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Preface

As in the first edition in 1997 in Gifu, Japan, the second one in Nyborg, Denmark, in 2004 and the third in 2007 in Yokohama, Japan, ICTMP 2010 ambition is to gather the international community involved in the tribology of manufacturing processes, from academia as well as from industry. Apart from the everlasting trend towards more efficiency and productivity associated with lower costs, recent years have witnessed the emergence of new orientations, such as microforming for microsystems and MEMS, or micro- to nano-patterning of surfaces for improved tribological properties or more generally for surface functionalization; both raise new questions of scale effects on friction. Environmental concerns bring to the forefront the need for new, “greener lubricants”, or for using less lubricant (Minimal Quantity Lubrication, or MQL) for example with the help of improved coatings. New coatings from non-toxic and easily disposable baths, or new coating deposition or surface hardening and texturing techniques, are also central in the industrial evolutions. From another point of view, friction measurement and friction models are more and more requested to account for its space- and time-dependence, both in view of the local or time-varying control of friction in the shop, and in the modelling of processes.

All these trends are both new constraints imposed on the mechanical engineer, and sources of new thrilling research topics for his advisor, the Tribologist, as will become obvious at reading the following research reports. The present two volumes present a welcome review of advances in the tribological practice and knowledge of such traditional processes as deep-drawing and stamping, hot and cold forging, wire-drawing, strip rolling, or assembling processes, cutting and machining, while giving an insight into newer or less vulgarized forming, assembling or finishing techniques.

The Organizing Committee heartily thanks the authors of the 88 contributions to this Conference and to the present Proceedings, and specially the Programme Committee whose members worked hard to review the papers and improve their quality.

Eric FELDER, Pierre MONTMITONNET
Chairmen, ICTMP 2010
PLENARY LECTURE
GREEN LUBRICANTS FOR METAL FORMING

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Abstract
The increasing focus on legislation towards diminishing the impact on working environment as well as external environment has driven efforts to develop new, environmentally benign lubricants for metal forming. The present paper gives an overview of these efforts to substitute environmentally hazardous lubricants in cold, warm and hot forging as well as sheet forming and punching/blanking with new, less harmful lubricants.

Keywords: metal forming tribology, lubricants, environmental impact

1 INTRODUCTION
Since 2000, legislation in Europe, Japan and USA has been increasingly restrictive with respect to the industrial application of hazardous lubricants, [1-4]. Due to these legislative initiatives, manufacturers are increasingly focused on environmental concerns and request their suppliers to act proactively to establish safe and healthy working conditions while limiting the strain on the environment.

Environmental problems in metal forming tribology, can be divided into the following areas, [5]: a) health and safety of people, b) influence on equipment and buildings, c) destruction and/or disposal of waste and remaining products. Improvement efforts are concentrated on 1) elimination of hazardous chemicals, e.g. chlorinated additives or phosphates with (heavy) metal sludge, and 2) reduction of waste, including prolonging tool and lubricant life, recovery and reuse of lubricants and Minimal Quantity Lubrication (MQL).

Due to the very varied tribological conditions in different metal forming processes the lubricants applied are quite different in different production processes. The present paper gives an overview of the environmental problems regarding traditionally applied lubricants and the development and testing of new, environmentally benign lubricants for cold forging, warm/hot forging, rolling, sheet metal forming and punching/blanking.

2 COLD FORGING
Development of the cold forging process of steel and its successful application in the automotive industry since 1960 is closely connected to the development of efficient lubrication systems consisting of a conversion coating of zinc phosphate chemically
bonded to the metal substrate. The coated part is provided with a lubricant by dipping into a hot bath of alkaline soap (typically sodium stearate) that reacts with the zinc phosphate to form zinc stearate, which is eventually covered with excessive sodium soap [6,7]. The crystalline layer of zinc phosphate partly acts as a chemical agent binding the soap to the surface, and partly as physical carrier for the soap. The coating procedure has several environmental drawbacks [8-[13]: a) Sludge of (heavy) metal phosphates, which need to be reclaimed or buried, b) Large water requirement in the rinse baths, c) Periodic replacement of baths for degreasing, neutralizing, pickling and lubrication required, d) Large amounts of waste water, typically containing grease and tramp oils, acid, and soap. In addition to these environmental concerns, the phosphating process requires prolonged treatment time, typically 5-15 min. and high bath temperature, 80-90°C, [6,9].

Zwez and Holz [14] report that modification of zinc phosphate coatings with calcium reduces the load of heavy metal zinc by 33% thus reducing the impact on environment. Within this conventional chemical treatment much progress has been made in the last decades to reduce the consumption of chemicals and the amount of waste water. The use of advanced products for cleaning, pickling, phosphating and lubrication as well as improved monitoring and adjustment of the chemical process prolongs the service life of baths considerably and reduces the consumption of chemicals by approximately 20%. For cold heading and drawing of wire, tubes and profiles, phosphating agents with nitrite or chlorate as accelerator are still widely used. This so-called “iron-free” phosphating process results in huge amounts of sludge of iron and heavy metal phosphates, which has to be disposed by burying. By introducing new phosphating agents without the accelerating compounds of nitrite and chlorate the consumption of phosphating agents can be reduced by one third and the amount of sludge by 80-90%. For less demanding cold forging operations such as bolt production, the soap is replaced by oil with extreme pressure additives in form of sulphur and phosphor, [9,[15,[16].

As alternatives to phosphate coating and soap, a number of lubrication systems for cold forging have been developed. They may be organized into the following groups:

- New conversion coatings
  - Electrolytic phosphate coating
  - Microporous coating
- Lubrication without conversion coating
  - Dual bath systems
  - Single bath systems

2.1 NEW CONVERSION COATINGS

2.1.1 Electrolytic Phosphating

Many of the drawbacks associated with zinc phosphates are eliminated by electrolytic phosphating, [12,17,18]. A sludge free phosphating bath is obtained, the use of acid for pickling may be avoided by electrochemical pickling, the treatment time is considerably shortened, the working environment is improved and the electrochemical procedure makes it possible to phosphate high alloyed steels and stainless steel, as developed in the
late 1990s by Bjerrum et al. [19,20]. Figure 1 shows a comparison of the two procedures. In the chemical phosphating process the slugs are initially cleaned by mechanical descaling and/or chemical pickling in an acid bath (either cold hydrochloric acid or warm sulphuric acid) followed by a water rinse before dipping into the phosphating bath consisting of phosphoric acid, primary zinc phosphate and accelerating additives in form of nitrite or chlorate. In the e-Phos procedure the initial cleaning is similar but as shown in Figure 2 the method ensures a much more uniform and fine crystalline coating, which furthermore has smaller film thickness. The phosphating time is 4 s for the electrochemical procedure compared to 5 min. for the chemical procedure. Coating thickness can furthermore be much better controlled, since it is linearly related to current density and treatment time, [18]. Application of an electrolytical coating combined with zinc stearate as lubricant has demonstrated feasibility of severe cold forging operations such as backward can extrusion in AISI 304 stainless steel with reductions \( r = \left( \frac{D_p}{D_o} \right)^2 = 0.5 \) and can heights \( h = 2D_p \), [21].

Nittel [12] reports substitution of chemical zinc or zinc-calcium phosphating with electrolytic calcium phosphating carried out at 25°C bath temperature. The process has the same advantages as electrolytic zinc phosphating, i.e. heavy metal sludge in the phosphating bath is avoided. In fact, even the coating is free of heavy metals such as Zn and Ni, and primarily consists of CaHPO4. It may be applied to highly alloyed steel and stainless steel and Ti, although the latter has yet to be demonstrated. Due to energy savings (no heating of the phosphating bath) and in disposal of chemicals, the new conversion coating system should have economic advantages too. Lubricants may be similar to those applied to zinc phosphate coatings, i.e. mineral oil or metal stearate, but good results have also been obtained with polymer emulsions and dispersions consisting
of polyamides, polyimides, polyurethanes and/or polyolefines such as polyethylene and/or polypropylene, [12,22]. The film weight of the polymer lubricant is 1.5-2.5 g/m² compared to 5-10 g/m² for soap, which leads to improved tolerances of cold forged components. The dust problems in wire drawing with soap lubrication are avoided and higher production speeds in bolt making machines are reported. Furthermore the problems of tramp oil (mixture of the process lubricant with the lubricating oil for the machinery) are avoided.

2.1.2 Microporous coating

Tang et al. [23,24] have developed a porous coating that serves as an efficient lubricant carrier. A two-phase alloy of Sn and Zn is electrochemically deposited on the workpiece surface after which one of the two metals is selectively etched leaving a micro- or even nanoporous layer of the remaining metal on the workpiece surface, see Figure 3. The layer thickness is typically 5 µm. When a lubricant subsequently is applied to the porous coating, it will be trapped in the pores acting as numerous small lubricant reservoirs and will be entrained in even the most demanding applications.

Ring tests and double cup extrusion tests in St 1.0303 provided with the new lubricant carrier combined with plain mineral oil with no boundary lubricants and a viscosity of
Green lubricants for metal forming

60 cSt at 40°C produces friction as low as with phosphate coated and soap lubricated conditions. Single cup extrusion tests in the same material with high reduction \( r = (D_p/D_0)^2 = 69\% \) showed no lubricant film breakdown in cup extrusions up to cup heights \( h = 2.7D_p \).

2.2 LUBRICATION WITHOUT CONVERSION COATING

2.2.1 Dual bath systems

Together with Sumico Lubricant, Nakamura et al. [25,26] have tested a number of alternatives including single as well as dual bath systems. The dual bath systems form a base coating adhering to the slug surface and an over-coating to further reduce friction. Two types of lubricants were investigated, a white lubricant consisting of wax and metal soap, and a black one consisting of MoS\(_2\) and graphite. Based on laboratory cold forging tests, two dual bath systems (with the two above mentioned lubricants) were selected for industrial testing in a multistage cold extrusion operation. Both systems showed good performance with no sign of pick-up on the tools.

2.2.2 Single bath systems

Lazzarotto et al. have tested commercial oils with extreme pressure additives for less demanding cold forward extrusion operations using an upsetting-sliding test showing the importance of the tool temperature as regards the limits of lubrication, [27]. In the case of more demanding cold forging operations, alternative single bath lubrication systems have been developed, especially in Japan. After descaling/shot blasting and hot water rinsing, the slugs are dipped in an aqueous bath containing inorganic salt and an organic lubricant and subsequently dried, after which they are ready for cold forging. The whole procedure takes about 2 min. implying that in-process lubrication is attainable in many cold forging lines, [9,28].

Development of such lubricants was initiated by Toyota Motor Corp. together with MEC Int. Initial investigations were directed towards a series of different water based compounds with fatty acid, phosphates, polymer based dispersant and Zn- and Mo-compounds [29-31]. The research work resulted in the product MEC-HOMAT, a solid film lubricant applied by dipping in a water bath. During cold forging the heat developed by deformation and friction results in a chemical reaction between the steel slug surface and the lubricant film containing a chelating agent. The reaction generates iron sulphide and forms a boundary lubricating film with Zn and sulphur components, [9,32], see Figure 4. Moroi, et al. [28] report the lubricant to be industrially applied in a three stage cold forging production of a drive pinion shaft and a four stage production of a rear axle shaft.

Daido Chemical Industry has developed Daido AquaLub [33] based on a phosphoric compound with adsorption ability onto metallic surface and solid lubricants. The generic chemical compositions are: a) calcium compound 5-10%, b) water soluble inorganic salt 1-5%, c) phosphorous organic compound 0.5-1%, d) lubricant surfactants 5-10%, e) synthetic alcohol 5-10%, f) water insoluble inorganic salts 5-10% and water 60-80%. The application of this lubricant requires preparation of the billets by shot peening.
Ngaile et al. [34] describe the systematic development of new, environmentally friendly metal forming lubricants for steel based on co-polymer emulsions containing acrylic and methacrylic monomers. Conditioning provides the steel billets with an inorganic layer primarily consisting of iron phosphate and iron oxide. This layer ensures a greater quantity of polymer coating to be bonded in the subsequent step. Compared to conventional zinc phosphate coating and soap lubrication the treatment time is reduced by 25%, the number of process steps are reduced from 9 to 7 and the water consumption is reduced by 75%. Field trials in C-steel tube drawing showed good performance. The coating was capable of sustaining its lubrication layer even during multi-blow extrusion and multi-pass drawing.

Gariety et al. [35] have tested the performance of MEC-HOMAT lubricant as well as well as Daido AquaLub and compared their performance to conventional zinc phosphate coating and soap lubrication in cold forging of AISI 8610 steel using the double cup extrusion test. The friction factor obtained was lower for both of the two new, single-bath lubrication systems than for the zinc phosphate coating/soap system. Microscopic inspection of the upper cup inner surface showed no sign of lubricant failure. Common to the two new lubricant systems is that the lubricant is firmly bonded to the surface without creating hazardous chemical waste and with substantially reduced time for billet treatment. Groche and Koehler [36] have also tested a single bath lubricant including a compound of salt and wax. The workpiece material was 16MnCrS5, which was shot blasted before extrusion in a three-stage operation. Results showed the same low process force and ejector load as phosphate coating plus soap and good surface appearance.

Nihon Parkerizing has developed a single bath, water based lubricant for cold forging of steel, [8]. This product consists of an inorganic salt as base component and a wax as a lubricant. The application method is called “Dry-in-Place” and consists of a simple dip and dry process forming a double coating consisting of a lubricant carrier as base with a lubricant film on top, see Figure 5. The base layer plays an important additional role in protecting against galling. The coating is claimed to be similar to the conventional triple
layer coating formed by phosphating and soap lubrication. Production trials show it to be applicable in almost the same range as phosphate coating and soap lubrication as seen in Figure 6. The new lubricant has even been developed for cold forging of aluminium, where the requirements regarding surface expansion are much larger, [37].

Figure 5: Schematic outline of chemically adhering solid film with Zn-sulphide, [8].

Figure 6: Range of applicability of different cold forging lubricants, [37].

The new, single bath lubricants are now applied in numerous cold forging operations at Toyota and under trial in the most complex ones. Substituting zinc phosphate coating plus soap with the new lubrication system has reduced the waste from former 360 tons to a present 45 tons, corresponding to 88% less waste.
3 WARM AND HOT FORGING

In hot forging of C-steel, the workpiece is heated to 1000-1200°C, but the die interface temperature has to be kept below 600°C. This is achieved by spraying with lubricant containing a cooling medium or by using insulating films like glass and by keeping the contact time with the workpiece low. Since oxides themselves prevent seizure and reduce friction, many forging operations are done without lubrication. Low friction may furthermore not be desirable in hot forging, since this leads to increasing relative sliding between the workpiece and die which may cause increased wear, [38,39]. The role of the “lubricant” is then merely to ensure easy die release and saw dust has traditionally been used for this purpose. In complicated die forgings colloidal graphite dispersed in water or oil has been applied by spraying.

Efforts to find alternatives to graphite based lubricants have been driven by: a) Bad working environment, b) Earth leakage (electric conductivity of oil), c) Pipe corrosion due to electric conductivity, Low recovery rate due to poor oil separation, [10].

In 1983 a water soluble, carboxylic acid based high molecular weight, short chained compound was developed as a first substitute to graphite based lubricants, [40]. This lubricant, which has good adherence to hot die surfaces at a temperature of 400°C and good lubricity were soon introduced in forging production of automotive parts and started the development of non-graphite based lubricants for warm and hot forging, [41]. From around 1985 a number of alternatives to the graphite based lubricants were actively promoted in industry.

Nakamura [42] gives a comprehensive overview of the lubricants applied for warm and hot forming of C-steels, high alloyed steels, Ni-alloys and Al-alloys. The lubricants include calcium stearate, water soluble high-molecular weight polymer, high-molecular weight carboxylate, water soluble glass, super high-molecular weight polyethylene, BN + glass + graphite, graphite + B_2O_3, graphite + resin, etc. Kawabe [43] reports results of a Japanese industry survey in 1993 disclosing that 21% of the companies had totally abandoned graphite based lubricants and were exclusively using white lubricants, but die life was considerably lowered. Less than 10 years later, in 2001 white lubricants were narrowed down to the following [9,30]: 1) Polymer base, 2) Carvone base, 3) Liquid glass base.

Hibi [44] gives a good overview of possible water soluble high-molecular weight polymers for warm and hot forging. The main element in the polymer base is alkyl maleate. The carvone base oils are essential oils such as volatile or ethereal oils from plants. The main content of these lubricants are carboxylic acids such as fumaric acid and isophthalic acid. The liquid glass base lubricants are Si-glass containing colloidal silica. Figure 7 shows the range of applicability of these white lubricants with a number of industrial component examples. Today Toyota has completely replaced black lubricants in warm and hot forging with white ones, which are claimed to have excellent oil separation properties and high recovery rate, reducing the amount of waste liquid per forging line to less than 10% of that of graphite based lubricants. They imply, however, drawbacks such as lower lubricity and more difficult die release. This eventually reduces die life if no special precautions are made such as considering the film thickness and spraying conditions to optimize die cooling.
4 ROLLING

Cold as well as hot rolling is characterized by high volume production with corresponding large consumption of lubricant. Over the past two decades, advances in emulsion lubrication have allowed the proliferation of emulsions in metal forming operations, and especially metal rolling. An emulsion is a heterogeneous system, consisting of at least one immiscible liquid dispersed in another in the form of droplets whose diameters exceed 0.1 µm, [45]. A typical emulsion consists of roughly 95% water, with the remainder being oil, emulsifier and additives such as brighteners, biocides, detergents, etc. The application of emulsions has become prevalent not only because of the environmental and economic advantages; they also have performance advantages. Not surprisingly emulsions have better cooling efficiency than neat oils, as few fluids are better than water at conveying heat, but surprisingly an emulsion can lubricate almost as well as neat oil.

4.1 EMULSIONS

Due to the difference in density of oil and water, buoyancy causes the phases to separate, i.e., emulsions are inherently unstable. To add stability, emulsions are aggressively agitated to achieve very small droplet sizes and tight distributions, or alternatively emulsifiers are added to the system. Emulsifiers are usually surfactants, although some formulations use macromolecules, fine particles and/or simple electrolytes as emulsifiers, [46].

Figure 7: Range of applicability of white lubricants [10].
An emulsion is formulated and provided by a lubricant supplier as a mixture of base oil, typically 80-95% by volume, emulsifier, and a recipe of additives including brighteners, anti-foaming agents, biocides, lubricity additives, etc. Deionized water is added by the end user and the mixture is agitated to form the emulsion.

4.2 EXPERIMENTAL TESTING OF LUBRICANTS FOR ROLLING

4.2.1 Cold rolling

Laboratory scale rolling mills are needed for proper evaluation of lubricants [47-49]. Such mills typically have a two-high or four-high configuration. Aside from qualitative evaluation of anti-staining, antigalling and pickup prevention and the like, these instruments are applied for evaluation of friction and lubricity [50-52] and film thickness [53], allowing inference of high pressure lubricant properties.

Dubar et al. have developed an upsetting-rolling test for simulation of cold rolling to study the influence of rolling parameters like reduction, speed and tool temperature on friction and lubricant film breakdown applying emulsions of mineral oil with additives of fatty acids, sulphur and phosphor compounds. They compared their results with experiments in an industrial Sendzimir rolling mill and concluded that the combination of simulative testing with numerical modelling provided a good method for optimisation of industrial rolling parameters, [54-56].

4.2.2 Hot rolling

Azushima et al. have developed similar lubrication test stands for hot rolling as for cold rolling, [48,49]. Both test stands include a main stand performing the rolling and a sub stand delivering back tension causing a larger peripheral speed of the main roll than of the work piece to ensure skidding (neutral plane moved to the exit). The main stand is provided with load cells and a torque transducer enabling determination of the average coefficient of friction \( \mu \) during testing as: \( \mu = M/PR \), where \( M \) is the torque, \( P \) is the load and \( R \) is the roll radius. As regards hot rolling an infrared furnace heating a strip with length of 960 mm to a maximum temperature of 1100°C is located between the sub stand and the main stand. A comprehensive test program has been carried out studying the performance of a large number of lubricants based on five different base oils (see Table 1) with various additives: Colza oil (vegetable oil based on the seeds of Brassica campestris, Swedish turnips), mineral oils and synthetic ester oils with low as well as high viscosity. Additives investigated include oleic acid, fatty oil sulphide, graphite, MoS2 and Mica, [57].

The lubricants were tested in rolling 9 mm JIS SPHC (hot rolled, mild C-steel) at 800°C with a 0.3 mm thickness reduction. The peripheral speed of the main roll stand was 50 m/min and the ratio between roll and strip velocity was 20. Figure 8 shows the coefficient of friction as a function of the emulsion concentration for the three different base oils. The two lubricants with boundary lubrication effects give lower friction than the mineral oil, which does not have this effect. In all cases friction decreases with increasing emulsion concentration up to 1% after which it reaches a constant value. This is explained by the change in lubrication mechanisms when changing from low to high emulsion concentration. At higher emulsion concentration effective separation of the
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<table>
<thead>
<tr>
<th>Lubricant</th>
<th>Type of base oil and kinematic viscosity at 40°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Colza oil, 35 mm²/s</td>
</tr>
<tr>
<td>B</td>
<td>Mineral oil with low viscosity, 40 mm²/s</td>
</tr>
<tr>
<td>C</td>
<td>Synthetic ester oil with low viscosity, 50 mm²/s</td>
</tr>
<tr>
<td>D</td>
<td>Mineral oil with high viscosity, 170 mm²/s</td>
</tr>
<tr>
<td>E</td>
<td>Synthetic ester oil with high viscosity, 200 mm²/s</td>
</tr>
</tbody>
</table>

Table 1: Base oils investigated in hot rolling test, [57].

![Coefficient of friction versus emulsion concentration](image)

Figure 8: Coefficient of friction versus emulsion concentration for: A. Colza oil, B. Mineral oil, low viscosity, C. Synthetic ester, low viscosity.

The workpiece and tool surface is obtained, whereas contact between workpiece asperities and roll surface appears in case of low emulsion concentration. Tests of similar oils with low and high viscosity at 40°C show the higher viscosity to provide lower friction in the range where asperity contact occurs ($c<1\%$), whereas viscosity shows no influence on friction at higher concentration, where full separation appears [57].

The Finnish company Pinifer has developed a biodegradable hot rolling oil based on tall oil (from pine tree), [58]. They claim the benefits to be: decreasing rolling load and energy consumption, reduced wear and improved surface quality of the rolled sheet.
5 SHEET FORMING

Sheet stamping production in advanced high strength steels and stainless steels implies very severe tribological conditions. This is partly due to their high strength, implying large contact stresses and temperatures at the tool/workpiece interface, partly due to the microstructure of the sheet materials involving multiphase structures and large tendency to pick-up and galling when the lubricant fails. The problems have been solved by adopting chlorinated paraffin oils, which are highly reactive creating a boundary film by reacting with the workpiece material, often combined with CVD or PVD coated tools improving the galling resistivity. The chlorinated paraffin oils contain short-chained C10-13 as well as medium-chained C14-17 chloroparaffins and they are suspected to have harmful effects on human health. The EU classification of short-chained chlorinated paraffins is carcinogenic in category 3 with risk phrase R40: “Limited evidence of a carcinogenic effect”. Due to the chloroparaffins’ persistent and bio-accumulating properties increasing concern towards the disposal problems further emphasizes the attempts to abandon the lubricants, and legislation has therefore been aimed at minimizing the use in EU, USA and Japan for the last decade, [4,11,59,60].

5.1 STAMPING WITH DRY FILM LUBRICATION

Stamping lubricants can be divided into oil-based liquid lubricants and dry film or coil lubricants (DFL). The liquid lubricants may be mineral oils or emulsions. Dry film lubricants are divided into water-soluble dry film lubricants and water-free dry film lubricants (the so-called “hotmelts”). Water-soluble dry film lubricants are applied in amount of 0.5-1.5g/m² at the rolling mill. They stick to the surface of the stamped sheet parts and offer sufficient corrosion protection but are not compatible with most adhesives used in automotive body construction [61]. The water-free dry film lubricants are also applied on the sheet material in small amounts at the rolling mill. Besides their superior drawing performance compared to oil-based lubricants, the most important advantage is their compatibility with almost all commonly used adhesives. In today’s automotive stamping plants, DFL is increasingly popular, due to improved performance, cleanliness and reduced requirements for recycling and disposal [62,63]. In addition, DFL: a) provides uniform coating thickness on the sheet blanks, b) reduces the amount of lubricant (typically 0.5-1.5 g/m² vs. oil-based lubrication 1.5-3.0 g/m²), c) may eliminate washing of stampings which are necessary with wet lube, d) is compatible with assembly operations (welding, bonding, clinching and riveting), e) is more environmentally benign than the petroleum based wet lubes. On the other hand, DFL has no cooling effect and makes it difficult to remove deposits of metal debris left on the die surface.

Altan et al. have carried out several larger investigations on new lubricants for automotive sheet metal forming as substitutes to petroleum based oils [63-66] based on a system of laboratory tests emulating the varied conditions in sheet metal forming. The tests include Twist Compression Test (TCT), Deep Drawing Test (DDT), Ironing Test (IRT) and Bending Under Tension test (BUT). Testing was performed on mild steel AKDQ 1008, [63], HSLA steel, ASTM A1011, [63,64], Advanced High Strength Steel (AHSS), DP 500, DP 600, with and without zinc coating, [65,66] with straight mineral oil, water based oil emulsions, dry films, chlorinated water emulsions and polymer
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films. Tool materials were uncoated AISI D2, Vancron 40 (a nitride alloyed PM HSS), Spheroidal graphite cast iron, as well as CVD and PVD coated tools. In deep drawing ranking of the lubricants was based on measurements of the maximum drawing force as well as the the size of the remaining flange. In ironing performed with reductions in the range 4-9% ranking of the lubricants was done by measuring the load-stroke curves and the relative wall thinning. Both tests showed the two polymer coatings to perform best.

Together with BMW, Merklein and Geiger et al. [67-69] have worked on the replacement of mineral oil with dry film lubricants in aluminium sheet forming. The workpiece material was hot rolled AlMgMn alloys typically used with two different surface textures, MillFinish (MF) and Electro Discharge Textured (EDT), both with different roughness levels. The MF sheet is normally used for interior sheet and structure parts, whereas the EDT sheet is state-of-the-art for skin panels, [70]. Four different lubricants were tested in plane strip drawing test as well as in deep drawing. The lubricants tested are listed in Table 2.

<table>
<thead>
<tr>
<th>Lubricant</th>
<th>Type</th>
<th>Amount g/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lub A</td>
<td>Mineral oil KTL N 16</td>
<td>≥ 3.0</td>
</tr>
<tr>
<td></td>
<td>Viscosity 160 mm²/s at 40°</td>
<td></td>
</tr>
<tr>
<td>Lub B</td>
<td>Water-soluble dry film, Drylube C2</td>
<td>0.5, 1.0, 1.5, 2.0</td>
</tr>
<tr>
<td>Lub C</td>
<td>Water-free dry film</td>
<td></td>
</tr>
<tr>
<td>Lub D</td>
<td>Drylube E1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 2: Lubricants tested in Al sheet forming, [68].

The results showed especially the water-free coil lubricant C and the mineral oil A to be quite independent on surface roughness and amount of lubricant within the range $0.9 \leq R_s \leq 1.6 \mu m$ and 0.5-1.5 g/m², respectively, [69]. Based on the good results obtained with the water-free dry film this has been introduced in production of a number of aluminium parts at BMW, see Figure 9.

On steel sheets the maximum limit for compatible amounts of mineral oil lubricant for later assembly is usually 3.0 g/m², while in special cases it goes down to 1.5 g/m². With higher amounts the components have to be washed after forming. Tolazzi, et al. [71] have investigated the possibility of applying dry film lubricant for sheet forming of steel as an alternative to lubrication with mineral oil. Figure 10 shows the difference of the two processes. Applying a dry film lubricant in an amount of 1 g/m² is sufficient for most forming operations implying that washing in many cases can be avoided [68]. The drylube E1 investigated in [71] is a water-free lubricant applied at the rolling mill. This so-called “hotmelt” does not run off the panels’ surface and offers good corrosion protection to all kinds of steel qualities. It furthermore has better performance in drawing operations and it complies with almost all commonly used adhesives. Four different steels were examined, two mild steels, galvanised and electro-galvanised and two high strength steels, H400 and H300, the latter with a ground surface. Testing in deep drawing showed it possible to reduce the amount of lubricant from 1.0 g/m² to
0.5 g/m² with only a slight reduction of the process window if suitable texturing of the sheets were present.

Groche et al. [72] report the influence of lubrication on galling of hot-dip galvanized mild steel in deep drawing. Galling is especially pronounced in connection with draw
beads, and a simulative draw bead tester with multiple stroke capability is applied to simulate production conditions. The tested sheet was EDT textured deep drawing steel, DX54Z, and the tool material was globular cast iron, GGG70L. Besides testing as-received sheet provided with \( \sim 1 \) g/m\(^2\) anti corrosion oil, tests were performed with additional lubrication with the same oil, deep drawing oil, sprayable drylube and roller-applied hot-melt drylube. Whereas friction was lowered by adding sprayable drylube, all the other lubricants resulted in increased friction. In all cases additional lubrication resulted in significant increase of galling. Microsections of drawn sheet showed the mechanism of re-adherence of abraded zinc onto the sheet surface, which was predominant in case of no additional lubrication. Additional lubrication separates the abraded particles from the sheet leaving the tools surface as adhering partner resulting in galling.

Like the automotive industry, the can manufacturing industry is of enormous scale worldwide with approximately 400 billion cans produced of all types every year, and roughly one-half of these made for food and beverage products. Almost all food containers are made from steel-base stocks, while beverage containers are aluminum or steel, [73]. Current can making includes the sheet-metal forming operations of drawing, redrawing, and ironing, all of which require proper lubrication to ensure overall process efficiency. Residual liquid lubricant collects on the workpiece and must be removed, as it can be toxic and contributes adversely to product taste. This is done during a solvent wash cycle. The interior can surface is not suitable for food contact after ironing, because the metal will adulterate food quickly, either from metal particulate contamination or chemical attack. This is prevented by isolating the can wall from the contents with either a thermoplastic or thermosetting resin which is safe for food contact. This is done by dissolving the polymer in a carrier fluid, usually methyl ethyl ketone or equivalent, and applying this solution to can interiors. After application of the resin/carrier fluid spray, an oven-curing operation allows the resin to bond to the interior surface, while the toxic carrier fluid boils off and is released as a volatile organic compound (VOC). In order to make this harmful by-product environmentally safe, an afterburner is used to reduce it to water vapour and carbon dioxide.

An alternative to the traditional process is to use a polymer laminated steel sheet stock. This polymer is a thermoplastic, similar to those applied to the traditional can via spray deposition, and it is naturally suitable as the food contact surface. However, to be successful, the polymer would need to fulfil the following requirements: a) Survive the manufacturing operations without rupture, b) Possess low friction properties to allow elimination of lubricants, and hence cleaning operations to remove lubricants from the cans before filling, c) If used on can exteriors, it needs to be semi-permeable or suitable for decoration and printing. Jaworski, et al. [74,75] demonstrated that laminated polymer-coated sheet steels can be used as ironing stocks. Experiments found that low die angles result in a successful ironing, while large die angles result in shaving of the polymer film off of the steel. The critical die angle at which ironing occurs was shown to be a function of the laminate strength, and was found to be 6°-9° for the investigated materials. Recently, Sellés-Cantó et al. [76] extended the concept of ironing with a polymer coated steel to a three-layered polymer. Such a coating consists of a “tie” layer bonded to the steel sheet-metal, a “top” layer at the exterior and a “bulk” layer between these two polymers. This system is more flexible, and allows tailoring of the thicknesses...
and material properties for particular applications. For example, the top layer can be formulated for frictional purposes and with permeability to allow printing, the tie layer can be selected to maximize adhesion to the steel and the bulk layer can be selected to improve ironability.

In Japan replacement of petroleum based lubricants has been obtained by development of a combined drawing, stretch-redrawing and ironing process of aluminium cans, using a polyester film as lubricant, [77-79], see Figure 11. The redrawing with a die radius less than the sheet thickness and with high back tension caused by the bending and flange drawing-in reduces the required blank thickness and reduction in the subsequent ironing process. Due to the process development and use of solid polymer coating as only lubricant the load on environment is claimed to be significantly reduced regarding CO₂ (67%), solid waste (99.7%), electricity consumption (50%), water consumption (95%), fuel gas consumption (67%), [78].

![Figure 11: Stretch-drawing and ironing of aluminium cans, [78].](image)

### 5.2 ALTERNATIVES TO DRY FILM LUBRICATION

In multistage deep drawing and ironing operations of materials prone to galling such as stainless steel and titanium, attempts to introduce polymer films have failed and several Danish and an EU research programme have focussed on developing alternative solutions [80, 81]. In this connection a system of test methods representing the varied conditions in sheet metal forming have been developed including simulative tests: Bending-Under-Tension (BUT) [82], Draw-Bead-Test (DBT) [83], Strip-Reduction-Test (SRT) [84,85] as well as process tests: Deep-Drawing-Test (DDT) [85,86] and PUnching-Test (PUT), [87,88]. In order to emulate real production conditions, pre-heating of the tool temperature to typical production level is possible in all the simulative tests. Table 3 shows a small selection of the many lubricants tested.
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<table>
<thead>
<tr>
<th>No.</th>
<th>Lubricant manuf.</th>
<th>Code</th>
<th>Description</th>
<th>Kin.viscos. 40°C cSt</th>
<th>Environm. hazard.</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>Castrol</td>
<td>TDN81</td>
<td>Highly chlorinated paraffin oil</td>
<td>165</td>
<td>Yes</td>
</tr>
<tr>
<td>L2</td>
<td>Castrol</td>
<td>PN226</td>
<td>Medium chlorinated paraffin oil</td>
<td>66</td>
<td>Yes</td>
</tr>
<tr>
<td>L3</td>
<td>Pinifer</td>
<td>P1</td>
<td>Vegetable oil based on fatty acid methylester</td>
<td>205</td>
<td>No</td>
</tr>
<tr>
<td>L4</td>
<td>Pinifer</td>
<td>P3</td>
<td>Vegetable oil based on trimethylol propan ester</td>
<td>17</td>
<td>No</td>
</tr>
<tr>
<td>L5</td>
<td>Chemetall</td>
<td>L6250</td>
<td>Water based polymeric dispersion, incl. water soluble waxes, defoamer and additives</td>
<td>-</td>
<td>No</td>
</tr>
<tr>
<td>L6</td>
<td>Houghton</td>
<td>CR5</td>
<td>Naphthenic mineral oil without any EP additives</td>
<td>660</td>
<td>No</td>
</tr>
<tr>
<td>L7</td>
<td>Rhenus</td>
<td>SF135</td>
<td>Mineral oil with Ca-, P- and S-additives</td>
<td>135</td>
<td>No</td>
</tr>
<tr>
<td>L8</td>
<td>Rhenus</td>
<td>CXF125</td>
<td>Mineral oil with Ca-, P- and S-additives</td>
<td>125</td>
<td>No</td>
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<tr>
<td>L13</td>
<td>Int. Comp.</td>
<td>IC345</td>
<td>Commercial drawing grease</td>
<td>5000</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 3: Sheet forming lubricants tested.

As an example on BUT testing of AISI 304 with different lubricants Figure 12 shows the results from five different lubricants at a tool rest temperature of 70°C. It is noticed that P1 and the polymer coating L6250 perform similarly to TDN81, whereas P3 and mineral oil CR5 show very poor performance with much higher friction that increases with the sliding length. As regards the mineral oil, which was tested at 60°C, since it broke down immediately at 70°C the large oscillations at sliding lengths above 100 mm are due to stick-slip. Visual inspection of the strips and the tool surfaces showed severe galling when using P3 and CR5 corresponding to these measurements, whereas slight galling was observed with P1. No galling was observed with TDN81 and the decreasing friction with increasing sliding length observed for TDN81 may be attributed to chemical reaction with the tool surface forming a boundary film at elevated temperature. If testing were done at room temperature all lubricants performed well, implying that it is vital to test at temperatures normally seen in production.
In the strip reduction test galling is quantified by surface roughness measurements across the strip after testing, [84,85]. With increasing sliding length the tool becomes heated due to workpiece deformation and friction implying eventual breakdown of the lubricant film. From Figure 13 it is noticed that the chlorinated paraffin oil and the polymer coating are sustaining the test even after 270 mm sliding length, whereas P1 and CR5 break down at 120 mm and 150 mm, respectively. Pre-heating of the tool results in earlier breakdown.

In the EU project [80] a number of different environmentally benign oils were tested in production as alternatives to chlorinated paraffin oil. A progressive tool for production of a pump cover in stainless steel including deep drawing, collar drawing, ironing and punching operations were provided with transducers measuring process as well as backstroke forces and tool temperatures in the most critical collar drawing and ironing operation, see Figure 14, Friis et al. [89]. After screening tests of various lubricants and tool coatings the following lubricants were selected for the production test: the chlorinated paraffin oil PN226 and the environmentally benign oils Rhenus SF135 and Rhenus CFX125, see Table 3. Tool materials tested in the critical ironing operation were Vancron 40 and TiAlN coated PM HSS.

The production tests using Vancron 40 tools showed that SF135 lubricant was practically useless and galling was initiated immediately from the start of the test regardless of the production speed. CXF125 performed significantly better, showing no galling at 50 spm while after approximately 700 strokes at 100 spm galling appeared causing an increase in temperature as well as process and backstroke force. The chlorinated paraffin oil performed well even at 100 spm. Using the TiAlN coated tool and CXF125, no galling was observed at the maximum production speed of 100 spm.
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Figure 13: $R_a$ as function of sliding length in strip reduction testing of stainless steel, AISI 316 against PM HSS with different lubricants, [81]. Curve legends refer to lubricants listed in Table 3.

![Figure 13](image)

Figure 14: a) Schematic outline of combined collar drawing and ironing operation, b) punch nose with insert and channel for mounting of thermocouple.

The same was the case for the chlorinated paraffin oil. Applying the poorer performing lubricant SF135 resulted in mild galling after 600 strokes at 100 spm. The performance of the individual tribo-systems was consistent with the results from the laboratory testing using the strip reduction test.

The tool temperature development with stroke number was calculated in the combined collar drawing and ironing operation for the two different production speeds, 50 and 100 spm. Figure 15 shows the results compared with the measured average values in each stroke. It is noticed that temperature increases rapidly, reaching a steady state within two minutes. The results suggest that the maximum thermal load may be lowered significantly by lowering production speed, leading to lower risk of galling. This correlates well with the production experience at Grundfos.

Rao and Xie, [90], have tested boric acid, $\text{H}_3\text{BO}_3$, as a lubricant for sheet forming of aluminium with good results. The boric acid forms a strong, chemically bonded film on oxidized aluminium. Testing in deep drawing and stretch forming proved it to produce friction as low as teflon, and it has the benefits of being environmentally benign and easy to remove.
Mori et al. [91] have developed an electrochemical coating technique providing titanium sheet with an artificial layer of oxide for prevention of seizure in multistage deep drawing and ironing. Using aluminium bronze dies and commercially coloured sheets lubricated with calcium stearate powder it was possible in a 7 stage progressive tool to produce cups with a height/diameter ratio of 6 without intermediate annealing, avoiding the use of chlorinated paraffin oil.

5.3 MANUFACTURERS OF ENVIRONMENTALLY BENIGN LUBRICANTS FOR SHEET METAL FORMING

A few lubricant manufacturers have established a niche in developing new, environmentally acceptable lubricants for sheet metal forming. The Finnish company Pinifer has special expertise in manufacturing biodegradable oils derived from tall oil (pine tree). These fatty acid ester based oils have been successfully introduced in deep drawing production having good lubrication and anti wear properties, good corrosion resistance, good compatibility with paints, coating and seals, [58].

The German company Rhenus Lub has developed environmentally benign lubricants for cold metal forming based on refined mineral oils with special additives of natural fatty components, synthetic esters, sulphur additives and PEP additives, [92,93]. They have had particular success with these oils in fine blanking of C-steel as well as alloyed steel and stainless steel. As mentioned in Section 5.2 they have also shown very good performance in multistage deep drawing and ironing of stainless steel.

The American company IRMCO Fluids produce oil free, low viscosity metal forming lubricants, [94]. When deformation heat is applied, the high solid polymers (HSM) thicken and attach to the metal surface creating a friction reducing film barrier. Cleaning of the formed components may be done with water or a mild alkaline solution. The lubricants have been successfully implemented in stamping and punching of mild steel, advanced high strength steel, stainless steel, aluminium and titanium.
6 PUNCHING AND BLANKING

Punching and blanking including fine blanking represent some of the most severe tribological conditions in metal forming. Normal pressure as well as temperature at the tool/workpiece interface is high but the most severe conditions are due to the formation of virgin metal surface in contact with the punch stem. Due to these conditions it is very difficult to ensure access of lubricant into the interface. In order to prevent galling under these severe conditions, chlorinated paraffin oils are normally applied eventually in combination with ceramic tool coatings. The most common interpretation of the lubrication mechanism involved when applying chlorinated paraffins is the formation of hydrochloric acid under the influence of humidity from the ambient air reacting with the steel surface to form a boundary film of FeCl₂, [95,96].

Klocke et al. [95] emphasizes that very little has been done to develop new, non-chlorinated lubricants for fine blanking. They studied fine blanking of 16MnCr5 steel (AISI 5115) with punches coated with TiCN investigating different types of new lubricants, see Table 4. Lubricant C is developed as a lubricant with good chemical bonding properties containing high amounts of EP additives, whereas lubricant D with high amounts of polar substance has better physical bonding properties. The results show very good anti-galling performance of the latter, whereas lubricant C resulted in severe galling. Based on these studies they propose the mechanism of lubrication in fine blanking to be physisorption of the lubricant instead of chemisorption, which is reasonable considering that the punch is coated with an inactive coating of TiCN.

<table>
<thead>
<tr>
<th>Lubricant</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Commercial fineblanking lubricant with chlorinated parafins and S-additives</td>
</tr>
<tr>
<td>C</td>
<td>Non-chlorinated paraffin oil with high content of polysulphide and anti wear additives, low content of native ester</td>
</tr>
<tr>
<td>D</td>
<td>Non-chlorinated paraffin oil with high content of native ester and emulsifier, low content of polysulphide</td>
</tr>
</tbody>
</table>

Table 4: Tested oils, [95].

Olsson et al. [87,88] have developed a process test for evaluation of punching lubrication measuring the backstroke force, which is very sensitive to pick-up and galling. Figure 16 shows the maximum, nominal friction stress on the punch stem during backstroke versus the number of strokes for four different lubricants in punching Ø 2.0 mm holes in 1.0 mm stainless steel sheet AISI 316. Punching with chlorinated paraffin oil PN 226 and with P1 shows insignificant pick-up and accordingly small and almost constant backstroke friction, whereas much larger backstroke friction increasing with the number of strokes is noticed with the pure mineral oil CR5 and the polymer coating, which both showed heavy pick-up on the punch stem. The poor performance of the mineral oil compared to the two other oils may be attributed to the fact that the latter two have chemically active additives reacting with the punch stem to form a boundary layer,
while the mineral oil does not [87]. Differential Thermal Analysis (DTA) proves that the chlorinated paraffin oil as well as P1 reacts chemically with the punch material, PM HSS, at elevated temperature implying that it is likely that a thin boundary film is established on the punch. The poor performance of the polymer coating is to be expected due to the small punch clearance (10-15 μm) and the fact that this semi-solid film lubricant has difficult access to the clearance area between punch and die.

![Image](image.png)

*Figure 16: Maximum punch stem friction stress during backstroke as a function of stroke number. Curve legends refer to lubricants listed in Table 3.*

7 CONCLUSIONS

The increased focus on environmental issues in industrial production as well as on external environment has resulted in important developments of new, environmentally benign lubricants for metal forming. As regards cold forging new, single bath lubricant systems depositing a double layer of an inorganic salt and a wax on the slug surface have proven very efficient in substituting phosphate coating and soap lubrication. In warm and hot forging the black lubricants have been abandoned by many industries now using white lubricants on either polymer base, carvone base or liquid glass base. The huge amount of lubricant consumption in rolling has promoted the application of water based emulsions, which lubricate almost as well as the oil based and have better cooling efficiency.

In sheet metal forming pre-lubrication at the rolling mill with polymer coating is replacing in-process lubrication with mineral oils. Regarding more severe sheet forming of materials
prone to galling a number of lubricant manufacturers have developed promising alternatives to chlorinated paraffin oils, such as mineral oils with Ca-, S- and P-additives and vegetable oils with fatty acid esters.

8 ACKNOWLEDGEMENTS


9 REFERENCES


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