because it is retracted between the top and medium
plates. The strip is fed from right to left. The process currently applies chlorinated paraffin oil because other chlorine free lubricants have failed so far. Operation three has shown to be the most critical, where galling occurs if the lubrication breaks down. The current annual production is around 100,000 parts. The production rate is 40 parts/min. The three dies in operation 1, 2 and 3 have three different radii of curvature: $R_1 = 3.5$ mm, $R_2 = 2.5$ mm and $R_3 = 1.5$ mm. The lubricant is applied by nozzles on the strip at the entrance of the tool. An extra supply station before operation 1 applies additional amount of lubricant on both sides of the strip. In operations 2 and 3 channels in the dies ensure further lubrication by pumping extra amount in each stroke (see Figure 3.6).

![Figure 3.4](image)

**Figure 3.4.** Bottom part of the EL-TUBE progressive tool. The strip feeds from right to left. The three dies indicated with numbers correspond to the three operations forming the cup.
Figure 3.5. Top part of the EL-TUBE progressive tool. The strip feeds from right to left. The three punches indicated with numbers correspond to the three operations forming the cup.

Figure 3.6. Die nr 2. The red circle indicates the hole through which the lubricant is pumped inside the die.

It is thus clear that the tool receives a fairly high amount of lubricant to avoid pick-up formation. The tool is mounted in a 250 ton mechanical press, which has a drag crank regulating the tool speed. The drag crank modifies the speed-displacement curve of the press reducing the speed when the upper tool is close to the bottom dead center. Figure 3.7 shows the comparison of the ram speed between a normal eccentric press and the drag crank press, which is used at the Grundfos production. This principle has the advantage of decreasing the tool speed when forming the part and accelerating during the backstroke. The top plate has a total displacement of 102 mm as shown in the graph.
and the production rate is set constant to 40 parts/min. Looking at the three configurations in Figure 3.3, position a) corresponds to point (102,0), b) corresponds to point (20,-100) and c) corresponds to point (0,0) in Figure 3.7. Negative velocity means that the ram is moving downward. When the tool closes, operation 3 is the first taking place. Acquiring the force signal and position of punch 3 it was observed that the contact between workpiece and die 3 starts about at 40 mm above the bottom dead center. Since the cup height is about 20 mm, operation 3 takes place between 40 and 20 mm height from the bottom dead center. Reading the graph in Figure 3.7, one can see that punch 3 decelerates from about 150 mm/s to 100 mm/s. Considering the height of the cup equal to 20 mm (this is the sliding length in operation 3 $l = 20$ mm), the forming time is then about 166 ms.

As earlier mentioned, operation 3 is the most critical one, tribologically speaking. The specifications of the component define, among others, a circularity tolerance of the inner diameter. On the inner surface there is also a scratch-free requirement. These two specifications identify the inner surface as the critical part of the component. Experience from Grundfos production shows that lubrication fails first on the outer workpiece surface (see Figure 3.8), which is in contact with die 3. The chances of galling occurring on the inner surface are very low because the relative sliding and the normal pressure between punch and workpiece are limited.

So far, it seems like there might only be a minor problem having massive pick-up and galling on the outer surface even though it is true that galling could affect the circularity.

Figure 3.7. Ram speed as a function of displacement.
tolerance. The hidden problem in this case is the safety of the tool. Considering that the clearance between punch and die is fairly small (10% of the strip thickness) and that pick-up is a localized phenomenon, it could introduce a non-concentric movement of the punch as respect to the die. This would lead to a deflection of the punch stem, which might cause fracture. This is a critical factor as regards the tool life and unfortunately it is not possible to estimate a critical amount of galling, which leads to tool damage. One can assume that a critical amount of pick-up on the die surface is equal to the clearance between die and punch. However, it is not easy precisely to monitor pick-up formation during production running since its slow growth depends on many factors. This means that there are no quantitative measurements of the galling in EL-TUBE production. For this process the operator has the responsibility of assessing the amount of galling by visual inspection. For example, the specimen in Figure 3.8 presents clearly a critical amount of galling. The operator considered this amount too dangerous for the tool. Therefore, the part is discarded and production is stopped to polish the tool.

![Figure 3.8. EL-TUBE component with galling.](image)

### 3.2 Identification of potential tribo-systems

At this point the potential tribo-system candidates can be identified. Since three of the project partners are producers of workpiece material and tool steels, the choice of workpiece materials and tool materials was fairly straightforward. The partners proposed some materials they were interested in analyzing and then the list was narrowed to few candidates. It was planned to investigate four different workpiece materials:

- Dual phase high strength steel Docol® DP 800 from SSAB. $R_{p0.2} = 620$ MPa.
• Fully martensitic electro galvanized ultra-high strength steel Docol® 1200 MZE from SSAB. $R_{p02} = 950$ MPa.
• Austenitic stainless steel EN 1.4301, surface 2B from OUTOKUMPU. $R_{p02} = 220$ MPa.
• Lean duplex stainless steel EN 1.4162 (LDX 2101®), surface 2E from OUTOKUMPU. $R_{p02} = 530$ MPa.

DP 800 and 1200 MZE are cold rolled Advanced High Strength Steels (AHSSs) mainly used in automotive industry to produce part of the car body and seats. The DP 800 coils are delivered pre-lubricated with low viscosity anticorrosion oil (viscosity $\nu = 30$ mm$^2$/s at 40°C). The 1200 MZE has an electro galvanized zinc layer of about 2.5–10 µm thickness [115]. Table 3.1 shows the composition of the AHSSs.

EN 1.4301 (AISI 304) is an austenitic stainless steel grade commonly used for stainless steel products. Typical applications are pipes and heat exchangers. The lean duplex EN 1.4162 is characterized by higher strength than the austenitic grade and a similar corrosion resistance. Typical applications are domestic heaters and pipes. Table 3.2 shows the composition of the stainless steels.

The tool materials investigated were:
• Powder metallurgical tool steel Vanadis® 4 Extra (V4E). Hardness 62 HRC.
• Powder metallurgical tool steel Vancron® 40 (V40). Hardness 63 HRC.

Table 3.3 shows the composition of the tool materials. Vancron® 40 is a nitrided powder metallurgical tool steel with excellent anti-galling/adhesive wear properties described in the introduction chapter of this thesis. The surface topography after polishing is shown in Figure 2.6.

<table>
<thead>
<tr>
<th>Material</th>
<th>C [%]</th>
<th>Si [%]</th>
<th>Mn [%]</th>
<th>P [%]</th>
<th>Al [%]</th>
<th>Nb [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP 800</td>
<td>0.128</td>
<td>0.18</td>
<td>1.55</td>
<td>0.013</td>
<td>0.042</td>
<td>0.015</td>
</tr>
<tr>
<td>1200 MZE</td>
<td>0.11</td>
<td>0.2</td>
<td>1.4</td>
<td>0.01</td>
<td>0.04</td>
<td>0.015</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>C [%]</th>
<th>Cr [%]</th>
<th>Ni [%]</th>
<th>Mo [%]</th>
<th>N [%]</th>
<th>Mn [%]</th>
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</thead>
<tbody>
<tr>
<td>EN 1.4301</td>
<td>0.04</td>
<td>18.1</td>
<td>8.1</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>EN 1.4162</td>
<td>0.03</td>
<td>21</td>
<td>1.5</td>
<td>0.3</td>
<td>0.22</td>
<td>5</td>
</tr>
</tbody>
</table>
Chapter 3 - Industrial motivation

Table 3.3. Chemical composition of tool steel materials in % weight.

<table>
<thead>
<tr>
<th>Material</th>
<th>C [%]</th>
<th>Si [%]</th>
<th>Mn [%]</th>
<th>Cr [%]</th>
<th>Mo [%]</th>
<th>V [%]</th>
<th>W [%]</th>
<th>N [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vanadis® 4 Extra</td>
<td>1.4</td>
<td>0.4</td>
<td>0.4</td>
<td>4.7</td>
<td>3.5</td>
<td>3.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Vancron® 40</td>
<td>1.1</td>
<td>0.5</td>
<td>0.4</td>
<td>4.5</td>
<td>3.2</td>
<td>8.5</td>
<td>3.7</td>
<td>1.8</td>
</tr>
</tbody>
</table>

The identification of possible lubricant was done based on the experience of the partners in collaboration with selected lubricant manufacturers. The following lubricants were chosen:

- Anticorit PL 3802-39s from FUCHS Europe (tested with DP 800 and 1200 MZE materials). Thixotropic chlorine free oil with anticorrosive properties. Viscosity \( \nu = 60 \text{ mm}^2/\text{s} \) at 40\(^\circ\)C.
- Anticorit PLS 100 T from FUCHS Europe (tested with DP 800 and 1200 MZE materials). Thixotropic chlorine free oil with anticorrosive properties. Viscosity \( \nu = 100 \text{ mm}^2/\text{s} \) at 40\(^\circ\)C.
- Rhenus SU 166 A from Rhenus lub (tested with EN 1.4301 and EN 1.4162 materials). Base mineral chlorine free oil with additives. Viscosity \( \nu = 160 \text{ mm}^2/\text{s} \) at 40\(^\circ\)C.

The Rhenus oil has a higher viscosity than the Fuchs oils. Grundfos had already performed preliminary tests with it and promising results were achieved. The focus is now directed on defining the working window of the lubricant and understanding how it works when combined with different tool and workpiece materials. SSAB has more focus on lubricants with anticorrosive properties, which can work as forming lubricant at the same time. In fact AHSSs are generally delivered pre-lubricated to avoid corrosion. The film applied at the mill is very thin and the lubricant viscosity is typically low, which makes it unsuitable for most of the sheet metal forming processes used in automotive industry (this is one of the biggest market for AHSS).

Table 3.4 shows the experiment matrix. These tribo-systems will be investigated in the BUT test. As mentioned before the two Anticorit oils are tested only with the two AHSSs, whereas the Rhenus oil is tested only with the two stainless steels. Each combination of workpiece material and lubricant was tested with the two tool materials: Vanadis® 4 Extra and Vancron® 40.
Table 3.4. Table of experiments. V4E = Vanadis® 4 Extra; V40 = Vancron® 40.

<table>
<thead>
<tr>
<th>Lubricants</th>
<th>Workpiece materials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V4E</td>
</tr>
<tr>
<td>Anticorit PL 3802-39s</td>
<td>DP 800</td>
</tr>
<tr>
<td>Anticorit PLS 100 T</td>
<td>V4E</td>
</tr>
<tr>
<td>Rhenus SU 166 A</td>
<td>V4E</td>
</tr>
</tbody>
</table>

3.3 Conclusion

The industry has the challenge to substitute the hazardous lubricants normally applied with a more environmentally friendly one due to restrictive legislation and possible sustainability strategy, which companies adopt. The process described in this chapter is a clear example, where the chlorinated paraffin oil can and has to be substituted with a more environmentally tribo-system. The present work focuses on finding a solution. The following chapter will describe the philosophy adopted to tackle the problem. After that the production process will be analyzed numerically in order to identify the critical tribo-parameters.
This chapter deals with the methodology for off-line testing of tribo-systems in sheet metal forming. The methodology is first presented and described. A discussion is then presented where some aspects, connected to the methodology and its application, are discussed.

4.1 The methodology

How should a tribo-system be tested? What is the right procedure to introduce a new tribo-system in an existing production line? Until now the procedures has been based on costly “trial and error”. The present work proposes a systematic approach instead. Figure 4.1 shows the methodology starting from the top left corner. The point of origin is the product design with its geometrical and mechanical properties. Information such as workpiece material, initial shape of the blank and final shape of the product is known. From here the production platform is then defined and some process parameters are given such as sliding speed, production rate, tool geometry etc... After all possible information is obtained, a FE analysis can be performed in order to investigate the tribological parameters such as normal pressure, contact area, tool/workpiece interface temperature (even though this requires validation), etc. When the production process is fully analyzed and all possible parameters are acquired, a suitable laboratory test is chosen according to the type of deformation the product undergoes. A FE analysis can then be performed in order to investigate the tribological parameters in the laboratory test. This step has the main goals of verifying that the tribological conditions are the same as in production and, depending on the laboratory test, calibrating the simulative test equipment. At this point a planning of the test campaign is done and a new tribo-system is chosen. A first laboratory screening test is then run, usually setting the same production conditions such as production rate, sliding length, sliding speed, etc. This gives immediately an understanding of the potential of the tribo-system. The test may give promising results or poor results. In case of poor results, the test procedure is stopped and one of the following two routes is chosen: either a new tribo-system is selected or, if possible, the production platform and/or the geometry of the component are changed in order to vary the tribological conditions. In case the screening test gives good results, a more thorough and complete testing campaign is performed in order to define the working window of the tribo-system as regards the critical tribo-parameters. As described before, two possible results are possible: either the results are satisfactory or poor. The latter can happen either when the screening tests gave promising results but the wider test campaign enlightens a very narrow working window around the production conditions or when the production conditions are very close to the tribo-system’s limit of lubrication, which might not be acceptable in production.
As shown in the graph, the two paths, in case of poor results, are the same as explained above. In case of satisfactory results the user can, with confidence of success, carry out production tests. In principle the production results should give positive response if the tribological conditions were correctly simulated in the laboratory test. However it is not
always possible to establish exactly the same conditions and failure of the lubrication can occur. Again, the test should be stopped and either a new tribo-system could be chosen or a modification of the component geometry/production platform could be introduced. On the contrary if the production tests are positive the old tribo-system has been successfully replaced. This methodology is here presented to give a clear indication of how to proceed when investigating whether a new tribo-system can replace an old one or not. The methodology can be applied also to a new product design, which has to be produced in the future. In this case some information might be missing such as the exact process outline, which then will have to be proposed based on experience. This gives however more flexibility because the changes in the tool or workpiece geometry will have a lower economic impact.

One should keep in mind that the flow chart in Figure 4.1 is not a rigid path the user has to follow. In some cases modification of the product or the tool geometry can be introduced before the screening tests. For example the FE analysis of the laboratory test might show that the production conditions are too severe and impossible to emulate in the lab. A very nice example will be presented later in this thesis, which explains how a designer can improve the production process already after a first, thorough analysis of the numerical results.

4.2 Discussion

So far the methodology does not explain what a satisfactory result is. In fact one of the main unknown regarding galling is the definition of critical amount of pick-up or as the author would say, “The galling criterion”. Figure 4.2 shows pick-up on Vanadis® 4 Extra tool material (from Uddeholm), testing DP 800 with BUT test. Is this amount acceptable in production? If the final product has a defined surface requirement, such as a limit on the maximum roughness, it is quite easy to establish a galling criterion. In this case a quantitative parameter, the roughness, can be measured leaving no doubt on whether a component should be discarded or not.

**Figure 4.2.** Pick-up (DP 800) on Vancron® 40 tool material.
It is much more difficult when there are no quantitative parameters defining a limit. In some cases galling is not acceptable because there is a risk of damaging the tool but the exact amount that leads to fracture is difficult to assess. Most of the time, the evaluation of galling and pick-up is a responsibility of the operator, who checks production samples and assess the risk for the tool. Figure 4.3 shows part of a tool, which fractured due to galling. The punch in Figure 4.3a slides inside the sleeve and pushes the workpiece (the small cup shown in Figure 4.3b) down inside a die where the collar is shaped.

![Figure 4.3.](image)

Figure 4.3. a) punch and sleeve. The sleeve has fracture of the top collar due to asymmetric load; b) galling on specimen, which caused the asymmetric load.

The punch must be coaxial with the workpiece and the die. Galling occurred on the component and this generated a side load on the punch, which produced a stress state on the sleeve. The amount of galling reached a dimension to which the induced stress in the sleeve, which caused fracture at the top. This is a clear example on what galling might cause, not only to the component and tool locally but also to other parts of the tool. It emphasizes the importance to define a limit. In this operation galling has never been an issue because the tribological conditions, at this stage, are mild. Galling was evidently initiated in the previous operation and it grew to a critical volume, which initiated pick-up in the successive operation.

An important parameter, which affects the lifetime of a tool, is wear. Wear affects negatively the performance of the lubrication since it mainly changes the surface texture of the tool. Wear is not investigated in this project but it should be remembered that eventually it affects the characterization of the limit of lubrication. Looking at a tribo-system from the industry point of view there is another factor, which plays an important role in defining the galling criterion: the number of strokes at which the film lubricant breakdown occurs. A poor tribo-system could technically be considered good if it only fails at a large number of produced parts. Of course every progressive tool has different
annual production target and it should be considered how many parts a tool should be able to produce per series as well as in its total life. As said before a tool cannot produce an infinite number of parts since wear limits the lifetime. It is therefore important to analyze the limit of lubrication before wear becomes the predominant cause of failure.

Previously it was mentioned that a working window of the tribo-system should be identified. How can that be obtained? First of all the parameters governing the process have to be defined. The deep drawing process is taken as an example. Tribologically speaking, there is a series of process parameters that affect the performance of the deep drawing. The mains are: radius of curvature, sliding length (height of the product), idle time between strokes, sliding speed, shape of the blank and blank holder force. The temperature is not included in the list because it is considered a dependent parameter. The radius of curvature affects the contact area: a big radius means a large contact area, which leads to a large frictional heat contribution. On the other hand a small radius means a small contact area, which increases the normal pressure; therefore a thinner lubricant film separates the surfaces. As an advantage the thermal exchange is lower as well as the frictional heat generated. This means that an optimum radius of curvature may exist. Regarding the sliding length, large values increases the frictional heat generated and consequently increase the temperature. This means that a short sliding length is preferable. The production rate can be split in two components: the sliding speed and the idle time between two subsequent strokes. The sliding speed affects the heat exchanged between workpiece and die. The lower the speed the bigger the amount of heat exchanged between workpiece and die but also into the rest of the tool (dissipated heat). Therefore a considerable amount of heat will be taken away from the contact interface. Besides that the sliding speed affects the possible hydrodynamic effect. High speed enhances this effect lowering the friction and establishing an effective separation of the die and workpiece with a thin lubricant film. It is expected that an optimum sliding speed exists. The idle time affects mainly the amount of heat dissipated toward the environment and the rest of the tool. The longer the idle time the better because the tool cools down to a safe “initial temperature” and it lowers the steady state temperature of the process. Of course it is not desirable from an economical point of view and the production planner would like to reduce the idle time as much as possible.

Figure 4.4 shows a schematic outline of limit of lubrication in deep drawing for a tribo-system. In this case three process parameters are shown: sliding speed, die radius and production rate. The graph defines a working zone, where the outer surface is the limit of lubrication. This is just a schematic representation and it does not mean that in a general application the limit is well defined as it is indicated here. Now the question is: how can this be used? The graph is obtained running a series of laboratory tests, varying the three parameters. When a galling criterion is defined, the test results will characterize the limit of lubrication and the boundary of the working zone. If the production conditions are inserted, they define a specific point in the graph. The point can lay inside, outside or on the outer surface of the working volume. In the first case
the tribo-system is defined as good because the production conditions are far from the limit. Therefore the tribo-system should work fine in production. In the second case the tribo-system is defined as poor because the production represents a too severe condition for the tribo-system. In the third case the tribo-system is defined as questionable. This means that it lies very close to the limit. Such a condition can be unacceptable in production and a modification of the platform might be introduced to move the production condition inside the working volume.

![Diagram](image)

**Figure 4.4.** Schematic outline of limit of lubrication for a tribo-system in deep drawing. The green point identifies the production conditions for a good tribo-system.
Chapter 5 A new universal sheet tribotest rig

In this chapter the new Universal Sheet Tribotester rig is described. The description starts from the concept idea and specifications of requirements of the new machine. The main features, such as axes, hydraulic system and electronic system are then described. A section is dedicated to the PID logic controller, where the tuning procedure is presented. The last section of the chapter describes, which simulative tests can be performed in the new test rig.

5.1 Concept

The Universal Sheet Tribotester (UST1) developed in 1991 at MEK-DTU has two hydraulic axes with a max pulling force of 50 kN (see Figure 5.1). These are controlled by electromechanical valves. The maximum sliding length is 300 mm and maximum sliding speed 150 mm/s. The main disadvantage of the equipment is the lack of possible automatically repeated runs in order to emulate a progressive tool. In fact, production tests performed by Friis [32] showed that galling is the result of a slow building up of pick up. This can only be simulated when repeated tests are run in the laboratory test at the production rate and with the same tribological conditions. Besides that, there is a need to better control sliding speed and sliding length. This has led to the decision to develop a completely new and more sophisticated universal tribotester.

Figure 5.1. First Universal Sheet Tribotester (UST1).
The requirements for the new Universal Sheet Tribotester (UST2) are:

- compatibility to mount old BUT equipment
- compatibility to mount old DBT equipment
- possibility to run SRT
- maximum pulling force of at least 50 kN
- accurate position and speed control
- force measurement on every axis
- possibility to implement new simulative tests
- automatic feeding of the strip from a coil
- possibility to fully control movements and acquire forces, position and speed by LabVIEW program
- automatic lubrication system
- safety feature according to local regulation
- possibility to run in manual mode
- automatic cutting of the strip at the machine exit

5.2 Design and construction of the UST2

The new machine was designed by IPU who are a company specialized in innovative press design. The first concept had electric servomotors to move the axes. This allows precise control of position and speed but a continuous feedback loop of the forces is required in order to avoid damage of the motors. Moreover the size of a motor that delivers a 50 kN pulling force is very large and it is expensive. It was then decided to use hydraulic power for the axes movement. The UST2 design (see Figure 5.2) can be split in two systems: mechanic and hydraulic. The mechanical part consists of a robust frame and three hydraulic axes.

Figure 5.2. New Universal Sheet Tribotester (UST2).
The frame is constructed by tubular elements in structural steel welded together. The axes are mounted on thick, rigid plates, which are bolted to the frame. The hydraulic system is designed to work with a constant pressure of 150 bar. The UTS2 has five axes: four are activated by means of hydraulic cylinders and one is a hydraulic axial motor. These are controlled by electromechanical valves. The hydraulic system has four extra valves: two of them by-pass the whole system (safety valves) and the other two open/close the clamping systems of axis 1 and 2. The valves can be seen in Figure 5.3.

5.2.1 Axis 1

The primary axis (axis 1) pulls the specimen during a test (see Figure 5.4a). The movement is generated by a hydraulic axial piston motor from BOSCH. The motor can deliver a maximum torque of 127 Nm at a nominal oil pressure of 280 bar, which means a maximum pulling force of about 57 kN. The maximum rotation speed is 4700 rpm. The motor is connected to a spindle, which transform the rotational movement in longitudinal displacement of a carriage with a maximum sliding speed of 150 mm/s. The carriage can move a total length of 500 mm. The carriage slides on two rails, which are mounted on a rigid thick steel plate. This ensures that the rails do not deform under heavy loads. There is an integrated inductive measurement system in the upper rail, which has a resolution smaller than 1 µm. The carriage has a clamping system, which is activated by a special hydraulic cylinder with short displacement. This closes on the strip with a pressure up to 800 MPa thanks to a mini-booster, which increases the pressure from the hydraulic system. The pyramidal texture and the elevated hardness of the clamps ensure enough grips to avoid relative sliding of the strip (see Figure 5.4b).
The pulling force is measured by a 50 kN strain gauge based load cell on one of the two connecting points, where the clamping system is mounted (see Figure 5.4c). This means that the load cell measures half of the pulling force. The correct value is acquired since the LabVIEW program doubles the signal.

5.2.2 Axis 2

When BUT test is performed, a secondary axis (axis 2) is activated (see Figure 5.5a). The axis is mounted vertically, on the bottom part of the machine and it has the same clamping system and force measurement as axis 1. The difference is that the movement is delivered by a 50 kN hydraulic cylinder. When BUT test is performed, axis 2 applies a constant back tension on the strip. The left side clamping surface in contact with the strip is nominally flat in order to avoid damaging the workpiece surface topography. In fact the corresponding side of the strip comes in contact and slides on the BUT tool pin. This avoids premature galling due to scratches on the workpiece or indentation marks created by a pyramid texture.
5.2.3 Axis 3

A tertiary axis is mounted vertically on the top-right side of the tribotester (see Figure 5.5b). Axis 3 is activated when SRT or DBT test is performed. It is a simple hydraulic cylinder with a maximum force of 100 kN. A load cell is mounted and measures the force applied. The speed is set manually by means of a flux valve. There is no position or velocity transducer on axis 3, since the function of this axis in SRT and DBT tests is simply to open and close the tool.

![Figure 5.5. a) axis 2; b) axis 3.](image)

5.2.4 Pumping station

The hydraulic pressure is supplied by an internal gear pump, which is actuated by a servo-motor (see Figure 5.6). The pump is connected to the PLC, which controls the activation/deactivation of the servo-motor, the nominal oil pressure and the maximum speed of rotation (the latter limits the maximum oil flow). The pump keeps the pressure constant using a feedback signal coming from a pressure transducer. This reduces the energy consumption and thereby the heat generated by the hydraulic work.
5.2.5 Electronic system

The UST2 is equipped with a Beckhoff PLC, which communicates with all electromechanical valves, load cells, safety features, pumping station, desktop PC, lubrication system and coil reel (see Figure 5.7). The PLC has a program, which runs cyclically every 10 ms. The program controls all input/output of the PLC and “filters” any command given by LabVIEW. Axis 1 and 2 are controlled by proportional directional valve with embedded electronic. Each of the two valves sends and receives signals from a digital controller (HACD), which communicates with the PLC. The program in the digital controllers run cyclically every 2 ms. Basically they receive the speed, position or force targets from the PLC and read the instantaneous values creating a feedback loop. In case the feedback value does not match the target one, the controller sends a signal to the valve in order to reduce the error to zero.

Figure 5.8 shows a representative outline of the connection between all electronic. The PLC may be interpreted as the “brain” of the test machine. The PLC exchanges information with the tribotester, the pumping station, the coil reel and the LabVIEW program. The latter is placed aside the PLC because it does not receive “orders” from the PLC but only information, whereas the other devices are controlled directly by the PLC.

The three load cells in the tribotester are strain gauge based and they send the measured signal to a digital amplifier, which convert the signal from analog to digital. The digital amplifiers send the information to the PLC through a CAN bus. This allows a better integration of the force measurement into the electronic system. It means that the force is not an independent signal that is sent to LabVIEW but it goes through the PLC. This avoids problems with frequency acquisition. On the other hand the frequency is limited to the PLC cycle time, which is 10 ms at best.
5.2.6 Coil reel

The innovative feature of the UST2 is the possibility to run tests automatically and continuously. In order to do that the strip has to be fed from a coil, which represent a “huge reserve of specimens” (see Figure 5.9). The reel can mount coils up to 1300 mm. external diameter, which means about 1.1 km long strip when strip thickness is 1 mm.
Chapter 5 - A new universal sheet tribotest rig

The PLC activates the reel when running a test and an electronic sensor monitors the demand of strip into the UST2.

Figure 5.9. Coil reel.

5.2.7 Lubrication system

The lubrication system consists of two felt rolls of diameter ø32 mm and width 50 mm. The oil is delivered through a pipe to the rolls. Figure 5.10a shows the lubrication system connected to axis 2 before the clamping system. The strip is fed through the rolls and a uniform film thickness is applied to the surface. The amount of oil applied depends on the viscosity and the oil flow into the rolls. A small piece of strip was weighted with and without oil on a precise scale. The oil film applied is in the range 5-8 g/m², which is fairly abundant. The rollers lubricator is connected to a pressurized tank containing an oil reservoir. The pressure is necessary especially when relatively high viscosity oils are used. Figure 5.10b shows the tank together with the electronic system that opens and closes the electromechanical valve at the bottom of the tank. The valve receives impulses, which can vary in frequency and duration. The electronic system is activated by the UST2 PLC.

5.2.8 PID controller

In the BUT test, axis 2 keeps a constant back tension. This is done in a feedback loop where the command value (CV), which is equal to the target back tension value, is set as an input and the instantaneous back tension is continuously acquired and compared to the CV. The device, which controls and compares the signals, is the HACD card of axis
2. The HACD has a BOSCH program running cyclically every 2 ms. The program has six different blocks, which have different purposes. Block 1 is activated when the feedback signal (FB) is the back tension (pressure control), block 2 and 3 control the manual movement in the two senses, block 4 is activated when FB is the axis position (position control), block 5 and 6 read respectively pressure and position, when switching between modes in order to avoid sudden movements of the axis due to old CV values still in memory.

In the following the control of the proportional electro valve is described. The HACD sends an electric signal \( u \) to the valve. This signal is calculated based on the error \( e = CV - FB \). The error is then manipulated in a Proportional Integrative Derivative (PID) controller in order to smooth the response of the hydraulic system and avoid fluctuation of the back tension. The feedback signal is created as follows. The HACD reads the pressures of the two chambers of the hydraulic cylinder \( P_1 \) (bottom chamber) and \( P_2 \) (upper chamber). The difference in pressure \( \Delta P = P_1 - P_2 \) is not directly equal to the back tension because the area \( A \) where the pressures are applied are different due to the piston stem. The bottom area \( A_1 \) is bigger than \( A_2 \). When calculating \( FB = \Delta P = P_1 - P_2 \), BODAC introduces the area ratio \( x = A_1 / A_2 \). Therefore the equation becomes: \( FB = \Delta P = xP_1 - P_2 \). This means that \( P_1 \) is scaled down in order to satisfy the equation. The back tension force \( F_b \) the piston applies to the strip is then \( F_b = \Delta PA_2 \).
The PID controller calculates the output $u$ as a function of the error $e = CV - FB$:

$$u(t) = K_p e(t) + K_i \int_0^t e(g) dg + K_d \frac{\partial}{\partial t} e(t) \quad (5.1)$$

where $K_p$ is the proportional gain, $K_i$ is the integrative gain and $K_d$ is the derivative gain. $K_p$ controls how the instantaneous error affects the response $u$ (the present), $K_i$ controls how the error’s evolution during time affects the response $u$ (the past) and $K_d$ controls how the error’s variation (or error’s speed) affects the response $u$ (the future). These three parameters can be set in the HACD in order to obtain an optimum response, which avoids big fluctuation of the back tension. In fact, preliminary tests have shown that, when axis 1 accelerate too fast, axis 2 might not be fast enough to keep the back tension constant and fracture of the strip might occur. Loop tuning of PID controller has been the research subject for many years in control theory field [116]. There are different methods to tune a PID but in this project the “trial and error” was used. The best combination of the three coefficients was found to be $K_p = 1$, $K_i = 1/20$ and $K_d = 0$. The BODAC software requires the inverse of $K_i$ therefore a value of 20 ms is inserted. This value represents the period of time after which the controller calculates the integral. Hereafter an example of how a PID affects the response system is given. Figure 5.11 shows three graphs, for three different PID configurations, taken from BODAC software. The command value CV in bar, the feedback value FB in bar, the output $u$ in mV, the axis 2 speed $s$ in mm/s and the axis 2 position $b$ in mm are plotted as a function of time. The ordinate axis has no unit because the graphs are presented here just to emphasize the fluctuation of the system response. Each graph shows four consecutive tests where sliding length was $l = 20$ mm, sliding speed was $s = 50$ mm/s, acceleration/deceleration axis 1 was $a_1 = d_1 = 100$ ms. The graphs correspond to three different PID configurations:

a) $K_p = 1 \quad K_i = 1/10 \quad$ and $\quad K_d = 0$

b) $K_p = 1 \quad K_i = 1/20 \quad$ and $\quad K_d = 0$

c) $K_p = 1 \quad K_i = 1/50 \quad$ and $\quad K_d = 0$.

In the first graph (Figure 5.11a), one can notice that FB is fluctuating. This means a considerable fluctuation of the axis speed, which is undesirable. The second graph has a much more stable FB, therefore a more uniform speed. The third graph (Figure 5.11c) shows how a further increase of $K_i$ leads to another instability problem. The FB curve is fairly uniform but one can see that, when the axis accelerates, FB has a considerable negative peak (indicated with arrows). This is caused by the retarded response of the control and it leads to an extra load in the strip causing plastic deformation and eventually ruptures. This indicates that tuning a PID control does not have a perfect setting but an optimum one.
Figure 5.11. BODAC graph of axis 2 command value CV in bar, feedback value FB in bar, the output in mV, the axis speed in mm/s and the axis position in mm.
Different values of the other parameters were also tried but instability was lowest when $K_p = 1$, $K_i = 1/10$ and $K_d = 0$. For example it was seen that $K_p$ controls the error when the axis is still. The higher $K_p$ is, the smaller the error. However, when the proportional term is high, the system response tends to overshoot generating large fluctuations.

The great advantage of a PID control is that it can be optimized for different cases but this is a time consuming operation. For example, the tuning can be done when running different sliding lengths and different sliding speeds in order to have the most stable condition. However it was decided to keep the PID parameter values constant in all tests. Axis 1 has the same PID control logic but the three parameter values are different from axis 2 since axis 1 works only in position control. The aim here is to have a uniform speed and a precise position. The values are $K_p = 10$, $K_i = 1/50$ and $K_d = 0$. In this case the proportional term is much higher than for axis 2 because a very small error in position is required. Moreover this combination ensures a low fluctuation of the axis speed.

5.2.9 LabVIEW® program

As mentioned before, the user controls the UST2 via a LabVIEW® program running on a pc. The automatic program runs cyclically sending instructions to the PLC. The cycle sends the order to move axis 1 a quantity equal to the sliding length. The program reads the instantaneous position as a feedback signal. When the target position is reached, the next stroke can start. Throughout each stroke the program activates axis 2 in order to apply the back tension. Besides these commands, the program acquires axis 1 position and force, axis 2 force and the torque. The torque signal is acquired by a piezoelectric torque transducer. The transducer is connected to a charge amplifier, which sends a signal to an acquisition card. The program then reads the values from the card. Unfortunately the reading procedure is computationally heavy, which means that the LabVIEW® cycle time increases considerably to an average of 30 ms. This affects the resolution of the data sampling, especially when a single stroke is run in less than 1 s. It means that the correct evolution of forces and torque cannot be read precisely, especially when very fast changes in the value occur.

One should keep in mind that the program was updated many times throughout the PhD project. Different functions were added and/or modified at different time. Therefore the nominally same tests can present different results based on the configuration under which, it is run.

5.3 Simulative tests in the UST2

5.3.1 Bending under tension test (BUT)

The BUT device developed by Andreasen et al. [40] can be mounted in the new UST2. Figure 5.12 shows an exploded view of the equipment. The equipment is fixed to the rig with six bolts and it is aligned in order to have the tool pin edges tangentially aligned to axis 1 and axis 2 as shown in Figure 5.13. The equipment was designed in order to
withstand a 50 kN vertical and horizontal force. The weakest structural point is the webs as shown in Figure 5.14, that connect the tool pin to the main frame of the BUT equipment. Strain gauges are glued on the webs, which also allow measuring the back tension force and the drawing force during the test. The original design comes from the equipment designed by Weinmann et al. [62]. At the present time, when this manuscript is being written, the equipment is about 15 years old. The epoxy glue, which binds the strain gauges to the webs, has usually a lifetime of 10 years. A first inspection of the glue showed that the strain gauges are still well bonded to the webs, but the effective adherence cannot be verified without removing the glue. The strain gauges were recalibrated using a hydraulic press machine. The force measured by the strain gauges has an error smaller than 5%, when compared with the force measured by the press. This leads to the conclusion that the strain gauges are still working fine.

The strain gauges have a good sensitivity of the force applied on the tool and are a relatively cheap solution to measure forces. The webs work as a bending beam and the elastic strain is measured by the strain gauges. The horizontal webs bend when a vertical load is applied, in this case the back tension force. The vertical webs bend when a horizontal load is applied, in this case the drawing force. However, this particular web design has the drawback of a cross-sensitivity affecting the measured forces. In fact, when only one of the two forces is applied, i.e. drawing force or back tension force, the structure deforms as a whole and a load in the other direction can be measured even though no force is applied. A calibration done in the press machine, where only one load was applied at time showed that the cross-sensitivity increases linearly as a function of the load. The error can be compensated introducing cross-sensitivity factors.

Figure 5.12. Exploded view of BUT equipment [40].
when calculating the force. This was not done in this project since the new test rig has already load cells mounted in all axes. The forces were then not acquired from the strain gauges avoiding any measurement error due to cross-sensitivity.

Figure 5.13. a) view of BUT with axis 1 clamping the strip; b) top view of the tool pin where the strip is bent and clamped by axis 2.

Figure 5.14. Detailed view of the webs in the BUT test equipment.

The BUT equipment has a 200 Nm piezoelectric torque transducer mounted on the tool holder (see Figure 5.15a). The transducer is connected to a charge amplifier, which transform the signal to a ±10 V signal. The charge amplifier is then connected to a modular data acquisition system from National Instrument, which acquires the signal
and sends it to the PC. The tool pin is a square prism with cross section 10x10 mm. This means that the radius of the curvature on the edges can vary from 0 to max 5 mm. Figure 5.15b shows a tool with $R = 3.5$ mm. the two ends of the prism are 6x6 mm square and they fit into the tool holder impeding relative rotation.

The tool holder can be heated up using either an electric cartridge or recirculating warm water. This helps to simulate the relative high temperature reached in the production tool after few strokes. The electric cartridge heats very fast and allows reaching temperature above 100$^\circ$C. However the max suggested temperature is 80$^\circ$C in order not to damage the strain gauges. The recirculation water system was initially developed to cool down sensitive parts (among them the webs) from surplus heat generated by the cartridge. But it can also warm the tool system by using warm water. It can therefore be used instead of the electric cartridge to rise the temperature of the tool pin.

As an example, recirculating water at 80$^\circ$C gives a max temperature of the tool pin surface of about 60$^\circ$C since the heat loss to the environment is quite high. The recirculation water system has a thermocouple that checks the water temperature and keeps it at constant temperature as long as necessary. This is very useful when running repetitive tests in the UST2. In fact some tests can last for hours and the electric cartridge will overheat the tool since there is no feedback control based on measurement of the tool temperature.

Although the BUT equipment is working fine, a new design is suggested. This was not implemented in the present project but the author strongly recommends it for future tests. A new equipment can be more robust, cheaper and much simpler since the webs can be avoided. The design can focus on how to heat up the BUT tool efficiently with an electric cartridge, implementing a feedback control of the temperature.

Figure 5.15. a) front view of the BUT equipment, b) BUT tool pin with radius of curvature $R = 3.5$ mm.
5.3.2 Draw bead test (DBT)

The DBT test device (see Figure 5.16) developed by Olsson et al. [41] can be mounted on the UTS2. The equipment can be assembled and mounted on axis 3, which can open and close with a force of 100 kN. Testing on DBT was planned at the beginning of the present project but due to limited time it was later decided to focus only on the BUT test. The DBT equipment has not been tried on the new tribotester so far, but the author is confident that the equipment will work fine. It would be very interesting to investigate tribo-systems in DBT test using the UST2 and see what the outcome is when running long and repeated sliding length.

![Figure 5.16. DBT test equipment [117].](image)

5.3.3 Strip reduction test (SRT)

As for the DBT, the SRT equipment has not been implemented. The current SRT machine presented in [42] is a stand-alone machine and the tool feature cannot be mounted in other test rigs.

Since the SRT equipment, in the UST2, was to be designed from scratch, a new concept was planned. The concept consists in reducing the thickness of the strip in a “modified” rolling process, where one roll is fixed and the other rotates freely (see Figure 5.17). Basically the idea is to replace the bottom holder of the actual SRT (see Figure 2.4) thereby avoiding friction between the bottom holder and the main frame, which affects the drawing force measured during a test. The new concept will however not represent
the common deformation that occurs in an ironing process. In fact in production tools the workpiece material usually slides on either the punch or the die, where the thickness is reduced. The other tool part remains still and the movement between workpiece material and the tool is relatively small.

Figure 5.17. New SRT test concept.
Chapter 6  
Analysis of the production process

After the component has been selected and the main process parameters have been collected, a numerical analysis of the production process can be performed. A brief brainstorming helps to identify the important outputs of the numerical analysis. In this case, the tribologically relevant parameters are the normal pressure and temperature at the workpiece/die interface in operation 3. It was decided to utilize the commercial FEA software LS-DYNA® to numerically simulate the process and the laboratory tests. The decision to gain experience with this software comes mostly because a collaborative network of experts is located in Denmark and Sweden. However, the experience of the author in FE-modelling of metal forming processes was practically zero at the beginning of the project. This explains why many mistakes during the project had to be overcome.

The chapter deals with the numerical model of the production process. The 2D model is presented with a deep discussion about the results. Some of the keyword commands of LSDYNA® will be mentioned. The simulation results will focus on sensitivity analysis of some key parameters and the forces will be compared with experimentally measured.

6.1  
2D analysis of the production process

6.1.1  
The numerical model

At the beginning of the project a 3D model of the EL-TUBE was implemented but many issues were encountered and some of them led to crashing of the simulation. The problems seen using a 3D model could be solved with more experience with the FEA software. However, it was decided to switch to a much simpler 2D model. First of all, this allows dramatically shortening of the solving time, which goes from few hours to few minutes. Besides that, a 2D mesh is much simpler to build and this facilitates the task of the user, who can then focus on refining the mesh only in critical zones of the model, where the results have to be investigated. The 2D model was solved using the implicit integration method since the dynamic effects of the process were negligible.

The tools of the three operations are modeled and the workpiece topology is imported in the next step. In Figure 6.1 the concept is illustrated with a flow chart. Figure 6.2 shows the three models of the three EL-TUBE operations, from left to right operation 1, operation 2 and operation 3 respectively. Figure 6.3 shows the three models when the progressive tool has reached the bottom and the workpiece has been deformed. As described before, only operation 1 has a blank holder and the process represents a conventional deep drawing. When operation 1 is completed, the mesh of the deformed workpiece with information about the strains and stresses is saved and imported in operation 2. The input file contains the strains and stresses at four integration points through the thickness of each element. The procedure is repeated when operation 2 is completed: the output file is created and uploaded in operation 3.
Chapter 6 - Analysis of the production process

Figure 6.1. Sequence of simulations for EL-TUBE.

Figure 6.2. 2D model of a) operation 1, b) operation 2 and c) operation 3.

Figure 6.3. 2D model of a) operation 1, b) operation 2 and c) operation 3. The tools have reached the bottom end.
The models of operation 2 and 3 have a small plate on the top-right corner of the punch, which moves with the same speed as the punch. In the real tool this component is a stripping plate, which avoids that the part remains stuck to the punch during the backstroke. It was necessary to include this in the model, because it was realized that the workpiece comes into contact with this plate, when the punch is about half way down as shown in Figure 6.4a. This implies an influence on workpiece deformation and load-displacement curve. All the critical tool dimensions such as diameters and curvatures are modeled with scale 1:1. A counterpunch is modeled in all three operations since this is also present in the real tool. Its function is to make sure the component is ejected after the forming operation.

The elements in the model use formulation 15, i.e. 2D shell elements in the XY plane. The formulation activates the axial symmetry property [118]. The elements are volume weighted, which means that all loads and masses are applied per unit radian. The axis of symmetry lies on the left side of the punch, along the Y axis as shown in Figure 6.4b. This type of formulation automatically implies that each node has only three degrees of freedom, corresponding to the movements on a plane. Two automatic constrains, movement along axis X and rotations, are applied to the nodes that lies on the axis of symmetry (with abscissa X = 0). Therefore they have only one degree of freedom, which is movement along axis Y. This means that the punch, the blank and the counterpunch do not need to be further constrained because they have some nodes with abscissa X = 0. The stripping plate (blankholder in operation 1) is manually constrained as regards movements along axis X and rotation on the XY plane. The die is constrained in the following way: the nodes at the bottom have vertical movement constrained, and the nodes on the right edge have horizontal movement constrained.

Figure 6.4. a) contact between workpiece and stripping plate; b) coordinate system in operation 1.
It is immediately clear that the sliding of the blank over the die curvature is the area with critical lubrication. This is why it is important to investigate the normal pressure and temperature right there. Figure 6.5 shows a detailed view of the mesh on the curvature of the die. The outer elements are rectangles of about 0.04x0.05 mm² area.

![Figure 6.5. Detailed view of the mesh in the curvature of the die.](image)

Such a fine mesh allows accurate results at the contact interface to be achieved. The blank in operation 1 is modeled with 8 elements through the thickness. The elements are squares with side 0.125 mm. The deformation stretches the elements in one direction and become rectangular. In order to obtain more accurate results, the workpiece is manually remeshed in operation 3. Each element in the first two rows, on the outer side of the workpiece, is split in four sub-elements and the elements in third row are split in one triangle and two trapezoids. Figure 6.6 shows in detail the new mesh. In the results section the old and new mesh will be compared in order to investigate the effect of the mesh size.
Figure 6.6. Detailed view of the new workpiece mesh. The elements on the right side of the workpiece have been split.

The contact between objects is modeled with the penalty method, which is widely used in FEM software. This method simply applies a reaction force to every node of the workpiece that penetrates another object mesh. The reaction is proportional to the penetration and can be illustrated as a spring connected to the node and the surface. The penalty force stiffness can be scaled adjusting a scale factor \( p \). The friction between die and workpiece is modeled using the Wanheim-Bay model [119]:

\[
\mu = \frac{m}{1 + \frac{\pi}{2} + \arccos(m) + \sqrt{1 - m^2}}
\]

\[
\frac{q^*}{\sigma_0} = \frac{1}{\sqrt{3}} \left( 1 + \frac{\pi}{2} + \arccos(m) + \sqrt{1 - m^2} \right)
\]

where \( m \) is the friction factor, \( \mu \) is the coefficient of Coulomb friction, \( q^* \) is the normal pressure at the limit of proportionality for the Coulomb model and \( \sigma_0 \) is the yield stress of the workpiece material. Using this model the maximum friction stress \( \tau_{max} \) (LSDYNA® calls \( \tau_{max} = \) coefficient for viscous friction) is calculated tuning the friction factor \( m \) until the desired Coulomb friction is obtained. Figure 6.7 shows the model graphically. The \( \tau \) value is then inserted in the simulation together with the coefficient of Coulomb friction \( \mu \).
Chapter 6 - Analysis of the production process

One of the crucial settings in the simulation is the punch movement. The exact movement and speed of the punch can be obtained from the kinematic curve of the press showed in Figure 3.7. This curve is constructed plotting a number of points in the graph and connecting them with a straight line. This means that there is a discontinuity of the speed in each point, which leads to convergence problems in the simulation. The sliding speed is not a critical parameter in the present numerical model (however it is for thermal analysis) and it is preferred to apply a smoother kinematic curve. Figure 6.8a shows the applied punch speed in the simulation, where the top speed is kept constant for most of the stroke and equal to \( s = 100 \text{ mm/s} \). The curve is generated automatically by a special function in LSDYNA®. The detail of the acceleration part is shown in Figure 6.8b and this is clearly a smooth increase of the speed, which avoids fluctuations of the speed, and of the punch force, when the simulation runs.

A dynamic damping is introduced in the model to have stable convergence. The model is singular at the beginning, when the tool is not in contact with the workpiece. When solving the problem, the dynamic terms are included in the equation system:

\[
M\ddot{b}^{n+1} + D\dot{b}^{n+1} + K_t(x^n)\Delta b = P(x^n)^{n+1} - F(x^n)
\]  

(6.2)

where \( M \) is the lumped mass matrix, \( D \) is the damping matrix, \( K_t \) is the stiffness matrix, \( b^{n+1} \) is the nodal vector at time \( n+1 \), \( \dot{b}^{n+1} \) is the nodal point velocities at time \( n+1 \), \( \ddot{b}^{n+1} \) is the nodal point accelerations at time \( n+1 \), \( x_n \) is the nodal position at time \( n \), \( P \) is the body force and external load vector and \( F \) is the stress divergence vector. The damping introduces a loss of energy of the system. When contact occurs, the dynamic terms are removed from the equation system and the problem becomes static. Contact
between the punch and the blank occurs immediately in the simulation, before any plastic deformation takes place. Therefore the loss of energy is here negligible.

The initial time step is $t_s = 10^{-5}$ s. The time step is automatically controlled by the solver and varies in the range $t_{s\text{min}} = 10^{-8}$ s and $t_{s\text{max}} = 10^{-4}$ s. When convergence is reached in less than 35 iterations, the solver increases the time step in order to speed up the calculation. On the other hand, when convergence is not achieved within 45 iterations, the time step is decreased. If the solution is achieved with a number of iteration between 35 and 45 the time step remains constant.

![Figure 6.8. Kinematic curve describing the punch movement: a) complete speed curve. The red circle indicates the acceleration; b) detail of the acceleration.](image)

### 6.1.2 Material model

Initially a simple power law material model was implemented using tensile test data from the material suppliers. The simulation results showed that the effective plastic strain reaches values higher than $\varepsilon = 1$ as shown in Figure 6.9. Usually the tensile test gives the flow stress curve in a relatively small strain range (up to necking at the instability strain) implying that the test is insufficient to describe the behavior at high strain. The solver extrapolates the flow stress curve to higher strains from the tensile test curve determined, and this could affect the results very much. In order to obtain a better stress-strain curve including higher strains, a plane strain compression test was selected and performed on the four workpiece materials [120]. Even though the assumption of plain strain is not true in redrawing, the tests can give an indication of the flow stress curve at high strain and the data can be combined with the tensile test to get an improved flow stress curve. The tests consist of compressing a strip, which has the width at least 5 times bigger than the thickness in order to satisfy the plane strain condition. The strip is pressed between two flat tools, where the ratio strip thickness/tool width has to lie in the range 0.25-0.5. The lower value limits the friction contribution, whereas the upper value limits the inhomogeneity of the deformation. The
thickness was reduced in subsequent steps and the force and deformation were measured in each step.

Figure 6.9. Effective plastic strain in operation 3.

The effective strain and stress were then calculated giving a number of points of the flow stress curve. In order to obtain as many points as possible of the flow stress curve a thick plate is required, especially when high strain is investigated. This means that the width of the strip and the tool have to be larger to fulfill the plain strain condition, to avoid friction contribution and to have homogeneous strain through the thickness. However this increases the load required for the deformation and therefore a more powerful press is necessary. A solution to increase the achievable deformation is to use multiple tool sets with different widths. The sets are used in sequence from the larger width to the smaller and they deform always the same zone, so that the strain accumulates. The equipment used has three tool sets: set 1 has width of 10 mm, set 2 width of 5 mm and set 3 width of 2.5 mm. Figure 6.10a shows the bottom tool for the three sets, whereas Figure 6.10b shows the equipment mounted in the press. According to the strip thickness/tool width ratio the initial strip thickness, using set 1 can be maximum 5 mm and the smallest thickness achievable, using set 3, is 0.625 mm. The three sets allow the achievement of an incremental deformation that gives enough data points for constructing the flow stress curve up to strain higher than $\varepsilon = 2$. In this project the two main limitations were thickness of the strip and maximum press load. The workpiece materials supplied have a thickness of 1 mm and the press used for the tests can reach maximum 560 kN compression force. Especially the small thickness was a main issue, because fracture of the strip occurred at small-medium strain. In order to acquire as many data points as possible a stack of 5 strips was used as test specimen.
giving a total thickness of 5 mm. This configuration corresponds to a stack compression test. Merklein et al. [121] and Alves et al. [122] performed stack compression test on cylindrical specimens and showed that the results are acceptable for constructing the flow stress curve. Originally the test was developed by Pawelsky [123] in 1967 to obtain flow stress curve from materials delivered as thin sheet.

Figure 6.11 shows the curves obtained for the four workpiece materials tested. The compression test data are combined with the tensile test ones from the companies. The flow stress curves obtained from the tensile test describe the first part of the curves in Figure 6.11, where strain ranges from $\varepsilon = 0$ up to $\varepsilon \approx 0.3$ for stainless steels, $\varepsilon \approx 0.1$ for DP 800 and $\varepsilon \approx 0.03$ for 1200 MZE. This is done because the data from the partners have high resolution meaning that the curves are better described in those ranges than if using data from the compression tests.

Figure 6.10. Plain strain compression test: a) half tool sets (10 mm, 5 mm and 2.5 mm); b) test equipment.

Figure 6.11. Flow stress curves obtained from the plain strain compression tests: a) stainless steels and b) AHSS.
Figure 6.11a shows the total curves for the two stainless steels and the characteristic strain hardening of these materials is clearly visible. The curves have not a smooth trend due to the fact that only few points are plotted. Figure 6.11b shows the curves for the AHSSs. In this case the strain hardening effect is smaller. For EN 1.4301, DP 800 and 1200 MZE materials it was not possible to reach a strain of $\varepsilon = 1$ because fracture of the specimens occurred at lower values. The curves shown in Figure 6.11 were inserted in LSDYNA®. The material model nr 24 “piecewise linear plasticity” was used for modeling the workpiece.

6.1.3 Results

One could argue that the results obtained from a 2D model of a redrawning process are biased by the anisotropy, which is not taken into account in the computation. The author suspects that this does not affect much the normal pressure since the specimen undergoes severe deformation in operation 1 and 2 already. Moreover the model does not take into account the ribs connecting the specimen to the remaining strip as shown in Figure 6.12. These ribs pull the collar of the component in perpendicular direction to the strip and introduce a force, which may affect the normal pressure. The tribologically most important parameter investigated in these simulations was the normal pressure at the workpiece/die interface in operation 3. In Figure 6.13 it is clear that the contact is very localized on the die curvature. In order to determine the normal pressure on the die interface, the die was modeled as pure elastic material. The elements on the outer periphery of the die curvature were displaced with the local Y axis perpendicular to the outer periphery. It was then possible to read the normal pressure on those elements as the local stress in Y direction. This means that the stresses displayed on inner elements are meaningless as regards the normal pressure investigation.

Figure 6.12. EL-TUBE. The width circles show the ribs connecting the workpiece to the strip. Feeding is from right to left.

Figure 6.13 shows the local Y axis of some elements on the outer surface of the curvature as white arrows. The X axis, which is not shown, is then perpendicular to Y. In all following illustrations of the numerical analysis, where the normal pressure is
shown, the scale represents the local Y stress; it has a negative value, since it is a compression stress. When it is plotted and presented as a normal pressure on the tool surface it is displayed with positive values.

Figure 6.13. Contact interface workpiece/die with radius of curvature $R_j = 1.5$ mm. A detailed view of the die curvature is also shown: local Y axis direction on outer elements.

The first results showed that the normal pressure at the workpiece/die interface is very high. Figure 6.13 shows how the contact area is smaller than the thickness of the workpiece. The contact arc length can be measured in the software and it corresponds to a length of approximately 0.2 mm, at this particular position of the punch. This is the main reason why the pressure increases so much. It was decided to try to “validate” the contact area with a qualitative visual inspection on the real tool. Basically, a specimen was partially formed moving the punch just half the total height of the cup. In this way about half of the specimen was drawn in. The punch and workpiece was then retracted and the die curvature was marked with a black mark. The punch was subsequently moved downwards until the cup contacted the die again. The cup was then drawn in again for a couple of millimeters. The specimen would wear the black mark off on the die surface, where sliding occurred. Figure 6.14a and b show the partially formed specimen and the die curvature where the mark had disappeared. It was not possible to measure accurately the peripheral extension of the contact area where the mark has disappeared. But at first glance one can see that the magnitude is comparable with the numerical result.
Figure 6.14. Operation 3. Contact interface between workpiece and die: a) half deformed specimen and b) die 3.

Figure 6.15 shows the stress in local Y direction for operation 3 with a radius of curvature $R_3 = 1.5$ mm. The results show that the peak of pressure reaches almost $q = 3000$ MPa and is localized on a very small area inside the contact interface. Even though the analysis is not validated yet, it is the author opinion that the numerical simulation is correct and close to the real case. This means that the tribological conditions are extreme and explain why chlorinated paraffin oil is necessary to run the process. The tool was designed about 20 years ago and the small die radius of 1.5 mm was chosen in order to facilitate the subsequent operation 4, where the collar is shaped with an internal radius of 1.5 mm. The first doubt popping up at this point is whether it is possible or not to reproduce such a high normal pressure in the BUT test. In fact previous work done by Andreasen [40] in BUT showed that the maximum analytically calculated average normal pressure achieved testing EN 1.4401 with radius of curvature $R = 5$ mm, was about 69 MPa, which is less than 3% of the pressure reached in operation 3. Besides that, it is immediately realized that increasing the radius of curvature of die 3 will increase the contact area, which implies a decrease of the normal pressure and tribological severity.

It was therefore proposed to increase the die radius of curvature in operation 3 to $R_3 = 3.5$ mm. A numerical analysis with the new radius was carried out. Figure 6.16 shows the normal pressure and it is clear how the peak value is much lower than using the smaller radius.
Figure 6.15. Normal pressure at the interface workpiece/die with radius of curvature $R_3 = 1.5$ mm.

Figure 6.16. Normal pressure at the interface workpiece/die with radius of curvature $R_3 = 3.5$ mm.

Figure 6.17 plots and compares directly the two cases. The maximum peak of pressure is plotted as a function of the time the punch travels. The larger radius yields a decrease of pressure $\Delta q = 1000$ MPa. In agreement with all partners it was then decided to manufacture new dies for the test with $R_3 = 3.5$ mm.

The calculated normal pressure can be affected very much by the penalty method. In fact when a large penetration is allowed, the contact area is generally larger and the resulting normal pressure becomes smaller. LSDYNA® has the option to scale the penalty force with a coefficient $p$ that range from 0 to 1. When $p = 1$ no penetration is allowed. Generally there is no recommendation on a common value for $p$. A sensitivity analysis was therefore performed.
Figure 6.17. Comparison of peak normal pressure versus time for radius 1.5 and 3.5 mm.

Figure 6.18 shows the comparison between the three values of $p = 0.1$, $0.5$ and $1$. As expected the normal pressure is highest when $p = 1$. When $p = 0.5$ the pressure is lower by about $\Delta p = 200$ MPa. For $p = 0.1$ the difference increases to about $\Delta p = 500$ MPa compared to $p = 0.5$. The normal pressure plotted in the graph is the peak value all over the contact area. Basically the pressure values of all the die elements in contact with the workpiece were plotted and the maximum value was picked at each time point. Figure 6.19 shows the penetration between workpiece and die for the three penalty factor values. The difference between $p = 1$ and $p = 0.5$ is imperceptible even though the pressure differs, whereas for $p = 0.1$ the penetration is about 1/3 of the element size, which is considered unacceptable. This means that $p = 0.5$ is a good compromise and is applied for the following investigations.

Figure 6.18 show a peak of pressure at around 0.03 s. A possible explanation is that the bottom curvature of the workpiece helps to bend the cup wall toward the punch in the first part of the draw in. This is shown in Figure 6.20a and b, where the workpiece bottom curvature lies below section 1. When section 1 reaches contact with the die (Figure 6.20b) the normal pressure drops as shown in Figure 6.18 at around 0.037 s. A small increase of the contact area is observed at this point resulting in a decreased pressure.
Figure 6.18. Comparison of peak normal pressure versus time for three different penalty factors $p$.

Figure 6.19. Penetration between workpiece and die: a) $p = 1$, b) $p = 0.5$ and c) $p = 0.1$. 
To better clarify what causes the pressure drop it can be imagined that the workpiece in Figure 6.20c is a beam constrained in section 2. During the draw, the die bends the beam toward the left side generating a moment. Looking at the steady state conditions in the process, there is a bending and unbending of the beam before and after the contact area respectively (see Figure 6.20c). When contact is created between workpiece and die, at the beginning of the process, the bending deformation becomes steady state before the unbending. When the unbending also becomes steady state the contact area increases for an instant, generating the lower pressure peak.

It is well known that mesh size affects the results in FE analysis. A sensitivity analysis was performed to investigate this parameter. Three different mesh sizes of the workpiece were analyzed. Figure 6.21a, b and c show the three different workpiece meshes. Mesh nr 1 is a coarse mesh, where the ratio between workpiece and die elements is about 5. Mesh nr 2 has a ratio 2 and mesh nr 3 has a ratio 1. Figure 6.21d shows the peak normal pressure development for the three meshes. It is seen that mesh 2 gives the lowest values of the normal pressure. In principle the mesh sensitivity analysis should display an asymptotic trend but it is difficult to ensure a stable convergence and the error between curves is about 5%, which is considered fairly low. This means that the results are not very much affected by the mesh size.

Figure 6.20. a) EL-TUBE numerical model at the beginning of the simulation. Section 1 shows where the curvature of the cup ends; b) section 1 is in contact with the die and the normal pressure drops; c) the bending and unbending zones.
As mentioned in Chapter 3, there are four different workpiece materials planned for the investigation: EN 1.4301, EN 1.4162, DP 800 and 1200 MZE. This means that all four materials were introduced in the material model and the normal pressure was investigated for each of them. Figure 6.22 shows a comparison between the materials. The two stainless steels have a significant work hardening contribution and one can see that the pressure value has a slightly higher slope between $t = 0.01$ and $0.08$ s. For example EN 1.4301 and DP 800 are compared: the high strength steel has higher pressure values in the beginning (between $t = 0.01$ and $0.04$ s) but then the slope does not raise much, whereas the stainless steel curve starts with lowest pressure (compared with the other curves) at $t = 0.01$ s but then it reaches the same peak values as DP800 after $t = 0.06$ s. The same can be seen when comparing EN 1.4162 and 1200 MZE. One can also see that, at the maximum peak of each curve, around $0.09$ s, EN 1.4301 and DP 800 have the same value, whereas EN 1.4162 and 1200 MZE have the same value.

In the simulations illustrated so far the Coulomb coefficient of friction was set equal to $\mu = 0.1$. Figure 6.23 shows a sensitivity analysis of the friction and it is clear that it does not affect the normal pressure. Nevertheless $\mu$ was calibrated since the punch force was measured in the process. This gives an idea of the magnitude of the coefficient of friction and will verify whether the material model is correct or not. Moreover the friction plays an important role in the frictional energy, which contributes to the heat generated. One should keep in mind that the material model can, in this case, affect very
much the load in the numerical analysis. The following analysis will demonstrate that the contribution of the friction is fairly small compared with the load necessary for the deformation. Therefore, the values of friction reported here should be regarded as approximate.

![Figure 6.22](image1.png)

**Figure 6.22.** Normal pressure peak on the contact area of EL-TUBE ($R_t = 3.5$ mm). Comparison between four different workpiece materials.

![Figure 6.23](image2.png)

**Figure 6.23.** Sensitivity analysis of Coulomb coefficient of friction. Comparison between $\mu = 0.1$ and 0.2.
As described before (Figure 6.4) the tool has a stripping plate on the top part of the punch, which comes in contact with the workpiece at a certain point of the draw in. This means that the load necessary to push downward the workpiece is redistributed between the punch and the stripping plate. A load cell was mounted on the punch and the force recorded shows exactly, when contact occurs. The acquired load for EN 1.4301 material is shown in Figure 6.24. The force is compared with the simulated one for $\mu = 0.1$. The load in the first 3.5 mm of displacement corresponds to the load on the gas spring located inside the die (ejection punch). This is a constant load of 3500 N. When contact with the stripping plate occurs at 12 mm punch displacement, the punch force drops and it rises again when the tool closes. The simulation shows a similar behavior but has a faster drop of the load. The position where the drop begins seems to be in good agreement with the experiment. The redistribution of load is quite dependent of the friction between stripping plate and workpiece. It was then decided to simplify the friction analysis removing the stripping plate. This configuration applies only for few tests, which were run manually in a smaller hydraulic press instead of the production press. In this setup the punch speed was decreased to 10 mm/s and kept constant throughout the stroke. It would be impossible to run the process in a mechanical press without using the stripping plate.

![Figure 6.24. Punch force of operation 3 with stripping plate. Comparison between experiment and simulation.](image)

Figure 6.25 shows the comparison for EN 1.4301 between the force measured in the experiment and the simulated one without the stripping plate. Three different values of $\mu$ were investigated and $\mu = 0.1$ seems to give the best fit. Although the result is satisfactory because the coefficient of friction is expected to lie around that value, one
should keep in mind that due to the complexity of the process the friction is likely to change during the draw. Anyway the variation in load due to friction is fairly low compared to the force as noticed by the small difference between the loads curves in Figure 6.25. Another interesting aspect of the curves is the difference in the last part, when the tool reaches the maximum displacement. All curves raise very fast but the experimental one does it a couple of millimeters after the simulated ones. This could be due to an inaccurate material model, which might not calculate the correct deformation of the cup.

![Figure 6.25. Punch force of operation 3. Comparison between simulation ($\mu = 0.05, 0.1$ and $0.2$) and experiment.](image)

Figure 6.26 shows the calibration for the EN 1.4162 material. In this case a good fit was found with $\mu = 0.05$ even though the simulation overestimates the force toward the end of the stroke. Figure 6.27 shows the results for DP 800. The experimental curve seems to have the best fit with $\mu = 0.02$. This value seems too low and it is suspected that the material model affect this result considerably. In fact the flow stress curve obtained from the plain strain compression test (Figure 6.11b) does not go beyond $\varepsilon = 0.4$. This means that LSDYNA® extrapolates the flow stress curve at higher values and a small error on the slope can give significant differences on the stress at high strain. It was shown before that the accumulated strain in the component reaches in operation 3 is well beyond $\varepsilon = 1$. 

68
Figure 6.26. Punch force of operation 3. Comparison between simulation ($\mu = 0.05, 0.1$) and experiment.

Figure 6.27. Punch force of operation 3. Comparison between simulation ($\mu = 0.02, 0.1$) and experiment.

Figure 6.28 shows the results for 1200 MZE. In this case none of the numerical results fit the experimental curve. It is clear that the software overestimates the strain hardening leading to higher punch force. Also for this material the flow stress curve describes the material in a small strain range (below $\varepsilon \approx 0.1$). The overestimation of the punch force explain how important it is to model the material behavior at high strain and how big error the software makes when extrapolating stress values at high strain. As an example, it was decided to introduce in LSDYNA® two modified flow stress curves of 1200 MZE, where the stress at strain equal to $\varepsilon = 1$ was “guessed”. Figure 6.29 shows the two flow stress curves inserted in the model. In the first one the stress at strain $\varepsilon = 1$ was set
equal to the last value of the curve obtained from the plain strain compression test \( \sigma_{\varepsilon=1} = 1347 \) MPa. This means that the curve has a horizontal plateau from \( \varepsilon = 0.1 \) to 1, describing an almost ideal plastic material. In the second curve the stress was set equal to \( \sigma_{\varepsilon=1} = 1600 \) MPa.

Figure 6.28. Punch force of operation 3. Comparison between simulation (\( \mu = 0.05, 0.1 \) and 0.2) and experiment.

Figure 6.29. Flow stress curves for material 1200 MZE. Flow curve 1 is obtained setting \( \sigma_{\varepsilon=1} = 1374 \) MPa (no strain hardening) and flow stress curve is obtained setting \( \sigma_{\varepsilon=1} = 1600 \) MPa.
Chapter 6 - Analysis of the production process

Figure 6.30 shows the punch forces obtained inserting the two flow stress curves. The simulations were performed with a coefficient of friction $\mu = 0.1$. The results indicate that the “correct” material model lies in between the two presented. This means that the 1200 MZE material has little strain hardening.

![Graph showing punch forces](image)

**Figure 6.30.** Punch force of operation 3. Comparison between simulations ($\mu = 0.1$) and experiment. The simulated curves have two different flow stress curves.

In Figure 6.31 the influence of strain hardening from operation 1 and 2 is illustrated. The figure shows the punch force in operation 3 simulated with and without the strain hardening history from the former two operations. For EN 1.4301 material the difference is considerable. The small slope of the load curve for no pre-strain indicates the contribution of the increasing wall thickness with the cup height. In fact an ideal plastic material model was selected for the simulation. This truly explains how the strain hardening is a key factor, which makes the process so severe and is responsible for the high normal pressure at the tool/workpiece interface.
A validation of the numerical analysis can also be done comparing the specimen thickness. The measuring strategy was to obtain the thickness of the cup wall, produced in operation 3, measuring the external and internal diameter and subtracting the two quantities. The easiest and most precise way was to perform the measurement in a Coordinate Measuring Machine (CMM). The CMM is a tactile measuring machine, where a probe acquires points touching the specimen surface [124]. In order to measure the thickness accurately and to allow the probe an easy access to the inner diameter, the bottom of the cup was cut off by Electro Discharge Machining. The specimen was placed upside down and fastened to the CMM table as illustrated in Figure 6.32. The diameter was measured at a depth of 2 mm from the top edge. In the FEA model the thickness was calculated at the same depth, checking the nodal coordinate. Figure 6.33 shows the comparison between experiments and simulations for all four materials. The diagram indicates that the simulation underestimate the thickness. The error could be an effect of the normal anisotropy factor, which is not taken into account in the simulation. The results are anyway considered satisfactory since the error is 13% for EN 1.4301 and below 10% for the other materials.
6.2 Conclusion

In this chapter a numerical analysis of the production process has been presented. This is an important step of the methodology described in Chapter 4. The analysis showed that the normal pressure is the critical parameter, which has to be reproduced in the laboratory. Already from the first results it was evident that operation 3 is, tribologically speaking, not at all like a normal deep drawing process. The small radius of curvature
$R_3 = 1.5 \text{ mm}$ was identified as one of the main causes of the extremely high normal pressure obtained. It was suggested to increase it to $R_3 = 3.5 \text{ mm}$ since the numerical analysis proved that a larger radius would decrease the pressure substantially. Adoption of the larger die radius lowered the pressure although still very high values were achieved on the contact area between workpiece and die. This has to be emulated in the BUT test. The anisotropy was not taken into account in the 2D model since it is assumed that its contribution to the normal pressure is negligible.

The numerical analysis showed some differences between the four different workpiece materials and all of them reached pressure beyond 1500 MPa. Experimental results were performed on the progressive tool and the punch force was acquired for each material. The forces were compared with the simulated ones, calibrating the coefficient of friction. The comparison showed satisfactory results for the stainless steels, whereas the friction seems to be very low for the DP 800 and frictionless condition gave still higher force than the experimental one obtained with 1200 MZE. The problem was identified in the material model. The high strain reached in operation 3 has the drawback that a flow stress curve at such a high deformation is needed. The problem is quite evident in the case of 1200 MZE material because the flow stress curve obtained in the material testing has a very small strain range. Therefore the behavior at high strain is unknown. This means that the real coefficient of friction is unknown but it is believed to be around $\mu = 0.1$. 


Chapter 7  Bending Under Tension (BUT) tests

This chapter deals with the BUT tests. 2D numerical analysis of the BUT test is first presented. The setup and test procedure are then described together with a preliminary test. The screening tests are then presented and discussed.

7.1  2D model of BUT test

The 2D model of BUT test is built assuming plain strain deformation. This means that formulation Nr. 13 in LSDYNA® can be applied for all elements. The BUT model is extracted from a section of the real process lying on a plane parallel to the sliding direction (see Figure 7.1a). A similar model was implemented by Damborg et al. [125, 126] in 1998. Even though the real tool is a 10x10 mm square section with curvature on the four edges, as shown in Figure 5.15, it was here modeled as a circle with $R = 3.5$ mm, since this does not affect the results. The mesh was refined on the contact interface as shown in Figure 7.1b. The elements on the outer periphery are squares with side of about 0.04 mm. Two nodes at the tool center are constrained and impede rotation and translation. The strip is also shown in Figure 7.1a and it is modeled as 20 mm long and 1 mm thick. The front edge is already bended around the tool to facilitate the transition phase when the strip is accelerating. The mesh on the inner side of the strip, in contact with the tool is finer than that on the outer side and the elements are about the same dimension as the tool ones. The strip front edge slides from right to left as indicated in the figure. At the other end of the strip a constant nodal force is applied and the resultant is equal to the back tension. In fact the software considers the shell thickness, in the third dimension, 1 mm constant. Therefore the resultant back force is equal to the back tension stress in MPa since the surface is 1 mm². Figure 7.1b shows the normal pressure results for EN 1.4301 material, when a back tension of $\sigma_b = 300$ MPa is applied. The standard minimum yield stress limit of EN 1.4301 material is about 220 MPa. In BUT test it is not recommended to have a back tension higher than the yield stress since plastic deformation of the strip before bending is undesirable. One can see that the normal pressure on the contact area is around $q = 200-300$ MPa, which is very low compared to the value achieved in the production tool (about 1600 MPa). It is interesting to notice that the contact occurs in two localized areas: one at about 13° from the horizontal axis and the second one at about 62° in agreement with a common deep drawing process as also shown by Groche et al. [127]. This is caused by the bending and unbending, which the strip undergoes. Groche et al. obtained almost the same magnitude of normal pressure as the one shown in Figure 7.1, simulating deep drawing of DC04 material 1 mm thickness with a radius of curvature $R_d = 12$ mm.
These results show that the present BUT test is not able to simulate appropriately the tribological conditions in operation 3 in the production process. The 90° curvature does not allow higher normal pressure than 300 MPa, when the maximum value of the back tension is applied. Comparing the investigated redrawing process (EL-TUBE) and the BUT test, one can see that there are two fundamental differences, which explain why the normal pressure in BUT test is much lower than in the production process. The first is the contact area. It was shown in Chapter 6 that the contact area in operation 3 is localized to a small fraction of a 90° curvature. The second and more important difference is the pre-strain the workpiece material undergoes in operation 1 and 2. The work hardened material increases the force necessary to deform the part in operation 3. This together with a small contact area results in a much higher normal pressure. On the contrary the strip in the BUT test is not previously work hardened and the contact area, using a 90° curvature, is larger than that in operation 3. The main goal is now to increase somehow the achievable normal pressure in the BUT test to better emulate the production process. Pre-work hardening of the strip is possible but requires a dedicated device, which can deform the material to the desired strain. This solution was excluded since the implementation time was assessed to be too long. Another possible solution is the modification of the BUT tool geometry. A final solution was found using the tool geometry shown in Figure 7.2. Instead of using 90° of a circumference, the strip bends around a 45° curvature. In this way the contact area is reduced and the strip exits abruptly creating a local area with high normal pressure. The radius of curvature is still
Chapter 7 - Bending Under Tension (BUT) tests

\[ R = 3.5 \text{ mm}. \] One should notice that contact occurs only on part of the curvature. The detailed view of Figure 7.2 shows a gap between the strip and the tool at the bottom right corner meaning that there is no contact between strip and tool along the vertical wall and the first part of the curvature.

![2D model of new BUT tool geometry. The contact interface is a 45° of a circumference.](image)

The first simulation was performed with a coefficient of friction \( \mu = 0.1 \) since the normal pressure is not significantly affected by this parameter. The numerical analysis was aimed to find an appropriate back tension which gives a normal pressure of the same magnitude as in the production process. The numerical analysis of EL-TUBE process showed that the normal pressure increases as a function of the punch stroke. It was decided to implement the same trend in the BUT model. This is done applying an increasing back tension throughout the sliding length. A target value of the back tension is selected and, when the strip starts to accelerate, 80\% of that value is applied. The target value is reached by the end of the test. Figure 7.3 shows the peak of normal pressure as a function of the sliding length for all for workpiece materials. The following target back tensions were applied: \( \sigma_b = 200 \text{ MPa} \) for EN 1.4301, \( \sigma_b = 300 \text{ MPa} \) for both DP 800 and EN 1.4162 and \( \sigma_b = 340 \text{ MPa} \) for 1200 MZE. One can see that the curve in Figure 7.3, for the EN 1.4301, reaches about \( q = 1100 \text{ MPa} \) and EN 1.4162 almost \( q = 1500 \text{ MPa} \), which are fairly high but lower than the values in EL-TUBE. Unfortunately the back tension cannot be increased further for EN 1.4301; however the achievement of a pressure higher than 1000 MPa is considered a satisfactory result here. The normal pressure for the two AHSS materials reach about 1700 MPa, which is fairly close to the production results. The back tension could be increased for DP 800, EN 1.4162 and 1200 MZE but during laboratory tests it was realized that the chosen values of \( \sigma_b \) ensure no fracture of the strip caused by fluctuation of the force. It is not well understood what causes the sudden drop of the pressure at the
beginning of the sliding, shown in the graph, but the author suspects it is due to a variation of the contact area, which occurs when the initial part of the strip leaves the contact area. In fact the beginning of the strip does not undergo the full bending and unbending deformation since it is already bended around the tool.

![Graph](image)

**Figure 7.3.** Maximum value of normal pressure at the interface workpiece/tool in the BUT test simulation. Comparison between workpiece materials for an increasing back tension.

It is evident that the contact area in the revised BUT tool is fairly small and the peak of pressure is localized on the upper part of the tool, just before the strip leaves the contact. Figure 7.4 clearly shows that there are two contact zones: the first around 13° from the horizontal axis and the second one at about 42°. When running the simulation for the AHSSs, it is noticed that there is no contact between the two normal pressure peak areas. Figure 7.5a shows the interface tool/workpiece at about 22° and the thin white line is a small gap between the workpiece and the tool (a single element is a square of about 0.04 mm side length). Figure 7.5b shows a case without gap.

The back tension target values discussed above are the nominal ones selected for the BUT tests in order to emulate the production process conditions as good as possible. It is now realized that the achievable normal pressure in the BUT test is not as high as in the EL-TUBE process. The new tool geometry allows getting closer to those severe conditions in the production tool but a difference still exists.
7.2 Materials and experimental setup

7.2.1 BUT tool

Based on the precedent analysis, a new profile of the BUT tool was constructed in order to achieve higher normal pressure than with a common 90° curvature. 25 tools in Vancron® 40 and 25 in Vanadis® 4 Extra were provided and manufactured by Uddeholm and Grundfos with a raw section 10x10 mm and hardened to 62 (Vanadis® 4 Extra) and 63 HRC (Vancron® 40) respectively. The new geometry was then machined on a few of the tools. Technically the manufacturing process is simple. The curvatures on the four edges are first grinded with a radius $R = 3.5$ mm and then two of the four
Chapter 7 - Bending Under Tension (BUT) tests

Side surfaces are hard milled down until the curvatures reach an angle of 45°. Figure 7.6 shows a cross section of the tool. A detailed view of the curvature is also shown together with a picture of the real tool. The particular shape of the tool pin allows turning the tool four times. This means that four working surfaces are available.

![Figure 7.6. Sketch of the new geometry of BUT tool with detailed view of the curvature and a picture of the real tool.](image)

Figure 7.7 shows a representation of the test. The strip is bended 90° over the tool curvature and drawn along the sliding direction. The back tension is applied to the other end of the strip and it is perpendicular to the sliding direction. The strip shown in the figure does not represent the real length and it is shifted toward the right side of the tool in order for the reader to better understand the principle and see the curvature of the tool.

The dies in the production tool are grinded and polished in the circumferential direction, which means that the sliding occurs perpendicularly to the surface texture. Due to their rotational symmetric geometry, the dies are easily polished. They are mounted on a rotating spindle and the operator polishes the surface with diamond paste or emery paper, according to the specification. Grundfos has the possibility to polish the dies automatically using a Robot Assisted Polishing (RAP) machine [128]. It is of course essential that the same surface is reproduced on the BUT tool. In this project the effect of surface roughness on the limit of lubrication is not investigated and it is kept constant for all tools. The special new geometry makes the polishing operation of the BUT tool tedious and it cannot be performed automatically. Polishing was done locally on the curvature and the surfaces tangentially connecting the edges (right and left surfaces of the tool in Figure 7.6). The procedure was manually performed and precise guidelines were indicated by Uddeholm and Grundfos as described below.
Vanadis® 4 Extra was polished using diamond paste with grain size 15 µm. The paste was applied on the tool surface and using a plastic tool it was gently pressed and moved forth and back along the longitudinal direction (see Figure 7.8a). The final roughness is about $Ra = 0.06 \, \mu m$ and $Rt = 0.6 \, \mu m$. Vancron® 40 has the same roughness specifications but it is achieved by polishing with emery paper, grain 1000. The roughness was measured on the top surface showed in Figure 7.8a since measurement on the curvature were difficult. This means that it is difficult to ensure that the surface texture is the same all over the curvature. Moreover the author lacks experience in polishing procedure, which means that there could be significant differences between surfaces. However it is believed that the surface texture is not affecting the BUT results much. With this assertion the author means that the specifications indicated by Grundfos are guidelines and it is believed that the tool performance is not hugely affected by small variations of the roughness.

To recognize which surface was tested, every tool was marked with a capital letter and the four edges were also marked from 1 to 4 with dots. The edges indicated the four curvatures in a tool. Figure 7.8b and c show the marks on tool H, edges 3 and 4. The marks were made by a pneumatic engraving pen.
7.2.2 Workpiece materials

As shown in Chapter 5, the new UST2 can run tests from a coil. In this project the coil materials were provided by the two partners Outokumpu and SSAB. Outokumpu delivered coils of cold rolled EN 1.4307 (instead of EN 1.4301) with 2B surface texture and cold rolled EN 1.4162 with 2E surface texture. EN 1.4307 is the low carbon version of material EN 1.4301 but the mechanical properties do not differ much according to the producer [129]. The data sheet of the coils indicates that the yield stress measured by the manufacturer is $R_{p0.2} = 325$ MPa. SSAB delivered Docol® DP 800 and Docol® 1200 MZE. All coils have a strip cross section 30x1 mm.

7.2.3 Test procedure

In Chapter 4 it was discussed how a tribo-system can be described by its limit of lubrication and that the number of strokes at which the tribo-system fails is an important parameter. In this project the experience from Grundfos helped to define this factor. According to production experience if a tribo-system can run 1500 strokes without pick-up, it can then normally also sustain 5000 strokes. Of course every progressive tool has different annual production target and it is difficult to assess how many parts a tool should be able to produce in its life to be economically feasible. A “Grundfos rule of thumb” is that a good tribo-system should be able to run at least 50000 parts. Testing 50000 parts in BUT test is technically possible but, for the specific case of EL-TUBE, this is a very high amount, which requires a lot of material and time. In this case it was decided to set the limit to 1500 parts. This means that all tribo-systems tested in this project had the target of 1500 strokes. If critical amount of galling occurs before this
limit, the tribo-system is considered poor. The previous sentence introduce another challenge: what is the critical amount of galling in BUT test? In Chapter 3 the challenge was discussed for the EL–TUBE process. The outcome was that the evaluation of galling is left to the operator, who assess it by visual inspection. An idea was to apply the same method used at DTU-MEK for the SRT test, where the galling is evaluated measuring the number of scratches generated on the strip. When galling occurs the scratches multiplies. Preliminary results showed that this method is not applicable to the BUT test. A common strip tested in BUT, which is considered acceptable by a qualitative inspection, usually presents a high number of scratches, which would indicate galling if it was a SRT test. A careful investigation of the BUT tool surface shows that the pick-up on the tool is also small and acceptable. In fact the scratches measurement developed in the SRT test identifies the grooves deeper than 0.5 µm. These types of abrasion marks are very small and undetectable by naked eyes. In other cases, where failing of the tribo-system occurs in the BUT test, the measurement shows a number of scratches comparable or even smaller than a case where failing does not occur. Figure 7.9 shows the results for two tribo-systems tested in BUT. The experiment with DP 800 shows a lot of scratches but the tribo-system was considered good because galling was qualitative not critical after 1500 strokes. On the other hand the experiment with EN 1.4162 shows a much smaller number of scratches but the test showed massive pick-up and galling, which classified the tribo-system as poor. The problem is that the method was developed for strip surfaces tested in SRT, which have a very smooth and flat texture when galling is absent. As soon as little pick-up forms, abrasive marks start to form on the strip and they usually propagates quickly.

![Number of scratches deeper than 0.5 µm measured in a BUT strip specimen. The measurement is performed perpendicularly to the sliding direction.](image1.png)
As explained before this is not the case for BUT test. Therefore it was decided not to evaluate galling by measuring the number of scratches or the roughness of the strip. The evaluation was done mainly by visual inspection of the pick-up on the tool. The results were then discussed with Grundfos and the other partners. Two other parameters were used for assessing galling formation: the torque and the drawing force. The torque usually rises with increasing strokes when pick-up builds up. Summing up, the results are described in this work displaying the torque and the drawing force trends as a function of the number of strokes and the pictures of the tool surface, where contact occurs.

A generic description of the BUT equipment was given in Chapter 5. In the following, a brief explanation of the specific testing procedure is given. First of all the BUT tool pin is cleaned carefully with ethanol and placed in the tool holder. The coil is mounted on the coil reel and the strip is manually fed into the UST2 until it reaches the other end of the machine where the cutting station is placed. The clamping systems of axis 1 and 2 are activated to fasten the strip. At this point axis 2 is activated in order to bend the strip solid around the tool pin. This means that a small back tension force is applied without moving axis 1. When the strip is correctly bended, the clamp is opened and axis 2 is moved to the initial position of about $b = 10$ mm from the bottom end. The clamp is closed again and the test can start after all parameters have been set in the LabVIEW® program. As explained in the numerical analysis, it was decided to set a sliding length $l = 20$ mm according to the height of the EL-TUBE component in operation 3. Figure 7.10 shows a portion of a tested DP 800 strip. A sequence of strokes is clearly visible.

![Figure 7.10](image)

**Figure 7.10.** DP 800 strip after testing. The sliding length is marked ($l = 20$ mm).
Chapter 7 - Bending Under Tension (BUT) tests

The sliding length is then repeated 1500 times making the total strip 30 m long for one test. For each sliding length the axis 1 accelerate to a certain speed, keeps it constant and finally decelerate to a halt. Since the purpose of the BUT test is to emulate the redrawing process, it seems natural to apply the same velocity in the BUT test. In Figure 3.7 the punch speed, in operation 3, was illustrated. It varies between 100 and 150 mm/s. Preliminary tests showed that the strip in BUT test easily fractures when a high acceleration is applied. The problem is that the acceleration and deceleration time should be as small as possible but at the same time fracture should be avoided. It was then decided to apply the speed profile shown in Figure 7.11. Axis 1 accelerates in \( t = 0.1 \) s from \( s = 0 \) to 50 mm/s. The speed remains constant for \( t = 0.3 \) s and then decelerates to 0 in 0.1 s. This means that each stroke of \( l = 20 \) mm takes \( t = 0.5 \) s. The maximum speed of \( s = 50 \) mm/s was chosen as a balance between avoiding fracture and being close to the punch speed. The cycle is automatically repeated 1500 times.

![Figure 7.11. Velocity curve of axis 1 for one stroke in the BUT test.](image)

Figure 7.12 shows the drawing and back tension forces as a function of the sliding length. Three strokes are plotted, where a single stroke has a sliding length \( l = 20 \) mm. Each stroke presents a peak in both forces at the beginning of sliding. This is due to the acceleration of axis 1. The configuration in Figure 7.12a shows a case with constant back tension throughout the sliding length. In this test, the back tension was set equal to \( \sigma_b = 300 \) MPa. Looking at the value of the correspondent back tension force curve in the graph, the plateau value is about \( F_b = 8000 \) N. For a strip section of 30 mm\(^2\) the back tension is \( \sigma_b = 266 \) MPa, which is lower than the target value \( \sigma_b = 300 \) MPa. It was then realized that the hydraulic system has a systematic error, proportional to the target value. It means that the higher the target back tension, the bigger the error. For example
when applying a target value of $\sigma_b = 100$ MPa the measured back tension force is about $F_b = 3000$ N meaning that the error is practically zero. This constant load configuration was implemented in the first LabVIEW® program, which runs the automatic test. In all following test results the target value is mentioned instead of the real one since the real value fluctuates due to the kinematic nature of the experiment.

As described in the simulation analysis of the production process, the normal pressure at the interface is increasing as a function of the punch displacement, and the same trend should be attempted in the BUT test. This was implemented in a second LabVIEW® program, which controls the UST2. The program sets as initial back tension 80% of the input value. The force increases proportionally from 80% to 100% of the input value throughout the sliding length. The configuration in Figure 7.12b shows the load curve with an increasing back tension throughout the sliding length. One can see that the forces are lower compared with the previous configuration. Especially the force peak at the beginning of each stroke is reduced considerably and this lowers the risk to break the strip. In fact it was realized that the force peak, when axis 1 accelerates, causes a small localized reduction of the strip thickness, which takes place when the strip is in contact with the tool. This means that a smaller force is required to reach fracture. Most of the time when the strip fractured, it happened on the thinner section. Figure 7.13 shows the torque as a function of the sliding length for the two cases presented above: constant and increasing back tension. The trends are clearly visible also on the torque signal. Again the increasing trend has a lower curve than the constant one due to the reduced forces.

In Chapter 5 it was explained how the LabVIEW® program has a cycle that runs every 30 ms and, as mentioned before, each stroke is performed in 500 ms. This means that, for a sliding length of $l = 20$ mm the software acquires about 17 points of each parameter, which corresponds to almost a point for every millimeter that axis 1 moves. Looking at the peak values of the curves in Figure 7.12 and Figure 7.13, one can see...
that the resolution is fairly low and the real trend is not well described. Especially the maximum drawing force is important to monitor since it should be kept below a certain value to avoid strip fracture. The “large” cycle time in LabVIEW® affects not only the acquisition of data but also the signals that the program sends to the PLC. For example the function, which increases the back tension throughout the stroke, is implemented in LabVIEW®. The software will then send an updated increased back tension in each cycle.

In the next section the BUT tests results are presented. The main parameters acquired during the test, which are useful for evaluating a tribo-system, are the torque on the tool pin and the drawing force of axis 1. In the following, these two results will be plotted as a function of the number of strokes. In these tests the LabVIEW® program calculates the average value of the force and torque excluding the acceleration and deceleration parts of every stroke. The following shows an example. The software acquires the torque curves in Figure 7.13. Then it filters the data removing the initial peak and the drop at the end of the each stroke. What remains are three plateaus, which contain few data points. The average of the points in each plateau is then calculated obtaining one point for each plateau. This is displayed as the torque of the stroke. The same procedure is applied to the drawing force.

Furthermore pictures of the tool surfaces will be shown and discussed. The pictures show the two edges where the strip initiated contact with the tool and where it exits the tool. In Figure 7.14a an outline of the process is shown. The two arrows indicate the zones, where the pictures are taken (the reader should remember that the strip moves...
from bottom to top). Figure 7.14b shows the exit edge of a tested tool surface. The arrow indicates the edge, where the strip leaves the contact. This can also be noticed from the pick-up lump since it terminates exactly on the edge.

Figure 7.14. a) model of the BUT process. The two arrows indicate where pictures are taken with the microscope; b) LOM picture of a tool exit edges with pick-up. The two figures do not have the same scale.

7.3 Test results

In the spring 2012 preliminary BUT tests were run on the UST2. The first tests were performed on DP 800 workpiece material and Vanadis® 4 Extra tool material testing the anticorrosive pre-lubrication (Shell Ensis PQ144), which SSAB applies. This tribo-system is not in the experimental plan list of tribo-systems and it was only tested to verify the functionality of the UST2. However interesting results were obtained and they are here briefly shown. The lubricant film applied by SSAB is fairly thin and extra lubricant was added to the strip surface using the felt rolls of the UST2. Figure 7.15 shows the torque and drawing force as a function of the number of strokes. The torque presents an almost constant trend for the 1500 strokes, which indicates no apparent lubrication failure. The drawing force has a slight increasing trend, which indicates that something happened at the interface tool/workpiece. Figure 7.16 shows two detailed views of the exit edge taken with a Light Optical Microscope (LOM). The pictures show clear sign of pick-up on the tool surface. It is interesting to notice how the pick-up develops probably starting from the exit edge and slowly building up towards the entrance edge and at the same time it expands laterally producing the characteristic upside-down pyramidal shape. This is in agreement with the numerical simulation since the highest normal pressure is found at the exit edge. This amount of pick-up would be considered unacceptable in the production process because it has grown too fast, i.e. within 1500 strokes. Figure 7.15 and Figure 7.16 are somehow in disagreement because the torque is almost constant whereas the pictures show clear sign of pick-up. This illustrates that the BUT test needs more than one parameter to describe what happens in
the contact area. An explanation could be that the torque has already a fairly high value due to the high friction stress and the pick-up contribution is small and therefore undetectable by torque measurement.

In Figure 7.16 it is possible to see the horizontal polishing texture. This means that the strip slide perpendicular to the texture exactly as it happens in the redrawning process. As mentioned in Chapter 3 this should help entrapping the lubricant and ensuring a constant film thickness.

![Figure 7.15. DP 800 tested with Vanadis® 4 Extra and Shell Ensis PQ144: a) torque and b) drawing force.](image)

![Figure 7.16. LOM pictures of BUT tool surface. DP 800 material on Vanadis® 4 Extra tested with Shell Ensis PQ144. Sliding of the strip occurs from bottom to top.](image)

After solving all these issues on testing procedures, the screening test campaign started with the selected tribo-systems. In this test campaign the experiments were carried out applying a constant back tension since the implementation of the algorithm with increasing back tension was only developed later in the project. The first tests were performed selecting the same test rate as in production of the EL-TUBE tool: 40 strokes/min. This gave an impression of how the tribo-systems behave. In Chapter 3 the
experimental plan was presented describing the tribo-systems that will be tested. Table 3.4 is here reported again (now Table 7.1).

Table 7.1. Table of experiments. V4E = Vanadis® 4 Extra; V40 = Vancron® 40.

<table>
<thead>
<tr>
<th>Lubricants</th>
<th>Workpiece materials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EN 1.4301</td>
</tr>
<tr>
<td>Anticorital</td>
<td></td>
</tr>
<tr>
<td>3802-39 S</td>
<td></td>
</tr>
<tr>
<td>Anticorital</td>
<td></td>
</tr>
<tr>
<td>PLS 100 T</td>
<td></td>
</tr>
<tr>
<td>Rhenus SU 166 A</td>
<td>V4E</td>
</tr>
</tbody>
</table>

Figure 7.17 shows the torque and drawing force development of the tribo system DP800-V4E-Fuchs3802-39S. Both torque and force have a constant trend indicating that no critical amount of pick-up occurred. However the strip fractured after about 400 strokes. Figure 7.18a and b show the exit and the entrance edges of the tool respectively. The white frames in the pictures indicate where contact occurred. The area in the frames seems to be slightly covered with material but it is difficult to assess it in the LOM. The bright area in Figure 7.18a is just a reflection of the microscope light but it shows clearly that no contact was established with the strip there, since the polishing texture is perfectly visible. This verifies what was noticed in the numerical analysis, where a small gap was detected between strip and tool. Since the pictures show that there is no significant amount of pick-up on the surface, it is believed that the fracture is due to a sudden increase of the drawing force. The test was repeated with a new tool but the strip fractured again after about 100 strokes. These results do not give enough information about the tribo-system. It is not possible to categorize it as good, poor or questionable. The test was performed again applying the revised procedure with an increasing back tension. This solved the fracture problem. The results are presented in the next section.

The drawing force curve Figure 7.17 fluctuates with the same amplitude throughout the test. It was found out that it is due to a small misalignment of the carriage of axis 1. The misalignment induces a small distortion of the carriage and it affects the load cell measurement. This is considered a systematic error that does not affect the result. The error is basically a change of offset of the force. Unfortunately it was not possible to repair the UST2 and it was decided not to correct the error in the data. In fact the important result from the graph is the trend and not the absolute value of the force. Moreover an investigation of the misalignment showed that the error is constant.
Figure 7.17. DP 800, Vanadis® 4 Extra (V4E), Fuchs 3802-39S (F1): a) torque and b) drawing force.

Figure 7.18. LOM pictures of BUT tool surface. DP 800 material on Vanadis® 4 Extra tested with Fuchs 3802-39S: a) exit edge, b) entrance edge. Sliding of the strip occurs from bottom to top. The frames indicate where contact occurred.

Figure 7.19 shows the torque and drawing force development of the tribo-system DP800-V40-Fuchs3802-39S. Both torque and force have a constant trend indicating that no critical amount of pick-up occurred. Figure 7.20 shows the tool surface. In this case it was possible to run 1500 strokes without any failure. As for the previous tribo-system, there is no significant pick-up on the surface. In this case the tribo-system is considered good. The fact that the strip did not fracture in this test could be explained with the hypothesis that Vancron® 40 has a lower friction than Vanadis® 4 Extra. This could lower the contribution of friction to the drawing force, especially during the acceleration.
Figure 7.19. DP 800, Vancron® 40 (V40), Fuchs 3802-39S (F1): a) torque and b) drawing force.

Figure 7.20. LOM pictures of BUT tool surface. DP 800 material on Vancron® 40 tested with Fuchs 3802-39S: a) exit edge, b) entrance edge. Sliding of the strip occurs from bottom to top. The frames indicate where contact occurred.

Figure 7.21 shows the torque and drawing force for the tribo system DP800-V4E-FuchsPLS-100-T. The two parameters have constant trend throughout the test. Figure 7.22a and b show the tool surface, where small amount of pick-up is visible. This test is considered successful and the tribo-system is classified as good since torque and force are constant and the tool surface does not present critical amount of pick-up.

Figure 7.23 shows the torque and drawing force development of the tribo-system: DP800-V40-FuchsPLS-100-T. As for the previous test, the two graphs are constant indicating no critical amount of pick-up. The drawing force does not have the same fluctuation discussed above, because data were acquired only for every 10 strokes. Figure 7.24 shows the tool surface. The frame in Figure 7.24a indicates a scratch on the surface, which can be caused by a hard particle (dirt) from external source. It is interesting to notice that, even though this particle damaged the surface, lubrication continues to avoid any building up of pick-up. Besides this “small damage”, the surface looks free from any critical amount of pick-up. This tribo-system is considered good.
Figure 7.21. DP 800, Vanadis® 4 Extra (V4E), Fuchs PLS 100 T (F2): a) torque and b) drawing force.

Figure 7.22. LOM pictures of BUT tool surface. DP 800 material on Vanadis® 4 Extra tested with Fuchs PLS 100 T: a) exit edge, b) entrance edge. Sliding of the strip occurs from bottom to top. The frames indicate where contact occurred.

Figure 7.25 shows the tool surface investigated in a Scanning Electron Microscope (SEM). It is interesting to see that DP 800 forms “micro-pick-up” on the tool surface without causing severe wear. In fact the pictures clearly show the polished texture, along vertical direction underneath the pick-up with no sign of scratches along the sliding direction. It is believed that a thin transfer layer is formed preventing fast growth of pick-up, since DP 800 is probably not very affinity to itself. Moreover it helps to preserve the tool surface from abrasive wear. From the plain strain compression test it was clear that this material does not exhibit large work hardening. This means that the hardness of the pick-up is not much higher than the original material. This can explain why there are practically no scratches on the tool surface.
Chapter 7 - Bending Under Tension (BUT) tests

**Figure 7.23.** DP 800, Vancron® 40 (V40), Fuchs PLS 100 T (F2): a) torque and b) drawing force.

**Figure 7.24.** LOM pictures of BUT tool surface. DP 800 material on Vancron® 40 tested with Fuchs PLS 100 T: a) exit edge, b) entrance edge. Sliding of the strip occurs from bottom to top. The frame indicates a scratch.

**Figure 7.25.** SEM pictures of Vancron® 40 (V40) tool surface. The strip slides from left to right: a) micro-pick-up of DP 800, b) detailed view.
Figure 7.26 shows the torque and force development of the tribo-system EN1.4307-V4E-RhenusSU166A. Both graphs present an increase during the first 200 strokes. After that the curves become horizontal. This is probably due to a first generation of micro pick-up transfer layer, which becomes stable after about 200 strokes. In this test the back tension was set constant to $\sigma_b = 200$ MPa. The back tension measured by the load cell in axis 2 gave a value corresponding to $\sigma_b = 170$ MPa. Figure 7.27 shows the tool surface. It is clear that a transfer layer has formed. The polishing texture has almost disappeared especially at the entrance edge. However the pick-up is defined as no critical. Therefore the tribo-system is considered good.

![Figure 7.26](image1)

**Figure 7.26.** EN 1.4307, Vanadis® 4 Extra (V4E), Rhenus SU 166 A (Rh): a) torque and b) drawing force.

![Figure 7.27](image2)

**Figure 7.27.** LOM pictures of BUT tool surface. EN 1.4307 material on Vanadis® 4 Extra tested with Rhenus SU 166 A: a) exit edge, b) entrance edge. Sliding of the strip occurs from bottom to top. The frames indicate contact with the strip.

Figure 7.28 shows the torque and force development of the tribo-system EN1.4307-V40-RhenusSU166A. The test was stopped after 1255 strokes because the coil strip was not long enough. The test is anyway considered reliable since more than 80% of the
1500 strokes limit was achieved and also because the results are almost identical with the previous tribo-system. The torque showed high fluctuations. The cause for this is not clear but it seems not to affect the performance of the tribo-system, which is considered good. Further tests results will be shown later confirming that the tribo-system has excellent performance. Figure 7.30a shows a SEM picture of the exit edge. The strip slides from right to left. In the picture, a fairly large scratch has formed on the surface. This is probably due to the adhesive wear of work hardened workpiece material. In fact the tool surface around the scratch is covered with a thin layer of pick-up, which can initiate the adhesive wear mechanism. Figure 7.30b shows another area of the exit edge where scratches are also present. In this case it seems that the scratches are created by abrasive plowing. The grooves are too wide to be caused by tool particles, which could detach from the matrix. Looking at the number of scratches it could likely be extremely work-hardened particles of workpiece material, which work as abrasive tool. Compared to the DP 800, EN 1.4307 creates a more homogenous transfer layer pick-up on the tool surface, and the work hardening effect can indeed explain the plowing.

![Figure 7.28](image1.png)

**Figure 7.28.** EN 1.4307, Vancron® 40 (V40), Rhenus SU 166 A (Rh): a) torque and b) drawing force.

![Figure 7.29](image2.png)

**Figure 7.29.** LOM pictures of BUT tool surface. EN 1.4307 material on Vancron® 40 tested with Rhenus SU 166 A: a) exit edge, b) entrance edge. Sliding of the strip occurs from bottom to top. The frames indicate contact with the strip.
Figure 7.30. SEM pictures of Vancron® 40 (V40) tool surface tested with EN 1.4307. The strip slides from right to left: a) deep scratch generated by wear on the tool curvature (exit edge) and b) small scratches on the curvature generated by the strip.

Figure 7.31 shows the torque and force development of the tribo-system EN1.4162-V40-RhenusSU166A. In this test a problem arose with the acquisition system, which implied that the absolute value of the torque is wrong. However the trend is correct and it shows an increase after about 800 strokes. The test was stopped after 1050 strokes. The increasing trend in the torque and force clearly indicate that pick-up was formed on the tool. Figure 7.32 verifies this. The amount of pick-up is definitely beyond the critical one, and the tribo-system is defined as poor. It is interesting to notice that pick-up is formed on both entrance and exit edges. This means that the tribo-system is likely to fail even at low normal pressure.

Figure 7.31. EN 1.4162, Vancron® 40 (V40), Rhenus SU 166 A (Rh): a) torque and b) drawing force.
Chapter 7 - Bending Under Tension (BUT) tests

Figure 7.32. LOM pictures of BUT tool surface. EN 1.4162 material on Vancron® 40 tested with Rhenus SU 166 A: a) exit edge, b) entrance edge. Sliding of the strip occurs from bottom to top. The frames indicate contact with the strip.

Figure 7.33 shows SEM pictures of another Vancron® 40 tool surface tested under the same conditions. In Figure 7.33a the curvature is shown, where the strip slides from right to left. Large amount of pick-up is clearly visible. Figure 7.33b shows a detail of the exit edge zone where contact pressure is highest. The pick-up grows faster in this area yielding a thicker layer (10-20 µm) of pick-up. Figure 7.33c shows a detailed view of the red frame in figure b, just ahead of severe pick-up. Here the workpiece material is deposited as a thin layer (about 1 µm). It is interesting to notice that the tool surface, in this area, is completely covered by pick-up. Compared with what was seen for the DP 800, it seems that the stainless steel has larger affinity to the tool matrix and itself. However EN 1.4162 does not cause the characteristic scratches on the tool surface as EN 1.4307. It is therefore assumed that EN 1.4307 can reach much higher hardness than EN 1.4162 due to work-hardening. Figure 7.33d shows a magnification of the entrance edge. Here the pressure is much lower and the pick-up is less pronounced, since it is still possible to see the polished texture in vertical direction.
Chapter 7 - Bending Under Tension (BUT) tests

Figure 7.33. SEM pictures of Vancron® 40 (V40) tool surface tested with EN 1.4162. The strip slides from right to left: a) curvature of the tool with pick-up, b) detailed view of the exit edge, c) detailed view of pick-up layer (the picture refers to the red frame in fig. b), d) micro-pick-up at the entrance edge.

Figure 7.34 shows the torque and force development of the tribo-system EN1.4162-V4E-RhenusSU166A. In this case the back tension was reduced to $\sigma_b = 100$ MPa because the previous test showed massive pick-up and it has been seen from all previous tests that there is no big difference between the two tool materials. As for the previous case the absolute value of the torque is wrong due to a problem with the acquisition system. The trend is however correct and it shows an increase after about 1000 strokes. The test was stopped after 1100 strokes. The increasing trend in the torque and force clearly show that pick-up formed on the tool. Figure 7.35 shows the massive pick-up formed on the tool. The tribo-system is therefore considered poor.
Chapter 7 - Bending Under Tension (BUT) tests

Figure 7.34. EN 1.4162, Vanadis® 4 Extra (V4E), Rhenus SU 166 A (Rh): a) torque and b) drawing force.

Figure 7.35. LOM pictures of BUT tool surface. EN 1.4162 material on Vanadis® 4 Extra tested with Rhenus SU 166 A: a) exit edge, b) entrance edge. Sliding of the strip occurs from bottom to top. The frames indicate contact with the strip.

The tests with DP800-V4E-Fuchs3802-39S showed that the lubricant leads to a lower friction than Fuchs oil PLS 100 T. Due to limited time, the screening tests with workpiece material 1200 MZE therefore focused only on Fuchs oil PLS 100 T. In the tests with this material, a constant back tension of $\sigma_b = 350$ MPa was applied as target value. The back tension force measured during the test shows that the real value is about $\sigma_b = 300$ MPa. A test with $\sigma_b = 400$ MPa was also tried but the strip fractured. Figure 7.36 shows the torque and force for the tribo-system 1200MZE-V4E-FuchsPLS100T. In this case the two parameters are constant indicating that no severe galling occurred. Figure 7.37 shows some pick-up formation on the tool surface. The transfer layer is zinc from the galvanized coating. At first glance there could be doubt on whether the amount is considered critical or not. After discussing the results with Grundfos it was decided that the pick-up is close to the limit but acceptable. The tribo-system was therefore approved for production tests.
Chapter 7 - Bending Under Tension (BUT) tests

Figure 7.36. 1200 MZE, Vanadis® 4 Extra (V4E), Fuchs PLS 100 T (F2): a) torque and b) drawing force.

Figure 7.37. LOM pictures of BUT tool surface. 1200 MZE material on Vanadis® 4 Extra tested with Fuchs PLS 100 T: a) exit edge, b) entrance edge. Sliding of the strip occurs from bottom to top. The frames indicate contact with the strip.

Figure 7.38 shows the torque and force development for the tribo-system 1200MZE-V40-FuchsPLS100T. As for the previous test the two parameters are constant indicating no critical galling. Figure 7.39 shows the tool surface. In this case only slight pick-up is noticed on the contact area. This tribo-system was therefore considered good. Figure 7.40 shows the SEM investigation of the tool surface. As seen for the DP 800 material, it seems that a transfer layer of 1200 MZE is deposited on the tool surface. In this case the layer seems to be thicker. The subsequent new material from the strip slides on the transfer layer. It is believed that the pick-up is zinc and zinc oxides from the electro galvanized coating of the strip, which does not cause scratches in the tool surface as was seen for the stainless steel.
Chapter 7 - Bending Under Tension (BUT) tests

**Figure 7.38.** 1200 MZE, Vancron® 40 (V40), Fuchs PLS 100 T (F2): a) torque and b) drawing force.

**Figure 7.39.** LOM pictures of BUT tool surface. 1200 MZE material on Vancron® 40 tested with Fuchs PLS 100 T: a) exit edge, b) entrance edge. Sliding of the strip occurs from bottom to top. The frames indicate contact with the strip.

**Figure 7.40.** SEM pictures of Vancron® 40 (V40) tool surface (exit edge). The strip slides from left to right: a) micro-pick-up of 1200 MZE, b) detailed view.
7.4 Discussion and conclusion

In this chapter the BUT tests were discussed and analyzed numerically and experimentally. The numerical investigation focused on a 2D model, where the main goal was to calibrate the back tension in order to have the same normal pressure, at the interface workpiece/tool, as in the production process. The first results showed that the traditional 90° curvature of a BUT tool limits the achievable normal pressure. It was then proposed to modify the tool geometry implementing a 45° of a curvature in order to reach higher pressure. The new geometry is fairly easy to produce and the numerical results proved that the new tool can indeed result in much higher pressure. Unfortunately the limitation on the back tension does not allow reaching the same value of the maximum normal pressure 1600 MPa as in the production tool. However the values are above $\sigma_b = 1000$ MPa which is considered high enough to severely stress the lubrication.

The first evident result from the test campaign is that there seems to be small difference between the two tool materials as regard anti-galling properties. It should be pointed out, however, that the number of strokes is limited to 1500 and more significant difference could appear at higher test volume. In fact tests done on deep drawing showed better performance of Vancron® 40 after hundred thousands of produced parts [130]. The screening test campaign has shown that DP 800 material has low tendency to form pick-up on the tool surface. The Fuchs oil PLS 100 T, which has higher viscosity than Fuchs 3802-39S, gave positive results when tested with DP 800 and both tool materials. Fuchs 3802-39S did not show poor performance but it was not possible to run tests with Vanadis® 4 Extra and DP 800 since fracture occurred.

Tests with EN 1.4307 showed no critical amount of pick-up and no difference between the two tool materials. Both tribo-systems were therefore considered good. Tests with EN 1.4162 material showed poor but interesting results because it failed even when back tension was lowered to $\sigma_b = 100$ MPa. A first hypothesis to explain the failure is that the material is manufactured with a surface texture (2E) that does not enhance micro hydro dynamic lubrication. The surface is grind at the mill in order to remove all scales formed during heat treatment processes. The texture presents grooves parallel to the sliding direction and these allow lubricant escape when in contact with the tool surface.

The test on 1200 MZE material were conducted only with Fuchs oil PLS 100 T, using the 45° curvature. The results showed some pick-up on the tool surface but the amount was not enough to be detected from the torque measurements.
Chapter 8  Comprehensive BUT test campaign

This chapter deals with the BUT tests. A more comprehensive test campaign is presented and discussed. The results show that the tribo-systems with DP 800 and EN 1.4307 materials have a fairly large working window, whereas the tests with EN 1.4162 fail even under mild conditions. Tests with 1200 MZE material were limited in number since production tests were not possible to carry out due to lack of formability of the material. At the end of the chapter the temperature in the process is analyzed numerically and compared with experimental results.

8.1 Experimental tests

In the previous chapter, the screening campaign has given an understanding of how the proposed tribo-systems perform, when tested with BUT test. According to the methodology, a more extensive test campaign will characterize the working window of each tribo-system. In the following, tests are presented to give a better picture of how the tribo-systems behave.

As reference for the performance of the new tribo-systems, a parallel test was run using Iloform PN 226 chlorinated paraffin oil, which is currently applied in the production process. The test was conducted on material EN 1.4307 and Vanadis® 4 Extra (tribo-system EN1.4307-V4E-PN226) with a constant back tension of $\sigma_b = 200$ MPa. Figure 8.1 shows the torque and drawing force development in the two tests with Iloform and Rhenus oils. The graphs show a good agreement: the torque curves have the same constant values and so has the force curves. Figure 8.2 compares the tool surfaces of the two tests. These pictures also display a good agreement, since the amount of pick-up on the surface seems to be more or less the same.
Figure 8.1. Torque and drawing force for EN 1.4307, Vanadis® 4 Extra (V4E): a) and b) Iloform PN 226 (PN226), c) and d) Rhenus SU 166 A.

Figure 8.2. LOM pictures of BUT tool surface. EN 1.4307 material on Vanadis® 4 Extra tested with: a) exit edge, b) entrance edge (Iloform PN 226), c) exit edge, d) entrance edge (Rhenus SU 166 A). Sliding of the strip occurs from bottom to top. The frames indicate contact with the strip.
At this point it was decided to implement the algorithm in the LabVIEW® program, which ensured an increasing back tension throughout the stroke. The tests with the tribo-system DP800-V4E-Fuchs3802-39S were then repeated with the new program. The target back tension was set to $\sigma_b = 350$ MPa and the program applies 80% at the beginning of the stroke increasing to 100% at the end. Figure 8.3 shows the torque and force graphs. Also in this case the two curves are constant throughout the test. With the new program it was possible to run 1500 strokes without any fracture. This means that the problem in the screening test was indeed the peak of force during the acceleration phase. Figure 8.4 shows the tool surface and clearly no critical amount of pick-up is visible.

![Figure 8.3](image1.png)

**Figure 8.3.** DP 800, Vanadis® 4 Extra (V4E), Fuchs 3802-39S (F1): a) torque and b) drawing force.

![Figure 8.4](image2.png)

**Figure 8.4.** LOM pictures of BUT tool surface. DP 800 material on Vanadis® 4 Extra tested with Fuchs 3802-39S: a) exit edge, b) entrance edge. Sliding of the strip occurs from bottom to top. The frames indicate contact with the strip.

The test with the two workpiece materials DP 800 and EN 1.4307 were selected for further investigation of the limits of lubrication since they were defined as good tribo-systems. First of all the same tests performed in the screening step were run again with
an increased production rate for tribo-systems with DP 800 and EN 1.4307. The idle time between strokes was decreased to less than half second and the test production rate was increased from 40 spm to 95 spm, which is the maximum rate achievable with a sliding length $l = 20 \text{ mm}$ and sliding speed $s = 50 \text{ mm/s}$. All tests at this test rate were successful, i.e. torque as well as drawing force were constant and inspection of the tool surfaces showed no significant pick-up.

Besides an increase of the test rate, two other parameters were changed to analyze the working window of the tribo-systems: the sliding length and the tool rest temperature. A complete characterization of the working window requires a quite substantial amount of tests if all possible process parameters are to be included. The graph showing the limits of lubrication in Figure 4.4 has therefore to be interpreted as a guideline and not necessarily determined in full, especially since the remaining time in the present project was limited. The following experiments focus only on the aforementioned two workpiece materials and only on tool material Vancron® 40.

The tribo-system DP800-V40-Fuchs3802-39S showed very good performance in the previous tests, indicating that the working window is probably fairly large. It was therefore decided to start the investigation with severe process conditions, i.e. long sliding length, high sliding speed and tool rest temperature. The sliding length was set equal to $l = 100 \text{ mm}$ and the sliding speed was increased to $s = 80 \text{ mm/s}$. The back tension was set constant to $\sigma_b = 300 \text{ MPa}$. The acceleration time was increased to $a_1 = 500 \text{ ms}$. This allows reducing the peak of force, which implies that the old program, where the back tension is kept constant could be used. This configuration stresses the lubrication more than when increasing back tension is used, because high normal pressure is achieved for a longer sliding length. The tool rest temperature was increased by recirculating water at 80°C inside the tool holder. With this method the rest temperature of the BUT tool pin reaches a value of about 60°C. The lower value is due to heat loss to the environment. Figure 8.5 shows the torque and force results. The curves show a little increase after approximately 1000 strokes, but the micrographs in Figure 8.6 show a very clean tool surface. With such a sliding length and sliding speed the test rate naturally decreased to approximately 35 strokes/min.

The results show how efficient the tribo-system is. A sliding length of $l = 100 \text{ mm}$ is 5 times the height of the EL-TUBE component. In the author opinion, this proves that the tribo-system has great potential and should be tried in production. Another test was performed with sliding length up to $l = 200 \text{ mm}$ and sliding speed $s = 100 \text{ mm/s}$. Only 600 strokes were run since the production rate decreased below 30 strokes/min resulting in a long running time. The results were again successful.
Figure 8.5. DP 800, Vancron® 40 (V40), Fuchs 3802-39S (F1): a) torque and b) drawing force.

Figure 8.6. LOM pictures of BUT tool surface. DP 800 material on Vancron® 40 tested with Fuchs 3802-39S: a) exit edge, b) entrance edge. Sliding of the strip occurs from bottom to top. The frames indicate contact with the strip.

Figure 8.7 shows the torque and force development of the tribo-system EN1.4307-V40-RhenusSU166A. Since stainless steel is more prone to galling formation, it was decided to apply an increasing back tension profile instead of a constant one. The target value was set to \( \sigma_b = 200 \) MPa. The sliding length was \( l = 100 \) mm and sliding speed \( s = 80 \) mm/s. No heating of the tool holder was applied. The test was run up to 100 strokes to accelerate the procedure. The results show that no critical amount of pick-up occurred. Both torque and force are constant and the tool surface in Figure 8.8 shows no significant pick-up formation.

Further tests were run with sliding length \( l = 20 \) mm and sliding speed \( s = 50 \) mm/s, with a tool rest temperature of 60°C. Again successful results were achieved with no galling.
Even though the test with EN1.4162 showed that the material is very much prone to galling formation, it was decided to investigate the working window in detail. First of all it should be reminded that the new BUT tool geometry stresses the lubricant severely and that most industrial applications, using this material, have milder conditions. It was therefore decided to increase the radius of curvature of the tool pin to $R = 5\, \text{mm}$, i.e. a circular, cylindrical tool pin with diameter $\phi 10\, \text{mm}$. In this way the contact area will be larger and distributed on a 90° curvature, decreasing the normal pressure considerably. It was realized that it is difficult to polish such a tool along the longitudinal direction. Due to its cylindrical shape it is much easier to mount the tool on a spindle and spin it while polishing. However the circumferential texture would not enhance the micro hydrodynamic lubrication mechanism. A new polishing pattern was therefore introduced with crossing grooves about 45° with respect to the circumference. This is fairly easy to produce: the tool pin is spun and the operator polishes the surface moving the polishing tool (emery paper for example) forth and back along the spinning axis.
On the suggestion of Grundfos a new lubricant was tested. It is a high viscosity version of the Rhenus oil tested in the previous tests. The new lubricant is Rhenus LA 722086 with a viscosity $v = 800 \, \text{mm}^2/\text{s}$ at $40^\circ\text{C}$. Grundfos had already obtained interesting results with this product, and it is believed that the good performances were due to the high viscosity.

A series of tests were carried out with the tribo-system EN1.4162-V40-RhenusLA722086. Figure 8.9 shows an example of a test where galling clearly has occurred. The sliding length was $l = 20 \, \text{mm}$ and the sliding speed $s = 30 \, \text{mm/s}$. The torque suddenly shifts to higher value and it was noticed that pick-up built up very fast in few strokes. After galling had formed the torque remains constant. This is in contradiction to the slowly increasing trend seen in the screening tests, with the $45^\circ$ curvature tool. In all these tests the pick-up appeared as a localized lumped mass on the tool surface, which always starts from the exit edge, in this case around $60^\circ$. Figure 8.10a shows an example of the localized pick-up on the tool surface. In Figure 8.10b it is also possible to see the crossed texture from the polishing operation. Plotting the critical sliding length before galling as a function of sliding speed, Figure 8.11, it is interesting to notice that a linear relation appears. The critical sliding length is determined as the sliding length $l$ per stroke multiplied by the number of strokes until lubrication fails (the limit being assessed from the torque measurement). It is noticed that higher speed enables to run a longer total sliding length. This strengthens the hypothesis that hydrodynamic lubrication plays an important role. Figure 8.12 compares the torque of four different tests, in which the target back tension was the same for all cases. The graph indicates that higher sliding speed lowers the torque, i.e. the friction is lower.

Figure 8.9. EN 1.4162, Vancron® 40 (V40), Rhenus LA 722086 (Rh2): a) torque and b) drawing force.
Figure 8.10. LOM pictures of BUT tool surface. EN 1.4162 material on Vancro** 40 tested with Rhenus LA 722086: a) severe pick-up on exit edge, b) view of the crossed texture. Sliding of the strip occurs from bottom to top.

Figure 8.11. Linear relationship between limit of lubrication and sliding speed.
Figure 8.12. Comparison between torque of different tests (EN 1.4162, V40 and Rh2). The graph has the sliding speed as parameter.

A nether interesting fact supporting the hypothesis is that pick-up never formed at the edges of the strip. Figure 8.13 shows a detailed view of the strip edge. It is noticed that the strip surface is smoother at the edges having an almost completely flat surface topography, probably creating closed pockets, which enhances micro hydrodynamic lubrication. Galling occurs at the center of the strip and is enhanced by distinct longitudinal strip texture. Figure 8.14 shows a 3D mapping of a small area in the middle of the strip, after testing. The mapping was done utilizing SPIPTM software. The top left picture is the top view of the strip taken in Alicona optical microscope. The sliding occurred from right to left (axis X indicated). The picture at the top right corner shows the 3D mapping of the surface. It is possible to identify the grooves along the X axis. For a better visualization, the transverse profile is plotted in the bottom picture. The profile represents the surface along the Y axis as an average between the two white lines in the top left picture. The black arrows indicate some of the deep grooves. Figure 8.15 compares the texture of EN 1.4307 and EN 1.4162 before testing. In this case the measurement was taken with a profilometer FTS Taylor Hobson. It is clear that the austenitic grade has a random texture, whereas the lean duplex presents a directional pattern as described in Figure 8.14. As mentioned in the previous chapter the oriented texture is produced at the mill by grinding, which removes all scales from the surface. In fact, for this particular type of steel, pickling does not remove scales efficiently and the grinding is therefore necessary. As mentioned in the introduction, a random texture is preferable in sheet metal forming, since it enhances the micro hydrodynamic lubrication due to the micro pockets, which entrap the lubricant and create a thin lubricant film separating the tool/workpiece interface.
Figure 8.13. Detailed view of the strip edge: the white arrows indicate the grooves that still remain from the virgin texture of the EN 1.4162 material. The last 0.5 mm before the edge presents a smooth texture with no grooves. Sliding occurs from bottom to top.

Figure 8.14. Topography of EN 1.4162 strip surface after testing and relative profile generated in SPIP™.
The BUT tests with the increased radius of curvature have shown that the tribological condition of the tribo-system presented above are more critical than expected. Other tested were performed besides the one presented here, increasing the idle time between strokes without achieving better results. Galling and pick-up occurred within the 1500 strokes limit for all cases but one. The only test where the tribo-system did not fail was run with $l = 50\,\text{mm}$, $s = 50\,\text{mm/s}$ and low back tension $\sigma_b = 100\,\text{MPa}$. Even though no critical amount of pick-up occurred, this does not mean that the limit of the lubrication is found. In fact the test was repeated and the tribo-system failed. Figure 8.16 shows the tool surface of the successful test. The exit edge presents no sign of pick-up and the polished texture is still visible. On the other hand on the entrance edge the texture is completely covered by a transfer layer. The layer is very thin and therefore considered acceptable.

The performance of 1200 MZE material was tested with the two different Fuchs oils. This was done with the larger radius since the small radius $R = 3.5\,\text{mm}$ applied earlier is
not common in deep drawing. Moreover, redrawing is not common in this material. In these test only 1000 strokes were carried out since no lubricant breakdown was expected. The test was repeated twice and the same results were obtained. Figure 8.17a and b shows the torque for the two tribo-systems 1200MZE-V40-Fuchs3802-39S and FuchsPLS100T. Even though the torque fluctuates considerably, the average value remains constant around 6-7 Nm for both tests. Figure 8.18 shows the tool surface of the two tests. As expected the amount of pick-up is negligible although the tool tested with Fuchs PLS 100 T seems to have slightly more pick-up than the other.

**Figure 8.17.** Torque of tribo-systems 1200 MZE, Vancron® 40 (V40): a) Fuchs 3802-39S (F1) and b) Fuchs PLS 100 T.

**Figure 8.18.** LOM pictures of BUT tool surface. 1200 MZE material on Vancron® 40 tested with: a) Fuchs 3802-39S and b) Fuchs PLS 100 T. Sliding of the strip occurs from bottom to top. The frames indicate contact with the strip.

### 8.2 EN1.4162-PVDcoatedtool-RhenusLA722086

The special surface texture of EN 1.4162 material turned out to influence the tribological performance in sheet metal forming significantly. To solve the problem it was suggested to try TiAlN PVD coating on the BUT tool with radius of curvature \( R = \)
5 mm. The tool material was Vancron® 40 and the lubricant Rhenus LA 722086. The target back tension was set $\sigma_b = 100 \text{ MPa}$. Figure 8.19 shows the torque and force of a test run with sliding speed $s = 5 \text{ mm/s}$, which caused galling without PVD coating in a previous test. In this case both torque and force are constant. Comparing the torque with the ones in Figure 8.12 it is noticed to lie between the curve for $s = 5$ and 10 mm/s as expected. The PVD coating does not affect the hydrodynamic lubrication mechanism, but it prevents the formation of pick-up. Figure 8.20 shows the tool surface at the exit and entrance edges. Very tiny particle of pick-up are present at the entrance edge, which would be considered acceptable in production. This means that the tribo-system now can be considered good.

![Figure 8.19. EN 1.4162, Vancron® 40 TiAlN PVD coated (V40_PVD), Rhenus LA 722086 (Rh2), $l = 5 \text{ mm}, s = 5 \text{ mm/s and } \sigma_b = 100 \text{ MPa}: a) torque and b) drawing force.](image)

![Figure 8.20. LOM pictures of BUT tool surface. EN 1.4162 material on TiAlN PVD coated Vancron® 40 tested with Rhenus SU 166 A: a) exit edge, b) entrance edge. Sliding of the strip occurs from bottom to top. The frames indicate contact with the strip.](image)

The surprising results obtained with the PVD coating increased the confidence to the performance of the new tribo-system. It was therefore decided to perform a test with a
back tension $\sigma_b = 200$ MPa, sliding length $l = 50$ mm and sliding speed $s = 50$ mm/s. The test was successfully performed to 1500 strokes without any significant galling. Figure 8.21 shows the torque and drawing force of the test. The curve increases slightly in the first 700 strokes after which it becomes steady state. In this case the torque is of course higher if compared with the curve at same drawing speed 50 mm/s in Figure 8.12 because the back tension is doubled. It is however interesting to see that the average value is the same as in the previous test, where the back tension $\sigma_b = 100$ MPa. Figure 8.22a shows the exit edge of the tool. There is clearly no sign of pick-up, which is even better than the previous results, where tiny particle could be seen. Figure 8.22b shows the entrance edge. Here pick-up has formed as a more homogenous transfer layer, which is very thin and considered acceptable.

**Figure 8.21.** EN 1.4162, Vancron® 40 TiAlN PVD coated (V40_PVD), Rhenus LA 722086 (Rh2), $l = 50$ mm, $s = 50$ mm/s and $\sigma_b = 200$ MPa: a) torque and b) drawing force.

**Figure 8.22.** LOM pictures of BUT tool surface. EN 1.4162 material on TiAlN PVD coated Vancron® 40 tested with Rhenus SU 166 A: a) exit edge, b) entrance edge. Sliding of the strip occurs from bottom to top. The frames indicate contact with the strip.
8.3 Thermal analysis

It is well known that the temperature at the interface workpiece/tool affects the performance of a tribo-system. This is especially true when mineral oil is used because the viscosity diminishes at higher temperature leading to smaller film thickness at the contact interface. Prediction of limits of lubrication through the analysis of temperature at the interface workpiece/tool has been studied in the ironing process by Olsson [131]. The method is based on a measurement of the tool temperature as close as possible to the contact interface, a thermal numerical analysis of the process and a calibration of the thermal parameters comparing the numerical results with the experimental ones to obtain the temperature at the interface. This temperature can then be correlated to the performance of the tribo-system. There are of course many uncertainties and assumptions in the procedure otherwise the number of variable one should take into account would make the task too complex to solve. This is why the user should use the thermal analysis to get an impression of the temperature range is rather than to expect to find the correct value.

In this project, the thermal numerical analysis focused on the tribo-system DP800-V4E-FuchsPLS100T. First of all a local tool temperature in the BUT test was acquired. This was done through a thermocouple, which was welded close to the contact interface. One of the BUT tool pins was modified for the purpose. Based on the work of Olsson, two blind holes were machined in the BUT tool pin. The holes were ø2.2 mm and they cross each other as shown in the 3D CAD model in Figure 8.23a and b. A thermocouple type K was then inserted in each hole and percussion welded to the bottom of the hole, indicated by the red dot in Figure 8.23a. This means that the thermocouple measures the temperature at 2 mm distance from the exit edge of the curvature, where the normal pressure during testing is highest. Figure 8.23c shows a picture of the real tool with the thermocouple wires. The holes were placed in the center section of the tool. The thermocouple is connected to a dedicated acquisition card, which sends the data to LabVIEW®. The temperature is measured on the thermocouple closest to the working surface. One can see that this configuration does not allow turning the tool four times. Only two working surfaces are possible. Figure 8.23d shows an outline of the percussion welding operation of the thermocouple. The two wires of the thermocouple are bended around a copper tool pipe on opposite sides. This ensures that the temperature is measured at the bottom of the hole and avoid that the wires touch each other giving a erroneous value. The copper tool is a small tube, which press the wires to the bottom surface. A current is flown through it and melts the wires welding them on the tool surface. The copper tube is then removed.
Figure 8.23. a) half 3D CAD model of BUT tool (the red dot indicates the welding point of the thermocouple); b) detailed view of the symmetry section (the distance between the welding point of the thermocouple and the contact interface is indicated); c) picture of the real tool pin with thermocouple connection; d) outline of percussion welding operation of thermocouple.

Figure 8.24a shows the temperature trend as a function of the number of strokes for the tribo-system described above. The sliding length is $l = 20$ mm, sliding speed $s = 50$ mm/s, test rate equal to 40 strokes/min and constant back tension $\sigma_b = 300$ MPa. The temperature increases very fast in the first few strokes. After about 100 strokes the curve raises more slowly reaching almost 70°C at 1500 strokes. Steady state was not achieved but the absolute value increases about 1°C every 500 strokes. Figure 8.24b shows a detail of the temperature acquisition for one stroke taken after about 400 strokes. Unfortunately the acquisition system (hardware) has a maximum sampling rate of 14 Samples/s. This means that in this particular test only 7 points can be acquired in each stroke. However LabVIEW® has an acquisition rate higher than the hardware and that is why the curve presents flat plateaus. The temperature between strokes, during idle time, is not acquired. The curve shows a constant temperature in the first 10 mm sliding length. This is probably due to two factors: the slow heat flux that goes from the strip to the thermocouple through the contact interface and the heat capacity of the thermocouple. One of the main differences between the production process and the simulative test performed in the UST2 is that in the latter the two axes have a limited displacement. When they reach the end position they must return to the home position in order to start the test again. Unfortunately this means that the tool has time to cool
down, since no sliding takes place during the homing operation. Figure 8.24c shows the temperature for few strokes before and immediately after axis 1 and 2 returned at the home position. One can see that there is a consistent drop of about 9º. The homing time was measured to $t = 10$ s. The heat loss during homing means that the steady state temperature is lower than without homing. This of course lowers the severity of the process and may affect the results.

The objective of the numerical analysis is to determine the maximum temperature at the contact interface. Basically the 2D model used for the BUT test is utilized again enabling a coupled mechanical/thermal solution. In the BUT test there are two sources of heat: the plastic deformation of the strip and the frictional energy. Figure 8.25a shows the 2D model, where the tool holder was also modeled to account for the heat transfer from the tool pin to the holder. Figure 8.25b shows the detailed view of the curvature. The red dot indicates the approximate position of the thermocouple. In the calibration procedure the temperature of the node closest to the red dot is selected and compared with the experimental measurements. The thermal conductivity of the tool material Vancron® 40 is set constant $c = 21$ W/mK and for workpiece material DP 800 is $c = 47$ W/mK. The specific heat capacity is $c_p = 460$ J/kgK for tool material and $c_p = 480$
J/kgK for the workpiece material. The thermal parameters were given by SSAB and Uddeholm. The 2D model assumes adiabatic conditions in the third dimension.

Looking at the overall temperature measurement in Figure 8.24, three different transition states can be found: 1) the increase from room temperature to the steady state, 2) the increase of temperature in each stroke and 3) the increase of temperature after the homing operation.

![Figure 8.25. 2D thermal model of BUT test: a) complete model and b) detailed view of the contact interface. The red dot indicates the position where the thermocouple is welded in the real tool.](image)

It is now clarified that the temperature in the tool reaches a steady state after a certain number of strokes. It would be interesting to analyze the whole trend with a numerical model but this would imply that the simulation of a single stroke had to be repeated at least 1500 times. Even if a single stroke only takes about 5 minutes to solve, it still means that simulating 1500 strokes would take 125 hours. Besides the time factor, which already excludes the procedure, the model utilized is a simple 2D, which may introduce errors accumulating from stroke to stroke. The last but not less important challenge is the homing operation. The thermal model should simulate the temperature drop that occurs and this makes the model fairly complicated. It was therefore decided to simulate only a single stroke at a point in time, where the experimental temperature has achieved a steady state. This means that the initial temperature of the tool is not the room temperature. The first step in the analysis is to generate an initial temperature field, of the tool and tool holder, which corresponds to the beginning of the stroke. This is used as initial temperature in the coupled analysis. To do that a simple steady state
Chapter 8 - Comprehensive BUT test campaign

A thermal analysis can be carried out. This analysis solves the Laplace heat equation and calculates the nodal temperature based on defined boundary conditions. The only known boundary conditions at the beginning of the stroke are the temperature of the thermocouple node and the temperature on the outer surface of the tool holder. The latter was measured with a digital thermometer during the test and the measurement gave a steady state temperature of 41°C. Figure 8.26a shows the model utilized in the steady state analysis. The strip was not included. The red dots are the nodes on the outer surface in which the temperature of 41°C was assigned. Figure 8.26b is a detailed view of the tool pin. A temperature of 61°C was assigned to the nodes inside the red perimeter. The flux between elements is set equal to zero, which implies that only the temperature distribution due to the boundary conditions is calculated. Figure 8.27 shows the temperature field in the tool pin and tool holder as a result of the simulation. The field presents a gradient from the contact interface to the tool holder outer surface as expected. The temperature of each node can be saved in an output file, which is used as input for the coupled mechanical/thermal simulation.

LSDYNA® allows introducing a dedicated heat transfer coefficient for an artificial lubricant film whenever a defined gap is created between surfaces. A preliminary sensitivity analysis showed that the effect on the temperature by this heat transfer coefficient and the size of the gap is negligible. Therefore the effect of the lubricant on the thermal analysis is not modeled.

Figure 8.26. Tool and tool holder in the steady state analysis: a) the nodes with a temperature of 41°C as boundary condition, b) the red perimeter contains the nodes, where a temperature of 61°C was assigned.
Figure 8.27. Temperature field from the steady state analysis.

Figure 8.28a shows the comparison between the experimental and the simulated drawing force. The two curves have almost the same value in the plateau area. One should keep in mind that friction depends on many factors. It is therefore fairly difficult to obtain a correct value. The friction model utilized here is very simple and does not take into account temperature, wear, surface texture, etc. The value $\mu = 0.1$ is larger than $\mu = 0.02$ found for the production process. As already mentioned, the difference is probably due to the material model, since small inaccuracies in the material model can have vast influence on the friction value determined by comparison between measured and calculated load.

Figure 8.28b shows the calculated temperature as a function of time in the thermocouple node. The curve extends to a time $t = 1.3$ s, which is equal to the time of a stroke, when a test rate of 40 spm is applied. The strip moves in $t = 0.5$ s and then remains stationary exchanging heat with the tool until $t = 1.3$ s. The temperature starts at 61°C and it drops slightly in the first $t = 0.2$ s probably due to the temperature gradient toward the outer surface of the tool holder. It then starts to increase reaching 64°C at about $t = 0.6$ s, when the strip has just decelerated to speed $s = 0$ mm/s. The curve drops again down to 61°C in the remaining time, which simulates the idle time. Figure 8.28c compares the experimental and numerical temperature trends. Only the data acquired during the movement of the strip is plotted since no experimental values are available during the idle time. This is due to the way LabVIEW® program runs. Due to the low sampling rate of the experimental data, it is difficult to compare the curves directly. However the two temperatures shows a common trend. Both of them decrease slightly at the beginning of sliding and then reach a value of 64°C at the end of the stroke. These results are considered in good agreement since the thermocouple has an uncertainty of ±1°C.
The heat transfer coefficient between tool and workpiece was set equal to $HTC = 40$ kW/m$^2$K, which is in agreement with results found by Olsson in thermal simulation of SRT test. A sensitivity analysis showed that the heat transfer coefficient does not have a large influence on the temperature increase in a single stroke, since the simulated time is fairly small. Figure 8.28d shows a detailed view of the contact area. The maximum temperature achieved is 84.5ºC at the exit edge. This means that the average peak temperature for this tribo-system is around 85ºC. The BUT test of the tribo-system in question was successful, which implies that the tribo-system can withstand such a temperature without problems.

Figure 8.28. 2D numerical analysis results: a) comparison of drawing forces between experiment and FE analysis for $\mu = 0.1$, b) temperature of the node where the thermocouple is situated, c) comparison between experimental and numerical temperature results, c) temperature fields in the 2D model after $t = 1.3$ s.

Figure 8.29a shows the 2D model at the beginning of the stroke with the imported initial input temperature field. The initial temperature of the strip is set equal to room temperature. Heat dissipation through convection with the environment was investigated and it showed that the short time did not allow great exchange with the air. The model was therefore set adiabatic. Figure 8.29b shows the temperature field at the end of the simulation, after $t = 1.3$ s. The strip temperature has increased significantly due to plastic deformation, whereas the tool temperature only has increased slightly. The increase in the tool holder is imperceptible due to the big thermal inertia. The results show that the strip reaches an internal temperature of about 84ºC right when leaving the
contact zone. The strip temperature was measured with a digital thermometer, during the test, on the top surface of the strip, right after the bending. The results show a peak temperature of about 90°C confirming that the numerical result is fairly good.

Figure 8.29. Total temperature field in the 2D model: a) start and b) end of the simulation.

Figure 8.30 shows the calculated tool temperature of three consecutive strokes in the node located where the thermocouple is. In the second and third simulations the initial
node temperature of the tool and tool holder from the previous stroke is imposed. One can see that the small drop at the beginning of each stroke increases in magnitude, and becomes closer to the experimentally observed drop, Figure 8.24b. On the other hand the max temperature decreases almost 1°C from the first stroke to the third one. This is probably due to the simplified assumptions of the 2D thermal model.

![Figure 8.30. 2D model: temperature evolution for three consecutive strokes.](image)

In Figure 8.24c it was shown that the tool temperature drops significantly during the homing operation. This temperature evolution is here analyzed performing a thermal analysis of the tool pin. The mechanical deformation is not simulated, but only the heat transfer in the tool. To do this a 3D model of the tool pin is implemented. The mesh is generated from the 3D CAD model shown in Figure 8.23a (the symmetry properties applies also for the thermal analysis). The half tool is meshed with tetrahedral elements, and about 270,000 elements are used. Since the analysis is limited to a thermal solution, the solving time is about 5 minutes even with such high number of elements. Figure 8.31a shows the mesh of the 3D model. The whole investigation is split into three steps: the first step consists of a steady state thermal analysis to obtain a temperature field inside the tool, which represents the initial condition of a stroke. This is conceptually the same procedure done for the 2D model. The second step simulates the temperature development inside the tool during sliding of the strip. The third step runs a thermal analysis, where the tool dissipates heat to the environment and the tool holder, simulating the homing operation. The second step could probably be avoided but it is also interesting to see the temperature evolution inside the tool during the sliding of the strip.
In the following the first step is described. Figure 8.31b and c show the nodes in the 3D model, where a temperature of 61°C was assigned. As earlier mentioned this is one of the two known boundary conditions. The green perimeter delimits the nodes with the boundary conditions. It is extended to 15 mm along the tool axis according to half of the strip width. The other boundary condition is taken from the 2D model. The temperatures at the tool pin/tool holder interface are obtained from the nodes positioned at that interface, in the 2D model (see Figure 8.27).

Figure 8.31. a) 3D BUT tool pin model; b) and c) the yellow perimeters indicate the nodes, where a temperature of 61°C was assigned as boundary condition; d) surface where a temperature of 53°C was assigned.
The average value is 53°C. Figure 8.31d shows the nodes where the 53°C were applied. All the surface nodes of the square end of the tool pin were included in the second boundary condition since the surfaces are in contact with the tool holder. This is not indicated in Figure 8.31. The steady state analysis is carried out calculating the temperature of every node based on the boundary conditions. Figure 8.32 shows a comparison of the temperature field calculated between the 2D and 3D model showing good agreement. The two black lines help to compare the limit between the red and orange zone. It is noted that the 3D model has slightly bigger zone with a temperature of 61°C (red zone). Of course the extension of the different temperature zones depends on the amount of nodes the boundary conditions are applied. Moreover the thermocouple holes are not modeled in the 2D tool and the section of the tool pin is slightly different from the original one. In fact in the 2D, the contact area between tool pin and tool holder is larger.

![Figure 8.32. Comparison of temperature field between 3D and 2D model after steady state analysis.](image)

In the second step, the temperature field from the previous model is introduced as input, and the heat generated from the plastic deformation and frictional energy of the strip is simulated. In order to do so a “trick” is applied. Basically the physical sliding of the
strip is not modeled, but the heat is imported from the 2D analysis. The temperature evolution of seven nodes was acquired from the 2D coupled model. Figure 8.33a shows the selected nodes on the curvature and Figure 8.33b shows the temperature development of the nodes as a function of time. One can imagine each node as a row of nodes in the third dimension, which stretch along the tool axis. Figure 8.33c shows the area, on the curvature, were the seven rows of nodes were selected. The temperature of node 1 (Figure 8.33b) was applied to all the nodes in row 1, the temperature of node 2 was applied to all the nodes in row 2 and so on for all seven rows. Since the mesh is completely different from the 2D model, it is impossible to have exactly straight rows and the same node position as in the 2D model. The transient thermal analysis is performed with these boundary conditions active throughout the virtual time of $t = 1.3 \text{ s}$, corresponding to one stroke. Convection with the environment was activated as well as heat dissipation to the tool holder. Figure 8.33d shows the temperature distribution at the end of the simulation. The temperature on the curvature has increased from 61ºC to 63ºC, compared to the initial state.

Figure 8.33. a) the black dots indicate the nodes where the temperature evolution was acquired for the 3D model; b) the temperature evolution of the nodes is plotted as a function of time; c) the yellow perimeter indicates the nodes on the surface, where the seven temperature trends were applied; d) temperature field after $t = 1.3 \text{ s}$.

Figure 8.34 shows the temperature of the node where the thermocouple is located in the tool. The trend is similar to the one obtained in the 2D analysis (see Figure 8.28b),
which means that the thermal analysis is considered fairly correct even though the maximum temperature is about 1ºC higher. This is to be expected since the 3D model is taking the thermocouple hole into account, which introduces a discontinuity inside the tool and limits the thermal exchange toward the tool holder.

![Figure 8.34. Temperature of the node where the thermocouple is situated in the 3D model.](image)

At this point step three can be performed. The temperature field at the end of the previous simulation, step two, is imported as initial temperature in step three. In the experiment, the homing time of both axes was measured and, when setting maximum speed for the return travel, it takes about $t = 10$ s. This means that the simulation has to run with a virtual time of $t = 10$ s, where the tool exchange heat with the environment. During this time the temperature field inside the tool changes due to conductivity. The analysis gives information about the temperature drop inside the tool during the homing operation. As in the previous simulation, heat exchange with the environment was activated as well as heat dissipation with the tool holder. The heat transfer coefficient with the air was set $HTC = 0.1$ kW/m$^2$K, whereas the coefficient between tool holder and tool pin was set $HTC = 0.5$ kW/m$^2$K. The latter low value is calibrated in order to have a good correlation between the experimental and numerical results and it is also reasonable to assume that the heat transferred between two surfaces in contact is affected by many factors such as dirt, oil, real contact area, etc. In Figure 8.35a the temperature of the thermocouple node is plotted, when the curves from the second and third steps are joined. In the first 1.3 s the temperature increases, as shown before in Figure 8.34, due to the sliding. After that, the temperature drops to about 54.5ºC, which is close to the 55ºC measured in the experiment.
In Figure 8.35b it is interesting to see how the temperature becomes uniform in the tool pin (note the small range of the scale), while the high temperature zone moves from the curvature toward the symmetry plane and the inside of the tool, where contact with the tool holder takes place. This is a reasonable behavior since the tool holder sucks most of the heat due to the big thermal inertia. This also explains another phenomenon that is seen in the experimental results. Figure 8.36 shows the temperature evolution for ten strokes right after the homing operation. It is noticed that the maximum temperature in each stroke is highest right after the homing operation (about 66ºC). With subsequent strokes the maximum value drops to a steady state around 65ºC.
This could be due to the fact that during the homing operation the high temperature region moves inside the tool holder. This means that in the first stroke, after homing, the gradient of temperature between the contact interface and the center of the tool holder is smaller than when steady state is achieved. After few strokes the high temperature zone moves back to the curvature of the tool pin and the high gradient is reestablished from the contact zone to the tool holder, which implies that more heat is dissipated.

The temperature in BUT test was measured for other tribo-systems besides the one presented above. The results are hereafter shown and briefly discussed but no numerical analysis was performed. Figure 8.37 shows the temperature results for the tribo-system: EN 1.4307, Vanadis® 4 Extra and Rhenus SU 166 A. Only 600 strokes were performed since the temperature reached almost a steady state. The main parameters in the test were sliding length $l = 20$ mm, sliding speed $s = 50$ mm/s and back tension $\sigma_b = 200$ MPa. The temperature does not increase as much as for the DP 800 material. This is probably due to less energy required to deform the material combined with a probable lower friction due to the higher performance of the Rhenus oil.

The temperature was also acquired for the tribo-system EN1.4162-V40-RhenusLA722086. In this case the thermocouple was welded into a BUT tool pin with radius $R = 5$ mm. The holes were manufactured with a configuration similar to the tool with radius $R = 3.5$ mm but the inclination was changed. In this case the axis of the hole is inclined 65° from the horizontal plane since this corresponds to the zone with the largest normal pressure in a 90° curvature tool pin. Figure 8.38a shows the CAD model, whereas Figure 8.38b shows the symmetry section where the holes are placed. The
thermocouple is welded at the bottom of the hole located 2 mm from the contact interface. Figure 8.39a shows the torque and the temperature as a function of the number of strokes. The test had a sliding length \( l = 5 \text{ mm} \), sliding speed \( s = 5 \text{ mm/s} \) and back tension \( \sigma_b = 100 \text{ MPa} \). With such a short sliding length, 50 strokes were run in between homing operations. This allows reaching a steady state of about 34°C. At every 50 strokes it is possible to see the temperature drop due to the homing. The torque curve indicates that after 140 strokes the lubrication failed and galling occurred. At the same time the temperature raised about 2°C. In this case it is quite evident that such a low temperature does not play any important role in the lubricant film breakdown. Even though the measurement is done at 2 mm from the contact surface, the previous thermal analysis shows that the temperature peak is no more than 20-25°C higher on the contact area. Figure 8.39b shows the measured tool temperature trend for the same tribo-system but the process parameters sliding length and sliding speed were increased to \( l = 50 \text{ mm} \) and \( s = 50 \text{ mm/s} \) respectively. Also in this test the temperature reaches a steady state, namely 35°C, which is quite surprising since the sliding speed and length are 10 times the previous test. In this case the hydrodynamic lubrication mechanism effect could explain the low temperature. In a previous section the lubrication mechanism was proposed to explain the lower friction and the longer run before galling occurred. The mechanism could also prevent heat transfer from the strip to the tool besides lowering the frictional energy. This means less heat generated and transferred to the tool.

Figure 8.38. a) half 3D CAD model of BUT tool with \( R = 5 \text{ mm} \) (the red dot indicates the welding point of the thermocouple); b) detailed view of the symmetry section (the distance between the welding point of the thermocouple and the contact interface is indicated);
Figure 8.39. EN 1.4162, Vancron® 40 (V40) and Rhenus LA 722086 (Rh2): a) \( l = 5 \text{ mm} \) and \( s = 5 \text{ mm/s} \) (torque and temperature); b) \( l = 50 \text{ mm} \) and \( s = 50 \text{ mm/s} \) (only temperature).

8.4 Conclusion

In Table 8.1 the BUT test results are summarized. The tests with EN 1.4307 and DP 800 showed promising results and they are therefore marked with green color indicating that they are approved for production tests. The results showed no big difference between the tool materials. It is, however, possible that such a difference will be seen at much greater amount of strokes than tested here. Both workpiece materials were also tested with longer sliding length and higher sliding speed still leading to no galling. No big difference was observed between the two Fuchs oils tested with DP 800. These results give basis to qualitatively draw the working window explained in Figure 4.4. As an example Figure 8.40a shows a 2D graph of the limit of lubrication for DP 800 with two process parameters: production rate and sliding length. The BUT tests have shown positive results at 95 strokes/min and \( l = 100 \text{ mm} \). This means that the limit lies above that point but the exact position is unknown.

It is known that austenitic stainless steel forms martensite when deformed at temperatures below 50ºC. It is believed that some martensite is formed in the BUT test since the incoming strip has room temperatures. However the plastic deformation takes place in a very short time leading to internal temperature above 50ºC. The martensite formation could affect the normal pressure at the interface but it is believed that the contribution is negligible. In order to investigate this phenomenon, a tensile test was performed on two specimens: one undeformed and one deformed. The load curves were compared and they gave the same result.

EN 1.4162 material proved to be very prone to galling even when mild conditions are applied. The radius of curvature was increased and a full 90º curvature was adopted to lower the normal pressure but lubrication failed anyway. An interesting solution was found when the tool with larger radius and 90º curvature was PVD coated with TiAlN. In that case the tribo-system effectively functioned in BUT testing up to 1500 strokes. The results also showed a clear correlation between the sliding speed and the limit of lubrication for EN 1.4162 material. The critical accumulated sliding length increased...
linearly with speed. This was explained by the hydrodynamic lubrication effects. Figure 8.40b shows the limit for EN 1.4162 Vancron® 40 (with \( R = 5 \) mm not coated) and Rhenus LA 722086. In this case the two process parameters are: production rate and sliding speed. Two points are plotted, where the production rate is the same but the sliding speed differs. The points both lie above the limit because both tests failed but the results showed that at higher speed the tribo-system can run longer.

**Table 8.1.** Table of experiments. V4E = Vanadis® 4 Extra; V40 = Vancron® 40; green = good tribo-system, orange = questionable tribo-system, red = poor tribo-system.

<table>
<thead>
<tr>
<th>Workpiece materials</th>
<th>Lubricants</th>
<th>EN 1.4301</th>
<th>EN 1.4162</th>
<th>DP 800</th>
<th>1200 MZE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anticorital 3802-39 S</td>
<td>V4E</td>
<td>V40</td>
<td>V4E</td>
<td>V40</td>
<td></td>
</tr>
<tr>
<td>Anticorital PLS 100 T</td>
<td>V4E</td>
<td>V40</td>
<td>V4E</td>
<td>V40</td>
<td></td>
</tr>
<tr>
<td>Rhenus SU 166 A</td>
<td>V4E</td>
<td>V40</td>
<td>V4E</td>
<td>V40</td>
<td></td>
</tr>
</tbody>
</table>

The tests with 1200 MZE were performed with a bigger radius and 90° curvature. The purpose was to evaluate the performance of the two Fuchs oils. In this case no significant difference was found.

The temperature at the contact interface was investigated by direct measurements with a thermocouple mounted inside the tool pin. The tribo-system: DP 800, Vanadis® 4 Extra and Fuchs PLS 100 T was selected for comparison with numerical analysis, where the temperature at the interface was calculated. The experimental results show that the temperature increases rapidly during the first 100 strokes and then tends toward a steady state. The maximum acquired tool temperature was 70°C at a distance 2 mm from the contact surface. From the numerical analysis the maximum achieved temperature was about 85°C on the contact area. The experimental results showed that the homing
operation of the two axes lower the steady state temperature the system achieves. The evolution of the temperature inside the tool, during homing operation, was analyzed by a 3D model. The same drop, as experimentally seen, of approximately 10°C is calculated and it is furthermore noticed that the temperature distribution becomes uniform inside the tool pin. The temperature was also acquired in a test with EN 1.4307 and the same trend was seen, although the maximum temperature was lower.

A thermocouple was also welded in BUT tool with $R = 5$ mm for investigation of EN 1.4162 material. The results showed a fairly low temperature of 35°C. It is believed that such a low temperature does not cause the lubrication failure. This supports the assumption that the workpiece texture, due to the brushing, lowers the limits of lubrication.

In general it was realized that the UST2 cannot apply very high back tension, when high acceleration and sliding speed are set. This causes significant fluctuation of the drawing and back tension forces leading to premature fracture. This limits the achievable sliding speed.
Chapter 9  Production tests

In this chapter the production tests are presented and discussed. The results will be compared with the findings in the BUT tests. Numerical investigation of the temperature on the contact interface is presented and results are compared with experimental ones.

9.1  Test procedure

The final step of the methodology is the production tests of good tribo-systems found in the BUT tests. In Table 8.1 all tribo-systems tested were classified: those for DP 800 and EN 1.4307 were classified as good, the one with EN 1.4162 was classified as poor and the tribo-system tested with 1200 MZE were considered questionable. After a discussion with the project partners it was decided to tests all the tribo-systems in production. This is because the methodology should be verified also from the “poor” side, which means that the author has to be sure that what fails in the laboratory tests, also fails in production.

The test procedure is here described. The experiments were performed at Grundfos press shop, where EL-TUBE component is normally produced. Coils of all four workpiece materials were delivered to the factory. In the production test, EN 1.4301 was used instead of EN 1.4307. New dies for operation 2 and 3, made of tool materials: Vanadis® 4 Extra and Vancron® 40, were manufactured with die radius of curvature $R_2 = R_3 = 3.5 \text{ mm}$ and polished according the specification described in the previous chapter. As in the BUT tests no coating was applied on the dies. In order to measure the temperature at the contact interface in operation 3, two thermocouples were percussion welded inside die Nr. 3 at a distance 2 mm from the curved surface. Figure 9.1 shows a cross section of the die with the hole, where the thermocouple is inserted. The holes are machined in the same plane opposite to each other. The thermocouples should in principle measure the same temperature since they are at the same distance from the curvature but most of the time the results showed a considerable difference, probably due to a non-correct welding operation. The axes are inclined 45º from the horizontal line and have ø2.2 mm. The thermocouple is welded at the bottom of the hole. The same hardware as described in the previous chapter is used for the acquisition of the temperature.

The target production was set to 1500 parts. The specimens were controlled and evaluated during production. The dies were re-polished after each test. The production speed was set equal to 40 strokes/min.
9.2 Results

From time to time one of the two thermocouples did not work properly. The results showed hereafter present the higher of the two temperatures registered. The first test was performed on the tribo-system EN 1.4301, Vanadis® 4 Extra, Rhenus SU 166 A. The production successfully ran 1500 parts without galling. The same result was achieved when testing with Vancron® 40. Figure 9.2a shows the temperature results of the test with V4E. The curve is plotted until 600 strokes after which a steady state was reached. The temperature rises quickly to 100°C during the first 200 strokes, i.e. within 5 min. After that the temperature increases very slowly to a maximum value of about 108°C. The temperature fluctuates about 10°C in every stroke. This is due to the temperature drop that occurs when the workpiece is not in contact with the die. According to the kinematic curve of the press, the idle time (the time the part is not being formed) is about $t = 1$s. All produced parts fulfill the quality requirements for the external surface. A detailed measurement of all dimensional tolerances showed that the height is too short and therefore the part is not approved to be used in the final product. This is due to the bigger radius of the die it has been introduced. However this is of no importance for the tribological aspects of the test. Figure 9.2b compares the temperature of the tests with the tool material as parameter. It seems there is no significant difference between the two materials as also noticed in the BUT tests.

The first test on DP 800 material showed that the temperature is higher than that for testing stainless steel. This confirms the results obtained in the BUT tests. Figure 9.2c shows the curve for tribo-system: DP 800, Vanadis 4 Extra and Fuchs 3802-39S. The curve displays the same trend as seen for EN 1.4301 material. In this case the temperature reaches a maximum value of almost 120°C. The test was stopped after about 1000 stroke due to severe galling in operation 3. The same result was achieved when using Vancron® 40. It seems that the Fuchs oil F1 cannot withstand the severe tribological conditions of the process, no matter what tool material is used. The tests with Fuchs oil PLS 100 T, however, showed good results. The production ran for 1500 parts and no critical amount of galling occurred. Figure 9.2d shows the comparison
between the two Fuchs oils. F1 has slightly lower temperature than F2 even though the latter did not fail. The drop in temperature of about 40°C at approximately 100 strokes is due to an unexpected stop of the press. The machine was restarted immediately.

Figure 9.2. Temperature measurement in production tests: a) EN 1.4301, Vanadis® 4 Extra (V4E) and Rhenus SU 166 A (Rh); b) comparison between the two tool materials; c) DP 800, Vanadis® 4 Extra (V4E) and Fuchs 3802-39S (F1); d) comparison between two Fuchs oils.

Figure 9.3a shows the last component produced with EN 1.4301 and Vanadis® 4 Extra. The specimen has no scratches on the outer surface as specified from the requirement. Figure 9.3b shows a specimen from test with DP 800, Vanadis® 4 Extra and Fuchs 3802-39S. The part shows massive galling on the outer surface and it is considered unacceptable. It was in this test galling caused fracture of a punch as described in Chapter 4. Figure 9.3c shows the die curvature of the test. Pick-up is indicated by the arrow and clearly visible on the contact area. Figure 9.3d shows a picture of one of the last component produced with DP 800, Vanadis® 4 Extra and Fuchs PLS 100 T. The part has a small scratch, which is considered acceptable. It is noticed that the light galling occurs after 1000 strokes and the first 1000 strokes showed no sign of scratches. This indicates that the oil has better performance than type F1, probably due to the higher viscosity. The test with DP 800, Vancron® 40 and Fuchs PLS 100 T showed no galling after 1500 parts. Since galling in the previous test was very localized it is believed that the two tool materials perform equally well.
Figure 9.3. 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).

Figure 9.4a is a Scanning Electron Micrograph (SEM) showing the surface of die Nr. 3 on the curvature, where contact occurred. The red arrows indicate small scratches generated by the workpiece. The white arrows indicate the crossed polished texture generated by the automatic polishing procedure (this die was polished with a RAP machine). Figure 9.4b shows the die curvature tested with DP 800 and Fuchs PLS 100 T. In this case there is micro pick-up on the surface. It seems that the process creates a thin transfer layer of workpiece material on the tool surface without damaging the latter. The workpiece then slides on the thin layer, which is basically the same material but severely work hardened. It is interesting to compare the two surfaces and note that the two workpiece materials interact differently with the tool material. The stainless steel forms less pick-up but tends to scratch the tool surface, whereas the DP 800 does not scratches the surface but produces quickly a thin transfer layer protecting the tool surface.
Tests with workpiece material 1200 MZE were not performed on the mechanical press, since the first attempt showed that the part fractures in operation 3. Figure 9.5 shows two components produced with 1200 MZE material. The one on the left is complete in its overall shape but fracture occurred on the top collar. The one on the right fractured completely and the top collar is missing. Under these circumstances the production cannot be carried out. It is true that this type of operation is not really suitable for fully martensitic steels and the fact that the part can almost be deformed to such high strain is surprising in itself. Fracture was observed at high sliding speed, whereas the part could be produced without fracture in a hydraulic press running at $s = 10 \text{ mm/s}$. It was decided therefore to perform a test on such a different press lowering the production rate to 3 stroke/min. Due to the low speed, the total number of tests were lower, 200 instead of 1500.
Figure 9.6 shows the measured temperature development of 1200MZE-V4E-FuchsPLS100T. The temperature increases quickly in the first 20 strokes but the maximum value is limited to 60°C after about 120 strokes, which are performed in about 40 minutes. In every stroke the temperature drops down to 38°C. Obviously the maximum temperature here is much lower than the one obtained in the mechanical press. The same temperature trend was obtained with Vancron® 40 material. All produced parts showed no sign of galling.

![Temperature development graph](temperature-graph.png)

**Figure 9.6.** Temperature measurement in production tests 1200 MZE, Vanadis® 4 Extra (V4E) and Fuchs PLS 100 T (F2).

The thorough test campaign performed on EN 1.4301 with the BUT test showed that the tribo-systems, with this material, can run up to 95 strokes/min. This means that the working window, as regards to the production rate, is fairly large and beyond the capability of the UST2. The positive result encouraged to try it also in production. The tribo-system successfully ran for 1500 parts at a production rate of 95 strokes/min. Figure 9.7 shows the temperature trend for about 400 strokes. The temperature reaches a steady state value of 133°C against the 108°C in the test with 40 strokes/min. In this case the temperature drops after each stroke only about 5°C against the 10°C in the test with 40 strokes/min. Both tool materials yielded the same results. This means that the new, environmentally friendly lubricant Rhenus SU 166 A works better than chlorinated paraffin oil, namely with 140% higher production rate and no tool coating.
As mentioned before production tests with EN 1.4162 material were performed in order to verify, whether the tribo-systems also fail also in EL-TUBE tool. Tests were conducted only with Vancron® 40. The first tribo-system was: EN 1.4162, Vancron® 40 and Rhenus SU 166 A. Severe galling occurred almost immediately after 20 parts. This confirmed the results obtained in the BUT tests. It was then proposed to try the high viscosity oil Rhenus LA 722086 but poor results were again obtained. A special difficulty arose when using this lubricant. The high viscosity makes it difficult to supply enough oil on the contact interface since the oil channels machined through the die (see Figure 3.6) are very small and higher oil pressure is required especially at high production rate. Figure 9.8a compares the temperature development for the two oils. The high viscosity lubricant seems to keep the temperature slightly lower than the other one. Figure 9.8b compares the temperatures between the two stainless steels, EN 1.4162 lubricated with Rhenus LA 722086 and EN 1.4301 lubricated with Rhenus SU 166 A. EN 1.4162 yields a higher temperature probably due to the higher strength of the material. Figure 9.8c shows the part formed in operation 3. It should be noted that galling occurred only on those surfaces where the rolling direction of the workpiece material slides parallel or almost parallel to the die surface. The red arrow in the picture indicates the separation between galling and no galling. On the right side of the arrow it is clearly seen that the surface is full of scratches, whereas on the left side the surface is smooth with no sign of scratches. This is again a proof that the 2E texture of the workpiece material is the main cause of low tribological performance of the tribo-system. When the grooves due to scratch brushing are parallel with the sliding direction the lubricant is flowing away through the channels, which leads to premature galling. Figure 9.8d shows die Nr. 3. It is clearly seen that pick-up is limited to the zone between the two red lines, which corresponds to the zone when the grooves are parallel with the
sliding direction. The strip is fed from bottom to top and it is parallel to the rolling direction.

![Figure 9.8. a) temperature comparison between Rhenus oils (EN 1.4162, V40); b) temperature comparison between stainless steels; c) galling on EN 1.4162 (operation 3); d) pick-up on die 3 (V40).]

9.3 Thermal analysis

9.3.1 Thermal model

The thermal analysis focuses on finding the maximum temperature at the contact interface workpiece/die in operation 3. The production process is simpler to model from the repetitive point of view than the BUT test. In fact once the model for a single stroke is built, the production can be simulated performing n simulations, where the temperature of the tool at the end of stroke No. i is imported to stroke No. i+1. In this way the temperature development in the die can be analyzed in a more complete way, from the start to steady state. First of all a suitable thermal model has to be built. The 2D model presented in Chapter 6 is used as starting point. Since the production tool is much bigger than the BUT equipment, it is important to model the thermal inertia of the surroundings and not just the die and punch. Figure 9.9 shows the model developed. It is basically the 2D model of operation 3, where two heat sinks have been created and connected to the die and the punch. The heat sinks model the rest of the progressive tool and absorb heat from the die and punch. With a 2D model it is not possible to simulate
the hole for the thermocouple. This introduces an error leading to a lower temperature than measured. The simulation is a coupled mechanical/thermal solution. The heat is generated from plastic deformation and frictional energy. Besides that, the workpiece is not at room temperature at the beginning of the simulation, since it is pre-formed in operation 1 and 2. In the production tests the temperature of the workpiece was measured with a digital thermometer just before operations 2 and 3. The measurement is taken few seconds after stopping the press since it was not possible to monitor these temperatures while running. The values acquired were approximately 83°C and 110°C for operation 2 and 3 respectively, both for EN 1.4301 and DP 800. The initial temperature of the workpiece was therefore set equal to 110°C. In the thermal analysis the punch remains at the bottom end for about \( t = 0.9 \) s after it has formed the workpiece. This allows heat exchange with the die and basically simulates the time that the medium plate remains closed while the top plate of the real tool is still moving and forming the workpiece in operation 1, see section 3.1.

In order to have small input deck and output files, it was decided to build a Matlab® code in parallel to LSDYNA®. Basically the Matlab® code starts the LSDYNA® solver, creates the import file from the current stroke to the next stroke and saves the temperature of the thermocouple node in each stroke. Unfortunately, with this combination, it is only possible to extract the temperature at the end of each stroke, when the tool is completely closed. This means that it is not possible to compare the temperature trend including the drop of temperature in each stroke. The heat transfer coefficient between die/heat sink and punch/heat sink is set \( \text{HTC} = 20 \text{ kW/m}^2\text{K} \). A sensitivity analysis showed that this parameter does not affect the temperature inside the die much.
Figure 9.10 shows the node where the temperature is taken for comparison with experimental results. In the thermal analysis of the BUT test it was explained that the thermal effect of the lubricant can be modeled but it does not affect the general trend of temperature development. It was then decided not to model it in the production process as well.

![Figure 9.10. Detailed view of the die model. The red dot indicates the node closest to the nominal position of the thermocouple.](image)

### 9.3.2 Results

The thermal analysis focused only on DP 800 and EN 1.4301 materials. An uncertainty factor that should be taken into account in the simulation is the actual position of the thermocouple inside the die. The holes were manufactured by EDM process and it was not possible to measure the actual distance of the bottom of the hole from the curvature. A sensitivity analysis was carried out in the thermal analysis to study the influence of location of the bottom of the hole. Figure 9.11a shows the position of six nodes, where the temperature was investigated. The nodes are numbered from 1 to 6 and the distance between two neighboring nodes is about 0.4 mm. Figure 9.11b shows the temperature development in the six nodes for 200 strokes. Node 4 is supposed to be the nominal position of the thermocouple measurement. Looking at the closest nodes to the nominal one, a distance of 0.4 mm has a temperature difference of 4°C. The coefficient of friction plays an important role in the frictional energy especially in this model since the normal pressure is extremely high.
Figure 9.11. Sensitivity analysis of the thermocouple position: a) six nodes where the temperature was investigated, b) temperature evolution of the six nodes.

Figure 9.12a shows the sensitivity analysis of the coefficient of friction. The graph shows a significant difference between $\mu = 0.1$ and 0.2 but it is negligible between $\mu = 0.02$ and 0.1. The reader should remember that the calibration of $\mu$, through the punch force is affected by an error generated from the poor material model. This means that the difference in temperature shown in Figure 9.12a has to be interpreted and cannot be considered absolute. Figure 9.12b shows the sensitivity analysis for the initial temperature of the workpiece. Two initial temperatures were analyzed: 100 and 110°C. There seems to be no significant difference between the two curves. Figure 9.12c shows the sensitivity analysis for the heat transfer coefficient at the contact interface. It seems that there is no significant difference between $HTC = 40$ and 80 kW/m²K but there is a difference between $HTC = 40$ and 20 kW/m²K.

The numerical investigation was performed on a maximum number of strokes equal to 200. This allows having a sufficient number of strokes to almost reach the steady state and characterize the temperature development in the process with limit solving time, which is still about 24 hours. In some cases the analysis was stopped at 50 strokes, especially when the sensitivity analyses were performed. Figure 9.13a shows the model at the beginning of stroke No. 200. The punch temperature has increased to about 150°C since it is in contact with the deformed specimen during most of the travel and the exchange surface is fairly large. Figure 9.13b shows a detailed view of the contact area when the punch has completed about 80% of the stroke. The temperature rises quickly to about 210°C in a localized zone.
Figure 9.12. a) sensitivity analysis of the coefficient of friction; b) sensitivity analysis of the initial temperature of the workpiece; c) sensitivity analysis of the heat transfer coefficient between workpiece and die.

Figure 9.14a shows the temperature comparison between experiment and simulation. The experimental result was acquired with the tribo-system DP800-V40-FuchsPLS100T. The thermal parameters in the numerical model were: $HTC = 40 \text{ kW/m}^2\text{K}$, $\mu = 0.1$ and initial temperature of the workpiece $IT = 110^\circ\text{C}$. The numerical results describe fairly well the real trend of the temperature. This means that the temperature distribution in Figure 9.13 is probably close to the real one. As said before the fluctuation is not represented in the simulative curve because only one value of the temperature distribution is acquired in each stroke. Figure 9.14b shows the comparison for the tribo-system EN1.4301-V40-RhenusSU166A. In this case a good agreement is reached when the coefficient of friction is lowered to $\mu = 0.05$ against the 0.1 value calibrated with the punch force. The initial temperature and heat transfer coefficient are the same as in the previous simulation. The temperature field for this simulation is similar to the one in Figure 9.13 but the peak value reaches about 240$^\circ\text{C}$ at the contact interface.

It is believed that the lubricant cooling effect plays an important role since a huge amount is used in the real process. Unfortunately it is difficult to model it. The oil absorbs a great amount of heat and takes it away since new fresh oil is injected in the tool after each stroke.
Figure 9.13. DP 800 and Vancron® 40: a) temperature field at the beginning of 200th stroke; b) temperature field at the interface workpiece/die after 80% of the punch displacement.

Figure 9.14. Temperature comparison between experiment and simulation: a) DP 800, Vancron® 40, Fuchs PLS 100 T and b) EN 1.4301, Vancron® 40, Rhenus SU 166 A.

9.4 Discussion and conclusion

The production tests were carried out as the last step of the methodology for off-line testing of tribo-systems. The tests with the tribo-systems DP800-V4E-Fuchs3802-39S and DP800-V40-Fuchs3802-39S showed contradictory results compared with the laboratory ones. The lubrication clearly failed in production, whereas the BUT tests were performed without any problem, even at increased tool rest temperature, sliding length and sliding speed. This is the only tribo-system, which showed disagreement between the production and laboratory tests. A careful analysis of the tests conditions clarifies that there are substantial differences between the two. Table 9.1 shows a list of these. The most important seems to be the work hardening, which the workpiece material undergoes in the production process (operation 1 and 2). In Figure 6.31 the contribution of work hardened material on the punch force was simulated and compared with a non-pre-work hardened condition and the difference was very high. This affects the normal pressure at the contact interface therefore the tribological conditions. In the
BUT test, the material is fed directly from a coil without pre-work hardening. Even though the modified BUT tool geometry allows reaching pressures above $q = 1000$ MPa the peak value is still lower than the one in production, which beyond 1500 MPa. Another important difference is the initial temperature of the workpiece. The specimen in the progressive tool has a temperature of about $T = 110^\circ C$, whereas the strip in the BUT test is at room temperature. This results in substantial difference in maximum strip temperature and more important in the maximum tool/workpiece interface temperature. The latter difference is further emphasized by the cooling phase during homing operation in the BUT test. All these differences make a direct transfer of laboratory test results to production difficult, but trends in the influence of main parameters, e.g. normal pressure, slide length, velocity and tool/workpiece interface temperature can no doubt be usefully applied. On the other hand the “poor” results obtained in production help identifying the limit of lubrication for the tribo-system because it lies in between the BUT test and the production conditions.

<table>
<thead>
<tr>
<th>Work hardening</th>
<th>BUT test Low (max $\varepsilon = 0.3$)</th>
<th>Production (operation 3) High (max $\varepsilon &gt; 1$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface topography</td>
<td>Original from coil</td>
<td>Deformed from previous two steps</td>
</tr>
<tr>
<td>Normal pressure</td>
<td>$q &gt; 1000$ MPa (on a small contact area)</td>
<td>$q &gt; 1500$ MPa</td>
</tr>
<tr>
<td>Initial specimen</td>
<td>Room temperature</td>
<td>$T \approx 110^\circ C$</td>
</tr>
<tr>
<td>temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum temperature</td>
<td>$T &lt; 100^\circ C$</td>
<td>$T &gt; 200^\circ C$</td>
</tr>
<tr>
<td>in the workpiece</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum measured</td>
<td>$T \approx 45^\circ C$ (EN 1.4307)</td>
<td>$T \approx 110^\circ C$ (EN 1.4301)</td>
</tr>
<tr>
<td>temperature in the</td>
<td></td>
<td></td>
</tr>
<tr>
<td>die (thermocouple)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum tool/workpiece interface temperature</td>
<td>$T \approx 85^\circ C$ (DP 800)</td>
<td>$T \approx 240^\circ C$ (DP 800)</td>
</tr>
<tr>
<td>Sliding speed</td>
<td>$s = 50$ mm/s</td>
<td>$s = 100-150$ mm/s</td>
</tr>
<tr>
<td>Thermal exchange</td>
<td>Workpiece/tool contact during idle time and homing operation</td>
<td>No workpiece/tool contact during idle time</td>
</tr>
</tbody>
</table>

The production results with the tribo system DP800-V4E-FuchsPLS100T and DP800-V40-FuchsPLS100T showed agreement with the laboratory tests. Little galling occurred in the EL-TUBE specimens after 1000 strokes but the parts were considered acceptable. The author has the impression that the tribo-system cannot sustain very long production runs. In fact the only difference between the previous tribo-systems (which failed) and these ones is the lubricant. Fuchs PLS 100 T (F2) has higher viscosity than Fuchs 3802-39S (F1) besides a different content in additives, which is unknown. Based on the only
parameter known, the viscosity, it was expected F2 to perform better and indeed this has been proved. The thermal analysis shows that the temperature reaches more or less the same value, when comparing the two oils. This suggests that there is still a viscosity difference between the two lubricants at steady state. However the severity of the process suggests that probably a higher viscosity of the oil is required to reach longer production runs.

An interesting thing that links the production tests to the laboratory ones is the type of pick-up formed on the tool surface. The SEM picture showed that DP 800 forms micro-pick-up in form of a thin transfer layer on the tool surface. This thin layer seems to protect the tool from new workpiece material coming into contact. The force and temperature results showed that a steady state was achieved. This suggests that the transfer layer also achieves a steady state where it does not grow further and the workpiece slides on it.

The production tests with the tribo-systems: EN 1.4301, Rhenus SU 166 A and both tool materials showed surprising results considering the well-known fact that stainless steel is prone to galling. The tribo-systems were successfully run in both BUT test and production. Not only were these satisfactory results achieved but the production rate could be increased by 140% with no sign of galling. This means that normal production conditions, for these tribo-systems, are well inside the working window, which describes the limit of lubrication. Based on experience from Grundfos, Rhenus SU 166 A has shown good performance in critical sheet metal forming operations.

The production tests with 1200 MZE enlightened the difficulties in deforming the material at production high strain rates. The parts fractured completely in operation 3 and it was not possible to perform a full scale test. It was then decided to carry out production tests on a different press at much lower speed. The tribo-systems: 1200 MZE, Fuchs PLS 100 T and both tool materials showed no sign of galling on a 200 strokes test. The results cannot identify the tribo-systems as good since the number of strokes was below the target 1500. Anyhow the fact that no galling occurred in 200 strokes is a promising results.

The production tests with EN 1.4162 gave the same results as in the BUT tests, where severe galling occurred immediately. The results showed that galling occurs only along the rolling direction proving that the workpiece texture affects the limit of lubrication. One could argue that the surface texture is modified in operation 1 and this could flatten the asperities and create more closed pockets, which enhance the micro-hydrodynamic lubrication effect. However it seems that the texture is the only plausible explanation to the fact that the zones where galling occurs are very well defined. Moreover pick-up forms already in operation 2 and this affects operation 3 as well.

The thermal investigation showed that the temperature reaches high values in operation 3. Small differences in temperature were noticed between different workpiece materials whereas neither tool materials nor Fuchs lubricants seemed to have influence.
temperature trends showed that the temperature development tended toward a steady state. The temperature rose quickly in the first 200-400 strokes up to \( T = 100^\circ C \) or more. The numerical analysis gave very satisfactory simulation of the thermal evolution even though the 2D model was perhaps not the most adequate. Some simplifying assumptions had to be done such as the absence of the hole for the thermocouple and no cooling effect of the lubricant. The numerical results showed that the temperature at the interface reached peak values beyond \( T = 200^\circ C \). It is interesting to notice that such a value is above the flash point of all lubricants tested and, even if it is localized to a small contact area, this means that the oils are locally degraded and may not efficiently separate the contact surfaces.

It is now possible to summarize the test results in relation to the methodology. The following tribo-systems have successfully been tested and, they should be possible alternative:

- DP 800, Vanadis® 4 Extra, Fuchs PLS 100 T,
- DP 800, Vancron® 40, Fuchs PLS 100 T,
- EN 1.4301, Vanadis® 4 Extra, Rhenus SU 166 A,
- EN 1.4301, Vancron® 40, Rhenus SU 166 A.

The following tribo-systems failed:

- DP 800, Vanadis® 4 Extra, Fuchs 3802-39S,
- DP 800, Vancron® 40, Fuchs 3802-39S,
- EN 1.4162, Vanadis® 4 Extra, Rhenus SU 166 A,
- EN 1.4162, Vancron® 40, Rhenus SU 166 A,
- EN 1.4162, Vanadis® 4 Extra, Rhenus LA 722086,
- EN 1.4162, Vancron® 40, Rhenus LA 722086.

The tribo-systems including 1200 MZE material are not counted in the lists since full scale testing was not performed.
Chapter 10  Conclusion

This work has focused on the development of a methodology to find and evaluate new tribo-systems in sheet metal forming of advanced high strength steels and stainless steels. The project finds its motivation in the need of replacing hazardous tribo-systems currently used in sheet metal forming process. The advancements in metal forming have introduced new materials and processes that allow producing more complex products with higher quality. These innovations brings however other challenges, one of those the more severe tribological conditions. This means that the performance of the tribo-systems have to be improved to withstand higher normal pressures and temperatures. In sheet metal forming the challenge has so far been solved using chlorinated paraffin oils, which have great tribological performance but are suspected to be harmful to the operator and the environment.

The thesis presents a brief literature study of new environmentally friendly lubricants in sheet metal forming as well as a general description of three simulative tests developed at MEK-DTU. The breakthroughs in new lubrication systems have focused on the three main actors of the process: tool, workpiece and lubricant. Each of them can be modified and tailored for the purpose contributing with enhanced performances. This means that there is already a long list of ideas and technologies that can be applied in lubrication of sheet metal forming. The missing piece in the puzzle is the possibility to accurately test all these solutions. Usually new tribo-systems are tested either in production on a limited volume or in laboratory using simulative tests. The first method implies reluctance from the industries due to high costs of tools and production stops, the second one implies that often the laboratory conditions are far from the production ones meaning that the tribo-system could easily work in the laboratory but fail in production.

In the present work a methodology for off-line evaluation of new tribo-systems has been developed. One of the innovative key points is the development of a new automatic universal sheet tribotester (UST2) that can perform simulative tests repetitively simulating a progressive tool. The new machine is described in detail together with the simulative tests that can be performed.

The methodology is applied to an industrial case selected at Grundfos, where chlorinated paraffin oil is used. The process is a deep drawing with two subsequent re-drawings, where focus is directed to the second re-drawing (operation 3). This operation is the most critical and the numerical analysis reveals that the normal pressure and temperature achieved characterize the process as severe as cold forging. The Bending Under Tension (BUT) test was selected to simulate the production process in the laboratory. A numerical analysis of the BUT test was performed to calibrate the laboratory test in order to reproduce the same tribological test conditions. To this purpose, a new BUT tool geometry was introduced since a conventional one cannot achieve the high normal pressure experienced in production. A few new
environmentally friendly tribo-systems were selected and tested in the new UST2 to simulate a production volume of 1500 parts. The results showed that the DP 800 and EN 1.4301 workpiece material can be deformed without galling. EN 1.4162 proved to be very prone to galling. Tests were performed with conventional tool geometry without improving the results. A solution to this problem was found by coating the tool with TiAlN. Using this coating the tests were running successfully. The promising results open the way to production tests, which were not performed in this project due to limited time. It is believed that the PVD coating could significantly improve the lubrication performance also in production. Some of the tribo-systems were tested also in production and they yielded the same results as the laboratory tests except for those tested with Fuchs 3802-39S oil.

The temperature at the contact interface was investigated in both laboratory and production tests. The thermal numerical analysis, which was calibrated by local temperature measurement in the tool, showed that the production process reaches much higher temperatures than the BUT test. This factor and the fact that the component is severely work hardened make the tribological conditions of operation 3 much more severe than the laboratory test. This explain why the tests with Fuchs 3802-39S oil were successful in the BUT test but failed in production.

The overall results show that the methodology works and should be applied in order to investigate the potential of new tribo-systems. As pointed out it is very difficult to ensure satisfactory emulation of the tribological conditions in the laboratory tests. This is an aspect of vital importance for the whole procedure. This project, however, has proven that, even though there is a difference between the two, the results can be utilized for classifying the tribo-systems and investigating the relative influence of a large variety of parameters on limits of lubrication, e.g. normal pressure, sliding length, sliding velocity, tool/workpiece interface temperature, surface texture of the workpiece and tool, etc..

Looking in more detail at the selected industrial case, it is amazing to see how a simple sheet metal forming process, such as a re-drawing operation, can sometimes turn out to be much more complicated than expected, at least from the tribological point of view. The author had difficulties to find relevant literature on this process. Generally research focus on standard deep drawing processes and plenty of papers and books on this subject can be found. The present work brings some useful of information as regards the tribology aspects in re-drawing processes, which may help to realize how much more should be done in this topic.

The “unfortunate” choice of this particular production process as a case study has not been optimum, since it has shown how difficult it is to reproduce exactly the same conditions in laboratory tests. However the fact that the lubricant can be severely stressed helps to test the performance of new tribo-systems to the limit. If successful it can subsequently process with milder conditions.
From an industrial point of view this project has given useful knowledge to all the partners involved. Grundfos will implement the new increased radius of curvature $R_3 = 3.5$ mm in the daily production. Most of all the partners have learned that new tools must be numerically analyzed and the normal pressure should be investigated in order to ensure that the maximum value does not exceed 1500 MPa.
Chapter 11  Future work

This project has opened new frontiers in tribology in sheet metal forming. The author believes there are two main points, which should be further explored: the verification of the methodology for other processes and the development of new test equipment for the UST2. The first of course implies the second point.

The project had the ambition of performing strip reduction tests and draw bead tests besides the bending under tension test. The most exciting topic would be the implementation of an automatic Strip Reduction Test (SRT) equipment in the UST2. The work of Olsson [131], Friis [32] and Nielsen [74] have shown that the ironing process can be accurately simulated by the SRT test. This means that the production condition, as regards normal pressure, surface expansion, reduction, etc. can be reproduced almost 1:1 in the laboratory. The possibility to repeat the test many times as in a progressive tool would allow reaching almost the same steady state temperature as well as investigating the slow building up of pick-up.

Another interesting development could be the implementation of a device to pre-work harden the strip in order to achieve the same initial material properties as in the EL-TUBE process. Besides that, the initial temperature of the strip could also be increased. The tests results showed that the workpiece can reach temperature around 110ºC before the 3rd operation in the investigated production process.
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Appendix: Punching tests

Parallel to the PhD project, an investigation of the limit of lubrication in punch of advanced high strength steels and stainless steels was performed. The work was carried out by two M.Sc. students, Ruben Buelga Sanchez and Jacob Henckel, under the supervision of the author. The two small projects were carried out in 2011 and 2012 at DTU-MEK. This appendix includes the reports done by the students. First the equipment is described together with previous work done at DTU-MEK. Then the results are presented and discussed.
Testing of new, environmentally benign lubricants for punching and blanking

Ruben Buelga Sanchez (s102158)
Contents

List of Figures 2

1 Introduction 3
  1.1 Lubricants ................................................................. 3
  1.2 Test equipment ............................................................ 3

2 Test results 5
  2.1 High Strength Steel ...................................................... 5
  2.2 Stainless Steel ............................................................ 9

3 Discussion 12
  3.1 High Strength Steel ...................................................... 13
  3.2 Stainless Steel ............................................................ 14

4 Conclusions 16

References 18
List of Figures

1. Press with computer ......................................................... 4
2. Testing tool ................................................................. 5
3. Vanadis 6 tool with FUCHS anticorital PL 3802-39 s Lubricant ....... 6
4. Vancron 40 tool with FUCHS anticorital PL 3802-39 s Lubricant ....... 6
5. Vanadis 6 tool with Shell PQ 144 Lubricant .......................... 7
6. Vancron 40 tool with Shell PQ 144 Lubricant .......................... 7
7. Vanadis 6 tool with IRMCO 980 PF40-S Lubricant .................... 8
8. Vancron 40 tool with IRMCO 980 PF40-S Lubricant .................... 8
9. Vanadis 6 tool with IRMCO 980 PF40-S Lubricant .................... 9
10. Vancron 40 tool with IRMCO 980 PF40-S Lubricant ................. 10
11. Vanadis 6 tool with Rhenus LA 722065 Lubricant ................... 10
12. Vancron 40 tool with Rhenus LA 722065 Lubricant ................... 11
13. Broken needle from Test 1 - Channel 1 with IRMCO lubricant ....... 12
14. Results from the performance of different lubricants (taken from (1)) .... 13
15. Lubricant performance comparison for High Strength Steel with Vanadis 6 needles .......... 13
16. Lubricant performance comparison for High Strength Steel with Vanadis 6 needles .......... 14
17. Lubricant performance comparison for High Strength Steel with Vancron 40 needles .......... 14
18. Lubricant performance comparison for Stainless Steel with Vanadis 6 needles .......... 15
19. Maximum punching force with IRMCO 980 PF40-S lubricant, Vanadis 6 needles and stainless steel strips .......... 15
20. Lubricants performance comparison for Stainless Steel with Vancron 40 needles .......... 16
21. Needle bended when testing stainless steel strips with IRMCO 980 PF40-S lubricant .......... 17
22. Corrosion effect of the IRMCO 980 PF40-S lubricant in the high strength steel pieces .......... 17
1 Introduction

This report is the resume of the laboratory work during the special course called "Testing of new, environmentally benign lubricants for punching and blanking". During these tests some new, environmentally benign lubricants were tested in order to compare them with previous results made with lubricants that were tested earlier in (1) and (2). These new lubricants are going to be tested in the same conditions as the tests done before.

During this report is explained the process followed to conduct these experiments as well as the comments on the results obtained from them. It is also shown a comparison with the previous tests to compare the performance of these new lubricants.

1.1 Lubricants

During this project, two different tool materials (Vanadis 6 and Vancron 40) were tested onto two different sheet materials (High Strength Steel and Stainless Steel). The lubricants for each kind of sheet material were:

- **Lubricants for High Strength Steel**
  - FUCHS anticorital PL 3802-39 s
  - Shell PQ 144
  - IRMCO 980 PF40-S

- **Lubricants for Stainless Steel**
  - IRMCO 980 PF40-S
  - Rhenus LA 722065

1.2 Test equipment

The test is based on measurements of the continuous development of the backstroke force with the number of strokes. The testing equipment was the same used for testing in references (3), (1) and chapter 10 in (2). There are two identical punches which have a very small punch clearance with its corresponding die. As commented in (1), the small clearance creates a large hydrostatic pressure in the deformation zone similar to the conditions in fine blanking.

The load is measured by using a dynamic force measurement system based on piezoelectric transducers. The transducers are mounted as direct support of the punches in order to measure as close as possible to the deformation zone. in this way noise and vibrations from the press caused by spring-back in the press frame are eliminated.

The load transducers are mounted with a preload implying that not only the punching force but also the backstroke force can be measured during the process. A PC-based data acquisition system records measurements of load and corresponding punch displacement continuously from every stroke.

These loads transducers are very fragile, and extremely careful handling should be applied on them. During this test round, 3 of these transducer cables were broken, creating an extra cost on the test and time looses due to more testing time required.

The press machine was set up to work at 140 rpm, this means that 140 strokes were done every minute. The time elapse of the test varied from the shortest of around 2 minutes (250 strokes) to more than 48 minutes (6849 strokes) for the longest one. This differences on time elapse were created by the different load conditions of each case (tool material, lubricant, sheet material), and will be further discussed in this work.

The lubrication was done by a system consisting on a bottle-like container, with two draining
channels, that lead to the rolls where the strip was impregnated with the lubricant. This lubrication system have to be cleaned every time that a new lubricant is added, as well as the strip. The strip should be cleaned with alcohol to remove the protection oil (as in the case of High Strength Steel) or simply to clean it from impurities in the strip. The lubricant flow rate should be kept in control, as the viscosity in the lubricants is different, the flow rate is different in every lubricant; making the adjustment of the flow rate a must before starting the tests.

![Press with computer](image)

**Figure 1:** Press with computer
2 Test results

In this section are presented the results from the experiments, these graphs show the results from the measured backstroke force, and the scatter produced by the different experiments conducted.

2.1 High Strength Steel

First, the data generated by the experiments in high strength steel is shown, in the following plots can be seen the results straight from the measurements of the test equipment.
Testing of new, environmentally benign lubricants for punching and blanking

Figure 3: Vanadis 6 tool with FUCHS anticorital PL 3802-39 s Lubricant

Figure 4: Vancron 40 tool with FUCHS anticorital PL 3802-39 s Lubricant
Figure 5: Vanadis 6 tool with Shell PQ 144 Lubricant

Figure 6: Vancron 40 tool with Shell PQ 144 Lubricant
After having a look to these results some aspects should be pointed:

- The sudden drop of the backstroke for few strokes is the result of the discontinuity of the strip. This strip has, as mentioned in 1.2, to be cleaned and cut before the test; and this points represent "the end" of that strip.

- In figure 7 can be seen how the data from channel 0 in test 4 has completely no corresponding to the rest of the data in the analysis. A look to the tool after the test demonstrated that there was friction between the needle and the structure surrounding it.
• The scatter of the value is considerable, but due to sometimes very low forces, it seems to be bigger than what it actually is.

• The difference in force between both measured channels inside the same test can be considerable. Having sometimes very different behaviours depending on the channel.

• Even though the first thought was the opposite, the lubricant with lower viscosity (the IRMCO 980 PF40-S) was the one with lower backstroke force and lower pick-up formation during the test, some of them been stable (and with values considerably lower than the others) after 6000 strokes.

Further analysis of the results in this section and in 2.2 is done during the discussion in 3

2.2 Stainless Steel

In the following graphs are shown the test results for stainless steel, which was tested by using the lubricants listed in 1.1.

![Graph of Vanadis 6 tool with IRMCO 980 PF40-S Lubricant](image)

**Figure 9:** Vanadis 6 tool with IRMCO 980 PF40-S Lubricant
Testing of new, environmentally benign lubricants for punching and blanking

Figure 10: Vancron 40 tool with IRMCO 980 PF40-S Lubricant

Figure 11: Vanadis 6 tool with Rhenus LA 722065 Lubricant
Some remarks should be made about the results plotted above.

- As can be seen comparing figures in 2.1 and 2.2, the backstroke force is significantly higher in the test conducted on stainless steel than in high strength steel.
- As opposite to the high strength steel, the development of pick-up for the IRMCO lubricant was extreme when tested together with Vanadis 6 tools, leading to the break of the needle on a case 13 This can be also noticed in figure 9 where some peaks of the backstroke force can be seen due to these pick-up.
- The Rhenus lubricant is more stable and gives lower backstroke forces than the IRMCO one.
- The influence of the needle material is different depending on the lubricant. The Vancron 40 needles behave more stable and with lower forces than the Vanadis 6 with the IRMCO lubricant. Meanwhile, the opposite effect is seen when the Rhenus lubricant is applied.
- In the tests conducted with the Rhenus lubricant, a significantly reduction of the backstroke force can be seen with the increasing tests. Achieving lower and more stable values with the ongoing tests. This is maximum if we compare the first test and the last. While test number one was stopped due to extreme punching forces (as with the IRMCO lubricant), test number three had none of this problems. This can be due to a lubrication lack in the first experiment.

As mentioned earlier, these results are discussed deeper in section 3.
3 Discussion

During this chapter, the comparison between the results obtained in the experiments showed in the previous chapter are going to be compared with the data obtained in (1) and (2).

First of all, it is necessary to determine a relevant value of the data points, this "relevant" value is going to be the average of the test points. But some test series that had a behaviour different than the others are eliminated. This is, in example, the case of the test series number 1 in [1] or test series number 4 in [2]. This data points were completely different due to a bad alignment of the needles in the punching tool; which creates extra friction in the needle and invalidates the results to be compared. Also the test results are only shown until 1000 strokes; as this is the limit of the data for the experiments shown in the references [1] and [2].
Figure 14: Results from the performance of different lubricants (taken from (1))

In figure 14 are shown some test results obtained during previous tests in the literature, the aim of this study is to compare these results with the obtained during the tests.

Some difference are clear between the results shown in 2 and the ones shown in figure 14; like the big scatter during the tests realized in this project. It should be noticed that the scale of the results in the tests conducted during this project is much smaller than the forces obtained in the literature, giving the appearance of bigger variations than what they actually are.

3.1 High Strength Steel

Figure 15: Lubricant performance comparison for High Strength Steel with Vanadis 6 needles

If we set up the same scale as in the results from the literature, the results look as follows:
Now the scatter is still present, but it seems much smaller than in the previous case. It is difficult to set a tendency, as the values don’t differ as much as in figure 14.

3.2 Stainless Steel

In the case of stainless steel, the results are similar, but due to the extreme conditions with the IRMCO 980 PF40-S lubricant, the results show something interesting:
Both lubricants show a linear tendency, but when we have a look to the value of $R^2$, the data is completely different. While the Rhenus lubricant has a $R^2 = 0.74$; the IRMCO lubricant has a $6 \cdot 10^{-5}$. Which is extremely low. This is the results of the variations shown in 2.2 with the extreme pick up formation and the lubricant failure. The lubricant failure can be also seen in the results from the punching force, as shown in figure 19. This value is extremely constant in every case less with the IRMCO lubricant; where in connection with the stainless steel strips gives extremely high punching forces. This high values of the punching force leads to the failure of the needle, as shown in figure 13.
Testing of new, environmentally benign lubricants for punching and blanking

Figure 20: Lubricants performance comparison for Stainless Steel with Vancron 40 needles

With the Vancron 40 needles there is not a critical pick up formation with the IRMCO lubricant as seen with the Vanadis 6 needles.

4 Conclusions

With the exposed in 8 the following can be concluded:

- The backstroke force is comparable to the best tests of the data from the literature, between the results of the PN226 and the CR5 lubricants. with stable development of pick up, less in the case of IRMCO 980 PF40-S with stainless steel and Vanadis 6 needles, where both the punching force 19 and the backstroke force 9 can reach extremely high values.
- The best results obtained for high strength steel come from the IRMCO 980 PF40-S. This is surprising if we take a look to the literature; where the more viscous lubricants showed the best results. But when testing stainless steel, this is true.
- In stainless steel the IRMCO 980 PF40-S is unstable, giving peaks of extremely high backstroke and punching forces, leading to even the break of one of the needles 13. In figure 21 is shown the effect of this, when the needle was unable to fully penetrate the strip and the needle was bended.
- The data scatter in proportion to the test measurements. This is due to the small values of the backstroke force if we compare the results obtained with other previous data 14.
- Even that some test were conducted to even 7,000 strokes, the stability of the lubricants is clear. Less in the case of the IRMCO 980 PF40-S in stainless steel, in the rest of the situations the lubricants show a good stability and low pick up growth.
- There is a clear influence of the needle material in the performance of the tests, giving lower backstroke forces with the Vanadis 6 than with the Vancron 40.
- Other effect is the corrosion produced by the IRMCO 980 PF40-S lubricant in the high strength steel strips, as shown in figure 22. This effect is produced when the strip is left in contact with the lubricant during the night.
Figure 21: Needle bended when testing stainless steel strips with IRMCO 980 PF40-S lubricant.

Figure 22: Corrosion effect of the IRMCO 980 PF40-S lubricant in the high strength steel pieces.
References

[1] **D.D Olsson, N. Bay, J. A.**, Lubricant test for punching and blanking, Department of Manufacturing Engineering and Management, Technical University of Denmark, Lyngby, Denmark, October 2002.


Testing of new lubricants and tool materials for punching
Contents

1 Introduction 2

2 Theoretical background 2

3 Experimental set up 5

4 Results 11

5 Microscope inspection of pickup 16

6 FE-simulations 18

7 Conclusion 25

References 26

A Test results 27

B Maximum penetration force 31
1 Introduction

The aim of this project is to test new, environmentally friendly oils for punching and blanking in combination with different punch and workpiece materials. The results will be compared to findings by David Dam Olsson [4] and Ruben Buelga Sanchez [5]. The punches will, after having performed approximately 1000 strokes, be inspected under a microscope to analyse the pickup formation on the punch stem surfaces. Finally, a finite element (FE) analysis of a punching process is developed, and the penetration forces will be compared to the experimental findings.

Separating tool- and workpiece surface proves to be very difficult in punching and blanking due to the creation of highly chemically active virgin workpiece material that prevents lubricant access to the tool-workpiece interface. This causes workpiece material to adhere to the punch and form pickup, also known as galling. Thus, lubricants capable of reacting chemically with the tool- and workpiece surface and form a thin boundary film are used heavily in the industry. These lubricants, e.g. chlorinated paraffin oils, are however often very toxic. Thus, finding environmentally friendly lubricants that possess this property is greatly desired.

The project is supervised by Prof. Niels Bay and Ph.D. student Ermanno Ceron.

2 Theoretical background

The punching process can be split up into two main steps: The penetration and the backstroke. Figure 1 shows the force on the punch versus the punch travel with corresponding figures showing the relative position of punch and workpiece. The upper hatched part is referred to as the upper die and the lower hatched part as the lower die.

Figure 1 shows that the punching force increases as the punch enters the work piece. As a shear fracture initiates in the workpiece, the force starts dropping. Then punch force drops to zero as the punch starts to retract. Due to elasticity, and possibly cold welding of workpiece material to the punch stem called galling, the workpiece squeezes the punch. As the workpiece hits the upper die, the punch is pulled free which gives a negative punching force. David Dam Olsson [4] have shown that the maximum backstroke force is a good measure for the amount of pickup on the punch.

The gap between the punch and the lower die is called the radial punch clearance $u$ and is calculated as:

$$u = \frac{D - d}{2} \quad (1)$$

Where $D$ is the diameter of the lower die and $d$ is the diameter of the punch.

The punch ratio $L_u$ is given by:
Development of the curves may be divided into the zones A to F as indicated in the figure.

A. Increasing load due to work hardening of the workpiece material.
B. Gradual decrease in load due to decrease in remaining thickness to be sheared and finally abrupt load decrease due to fracture.
C. During further penetration a load of up to 50% of the maximum load appears. This is caused by frictional resistance between blank(s) and die and punch and sheet hole.
D. When the punch reaches the bottom dead center the direction of press movement is reversed in order to return the punch. The initial part of the backstroke occurs with zero punch load due to the play causing a short standstill of the punch.
E. When the play is passed, the punch is pulled back and a backstroke force is registered caused by frictional contact between the punch stem and the surrounding workpiece material, which clamps on the punch stem due to spring back of the bent sheet.
F. When the punch leaves the sheet the load drops to zero.

Comparing the curves corresponding to stroke No. 1 and stroke No. 1600 it is obvious that the change in backstroke force is pronounced compared to that of the punch force. Although the punch force shows a change, the difference is much smaller. The reason why the maximum punch force does not show the same sensitivity to pick-up is because the friction force between punch and workpiece material is relatively small comparable to the punch force.

From the backstroke force measurements, two different parameters were initially defined, the maximal backstroke force $F_{b,max}$ and the backstroke work $W_b$:

\[ F_{b,max} \]

Where $s_0$ is the workpiece thickness. A punch ratio of $L_s \leq 1$ is what is technically possible for conventionally punching in stainless steels [4].

Figure 2 shows a typical geometry of a punched hole.

It is seen, that the hole is not cylindrical, but consists of three major zones: The
edge rounding zone, the bright zone and the fracture zone with a small burr. The
bridge zone is rather cylindrical, while the edge rounding zone and the fracture zone
are conically shaped.

The punching process encompasses several lubrication mechanisms. As the punch
approaches the workpiece, lubricant get squeezed out between the punch tip and
the workpiece surface, yielding hydrodynamic lubrication. After the punch tip has
achieved full contact with the workpiece surface, a pocket of lubricant is trapped
between the punch tip and the workpiece surface yielding hydrostatic lubrication.
As the punch penetrates the workpiece, grooves in the punch stem surface will entrap
lubricant, depending on the punch stem surface topology. This yields a combination
of hydrostatic, hydrodynamic and possibly mixed lubrication, if the lubricant reacts
chemically with the punch surface.

If only the ability of punch material and lubricant to form boundary lubrication was
to be examined, the punches should be polished to remove grooves in the punch
stem surfaces that traps lubricant. This is however not done in this course. Hence,
it may not be possible to detect the effect of boundary lubrication.
3 Experimental set up

In this section, the laboratory equipment and experimental procedure will be described.

3.1 Press

The punching tests are performed in a C-frame eccentric press produced by Poul Møllers Maskinfabrik (PMB). The press has a maximum capacity is 320 kN and can perform between 100 strokes/min and 170 strokes/min. The stroke rate can be adjusted using an infinitely variable frequency converter that is mounted next to the press. The punch travel is set to 15 mm. The press is equipped with a pneumatic feeding system that pulls a contentious metal strip through the punching tool. The metal strip is coiled up and mounted next to the press. Figure 3 shows the press set up to perform punching tests.

Figure 3: C-frame eccentric press with punching tool and strip feeding system
3.2 Punching tool

The punching tool is developed by Grundfos and is equipped with two punches. Each punch is connected to a piezoelectric load cell capable of measuring both compression and tension. The tool is designed with a radial punch clearance of $10 \mu m < U_s < 15 \mu m$. The punch has a diameter of $d = \phi 2$ mm. This yields a punch ratio of $L_s = 2$, well below the limit value of $L_s = 1$.

![Figure 4: Punching tool with one punch mounted](image)

3.3 Punch

The punches have dimensions as shown in figure 5. Dimensions are given in [mm].

![Figure 5: Punch](image)
Two different punch materials are tested. Vanadis 6, which is a conventional powder metallurgically (PM) high speed steel and Vancron 40 which is a newly developed PM high speed steel. Vancron 40 contains vanadium nitride and vanadium carbide precipitates which makes it very resistant to galling. Table 1 shows the key chemical elements in the two punch steels.

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>N</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Mo</th>
<th>W</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vancron 40</td>
<td>1.1</td>
<td>1.8</td>
<td>0.5</td>
<td>0.4</td>
<td>4.5</td>
<td>3.2</td>
<td>3.7</td>
<td>8.5</td>
</tr>
<tr>
<td>Vanadis 6</td>
<td>2.1</td>
<td>-</td>
<td>1.0</td>
<td>0.4</td>
<td>6.8</td>
<td>1.5</td>
<td>-</td>
<td>5.4</td>
</tr>
</tbody>
</table>

Table 1 shows that Vancron 40 contains higher levels of vanadium (V) than Vanadis 6. A high Vanadium content increases the abrasive wear resistance. I.e. the resistance towards abrasive wear is lower for Vanadis 6 than for Vancron 40 [6].

### 3.4 Workpiece

The workpiece is a continuous steel strip with width and thickness: 30 mm × 1 mm. The strip is clean and coiled up, so no cleansing is needed before a lubricant is applied. Two work piece materials are tested: AISI 304L and LDX 2101.

### 3.5 Data acquisition system

The load cells are connected to a PC through a signal amplifier. The press is equipped with a displacement transducer that monitors the punch position. The PC logs the punch force and punch displacement simultaneously. A specially developed LabView program analyses the force-displacement signal for each stroke. The maximum penetration force and backstroke force are extracted and written to a data-file with the corresponding stroke number. A separate data file with the force-punch position signal for each stroke is also created.

### 3.6 Lubricants

Two lubricants are tested:

- Rhenus SU 166A+, which is a chlorinated free oil with additives. This oil have a viscosity of 166 mm²/s, similar to syrup.
- IRMCO PF40 BRIX 27.4 40%, which is a water based polymer oil in a 40% water solution. This oil have about the same viscosity as water.

Both oils are considered environmentally friendly and are the latest available versions of the Rhenus and IRMCO oils. The IRMCO lubricant works in a rather untraditional way: When the temperature on a surfaces increases sufficiently, the water evaporates leaving a polymer layer. This layer then separates the tool-workpiece surfaces, thus preventing galling.
3.7 Punching conditions

The punching tests are performed at a stroke rate of 150 strokes/min. This value is chosen, as it is the same value used in tests performed in David Dam Olssons Ph.D. thesis [4] and tests done by Ruben Buelga Sanchez [5]. In order to be able to compare the test results obtained in the present work to results from [4] and [5], the stroke rate must be held constant [4] (p. 10-45).

Lubrication is applied on both sides of the strip before it enters the punching tool in a thin layer. This is ensured by running the strip through the lubrication application system shown in figure 6, where two foam rolls spread out the lubricant. It is possible to connect the rolls to a lubricant container through two plastic tubes. This is done when using the IRMCO lubricant, but not when using the Rhenus lubricant since the viscosity is too high for the lubricant to flow.

![Figure 6: System that provides an even lubrication layer](image)

3.8 Test procedure

The test is started by mounting the punches in the punching tool. In order to do so, the tool have to be taken out of the press. When disconnecting the wire from the load cell, the protecting cap should be screwed onto the socket to avoid getting dirt into the wire connection.

The tool consists of two main parts: The stationary lower part and the moving upper part. In order to change the punches, the two parts are separated. Figure 7 shows the upper tool part clamped in an inverted position.
Figure 7: Upper part of punching tool clamped for punch mounting

Figure 7 only shows one punch since the other is dismounted. The reason for this will be explained later. The aluminium cup holding the punch in place is loosened using two wrenches. One is placed on the load cell opposite to the wire and the other is placed on the aluminium cup. It is important to be very careful not to loosen the bolt fastening the load cell to the fixing plate. If this occurs, the fixing plate must be removed in order to fasten the bolt again. This will cause the punch to be misaligned. To realign the punch, the fixing plate with load cells and punches attached must be inserted into the lower part of the tool. When the punches are positioned in the guiding holes, the load cell bolts are fastened and the fixing plate is reattached to the upper tool part. The tool is then put together and installed in the press. It is important to make sure that there is no scrap metal on the tool-press interface surfaces, since this may cause misalignment. Now, the strip is pulled through the lubrication system and the tool and attached to the feeding system. It is very important to make sure that the strip hangs loose from the coil so that the feeding system do not have to pull the strip directly from the coil. This will create too much tension in the strip, causing the punches to deflect. This happened and resulted in a broken lower die as shown in figure 8.

Figure 8: Broken left lower die.

Due to the broken die, it was not possible to use the two punches simultaneously.
To make up for this, the tests were run twice with one punch.

When the tool and strip is in place, the data acquisition system is started and the punching process is initiated. The LabView program requires the user to set a ‘Trigger value’. This value is a measure for the force required to log the measurements. If this value is set too low, the program will log useless data. If the value is set too high, the program won’t log any data. A trigger value of 3 was found to lead to a correct data logging sequence, but it should be reexamined if further tests are to be conducted.

It is important monitor the force level and stop the test if this becomes too high to avoid breaking the punch. After the desired number of strokes have been reached, the strip is cut off with a sheet metal cutter and removed from the press. It is a good idea to make a quick plot of the data in e.g. excel, to check if anything seems odd before the next test is conducted.

Since the punching tool produces very loud noises\textsuperscript{1} it is important to wear earplugs. These can be provided by the work shop manager. Also, since the punching tool weighs approximately 15 kg, wearing steel-toe boots when removing the tool from the press may be wise.

In order to avoid cleaning the test equipment, which is very time-consuming, all test combinations involving the Rhenus lubricant were conducted first whereafter the equipment was cleaned with odour free petroleum. The tests using the IRMCO lubricant were then conducted. The full test plan is shown in table 2.

\textbf{Table 2:} Test plan

<table>
<thead>
<tr>
<th>Lubricant</th>
<th>Workpiece steel</th>
<th>Punch steel</th>
<th>Repetitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRMCO</td>
<td>AISI 304L</td>
<td>Vanadis 6</td>
<td>2</td>
</tr>
<tr>
<td>IRMCO</td>
<td>AISI 304L</td>
<td>Vancron 40</td>
<td>2</td>
</tr>
<tr>
<td>IRMCO</td>
<td>LDX 2101</td>
<td>Vanadis 6</td>
<td>2</td>
</tr>
<tr>
<td>IRMCO</td>
<td>LDX 2101</td>
<td>Vancron 40</td>
<td>2</td>
</tr>
<tr>
<td>Rhenus</td>
<td>LDX 2101</td>
<td>Vanadis 6</td>
<td>2</td>
</tr>
<tr>
<td>Rhenus</td>
<td>LDX 2101</td>
<td>Vancron 40</td>
<td>2</td>
</tr>
<tr>
<td>Rhenus</td>
<td>AISI 304L</td>
<td>Vanadis 6</td>
<td>2</td>
</tr>
<tr>
<td>Rhenus</td>
<td>AISI 304L</td>
<td>Vancron 40</td>
<td>2</td>
</tr>
</tbody>
</table>

The test plan minimizes the number of times the coil had to be changed which saved a great amount of time. However, the test plan is not randomized. This may result in more consistent results for the Rhenus tests, since a lot of experience is gained in the IRMCO tests.

\textsuperscript{1}The workers measures sound pressure levels of 90 dB in the booth closets to the press
4 Results

Figure 9 shows the development of the backstroke force $F_b$ as the number of strokes increases when punching in AISI 304L steel. The combination of lubricant and tool- and workpiece steel is indicated on the left side of the plots. Each plot contains the data from two repetitions. One series is marked with crosses ($\times$) and one with circles ($\circ$). Plots of the individual test combinations, where some data points are left out to give a better overview of the backstroke force development, are attached in appendix A.

Figure 9: Maximum backstroke force for punching in AISI 304L steel with different combinations of lubricant and tool steel

Figure 9 shows some variation between the repetitions for the tests using Rhenus as lubricant. This may be contributed to small differences in the alignment of the punch. The effect is almost gone in the tests using IRMCO as lubrication. This is most likely due to the fact that the experiments using Rhenus were performed first. The experience obtained in these tests facilitated better alignment of the needle in the IRMCO tests, yielding more consistent results. However, it is clear to see that there is a significant difference in the backstroke forces between the various tool- and workpiece steel combinations. Many of the individual measurements show backstroke forces many times higher than the overall level. These outliers may be contributed to sudden vibrations causing the strip to shift slightly, resulting in an increased pressure between the punch stem and hole surface.

When lubricating with Rhenus, the lowest backstroke forces are obtained when a Vanadis 6 punch is used. This is also the case when lubricating with IRMCO, however, the reduction in the backstroke force is approximately twice as large as when lubricating with Rhenus. This may be caused by different punch stem surface topologies, allowing the Vanadis 6 punches to entrap more lubricant in surface pockets. It may also imply that boundary lubrication occurs for both lubricants and the Vanadis 6 punches, but is much more pronounced for the IRMCO oil. A different punch stem surface topology is however more likely, since the punches are
manufactured different places. Pictures of the punches taken through a microscope, shown later in the report, suggests that the Vanadis 6 punches have a slightly more coarse surface that the Vancron 40 punches.

The lowest backstroke forces when punching in AISI 304L, are obtained using a Vanadis 6 punch and lubricating with IRMCO.

Figure 10 shows the development of the backstroke force as the number of strokes increases when punching in LDX 2101 steel.

![Graph showing the development of backstroke force](image)

**Figure 10:** Maximum backstroke force for punching in LDX 2010 steel and different combinations of lubricant and tool steel

Figure 10 shows the same behaviour as figure 9: The backstroke force drops when switching from a Vancron 40 punch to a Vanadis 6 punch and the lowest backstroke forces were obtained using a combination of IRMCO and a Vanadis 6 punch.

Generally, when lubricating with Rhenus, the difference in backstroke force when varying the workpiece steel is not very significant. The data for AISI 304L is more spread out, but the 'baseline' is approximately the same. This is not the case when using IRMCO as lubrication. Here, the Vancron 40 punches yield 3.3 times higher forces when punching in AISI 304L instead of LDX 2101.
Table 3 shows the different oil types used in punching tests performed by David Dam Olsson [4] in 1 mm AISI 304 with punches made of ASP 23 non-coated hardened to 62-64 steel. The tool- and punch dimensions are identical to the dimensions used in the AISI 304L and LDX 2101 punching tests.

Table 3: Specifications for oils in figures 11 and 12

<table>
<thead>
<tr>
<th>Code</th>
<th>Name/Manufacturer</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PN226</td>
<td>Castrol PN226</td>
<td>Medium additivated mineral oil with chlorine based EP additives</td>
</tr>
<tr>
<td>CR5</td>
<td>Houghton CR-5</td>
<td>Pure mineral oil</td>
</tr>
<tr>
<td>SUN</td>
<td>SUN 60N</td>
<td>Pure mineral oil</td>
</tr>
<tr>
<td>D300</td>
<td>Houghton Stelloy D300</td>
<td>Aqueous emulsion combined with a polyol ester and sulphur additives</td>
</tr>
<tr>
<td>Stratos 250 E</td>
<td>Statoil</td>
<td>Based on biological degradable esters</td>
</tr>
<tr>
<td>W300 M</td>
<td>Houghton W300 Modified 1</td>
<td>Prototype oil</td>
</tr>
<tr>
<td>W300 MM</td>
<td>Houghton W300 Modified 2</td>
<td>Prototype oil</td>
</tr>
</tbody>
</table>

All oils in table 3, besides Castrol PN226, are considered environmentally friendly. Further information regarding the different oils can be found in [4]. Figures 11 and 12 show test results obtained by David Dam Olsson [4].

![Figure 11: Results for performance tests of different lubricants when punching in 1 mm AISI 304 [4]](image-url)
Additional test conditions were:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Punch material</td>
<td>ASP 23 non-coated hardened to 62-64 HRC</td>
</tr>
<tr>
<td>Punch dimension</td>
<td>( d = \varnothing 1.985 \pm 0.002 \text{ mm} )</td>
</tr>
<tr>
<td>Die material</td>
<td>ASP 23 non-coated</td>
</tr>
<tr>
<td>Die dimension</td>
<td>( D = \varnothing 2.020 \text{ mm} )</td>
</tr>
<tr>
<td>Radial clearance</td>
<td>( u = (D - d)/2 = 0.018 \text{ mm} )</td>
</tr>
<tr>
<td>Workpiece material</td>
<td>Stainless steel Wn. 1.4401 (AvestaPolarit)</td>
</tr>
<tr>
<td>Workpiece composition</td>
<td>C=0.029%, Cr=16.85%, Ni=10.56%, Mo=2.57%</td>
</tr>
<tr>
<td>Workpiece dimensions</td>
<td>Length=2000mm; Width=43mm; Thickness=1.25mm</td>
</tr>
<tr>
<td>Strokes per test</td>
<td>1000 strokes/test</td>
</tr>
<tr>
<td>Strokes per strip</td>
<td>Approx. 170 strokes/strip</td>
</tr>
<tr>
<td>Distance between holes</td>
<td>10 mm</td>
</tr>
<tr>
<td>Amount of lubricant</td>
<td>5 ml on each side of the strip (58.1 ml/m²)</td>
</tr>
<tr>
<td>Lubrication method</td>
<td>Manual lubrication. Lubricant uniformly spread</td>
</tr>
<tr>
<td>Speed of the test</td>
<td>150 strokes/min – Feeding system</td>
</tr>
<tr>
<td>Press type</td>
<td>PMB eccentric press</td>
</tr>
</tbody>
</table>

Table 10.6: Fixed test parameters.

Figure 12: Averaged maximal backstroke force versus number of strokes comparing chlorinated paraffin oil performance against environmental alternatives, when punching in 1 mm AISI 304 [4]

Figures 11 and 12 shows that the environmentally harmful oil, Castrol PN226, gives the lowest backstroke forces at about 90 N. This is slightly lower than the results obtained when punching in AISI 304L and LDX 2101, lubricating with IRMCO and using a Vanadis 6 punch. The results are of course not fully comparable due to the different steel-types\(^2\), but the overall backstroke force levels are of the same magnitudes.

In work done by Ruben Buelga Sanchez [5], punching tests in high strength steel, DP800 and stainless steel, AISI 304L with Vanadis 6 and Vancron 40 punches using different types of environmentally friendly lubricants were performed. The main results will be summarized, but no graphs will be shown.

For punching in DP800, three different lubricants were tested: FUCHS anticorital PL 3802-39 s, Shell PQ 144 and IRMCO 980 PF40-S. The lowest backstroke forces, at an average level of approximately 100 N, were obtained using either a Vanadis 6 or a Vancron 40 punch and lubricating with Shell PQ 144. These backstroke forces are of the same magnitude as obtained when punching in AISI 304L and LDX 2101 using a Vanadis 6 punch and lubricating with IRMCO PF40 BRIX 27.4 40%.

For punching in AISI 304, two different lubricants were tested: IRMCO 980 PF40-S and Rhenus LA 7222065. In these tests, the lowest average backstroke forces at approximately 200 N, were obtained using either a Vanadis 6 or a Vancron 40 punch and lubricating with IRMCO 980 PF40-S. These backstroke forces are approximately twice as large as the backstroke forces obtained when punching in AISI 304L and LDX 2101 using a Vanadis 6 punch and lubricating with IRMCO PF40 BRIX 27.4

\(^2\)The low carbon percentage in AISI 304L does first and foremost have an influence on the corrosion properties of the steel. The strength, ductility and hardness does not vary significantly between the two steels
4.1 Results conclusion

The tests showed, that punching in AISI 304L and LDX 2101 using a Vanadis 6 punch and lubricating with IRMCO PF40 BRIX 27.4 40% gives backstroke forces of the same magnitude obtained, when punching i AISI 304 using the environmentally harmful Castrol PN226 chlorinated oil. Furthermore, by comparing with tests done by Ruben Buelga Sanchez, it was found that IRMCO PF40 BRIX 27.4 40% performs better in punching than IRMCO 980 PF40-S and Rhenus LA 7222065. It is harder to compare the results to the tests done in DP800, since the steel type differs significantly from AISI 304L. However, backstroke forces obtained when punching in AISI 304L with a Vanadis 6 punch and IRMCO PF40 BRIX 27.4 40% combination, are of the same magnitude, as when punching in DP800 using either a Vanadis 6 or a Vancron 40 punch and lubricating with Shell PQ 144. AISI 304L is more ductile than DP800, so it could be expected, that more workpiece material would come in contact with the punch and hence increase the backstroke force when punching in AISI 304L. This does however not seem to be the case, so it is assumed, that the backstroke forces can be evaluated based on the punch-lubricant combination. If this assumption is correct, the tests show that IRMCO PF40 BRIX 27.4 40% is of equal quality as Shell PQ 144. It is not clear if the force reduction, when changing from a Vancron 40 punch to a Vanadis 6 punch, can be explained by boundary lubrication, since the surface topology of the punch stems may differ.
5 Microscope inspection of pickup

One punch for each test combination were inspected under a 10x Leica stereo microscope located in the basement of building 425. Figures 13 and 14 show the punch stem at the tip. The test combination is specified below the pictures. The white bar in each picture is 0.2 mm long. The workpiece sheet metal is, as earlier mentioned, 1 mm thick corresponding to 5 times the length of the white bar. Thus, the section of the punch stem shown in the pictures has been ‘submerged’ in the workpiece.

Figure 13: Punch tips seen through a 10x stereo microscope

Figure 13 shows that pickup is developing along the punch stem in the axial direction starting from the punch tip when lubricating with Rhenus. The grooves from the roundness grinding are very clear. In the tests using AISI 304L and Rhenus, the pickup zone seems more dense for the Vancron 40 punch than the Vanadis 6 punch. This corresponds to the force measurements in figure 9, where the Vanadis 6 punches display lower backstroke forces than the Vancron 40 punches. The tests using AISI 304L and IRMCO show a completely different surface topology. The surfaces have formed pickup patterns similar to scar tissue. The Vancron 40 punch has a circumferential pickup line at about 0.15 mm from the punch tip. Also, the
'scar tissue’ on the Vancron 40 punch seems most developed. This corresponds to the increased backstroke forces shown in figure 9. The strange 'scar tissue' pickup may be explained by the way the IRMCO lubricant works. If a local pickup formation develops, more heat will be generated here due to an increase in friction. The water will then evaporate faster, leaving a thicker polymer layer locally. This will result in an uneven polymer layer corresponding to the 'scar tissue’ pattern.

The punch tip edge on both Vanadis 6 punches miss relatively large chunks of material. This will decrease the quality of the punched hole. It is however not likely to influence the backstroke force significantly.

Figure 14: Punch tips seen through a 10x stereo microscope

Figure 14 shows no significant difference in the pickup density between the tests using LDX 2101 and Rhenus. However, the backstroke forces shown in figure 10 indicate that the pickup density should be highest for the Vancron 40 punch. The tests using LDX 2101 and IRMCO show very different surface topologies. The Vanadis 6 punch show no sign of pickup, while the Vancron 40 punch shows a massive amount of
pickup. This is consistent with the backstroke forces shown in figure 10. However, as in the AISI 304L tests, large chunks of material are broken off the punch edge on the Vanadis 6 punch, causing a decreased hole quality.

Figures 13 and 14 display two types of wear: Galling, where workpiece material cold welds to the punch stem and fatigue, where chunks of punch material break off the punch edge. The latter will have greatest influence on both the lifetime of the punch and, most important, the quality of the punched holes. Taking this into consideration, the Vancron 40 punches shows better performance than the Vanadis 6 punches.

Roughness tests on the punch stems on new punches were performed subsequently. The Vanadis 6 punch had a roughness of approximately $R_a = 0.34$ while the Vancron 40 punch had a roughness of approximately $R_a = 0.3$. I.e. the Vancron 40 punches are slightly smoother than the Vanadis 6 punches. This agrees with the lower backstroke forces obtained with the Vanadis 6 punches, since a high roughness implies a good ability to entrap lubricant in the punch stem surface. It was however not possible to obtain good roughness profiles, as the tests had to be rushed due to time constraints. The Vanadis 6 and Vancron 40 punches could therefore have different surface topologies causing a difference in their ability to entrap lubricant in the punch stem surface.

6 FE-simulations

In this section, the development of a simple FE model of a punching process will be described.

6.1 Geometry and mesh

The FE-simulations are performed using the software Deform 2D. A 2D model of the workpiece, punch and lower- and upper die is created by defining coordinates for the corners of the geometries. This is done by creating an object, choosing Edit and type in the points in the table. It is important to type in the coordinates so that the points run counter-clockwise. This ensures that Deform knows what is solid and what is empty space. The workpiece is 1 mm thick and the punch have a radius of 1 mm. Only half of the punch is modelled to exploit symmetry. The radial clearance between the punch and dies is 10 µm.

The punch and the lower- and upper die are defined as rigid materials and does thus not need to be meshed. The workpiece is defined as an elasto-plastic material in order to enable retraction around the punch stem. This is done under Object Type → Elasto-Plastic. The punch is chosen as the Primary Die by checking off the box in the bottom of the object page.

Figure 15 shows the finished model of the punching tool. The dash-dot line on the left side of the figure is a symmetry plane that applies symmetry constrains on the nodes located here.
As seen in figure 15, the mesh is refined in the shearing zone. This is achieved by setting three mesh windows. Two surrounding the coarse meshed areas and one surrounding the fine meshed area. It is important that the window boarders intersects the geometry edges. The mesh windows are created under Mesh → Detailed settings → Mesh window. The Relative element size is set to one in the coarse mesh windows and 0.05 in the fine mesh window. This makes the fine elements 20 times smaller relative to the coarse elements [7].

6.2 Material model

The material model for the workpiece is created under Material and choosing New. Then, the material model controlling the flow stress is chosen under Plastic as \( \sigma = \sigma(\varepsilon, \dot{\varepsilon}, T) \). The model is then modified by pressing the small pencil icon to the right of the window. Here, coordinates for the desired flow stress-strain curve is typed in. It is also possible to load in a .txt file with the data directly. The curves used for the simulations are supplied by Ermanno Ceron and shown in figure 16. The new material must be chosen as the workpiece material. The Young’s modulus is set to 210000 MPa.

![Figure 16: Flow stress-strain curves for AISI 304 and LDX 2101. Crosses indicate fracture](image-url)
To allow Deform to operate with large strains, the flow stress-strain curves are extended up until $\varepsilon = 5$ at a constant flow stress level.

Since punching produces large strain rates and elevated temperatures, the material model will prove to be very inaccurate, as it assumes the material to be independent of strain rate and temperature.

A failure criterion is set under Material → Advanced. The model Cockcroft & Latham is used. It specifies the strain energy $C$ an element has absorbed at fracture, also known as the toughness [7]:

$$C = \int \sigma^* d\varepsilon$$  \hspace{1cm} (3)

$C$ is calculated by integrating the flow stress-strain curves in figure 16. The values for AISI 304L and LDX 2101 are found to be: $C_{\text{AISI}} \approx 248 \text{ mJ/mm}^3$ and $C_{\text{LDX}} \approx 220 \text{ mJ/mm}^3$. The option Soften to □ (%) of original flow stress is set to 1. This lowers the flow stress of elements that has exceeded the critical strain energy to 1 % of the flow stress at zero strain.

The values for $C$ calculated above resulted in shear fracture too early in the punching process when comparing to a measurement from the real punching test. To obtain results similar to the physical test, the value had to be set to $C_{\text{LDX}} = 3000 \text{ mJ/mm}^3$. This is 13.6 times higher than the theoretically calculated value. This seems unlikely to be reasonable, as the stress strain curves in figure 16 are obtained from a tensile test, whereas the fracture in the punching process occurs due to shearing. The shear flow stress $k$ is from V. Mises yield criterion given by $k = \sigma^*/\sqrt{3}$. This implies, that the fracture strain in shearing is lower than in tension, and thus that the $C$-values should be lower for shearing. It is of course possible, that the premature shear fracture is coursed by other settings is Deform. This is not investigated in this project.

6.3 Punch speed

The velocity of the punch will, due to the eccentricity of the press, follow a cosine-like curve. However, since the material model assumes the material to be independent of the strain rate, the punching velocity can be set as being constant 150 mm/s. This is easily implemented in the Deform preprocessor under Object → Movement.

The simulation is divided into a number of steps. This number is chosen as 500 and set under Simulation controls → Simulation steps. In order to have the correct punch displacement, the amount of time spend in each step must be set. The time step is set to $10^{-5}$ sec/step. This is set under Simulation controls → Step increment.

6.4 Shear fracture

To model the sudden shear fracture that occurs in a real punching process, some elements have to be deleted after they have absorbed the critical strain energy $C$. 20
This is controlled by setting the workpiece parameters Fracture steps and Fracture elements under Properties → Fracture. Fracture elements determines how many elements are allowed to exceed the critical strain energy before the model is stopped and element deletion is performed. Fracture steps determines the step interval between element damage checks [7]. Suitable values are found to be: Fracture steps=10 and Fracture elements=5. Deleting elements will however result in a loss of volume in the shearing zone. This causes the punch stem to loose contact with the workpiece. Thus, it is not possible to model a backstroke force, since this would rely on friction between the workpiece and punch stem.

6.5 Contact definitions

The contact between the different parts of the punching tool is set under Inter-Object. Contact definitions between all objects is generated by pressing the small hammer icon and Initialize → Generate all. In all cases, the workpiece is chosen as the Slave. Different friction models can then be set to work in the contact zones. Coulomb friction is chosen, as it is expected that the normal pressure between the punch stem and workpiece is relatively low.

6.6 Other parameters

There are several other parameters to set before running a simulation. These are set under Simulation control:

Main:

- Geometry → Axisymmetric
- Mode → Deformation

Simulation steps:

- Starting step number → -1
- Step increment to save → 10
- Primary die → Punch

Step increment:

- General → Solution step definition → Time
- General → Database step saving → System
- General → Sub-stepping control → Uncheck box

3This feature divides a step into several sub-steps if contact problems in the simulation are encountered. This should not interfere with the overall number of steps, but does this anyhow. To avoid problems, this feature is unchecked.
Remesh Criteria:

- Object → Workpiece
- Interference depth → 0.01 mm
- Maximum step increment → 5

Iteration:

- Solver → Skyline
- Iteration method → Newton-Raphson
- Convergence limit error → Velocity error → 0.001
- Convergence limit error → Force error → 0.01
- Maximum iterations → Per deformation time step → 200

Process conditions:

- Environment temperature → Constant 20 C

Advanced:

- Primary workpiece → Workpiece
6.7 FE-results

Due to time constraints, only simulations with the LDX 2101 material model were performed.

Figures 17, 18 and 19 show the three major stages of the punching process: First, the workpiece deforms plastic (figure 17). When the punch travel reaches a little more than half the workpiece thickness, a shear fracture initiates (figure 18). As the punch continues, the scrap gets separated from the workpiece (figure 19). The colors indicate the effective strain.

Figure 17: Plastic deformation

Figure 18: Sheer fracture occurs

Figure 19: Separation of scrap from the workpiece with major zones indicated

It is possible to identify the three major zones\(^4\) in figure 19: A small edge rounding can be seen in the top of the shearing zone. The bright zone follows directly after

\(^4\)As mentioned in the theoretical section
the edge rounding zone and continues until about 0.6 mm into the workpiece. The
fracture zone occupies the last hole section and has a shape similar to a cone. This
corresponds well to the theoretical prediction seen in figure 2.

Figure 20 shows the numerically calculated penetration forces at different values of
Coulomb friction \( \mu \), and the experimental penetration force for stroke 724 in the
test-combination: LDX 2101, IRMCO and Vanadis 6\(^5\). The maximum backstroke
forces versus the number of strokes for all tests are attached in appendix B. The
overall force level lies between 4 kN and 5 kN.

![Figure 20: Numerically calculated penetration forces at different friction values
compared to an experimental test measurement](image)

Figure 20 shows that the numerically calculated penetration force curves have a
shape similar to the experimental curve. Then, the forces increases rapidly as the
punch penetrates the workpiece surface. The forces reach a maximum level where-
after they decrease slightly. At a penetration of approximately 0.6 mm, the forces
drop as the shear fracture develops. The numerically calculated forces drop to zero,
since the punch and workpiece lose contact due to element deletion. The experi-
mental curve reaches a force level of about 800 N since workpiece squeezes the punch
stem due to its elasticity. Figure 20 also shows that the numerically calculated pen-
etration forces increases slightly with an increasing Coulomb friction. The difference
increases as the penetration, and hence the area of the punch stem in contact with
workpiece increases. Despite rather large values of \( \mu \), the numerically calculated
forces does not reach the same level as the experimental force.

\(^5\)This combination gave the lowest penetration forces
7 Conclusion

The test results showed that a combination of the lubricant IRMCO PF40 BRIX 27.4 40% and a Vanadis 6 punch gave the lowest backstroke forces. These were comparable to backstroke forces obtained using the environmentally harmful Castrol PN226 chlorinated oil. Further more, IRMCO PF40 BRIX 27.4 40% performs better than a combination of either IRMCO 980 PF40-S or Rhenus LA 7222065 in combination with a Vanadis 6 or Vancron 40 punch.

Inspection of the punch stem surfaces at the punch tip showed that the different punch-lubricant combinations resulted in very different types of wear. Where the Rhenus oil caused galling along the punch stem in the axial direction extending from the punch tip, IRMCO resulted in a random galling pattern resembling scar tissue. This may be explained by differences in temperature giving differences in the thickness of the polymer layer separating the punch stem and workpiece.

The Vanadis 6 punches experienced fatigue wear resulting in large chunks of material breaking off the punch tip edge. This did not occur for the Vancron 40 punches.

In the FE-simulations, the magnitude of the numerically calculated forces did, as expected, not agree with the experimental forces. This can most likely be contributed to the over-simplified material model. In order to make the overall shape of the numerical curves fit the experimental curve, the toughness $C$ was set 13.6 times higher than an already over-estimated value.
References


A Test results

Plots showing the maximum backstroke force as the number of strokes increases. Some data points are left out to give a better overview of the force development. Each plot contains the data from two repetitions. One series is marked with crosses (×) and one with circles (○).

Figure 21: Backstroke force for the combination: AISI 304L, IRMCO and Vanadis 6

Figure 22: Backstroke force for the combination: AISI 304L, IRMCO and Vancron 40
**Figure 23:** Backstroke force for the combination: AISI 304L, Rhenus and Vanadis 6

**Figure 24:** Backstroke force for the combination: AISI 304L, Rhenus and Vancron 40
Figure 25: Backstroke force for the combination: LDX 2101, IRMCO and Vanadis 6

Figure 26: Backstroke force for the combination: LDX 2101, IRMCO and Vancron 40
Figure 27: Backstroke force for the combination: LDX 2101, Rhenus and Vanadis 6

Figure 28: Backstroke force for the combination: LDX 2101, Rhenus and Vancron 40
B Maximum penetration force

Plots showing the maximum penetration force as the number of strokes increases. Some data points are left out to give a better overview of the force development. Each plot contains the data from two repetitions. One series is marked with crosses (×) and one with circles (○).

**Figure 29:** Maximum penetration force for the combination: AISI 304L, IRMCO and Vanadis 6

**Figure 30:** Maximum penetration force for the combination: AISI 304L, IRMCO and Vancron 40
Figure 31: Backstroke force for the combination: AISI 304L, Rhenus and Vanadis 6

Figure 32: Maximum penetration force for the combination: AISI 304L, Rhenus and Vancron 40
Figure 33: Maximum penetration force for the combination: LDX 2101, IRMCO and Vanadis 6

Figure 34: Backstroke force for the combination: LDX 2101, IRMCO and Vancron 40
Figure 35: Maximum penetration force for the combination: LDX 2101, Rhenus and Vanadis 6

Figure 36: Maximum penetration force for the combination: LDX 2101, Rhenus and Vancron 40
Figures showing the plots of the maximum penetration force for the same steel type side by side for better comparison. All data points are included.

**Figure 37:** Maximum penetration force for punching in AISI 304L steel with different combinations of lubricant and tool steel

**Figure 38:** Maximum penetration force for punching in LDX 2101 steel with different combinations of lubricant and tool steel