 doi:10.20944/preprints201612.0047.v1

Peer-reviewed version available at *Lubricants* **2017**, *5*, 3; doi:10.3390/lubricants5010003

Article

The Influence of Tool Texture on Friction and Lubrication in Strip Reduction Testing

Mohd Hafis Sulaiman [1,2,*], Peter Christiansen [1] and Niels Bay [1]

[1] Department of Mechanical Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark; petc@mek.dtu.dk (P.C.); nbay@mek.dtu.dk (N.B.)
[2] School of Mechatronic Engineering, Universiti Malaysia Perlis, 02600 Arau, Perlis, Malaysia
* Correspondence: mhafsul@mek.dtu.dk; Tel.: +45-25 21 44

Abstract: While texturing of workpiece surfaces to promote lubrication in metal forming has been applied for several decades tool surface texturing is rather new. In the present paper tool texturing is studied as a method to prevent galling. Adopting a strip reduction test longitudinal pocket geometries oriented perpendicular to the sliding direction, with shallow pocket depth, small pocket angle to the workpiece surface and varying distance between pockets are investigated. The experiments reveal that the distance between pockets should be larger than the pocket width thereby creating a topography similar to flat table mountains to avoid mechanical interlocking in the valleys; otherwise an increase in drawing load and pick-up on the tools is observed. The textured tool surface lowers friction and improves lubrication performance provided that the distance between pockets is 2-4 times larger than the pocket width. Larger drawing speed facilitates escape of the entrapped lubricant in the pockets. Testing with low to medium viscosity oils leads to a low sheet roughness on the plateaus but also local workpiece material pick-up on the tool plateaus. Large lubricant viscosity results in higher sheet plateau roughness but also prevents pick-up and galling.

Keywords: tool surface texture; lubricant entrapment; strip drawing test

---

1. Introduction

The application of surface texturing to facilitate lubrication in engineering applications such as bearings [1], reciprocating contacts [2] and concentrated sliding contacts [3] is well known. The use of tailored workpiece surfaces in sheet metal forming to improve tribological conditions has been state of the art since the 1990s [4-5]. Studies of the lubrication mechanisms through transparent tools using mesoscopic pockets in the workpiece surface have shown the workpiece surface topography to facilitate lubrication by micro-plasto-hydrodynamic lubrication [6-7]. In industrial applications tailored sheet surfaces are made by skin-pass rolling in the final rolling step after annealing using large rolls roughened by Shot Blast Texturing (SBT) or Electro Discharge Texturing (EDT) [8]. A drawback is here the problem of reproducing the surfaces in large-scale sheet production due to wear of the textured roll surfaces. Besides this drawback comes economic considerations and the fact that the technique is less feasible in multistage operations, since the pockets are flattened out after the first forming operation [9].

Texturing of tool surfaces would be more feasible in large-scale production and multi-stage sheet stamping operations, since a textured tool surface can be utilized for thousands of workpiece components. A few tests of surface engineered deep drawing tools [10-11] have shown very promising results indicating that tailored tool surfaces may provide mechanical lubrication systems, which can function instead of chemical ones, and thereby replace environmentally hazardous lubricants with environmentally benign ones. In order to ensure successful design of such tailored tool surfaces it is important to understand the influence of surface texture parameters on friction and lubrication in metal forming. Manufacturing of the tailored tool surfaces into a table mountain like

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 December 2016 doi:10.20944/preprints201612.0047.v1

Peer-reviewed version available at Lubricants 2017, 5, 3; doi:10.3390/lubricants5010003

structure with flat plateaus and neighbouring flat bottomed valleys can be obtained by combined grinding, milling and polishing of tools [12-13]. A small pocket angle towards the workpiece surface facilitates escape of the trapped lubricant in the pockets, which increases the tool life [14]. These effects can be enhanced by utilizing transverse roughness profiles as well as oblong pockets oriented transverse to the sliding direction. In this way lubricant entrapment is promoted which can lead to low friction and prevent galling by micro-plasto-hydrodynamic lubrication [15-16]. In addition, larger sliding speed reduces the tendencies of mechanical gripping effects of the workpiece into the pockets as the normal pressures increases [17].

The present paper studies textured tools in strip reduction with a focus on a small pocket angle, shallow pocket depth, oblong pockets oriented perpendicular to the sliding direction and with varying distances between the pockets.

2. Test Setup

Figure 1 shows the strip reduction test equipment applied, whereas Figure 2 shows a schematic of the test setup with the textured tool. The front part of each workpiece strip was flattened by rolling in order to grip the workpiece. The reduction *r* in each test was 10 – 15%, which emulates an ironing operation in aluminium can production. Two different drawing speeds v = 240 mm/s and 65 mm/s were applied with four different tool surfaces as described in the following. The high and low drawing speeds were intended to identify possible influence of micro-plasto-hydrodynamic lubrication mechanism.

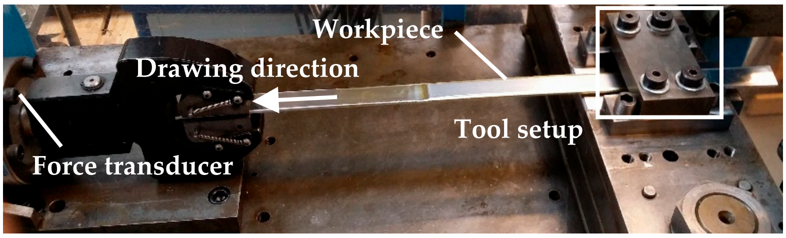

Figure 1. The strip reduction test equipment.

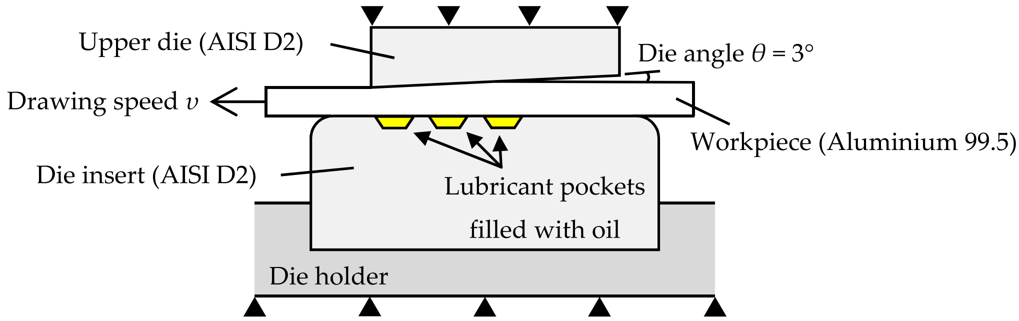

Figure 2. Schematic of the test with textured tool surface.

3. Manufacture of Surface Textures

A great number of surface texturing techniques are available for texturing of hard tool materials such as combined milling, grinding and manual polishing [12], chemical etching [15], rolling ball indentation [17] and laser radiation [18-19]. In this study, high speed, hard machining combined with manual polishing was chosen.

Figure 3 shows the die insert consisting of a deformation region, $X \times Y = 11.5 \times 20$ mm, and a transverse pocket length $y = 16$ mm. Two surface texture features are important parameters to promote the micro-hydrodynamic lubrication mechanism [20], which are 1) small pocket angle γ and 2) shallow pocket depth d, see Figure 4. The pocket angle γ and the pocket depth d were chosen to be 5° and 0.01mm respectively. Table 1 lists the surface texture parameters as calculated by Equation (1) and Equation (2). A TiA70 coated milling tool having a two-flute solid carbide ball-nose and a radius

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 December 2016 doi:10.20944/preprints201612.0047.v1

Peer-reviewed version available at Lubricants 2017, 5, 3; doi:10.3390/lubricants5010003

R of 12.5 mm was used for machining the transverse flat-bottomed lubricant pockets in the surface of the hardened tool.

$$\tan\gamma = \frac{d}{a}\,, \tag{1}$$

$$R^2 = a^2 + H^2 = a^2 + (R-d)^2\,, \tag{2}$$

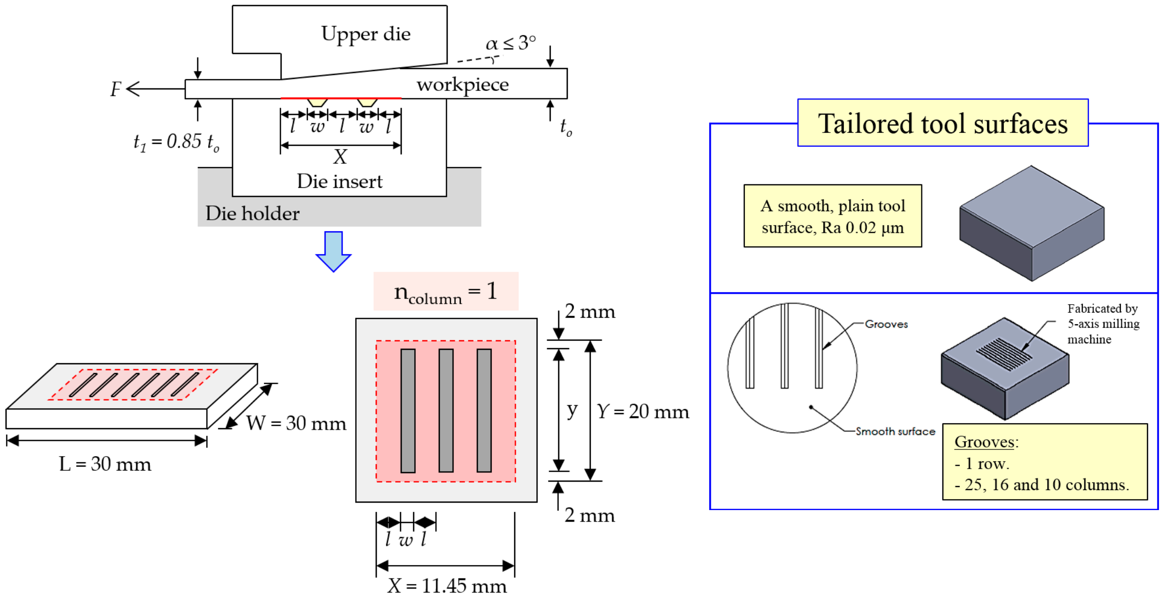

Figure 3. Texturing parameters: distance, depth, width and number of pockets.

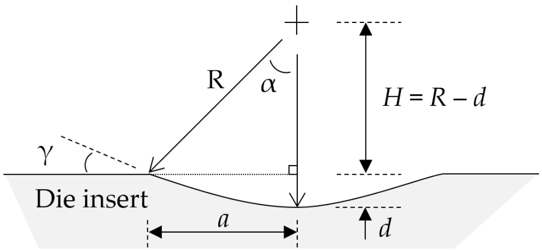

Figure 4. Selection of milling tool based on lubricant pocket geometry.

The process sequence of manufacturing a textured tool surface started with the plane tool surface being milled to Ra = 0.14 μm by the 5-axis high speed milling machine, Mikron HSM 400U LP. After this, the transverse pocket geometry was machined with the above mentioned milling tool running at 42,000 rpm and a feed of 600 mm/min. Figure 5 represents the resulting, measured pockets of nominal dimensions: length y = 16 mm, angle γ = 5° ± 0.5°, width w = 0.23 mm ± 0.1 mm, depth d = 7 μm ± 1 μm and distance between pockets of x = 0.23, 0.46 and 0.92 mm. Subsequent polishing of the tool surfaces were done in three steps with water based polycrystalline diamonds of grain sizes 3, 1 and 0.25 μm resulting in a final roughness Ra = 0.01 – 0.03 μm. The upper die and die insert surfaces were polished down to Ra = 0.01 μm. It is noticed that the pocket depths are reached within the tolerance gap, whereas the pocket angles turns out to be somewhat smaller than aimed at. This is, however, only promoting the micro-hydrodynamic lubrication mechanism and preventing mechanical interlocking.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 December 2016 doi:10.20944/preprints201612.0047.v1

Peer-reviewed version available at *Lubricants* **2017**, *5*, 3; doi:10.3390/lubricants5010003

Table 1. Surface texture parameters.

Parameters	Value		
Pocket angle γ (°)	5		
Pocket width $w = 2a$ (mm)	0.23		
Pocket depth d (mm)	0.01		
Pocket ratio d/w	0.05		
Distance between pockets l (mm)	1 x w	2 x w	4 x w
Number of pockets - row n_{row}	25	16	10
Number of pockets - column n_{column}	1	1	1
Initial pocket volume V_o (mm³)	0.61	0.39	0.24
Contact area ratio ($A_{r,o}/A_o$) (%)	60	74	84

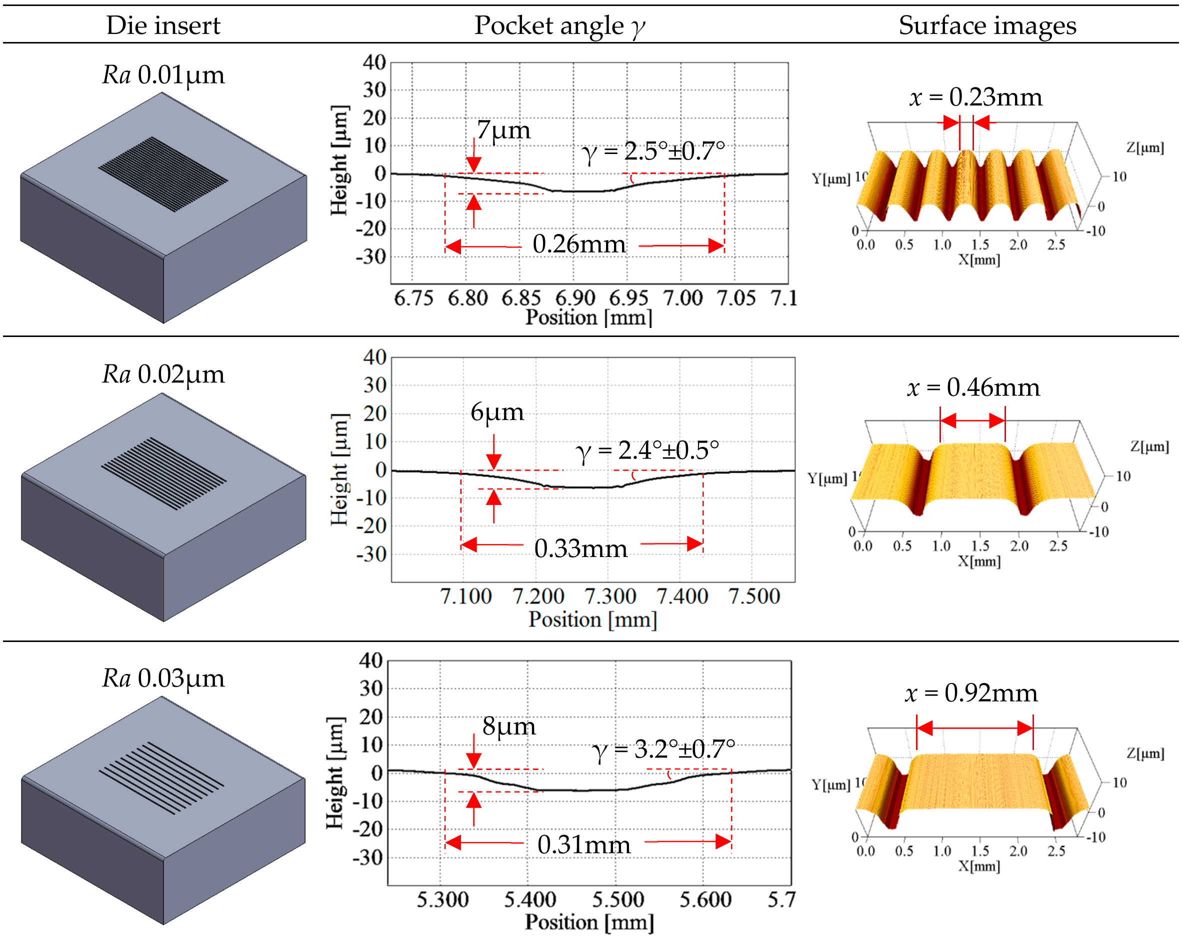

Figure 5. Manufacture of textured tools concentrating on pocket depth d and pocket angle γ.

4. Test Materials

4.1. Tool material

The tool material was made of AISI D2 cold work tool steel, a high carbon, high chromium tool steel alloyed with molybdenum and vanadium. The tools were through-hardened and tempered to 60 HRC before the surface texturing procedure described above. The tool material is feasible for forming of aluminium sheet material, due to high wear resistance, high compressive yield strength and resistance towards pick-up of ductile materials like pure aluminium. It is furthermore easy to remove possible pick-up of aluminium by etching in a warm sodium hydroxide solution.

Peer-reviewed version available at *Lubricants* **2017**, *5*, 3; doi:10.3390/lubricants5010003

4.2. Workpiece material

The workpiece material was a commercially pure Al 99.5, H111 with dimensions 480 x 20 x 4 mm. The 4 mm sheet thickness ensures sufficient deformation region (tool/workpiece contact length) for a fairly large number of pockets to be within the deformation zone. This will reduce the experimental scatter data due to the results being less sensitive to the exact number of pockets within the deformation zone. The sheet width was chosen large enough to ensure approximately plane strain conditions resembling ironing. The as-received workpiece surface roughness were *Ra* = 0.21 μm. The stress-strain curve of the material shown in Figure 6 was determined by plain strain compression testing. Figure 6 also shows a curve fit and the determined material constants according to the Voce flow curve expression.

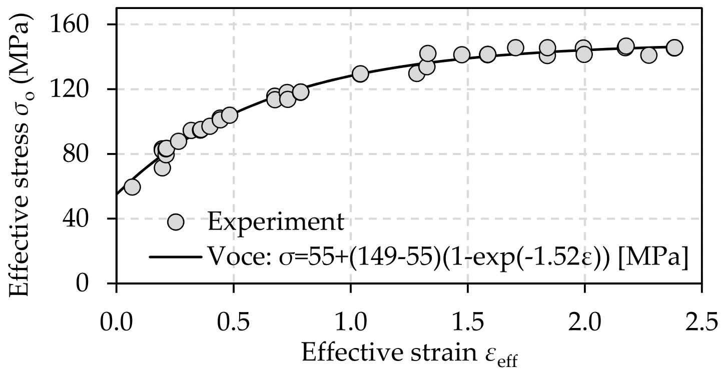

Figure 6. Voce flow curve expression for the aluminium 99.5 sheet.

4.3. Lubricants

Four different mineral oils were chosen for the experiments. Two of them, with medium and high viscosity respectively, contained additives with boundary lubrication properties. The other two were mineral oils with no additives. One of these was high viscous oil, and the other one was a mixture of this oil and low viscous oil giving a rather low resulting viscosity. Data on the test lubricants are listed in Table 2.

Table 2. Properties of the test lubricants.

Oil type	Product name	Kinematic viscosity η @ 40°C
Mineral oil with additives	Rhenus LA 722086	800 cSt
Mineral oil with additives	Rhenus LA 722083	300 cSt
Pure mineral oil	CR5 Houghton Plunger	660 cSt
Pure mineral oil	CR5 – Sun 60 [1]	60 cSt

[1] 50 wt. % mixture oil – Houghton Plunger CR5 (η=660 cSt) and Sunoco Sun 60 (η=10 cSt).

5. Test procedure

The test started by cleaning the tool and workpiece surfaces from any remnants of pick-up, oil, grease and other contaminants. Subsequently the lubricant was applied to the different tool surfaces, after which testing was carried out. During testing, the load measurements were recorded, and the load versus time data were saved in a LabView program. Same procedure was repeated with the different lubricants. The results plotted were based on three to five repetitions of each parameter investigated, i.e. lubricant, drawing speed and tool texture. Before and after testing, the tool and workpiece surfaces were scanned in a Light Optical Microscope (LOM) and measured by a tactile roughness profilometer, Form TalySurf Series 2 50i. The listed roughness *Ra* was based on an average of six measurements.

 doi:10.20944/preprints201612.0047.v1

Peer-reviewed version available at *Lubricants* **2017**, *5*, 3; doi:10.3390/lubricants5010003

6. Results and Discussion

The drawing load reaches steady-state condition after a short time as seen in Figure 7 and Figure 8 showing the results for the four different lubricants at drawing speeds υ = 65 mm/s and 240 mm/s respectively. The influence of tool texture is significant at larger speed, while at lower speed, no load difference is observed except that the transverse pocket with x = 0.23 mm leads to a larger forming load regardless of speed and lubricant applied. The small distance between the pockets x = 0.23 mm leaves no flat plateau between the pockets (see Figure 5 top). This promotes metal flow into the pockets, which will provide mechanical gripping effects of the workpiece. Marks of the die insert texture on the strip can be seen on the end of the reduction zone.

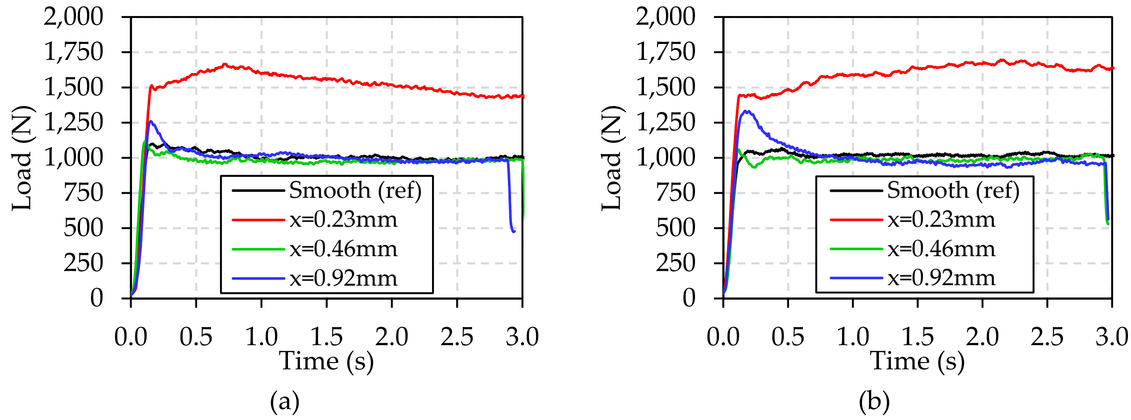

Figure 7. Forming load at speed υ=65 mm/s for (a) Rhenus oil η=800 cSt and (b) Rhenus oil η=300 cSt.

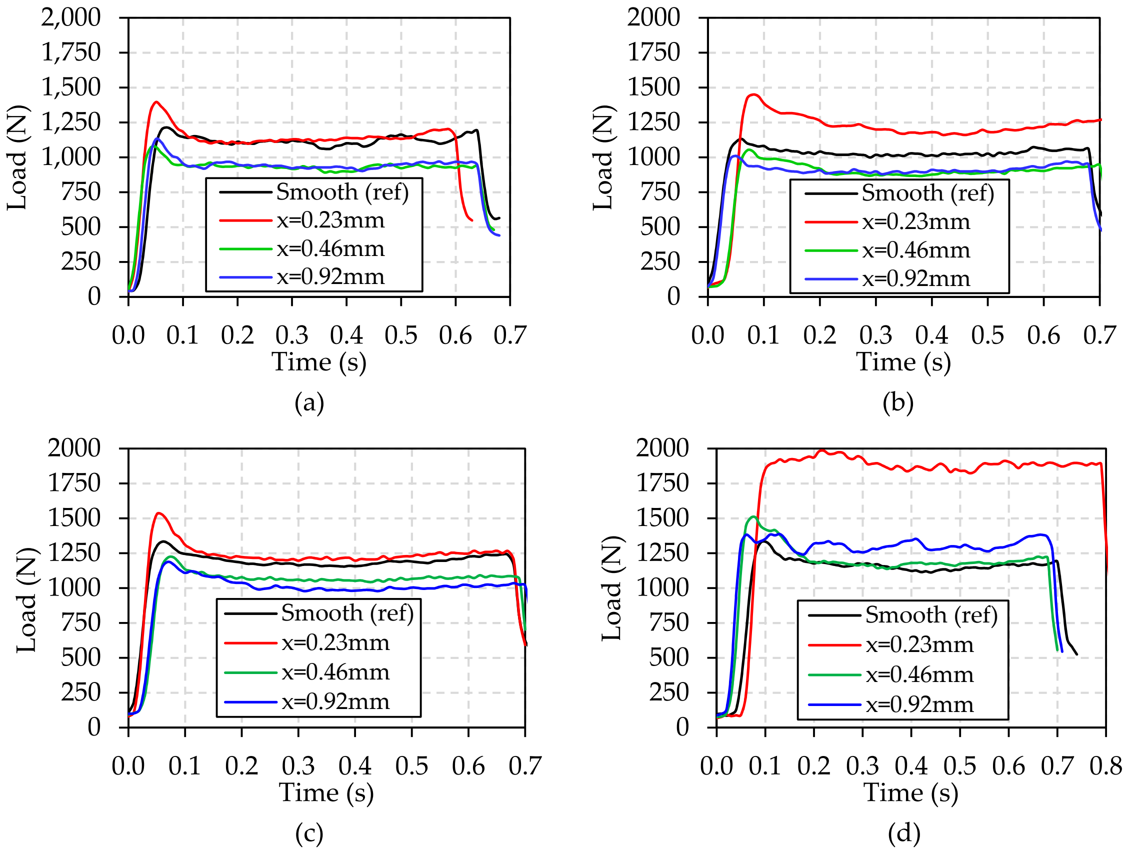

Figure 8. Forming load at speed υ=240 mm/s for (a) Rhenus oil η=800 cSt, (b) Rhenus oil η=300 cSt, (c) mineral oil CR5 η=660 cSt and (d) mineral oil mixtures CR5-Sun 60 η=60 cSt.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 8 December 2016 doi:10.20944/preprints201612.0047.v1

Peer-reviewed version available at *Lubricants* **2017**, 5, 3; doi:10.3390/lubricants5010003

The positive influence of high drawing speed is explained by micro-plasto-hydrodynamic lubrication, which is promoted by high sliding speed and high viscosity of the lubricant [21]. Since no improvement were noted on the drawing load, when testing tool textures at the lower speed 65 mm/s (Figure 7), the rest of the discussion is focused on the tool texture at larger speed 240 mm/s (Figure 8). It is here noticed that the tool texture with x = 0.46 mm and x = 0.92 mm (2-4 times the pocket width w) has reduced the drawing load as compared to the smooth tool surface, when testing with the larger viscosity oils, while testing with the low viscosity pure mineral oil CR5-Sun 60 had the opposite effect. This is due to the above mentioned relationship between viscosity and micro-plasto-hydrodynamic lubrication.

Figure 9 shows that tool texture reduces the sheet roughness as compared to the smooth tool surface regardless of the test lubricants investigated. The tool texture with pocket distance x = 0.23 mm gave smallest sheet roughness. It is furthermore noticed that increasing viscosity leads to increasing roughness. This may be explained by improved micro-plasto-hydrodynamic lubrication at higher viscosity leading to effective separation between tool and workpiece on the plateaus of the tool table mountain [22]. The sheet roughness profiles shown in Figure 10 confirm this. The Ra values on the plateaus are measured by a tactile roughness profilometer, Form TalySurf Series 2 50i. They are based on an average of 6 measurements. Ra values for x = 0.23 mm and x = 0.46 mm could not be measured due to small width of the plateaus.

The Rhenus oil contains additives providing a protective boundary film, which can carry the load and prevent metal-to-metal contact. This contributes to lower friction and prevents lubricant film breakdown. The additives in the Rhenus oils furthermore prevent these oils from decomposition and vaporization [23].

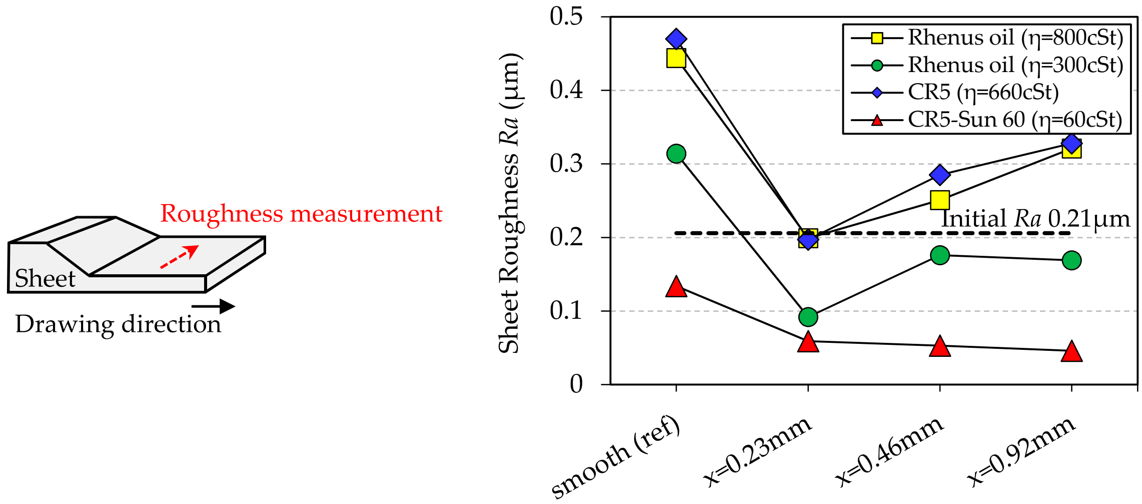

Figure 9. Sheet roughness on the plateaus at speed v=240 mm/s.

Figure 11 shows images of the tool surface using Light Optical Microscope (LOM) and Scanning Electron Microcopy with energy dispersive X-ray spectroscopy (SEM/EDX), utilized to observe possible pick-up of workpiece material on the tool surface in the contact region. Testing of the Rhenus oil with a viscosity of 800 cSt showed no sign of pick-up at all, which is explained by the complete separation between tool and workpiece surface as evidenced in Figure 10.

Pick-up of aluminium is observed on the plateaus of the table mountain structure especially in the last part of the tool/workpiece contact region corresponding to a thickness reduction r close to 15%. The rectangular frames in the LOM images marked A, B, C and D in Figure 11 indicate the approximate location of the SEM images although the frames are larger than the SEM images. Testing of the Rhenus oil with viscosity of 300 cSt and the pure mineral oil with a viscosity of 660 cSt resulted of 0.2 – 1.0 wt.% and 0.1 – 0.2 wt.% pick-up, respectively, while the low viscosity CR5-Sun 60 oil resulted in increased amount of pick-up of 0.3 – 17.9 wt.%. This is as expected, since the low viscous mineral oil with no additives does not promote micro-plasto-hydrodynamic lubrication and has no boundary lubrication properties, whereas the higher viscous Rhenus oil and the high viscous pure

doi:10.20944/preprints201612.0047.v1

Peer-reviewed version available at *Lubricants* **2017**, *5*, 3; doi:10.3390/lubricants5010003

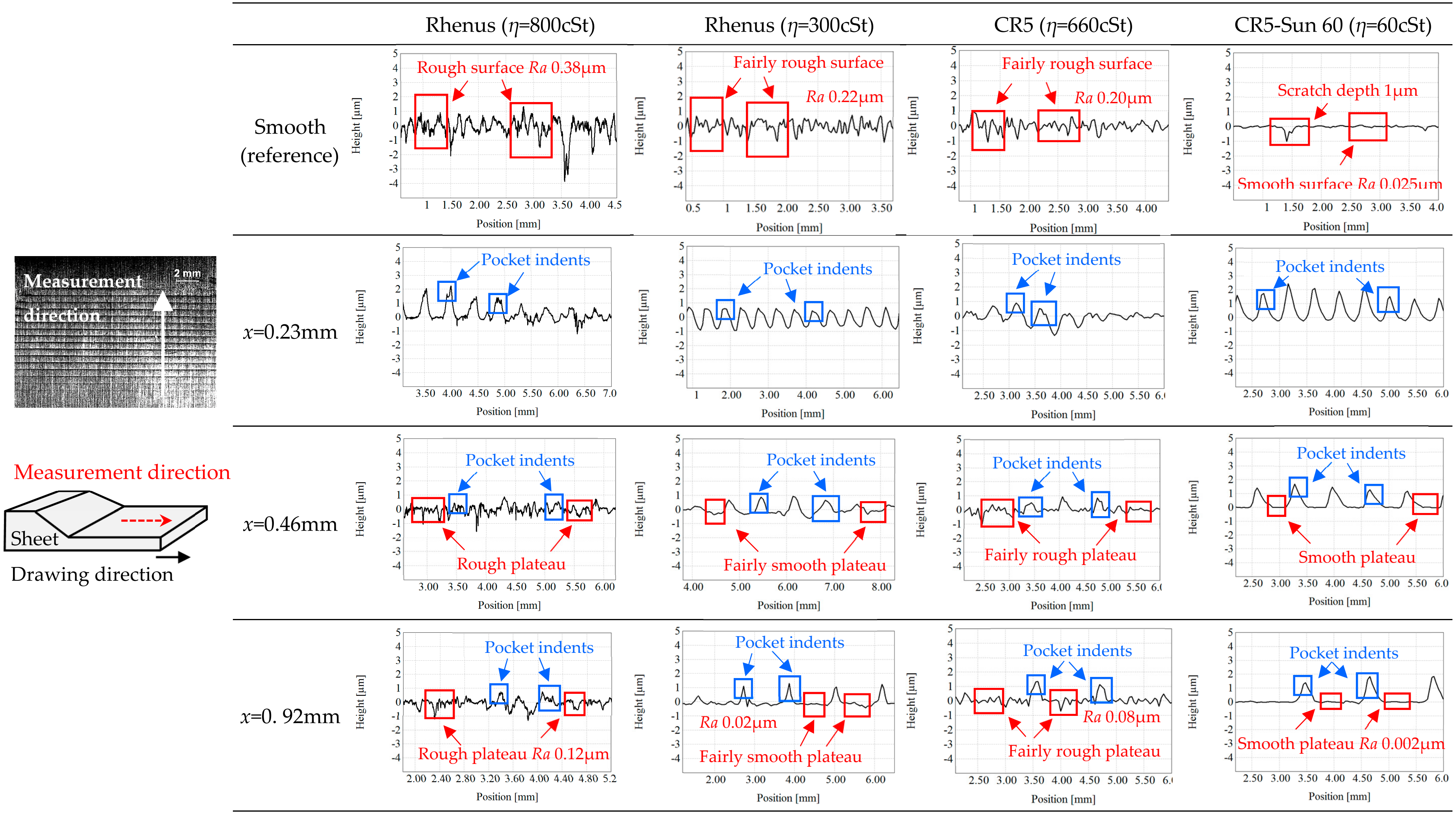

Figure 10. Roughness profiles of the sheets flowed into the pockets when testing with different tool textures and lubricants at speed v=240 mm/s.

Peer-reviewed version available at Lubricants 2017, 5, 3; doi:10.3390/lubricants5010003

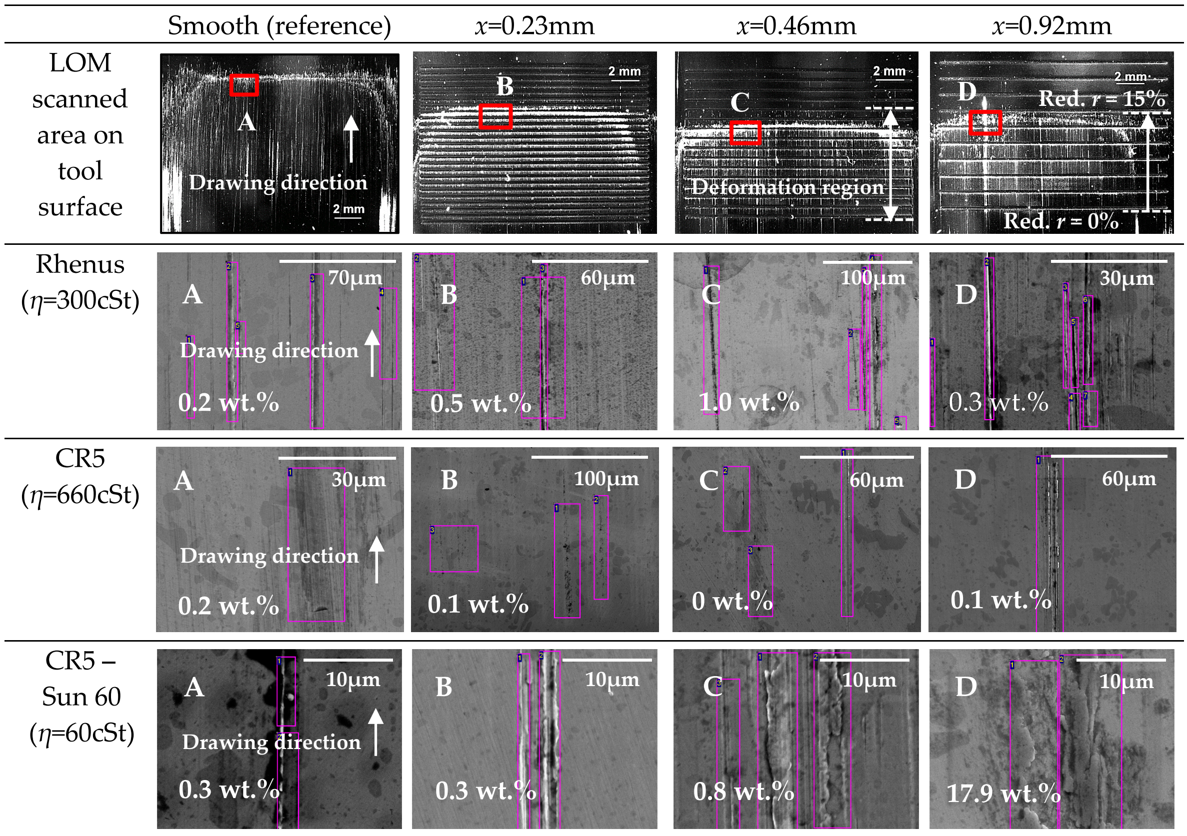

Figure 11. Pick-up occurred at the larger reduction region *r* of 15%, where the locations were marked with A, B, C and D.

mineral oil may support micro-hydrodynamic lubrication and the Rhenus oil furthermore has boundary lubricating properties. The slightly better performance of CR5 than the lower viscosity Rhenus oil supports the hypothesis of micro-hydrodynamic effects even further.

7. Conclusions

A technique to improve resistivity towards galling by applying textured tool surface topographies was investigated. Oblong, shallow pockets with small pocket angles, oriented perpendicular to the sliding direction with a distance of 1-4 times the pocket width were tested. The strip reduction test, which emulates the tribological conditions in an ironing process, was used for experimental measurements of friction and determination of possible pick-up and galling. The study included testing of four different lubricants, which were two plain mineral oils with a low and a high viscosity, and two mineral-based oils with boundary lubrication additives having medium and high viscosity respectively. The results confirmed that tool texture can lower friction and improve lubrication performance in comparison to that of a fine polished tool surface, when the pocket distance is 2-4 times the pocket width, which ensures a table mountain structure of the tool topography. The tool textures were advantageous at larger sliding speeds when using higher viscosity oils, which facilitates the escape of trapped lubricant by micro-plasto-hydrodynamic lubrication.

Acknowledgments: The work is supported by the Danish Council for Independent Research under grant no. DFF – 4005-00130. S.M. Hafis would like to thank the Universiti Malaysia Perlis and the Ministry of Education, Malaysia for providing sponsorship for his PhD study at Technical University of Denmark (DTU). The authors gratefully acknowledge the support from Ermanno Ceron from Grundfos A/S for providing the Rhenus oils. The authors are thankful for the support of the staffs and the facilities at DTU manufacturing laboratory and DTU tribology laboratory during the course of the research.

Author Contributions: S.M. Hafis conceived and designed the experiments under supervision of P. Christiansen and N. Bay; S.M. Hafis performed the experiments; S.M. Hafis analyzed the data and discussed the results with P. Christiansen and N. Bay; S.M. Hafis, P. Christiansen and N. Bay contributed with reagents/materials/analysis tools; S.M. Hafis wrote the paper; P. Christiansen and N. Bay revised the paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ibatan, T.; Uddin, M.S.; Chowdhury, M.A.K. Recent development on surface texturing in enhancing tribological performance of bearing sliders. *Surf. Coatings Technol.* 2015, *272*, 102–120, 10.1016/j.surfcoat.2015.04.017.
2. Vladescu, S.C.; Olver, A.V.; Pegg, I.G.; Reddyhoff, T. The effects of surface texture in reciprocating contacts - An experimental study. *Tribol. Int.* 2015, *82*, 28–42, 10.1016/j.triboint.2014.09.015.
3. Bruzzone, A.A.G.; Costa, H.L.; Lonardo, P.M.; Lucca, D.A. Advances in engineered surfaces for functional performance. *CIRP Ann. - Manuf. Technol.* 2008, *57*, 750-769, 10.1016/j.cirp.2008.09.003.
4. Geiger, M., Engel, U., Pfestorp, M. New developments for the qualification of technical surfaces in forming processes. *Annals of CIRP* 1997, *46*, 171-174, 10.1016/S0007-8506(07)60801-4.
5. Schmoeckel, D., Prier, M., Staeves, J., Topography deformation of sheet metal during the forming process and its influence on friction. *Annals of CIRP* 1997, 46, 175-178, 10.1016/S0007-8506(07)60802-6.
6. Kudo, H.; Azushima, A. Direct observation of contact behaviour to interpret the pressure dependence of the coefficient of friction in sheet metal forming. *Annals of CIRP* 1995, *1*, 209-212, 10.1016/S0007-8506(07)62309-9.
7. Bay, N.; Bech, J.I.; Andreasen, J.L.; Shimizu, I. Studies on micro plasto hydrodynamic lubrication in metal forming. In *Metal Forming Science and Practice: A State-of-the-Art Volume in Honour of Professor J.A. Schey's 80th Birthday*, 1st ed.; Lenard, J.G.; Elsevier, 2002; Chapter 7, pp. 115-134.
8. Kijima, H.; Bay, N. Contact conditions in skin-pass rolling. *Annals of CIRP* 2007, *1*, 301-306, 10.1016/j.cirp.2007.05.070.
9. Groche, P.; Stahlmann, J.; Hartel, J.; Köhler, M. Hydrodynamic effects of macroscopic deterministic surface structures in cold forging processes. *Tribol. Int.* 2009, *42*, 1173-1179, 10.1016/j.triboint.2009.03.019.
10. Lindvall, F.; Bergstrom, J.; Krakhmalev, P.; Bay, N. The effect of grinding and polishing procedure of tool steels in sheet metal forming, Tribol. Manuf. Proces. Volume 2: Proceedings of the 4th ICTMP 2010, Nice, France, 13th-15th June 2010; Felder, E., Montmitonnet, P.; Presses des MINES: Paris, France, 2010; 603-612.
11. Wiklund, D.; Liljebgren, M.; Berglund, J.; Bay, N.; Kjellsson, K.; Rosén, B.-G. Friction in sheet metal forming – A comparison between machined and manually polished die surfaces, Tribol. Manuf. Proces. Volume 2: Proceedings of the 4th ICTMP 2010, Nice, France, 13th-15th June 2010; Felder, E., Montmitonnet, P.; Presses des MINES: Paris, France, 2010; 613-612.
12. Eriksen, R.S.; Arentoft, M.; Grønbæk, J.; Bay, N. Manufacture of functional surfaces through combined application of tool manufacturing processes and Robot Assisted Polishing. *CIRP Ann. - Manuf. Technol.* 2012, *61*, 563-566, 10.1016/j.cirp.2012.03.020.
13. Godi, A.; Grønbæk, J.; Chiffre, L.De. Off-line testing of multifunctional surfaces for metal forming applications. *CIRP J. Manuf. Sci. Technol.* 2015, *11*, 28-35, 10.1016/j.cirpj.2015.06.001.
14. Popp, U.; Engel, U. Microtexturing of cold-forging tools - Influence on tool life. *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.* 2006, *220*, 27-33, 10.1243/095440505X32968.
15. Costa, H.L.; Hutchings, I.M. Effects of die surface patterning on lubrication in strip drawing. *J. Mater. Process. Technol.* 2009, *209*, 1175-1180, 10.1016/j.jmatprotec.2008.03.026.
16. Krux, R.; Homberg, W.; Kalveram, M.; Trompeter, M.; Kleiner, M.; Weinert, K. Die surface structures and hydrostatic pressure system for the material flow control in high-pressure sheet metal forming. *Adv. Mater. Res.* 2005, *6-8*, 385-392, 10.4028/www.scientific.net/AMR.6-8.385.
17. Franzen, V.; Witulski, J.; Brosius, A.; Trompeter, M.; Tekkaya, A.E. Textured surfaces for deep drawing tools by rolling. *Int. J. Mach. Tools Manuf.* 2010, *50*, 969-976, 10.1016/j.ijmachtools.2010.08.001.
18. Wagner, K.; Völkl, R.; Engel, U. Tool life enhancement in cold forging by locally optimized surfaces. *J. Mater. Process. Technol.* 2008, *201*, 2-8, 10.1016/j.jmatprotec.2007.11.152.
19. Podgornik, B.; Jerina, J. Surface topography effect on galling resistance of coated and uncoated tool steel. *Surf. Coatings Technol.* 2012, *206*, 2792-2800, 10.1016/j.surfcoat.2011.11.041.

20. Shimizu, I.; Martins, P.A.F.; Bay, N.; Andreasen, J.L.; Bech, J.I. Influences of lubricant pocket geometry and working conditions upon micro lubrication mechanisms in upsetting and strip drawing. *Int. J. Surf. Sci. Eng.* 2010, *4*, 42-54, http://dx.doi.org/10.1504/IJSURFSE.2010.029628.
21. Bech, J.; Bay, N.; Eriksen, M. A study of mechanisms of liquid lubrication in metal forming. *Annals of the CIRP* 1998, *47*, 221-226, 10.1016/S0007-8506(07)62822-4.
22. Bech, J.I.; Bay, N.; Eriksen, M. Entrapment and escape of liquid lubricant in metal forming. *Wear* 1999, *232,* 134-139, 10.1016/S0043-1648(99)00136-2.
23. Stachowiak, G.W.; Batchelor, A.W. *Engineering Tribology*, 3rd ed.; Butterworth-Heinemann Elsevier: Oxford, United Kingdom, 2014; pp. 1-852.