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New Tribo-systems for Cold Forming of Steel, Stainless Steel and Aluminium Alloys

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Abstract: Globalisation of industrial production and increasing demands for environmentally benign solutions has forced cold forging industry to search for new, economically optimized tribo-systems, which are less harmful to the working as well as the global environment. The present paper describes efforts to find new alternatives, which fulfill these demands including new lubrication systems, new tool coatings and introduction of tailored tool and workpiece surfaces. The large costs involved in testing of new tribo-systems in production have emphasized the necessity of developing appropriate off-line testing methods to evaluate these new alternatives. Examples of such tests are presented.

Keywords: Cold forging, Lubricants, Tool coatings, Surface texturing, Testing

1. Introduction

The globalisation of industrial production has caused heavily increased competition in cold forging production, which among others has forced industry to look for new, less expensive lubricant systems. Additional to this, legal restrictions have been a drive to develop new, environmentally benign tribo-systems both as regards the working and the global environment, [1-3].

Environmental problems in metal forming tribology can be divided into the following areas [4]: a) health and safety of people, b) influence on equipment and buildings, c) destruction and/or disposal of waste and remaining products. Efforts on improvements are concentrated on 1) abolition of hazardous chemicals, e.g. chlorinated additives, phosphates with (heavy) metal sludge, 2) reduction of waste, aiming at prolonged tool life, prolonged lubricant life, recovery and reuse of lubricant and Minimal Quantity Lubrication (MQL) [5-8].

Based on earlier reviews by the author [9-11] present paper is an updated overview of new lubricant systems for cold forging as well as other measures to ensure sound production without galling. The latter includes new tool coatings and application of textured surfaces on workpieces as well as tools. Finally a section on off-line test methods for evaluation of tribo-systems in cold forging is given.

2. Cold forging lubrication

Development of the cold forging process of steel and its successful application in automotive industry since 1960 is closely connected to the development of an efficient lubrication system. This consists of a conversion coating of zinc phosphate, chemically bonded to the metal substrate and a lubricant, which is applied by dipping into a hot bath of alkaline soap (mostly sodium stearate). The soap reacts with the zinc phosphate to form zinc stearate, which possibly is covered with excessive sodium soap [12,13]. The crystalline layer of zinc phosphate is partly acting as a chemical agent binding the soap to the surface, partly as physical entrapment of the soap.

The coating procedure has several drawbacks regarding environmental aspects: a) sludge of (heavy) metal phosphates, which has to be disposed by burying, b) requirement of continuous overflow of water in the rinsing baths, c) periodic replacement of baths for degreasing, neutralizing, pickling and lubrication, d) large amounts of waste water containing grease, acid and soap. Besides the above mentioned environmental aspects the phosphating process requires prolonged teatment time, 5-15 mins. and high bath temperature, 80-90˚C [6,12]. Very demanding cold forging operations such as cold forging of splines and cross pins for cardan joints often requires MoS_2 on top of the phosphate layer instead of or as a supplement to soap to avoid galling [12,13].

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 drawing of wire, tubes and profiles as well as for cold heading 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%. Recent developments have led to new, advanced aqueous dispersions both of polymer lubricants and MoS_2. The improved adhesion and increased forming capability allow a reduction of the number of complete chemical pre-treatment steps, e.g. lubrication without phosphating.

For less demanding cold forging operations such as bolt production, the soap is replaced by oil. Table 1 presents an overview of their major content [6,15]. The effects of sulphur and phosphorus based extreme pressure additives were intensively studied in the period 1986-1991 by Komatsuzaki [16,17] et al. and Ohmori et al. [18,19]. Phosphate compounds assist lubrication at lower temperatures, sulphur compounds in a somewhat higher range, but none of them is effective in the intermediate range from 200-300˚C.

Table 1. Oil lubricants for cold forging, [15].

Ingredient	Main compounds
Base oil	Mineral oil, fat and oil, synthetic ester
Extreme pressure additives	Phosphorus, chlorine and sulfur
Oiliness improving agent	Fatty acid, higher alcohols
Solid lubricant	Graphite, MoS_2, PTFE, metal soap etc.

Adding phosphate compounds like alkyl acid phosphate to a lubricant formulated with sulfur additives feasible for high temperatures makes it possible to obtain stable lubrication in this medium temperature range, [6,15]. Attempts to add metallic compounds of Ca and Zn have also occurred, and a variety of non-chlorinated cold forging oils are commercially available [20-22].

A number of alternative lubrication systems to the classical phosphate coating + soap have been developed. They may be organized into the following groups:

a) New conversion coatings
   - Electrolytic phosphate coating
   - Microporous coating

b) Lubrication without conversion coating
   - Single bath systems
   - Dual bath systems

2.1. New conversion coatings

2.1.1 Electrolytic phosphating

Many of the drawbacks in using zinc phosphates are eliminated by electrolytic phosphating [8,23,24]. 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 already earlier developed in the late 1990-ies in Denmark by Bjerrum et al. [25,26].

The chemical phosphating process relies on a delicate, local increase of the pH-value in the bath around the slug surface due to consumtion of H+-ions in an initial pickling reaction altering the balance of the bath near the slug surface. This causes the primary zinc phosphate available in the solution to transform into insoluble, tertiary zinc phosphate and free phosphoric acid. The tertiary zinc phosphate precipitates as hopeit from the solution and appears as a crystalline deposit in local spots on the surface. In the e-Phos procedure initial cleaning by mechanical descaling and electrolytic pickling and subsequent water rinsing is followed by electrolytic phosphating. This procedure ensures a much more uniform and fine crystalline coating with smaller film thickness, see Figure 1, and a phosphating time of 4 s compared to 5 min for the chemical procedure. Coating thickness can furthermore be much better controlled, since it is a linear function of current density and treatment time [24]. Applications of the Danish electrolytical coating combined with zinc stearate lubrication have shown it possible carry out severe cold forging operations such as backward can extrusions in stainless steel, AISI 304 with reductions r = $(D_p/D_0)2$ = 0.5 and can heigths h = $2D_p$, where D_p=19.1 is the punch diameter and D_0=27.0 is the container diameter [27].

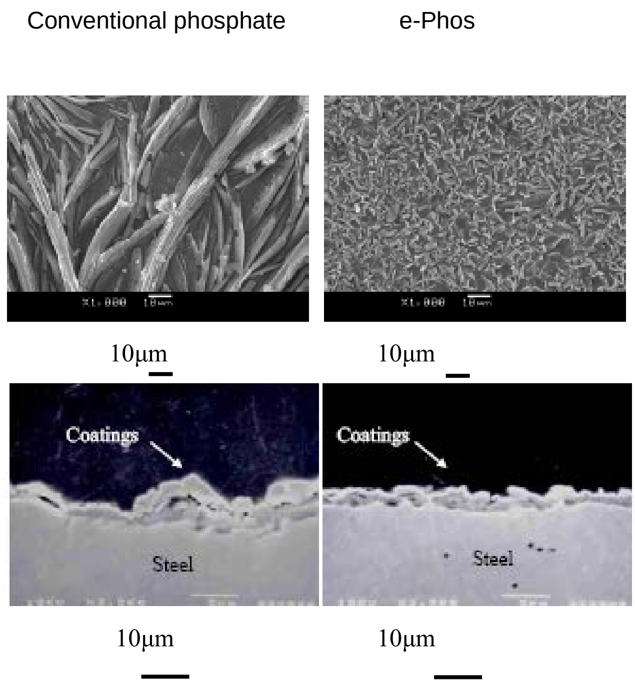

Figure 1. SEM and LOM micrographs of conventional and electrolytic phosphate coatings [24].

Nittel [8] reports about an electrolytic calcium phosphating carried out at 25˚C bath temperature. The process has the same advantages as the electrolytic zinc phosphating, i.e. (heavy) metal sludge in the phosphating bath is avoided and even the coating is free of heavy metal such as Zn and Ni, primarily consisting of $CaHPO_4$. It may be applied to high alloyed steel and stainless steel and Ti, although the latter has yet to be tried. Due to less energy consumption (no heating of the phosphating bath) and savings in disposal of chemicals, the new conversion coating system is claimed to lead to substantial overall savings.

Lubricants applied may be similar to the ones applied for zinc phosphate coating, i.e. mineral oil or metal stearate, but very good results have also been obtained with polymer emulsions and dispersions consisting of polyamides, polyimides, polyurethanes and/or polyoelfines such as polyethylene and/or polypropylene [8,28].

2.1.2 Microporous coating

Tang et al. [29,30] have developed a porous coating working 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-porous layer of the remaining metal on the workpiece surface. 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. Figure 2 shows the porous sponge-like coating obtained. The cross section in Figure 2 left, clearly shows the pores for entrapment of lubricant.

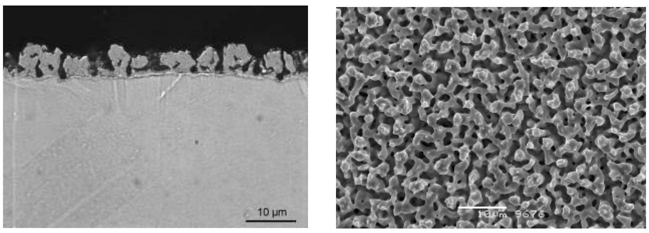

Figure 2. Cross section and top view of new porous coating [30].

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 60 cSt at 40°C proves it to give as low friction as phosphate coating and soap lubrication. Single cup extrusion tests in the same material with high reduction $r = D_p/D_0 = 69\%$ showed no sign of lubricant film breakdown in cup extrusions up to cup heights $h = 2.7D_p$ [30].

Utsunomiya et al. [31] have produced porous surfaces in steel by chemical reduction of pre-oxidized surface. Oxidation was carried out in oven with normal air atmosphere at 700°C in 30 min followed by reduction in the same oven with pure hydrogen at the same temperature in 15 min followed by slow cooling in argon atmosphere. The porous surface was lubricated with machine oil, kinematic viscosity 7.4 cSt at 140°C and tested in wire drawing, which gave a reduction in coefficient of friction from $\mu = 0.11$ to 0.056.

2.2. Lubrication without conversion coating

2.2.1 Single bath systems

As an alternative to lubrication with conversion coatings single bath lubrication systems have been developed in Japan and Germany. After descaling/shot blasting and hot water rinsing, the slugs are dipped in an aqueous bath containing inorganic salt and an organic lubricant. The slugs are subsequently dried after which they are ready for cold forging. The whole procedure takes about 2 min which implies, that in-process lubrication is possible and practiced in several cold forging lines.

Development of such types of lubricants was initiated by Toyota Motor Corp. together with the company MEC Int. investigating a series of different water based compounds with fatty acid, phosphates, polymer based dispersant and Zn- and Mo-compound [32-34]. The research work resulted in the product MEC-HOMAT, a solid film lubricant applied by dipping in a water solution of the above mentioned nature. 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 [35,36], see Figure 3.

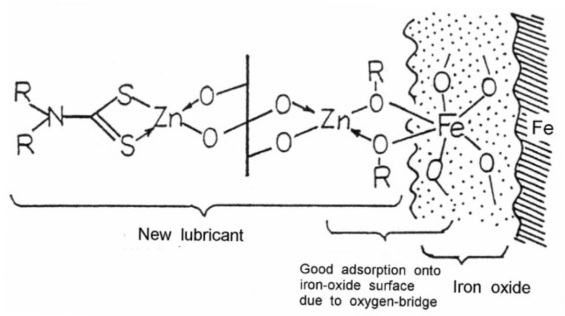

Figure 3. Schematic outline of chemically adhering solid film with Zn-sulphide [35,36].

Schoppe [37] also reports on the development of a single bath lubrication system forming a coating of inorganic salt and wax, which has successfully replaced the former ZnPh coating + soap coating in wire production and manufacturing of bolts. Treatment time is 20 s of slugs in water baths at 60-90°C.

Groche and Koehler [38] have tested a single bath lubricant including a compound of salt and wax. Workpiece material was 16MnCrS5, which was shot blasted before extrusion in a 3-stage operation. Results showed the same low process force and ejector load as ZnPh coating + soap and good surface appearance.

Holz [39] reports that application of MoS_2 by tumbling of in powder form has more or less totally been replaced by dipping in aqueous dispersion baths thus avoiding dust and noise problems and facilitating lubrication of hollow slugs. Successful cold or warm forging production without conversion coating has been of carried in manufacturing valve spring washers, small steering wheels and inner races for CVJ's. Attempts to use single layer polymer coatings have failed, but they work well, when applied to a conversion coating.

Nihon Parkerizing has developed a single bath, water based lubricant called PULS (Parker Ultimate Lubrication System) for cold forging of steel [5]. This lubricant consist 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 of that, see Figure 4. The base layer plays an important role protecting against galling and providing a carrier function, whereas the lubricant lowers friction. The coating is almost similar to the conventional triple layer coating formed by phosphating and soap lubrication.

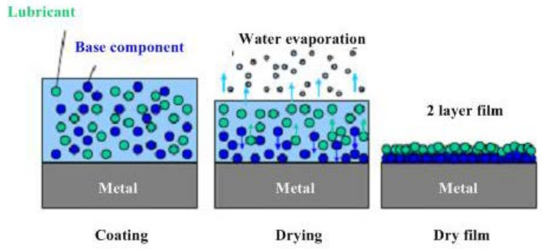

Figure 4. Schematic outline of Dry-in-Place method, PULS [5].

Production trials show the new lubricant to be applicable in almost the same range as phosphate coating and soap lubrication as seen in Figure 5. Cold forgers in Europe, however, indicate that PULS is only adequate for up to three multistage operations. PULS has also been developed for cold forging of aluminium, where the requirements regarding surface expansion are much larger [40].

The new, single bath lubricant systems are applied in numerous cold forging operations and under trial in the most complex ones at Toyota. Substituting zinc phosphate coating + soap with the new lubrication system has reduced the waste from former 360 t to a present 45 t corresponding to 88% less waste, [9].

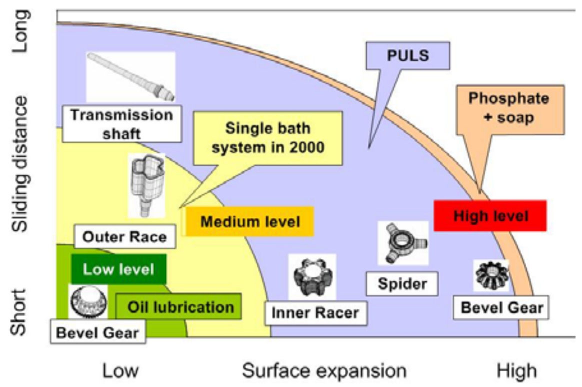

Figure 5. Range of applicability of different cold forging lubricants [40].

Rehbein et al. [41] have developed a new lubricant for aluminium alloys as an alternative to zinc stearate, which causes dust problems. The new lubricant is a suspension of carboxylic acid esters in water. The esters are derivatives from vegetable oils and are solid at room temperature. The suspension additionally contains emulsifiers and corrosion inhibitors. Successful spike testing in laboratory as well as production tests of a piston by backward can extrusion is reported.

2.2.2 Dual bath systems

Nakamura et al. [42,43] have tested a number of alternatives including single as well as dual bath systems. Table 2 gives an overview of the tested lubricants.

The dual bath systems form a ground coating adhering to the slug surface and an over-coating to further reduce friction. Two types of lubricants were applied, a white lubricant consisting of

Table 2. Tested lubricant systems [42,43].

		Main compositions	
White lubricant series		Solid lubr. etc.	Binder
6D917	General purpose single bath type		
6D918	Ground coat of dual baths type	High polymer	Inorganic salt
6D919	Overcoat of two baths type	Wax , metallic soap	—
MoS_2 lubricant series		Solid lubr. etc.	Binder
6D932	General purpose single bath type	High polymer, wax, metallic soap	Inorganic salt , aqueous high polymer
5D925	Single bath type (MoS_2 in high concentration)	MoS_2, graphite	Inorganic salt , aqueous high polymer
5D904	Ground coat of two baths type	MoS_2, graphite	Inorganic salt
6D919	Overcoat of two baths type	Wax , metallic soap	
SM201	Zinc phosphate + MoS_2	MoS_2, graphite	Aqueous high polymer

wax and metal soap, and a black one consisting of MoS_2 and graphite. The different lubricants were applied to annealed bearing steel JIS SCM420 (DIN 20CrMo2) and then subjected to the two laboratory tests shown in Figures 6 and 7. The first test is a combined forward rod and backward cup extrusion test, Figure 6. The second test schematically shown in Figure 7 is a combined forward, conical cup and backward straight cup extrusion test, where the conical punch with a spherical nose provides high surface expansion as well as high normal pressures. As such this test is more severe than the first one.

Using a coating without extra lubricant resulted in high friction factors, whereas the double coating using white as well as MoS_2 + graphite based lubricants gave low friction values comparable to that of phosphate coating + soap lubrication. The single bath type 5D925 gave similar, low friction.

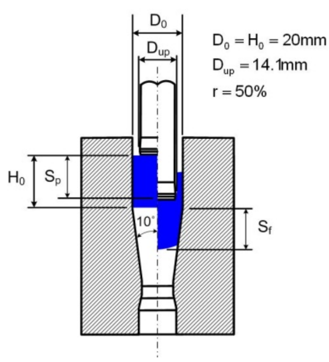

Figure 6. Lubricant testing by Forward-Rod/Backward-Straight-Cup [42].

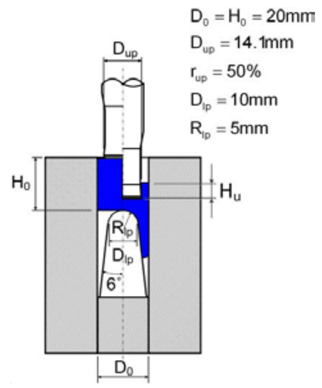

Figure 7. Lubricant testing by Forward-Conical-Cup/Back-ward-Straight-Cup [43].

Figure 8 shows a comparison of the amount of pick-up observed on the spherical punch in test No. 2 with different lubricants for varying punch stroke. All of the new lubricants break down at certain punch strokes, indicating that none of them are as efficient to prevent galling as phosphate coating + soap, and furthermore confirming that the second test is more severe than the first one. Industrial testing of the two new, dual type coatings (6D918+6D919 and 5D904+6D919) were carried out in a multistage cold extrusion [44]. The test showed good performance of both systems with no sign of pick-up on the tools in multistage shaft extrusion, and in 4 stage splines and gear extrusions Figure 9.

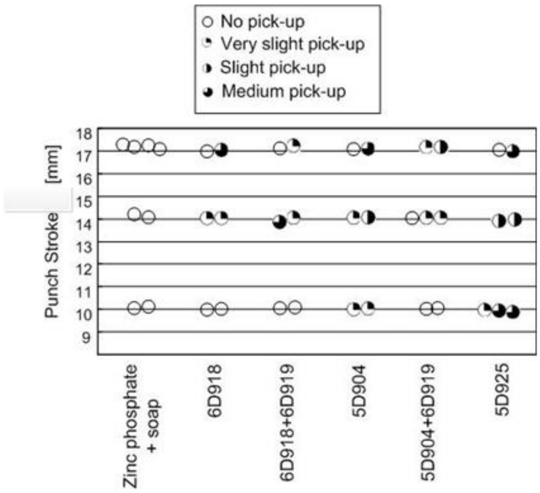

Figure 8. Limits of lubrication in Forward-Conical-Cup/ Backward-Straight-Cup [43].

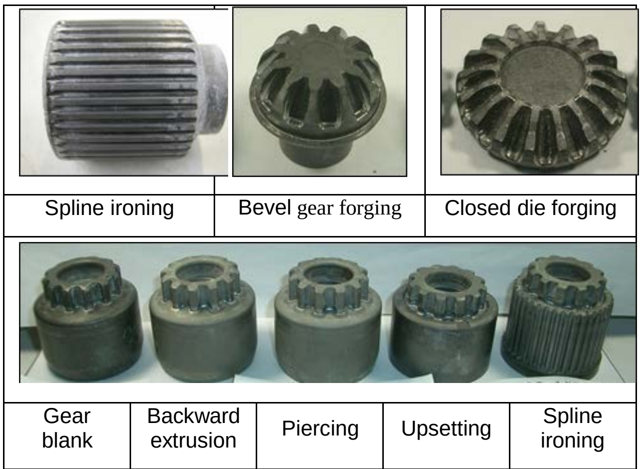

Figure 9. Multistage cold forgings without conversion coating [44].

3. Tool materials

Uddeholm has developed a new, cold work tool steel Vancron 40, a powder metallurgical, nitrogen alloyed, high speed steel with excellent anti-galling properties [45,46]. Nitrogen increases the stability of vanadium nitride and the size of the hard phases become very small in the final tool material.

Compared to cold work tool steel AISI D2 and conventional PM high speed steel AISI M3:2 Vancron 40 showed superior anti-galling properties as judged by a number of laboratory tests [47,48]. Examples on industrial tests in cold forging of Al 6082 steering parts with Vancron tool steel compared to conventional tool steels show improvements of tool life with a factor 10 or more.

4. Tool coatings

The report [49] presents a comprehensive investigation of attempts to replace phosphate coating and soap lubrication in cold forging of steel by applying anti-seizure tool coatings and new lubricants. The investigation concludes that three of the investigated tool treatments have potential to replace or at least reduce the use of phoscoating in cold forging. These are the MoST® PVD over TiC CVD coating, ion nitriding and the TD process.

One of the problems in applying PVD coatings for cold forging tools is the high hardness and Young's modulus compared to the base tool material leading to risk of coating fracture. Klocke et al. [50] report the development of a nanostructured multilayer coating (up to 40 layers) with intermediate bilayers of less than 20 nm with TiAlN layers closest to the substrate and on top of these a-Al_2O_3 layers. This coating was tested and proved to reduce Young's modulus and at the same time increase hardness [51].

Schrader et al. [52] reported a comprehensive study on alternative PVD coatings for cold forging tools testing monolayer coatings of TiN and TiAlN as well as multilayer coatings of TiAlCN, TiCN, AlCrN (nano-coating) and Si_3N_4/AlTiN (nano-structured). Double cup extrusion tests in 16MnCr5 were conducted to determine friction showing the main factor to influence the friction factor to be the applied lubricant rather than the tool coating. Wear resistance was tested in a 3-ball tester as well as in two different cold forging operations, i.e. backward can extrusion with conical, profiled punch for manufacturing of outer race CVJ's in 16MnCr5 and impact extrusion of torque screws in 37Cr3. In severely loaded tools multilayer coating of TiCN worked best due to its high hardness. In case of local minimal quantity lubrication the amount of aluminium in the coating should be small.

With the objective of eliminating the use of phosphate coatings in cold forging, Groche et al. [53] tested a number of tool coatings in a cold extrusion test of steel wire. They found better wear resistance of CVD coating with TiC+TiN than PVD coating with CrN and TiN. Lubricants extended from ordinary extrusion oil to pigmented oil and an emulsion. CVD coatings with TiC+TiN and Me-C:H (DLC) show low friction and attempts to test in industrial production proved promising as regards substituting zinc phosphate layers by applying tool coatings.

Dubar et al. [54] have performed a wear analysis of a cold forging tool for heading of a bolt in 34Cr4 steel comparing PVD with CVD coating with TiN of AISI M2 tool steel. A clear difference was notice showing the PVD coating to be chipped off at rather low number of operations leading to excessive friction. The better adherence of the CVD coating improved performance significantly. Osakada and Matsumoto [55] have studied dry metal forming of Al, Cu and low C-steel by ring test upsetting with cemented carbide tools CVD coated with TiC,

TiC+TiCN+TiN, and PVD coated with TiN, TiAlN and DLC. They found that DLC coating resulted in low friction in dry forming of aluminium and that the oxide layer on steel resulted in very high friction in cold forging. Friction was very sensitive to surface roughness of the tool when forming dry.

5. Structured workpiece surfaces

The application of structured workpiece surfaces is state-of-the-art in sheet metal forming applying specially textured sheets providing a topography with lubricant pockets to facilitate the forming process. Utilizing textured workpiece surfaces in cold forging by shot blasting or other methods is less common due to two major disadvantages [56]. First, a time-consuming treatment of each single workpiece is necessary, and second, this effect works only in the first forming step due to the large surface expansion and profound flattening of the surface asperities in bulk forming. This implies that later steps in multistage operations, which are common in bulk forming operations, are not supported. In case of single stage production as for instance in production of many aluminium components surface texturing by e.g. shot blasting is commonly used [57,58]

Groche et al. [59,60] have studied the performance of different surface texturing methods of cylindrical QSt36-3 billets in a two-step forward cold extrusion lubricated with a reduction oil Bechem KFP 10 as substitute to phosphate coating and soap lubrication. Structuring was done by the following methods: shot blasting with different sized steel balls as well as Al_2O_3 particles, laser structuring by a Nd:YAG laser with pulse and robot control and stochastic as well as deterministic electro-chemical etching. They found remarkable improvements as regards lowered friction force especially in the first operation, whereas the second extrusion step leveled the structured surfaces.

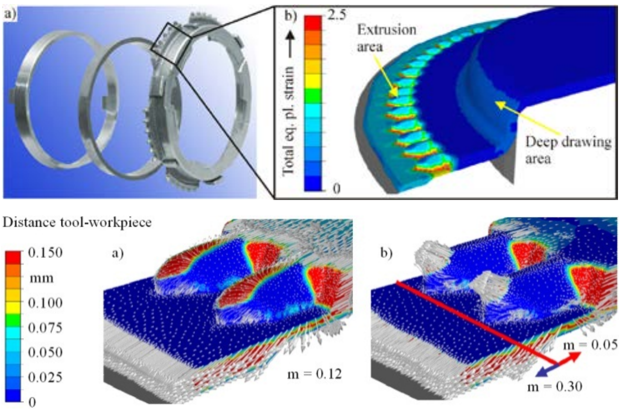

Figure 10. Synchromesh ring and FE analysis of local flow with uniform as well as locally controlled friction [61].

Vierzigmann at al. [61] utilized friction control varying the local size of friction in sheet-bulk metal forming in combined deep drawing and extrusion of a synchromesh gear ring, see Figure 10. Increasing friction in the outer part of the flange by roughening using local shot blasting of the blank and lowering friction in the inner part by micro coining of lubricant pockets it was possible to obtain good form filling as the FE analysis in Figure 10 indicates.

6. Structured tool surfaces

In contrast to the structured workpiece surface, the structured tool surface hardly changes even after prolonged use. Engel et. al. have utilized this effect to construct functional surfaces on cold forging tools by laser ablation [56,62]. Using an excimer laser, local flat bottomed micro-pockets have been produced on the end surface of punches for backward can extrusions. Width and depth of the circular texture elements were set to 10 µm and 1 µm respectively see Figure 11. The punch was made in high speed steel and PVD coated with TiN. A liquid lubricant of kinematic viscosity 100 cSt at 40°C was applied. Compared with the non-textured tool previously applied the tool life was increased by approximately 50%.

Popp and Engel explain the improved tool life by the pressurization of lubricant entrapped in the micro cavities of the tool surface, see **Error! Reference source not found.**Figure 12. In [62] Otto et al. report the relationship between flank angle of the single texture element and relative tool life, see Figure 13, in good accordance with earlier studies by Soerensen et al. showing the importance of the slope of the pocket wall in textured sheet blanks [63], where lower flank angles facilitate microhydrodynamic flow of lubricant from the pockets to the surrounding plateaus. Adjustment of the flank angle is achieved by laser texturing with controlled defocusing. With this discovery new production tests resulted in significant extension of the punch life, [64].

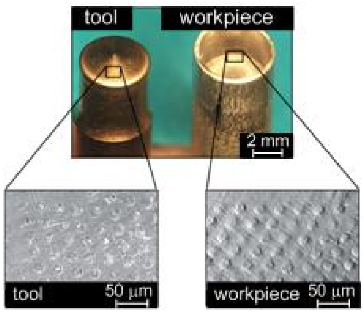

Figure 11. Textured tool and workpiece in backward can extrusion.

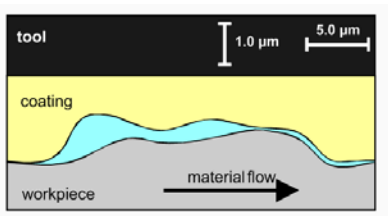

Figure 12. Tool pocket profile and suggested lubrication mechanism [56].

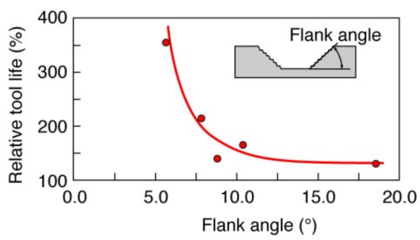

Figure 13. Relation between micropocket flank angle and tool life [62].

Sieczkarek et al. [65] have utilized surface texturing of the tool surface to faciltate form filling in sheet-bulk metal forming of a toothed rack. The tool surface was prepared by micro-milling of lubricant pockets in a bionic structure inspired by the surface of a scarabaeus beetle. It was subsequently coated with a multilayer CrAlN.

The development of a Robot Assisted Polishing machine has opened up for new possibilities to produce functional tool surfaces [66]. By milling a lay of micro-grooves in the tool surface followed by robot assisted polishing perpendicular to the lay, a surface of lubricant pockets with topography like a table mountain can be established.

7. Testing

Testing of new lubricant systems in the production line is costly and problematic due to the required production stops and cleaning of tools before introducing the new test lubricant, as well as production stops caused by possible lubricant film breakdown and pick-up of workpiece material on polished tool surfaces, which requires dismounting of tools and re-polishing. Literature lists a large number of metal forming tribology tests [67-71].

In order for such tests to be useful, it is, however, vital to ensure that they emulate the process conditions in real production. Of special importance is here to obtain similar normal pressures, surface expansion, sliding length, sliding velocity and tool/workpiece interface temperature. In the following a few of the most promising of these tests are presented.

Gariety et al. [72] have adopted the double cup extrusion test Figure 13 to compare new cold forging lubricants for steel without ZnPh precoat with ZnPh coated and soap lubricated ones. They proved MEC Homat, a single bath, two layer water based lubricant with metal compounds and organic sulphur components and Daido Aqualub, a water based lubricant with inorganic salts, phosphorous organic compound, lubricant surfactants and synthetic alcohol to give significantly lower friction than ZnPh coating + soap and good resistance towards galling.

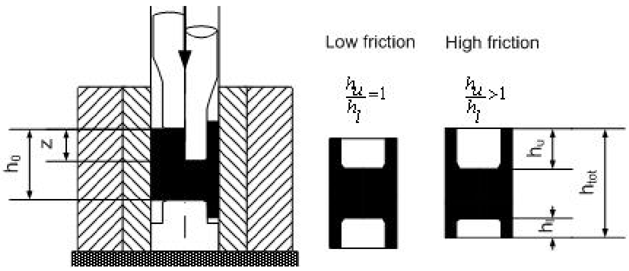

Figure 13. Schematic outline of double cup extrusion test.

Rehbein et al. [41] have used the spike test at Univ. Stuttgart Figure 14 to evaluate new lubricant systems for cold forging of aluminium. The small thickness of the forged disk makes it very friction sensitive and the long cone extrusion with small included angle 2α = 6° is very sensitive towards galling.

Figure 14. Spike test [73].

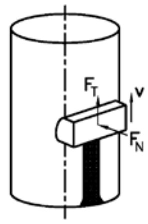

Fig. 15. Upsetting-sliding test [74].

Dubar et al. [74] have developed the upsetting-sliding test illustrated in Figure 15 and used it for estimation of friction and resistance towards galling of cold forging lubricants.

(a) (b)

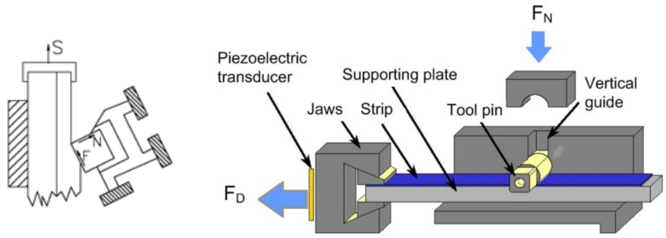

Figure 16. Strip-reduction tests [75] and [76]

Dohda et al. [75] have proposed the strip-reduction test shown in Figure 16a, and Andreasen et al. [76] have used a setup shown in Figure 16b to test new lubricants for sheet forming and ironing. Testing with pre-heated tools up to 200°C was done to emulate production conditions.

Nakamura et al. [42,43] have developed the two cold forging tests earlier discussed and shown in Figures 6-7. Especially the forward rod-backward conical can extrusion is very severe and as such suitable for testing limits of lubrication.

Ngaile et al. [77] have developed another severe tribo-test for cold forging by bar ironing with an inclined die provided with a wavy surface as shown in Figure 16. This test is suitable to evaluate lubricant systems for spline extrusions.

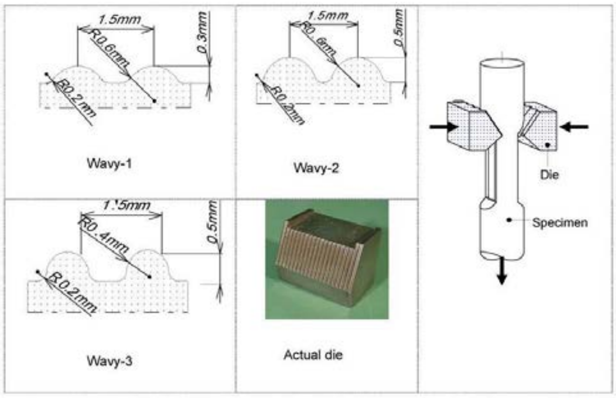

Figure 16. Spike test [75].

Sagisaka et al. [78] have proposed a similarly severe test by combined forward rod backward can extrusion using a conical die provided with ridges Figure 17.

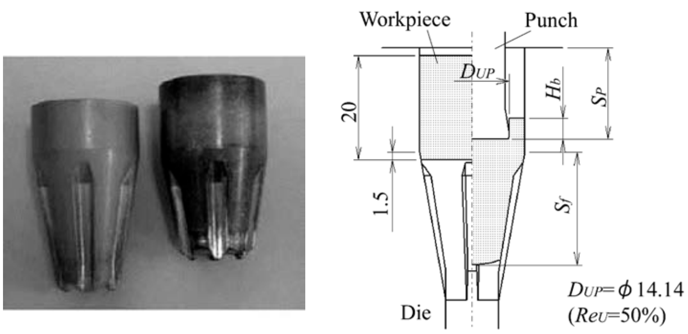

Figure 17. CombinedBackward can extrusion twist test [79].

Ceron et al. [79] have proposed a cold forging test, which combines backward can extrusion with simultaneous twisting of the workpiece with respect to the punch Figure 18a. In this way severe testing conditions with high normal pressures and large surface expansion is obtained. Pre-heating of the punch is possible and the test is suitable for determing friction as well as limits of lubrication. It has proven severe enough to break down even efficient ZnPh + soap coated mild steel slugs as seen in Figure 18b, which shows slight pick-up on the conical surface and punch land. In Figure 18c severe pick-up is formed on the punch testing the earlier mentioned single bath lubricant PULS. In all cases the pick-up evolution follows a helical pattern corresponding to the local sliding direction on the conical punch nose.

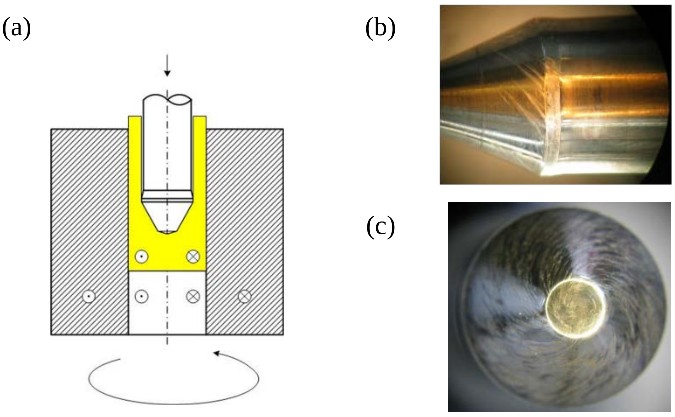

Figure 18. Backward can extrusion twist test [79].

8. 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 of steel new developments of chemical phosphating has ensured lower environmental burdens and electrophosphating minimize these ptroblems and provide a thinner and more uniform and effective conversion layer.

Other types of conversion layers, e.g. porous coating layer of Zn or porous surface layer produced in the slug material itself have shown to be efficient alternatives.

Single bath as well as double 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.

New multi-phase tool steel with finely distributed nitrides in a PM HSS matrix prevents seizure, probably due to a combination of anti-seizure properties of the nitrides and mechanical entrapment of lubricant in pockets in the tool surface. Application of multilayered ceramic tool coatings with anti-seizure properties has proven efficient in case of severe tribological conditions.

Construction of functional workpiece and tool surfaces by surface texturing, which facilitates entrapment and subsequent escape of lubricant by microhydrodynamic lubrication, is a technology with potentials, which should be further pursued to promote lubrication in bulk forming.

A number of laboratory test methods have been developed, which may be used for off-line testing. It is, however, imperative to emulate the production conditions accurately. Especially important is to ensure right tool/workpiece interface temperature, normal pressure, sliding length and sliding velocity (in case of liquid lubricants).

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