Eric FELDER, Pierre MONTMITONNET (Editors)

Tribology of Manufacturing Processes

Volume 2

Proceedings of the 4th International Conference on Tribology in Manufacturing Processes

(ICTMP 2010)

Nice, France, June 13th – 15th, 2010

FRICTION IN SHEET METAL FORMING - A COMPARISON BETWEEN MILLED AND MANUALLY POLISHED DIE SURFACES

D. WIKLUND[1], M. LILJENGREN[2], J. BERGLUND[3], N. BAY[4], K. KJELLSSON[5], B-G. ROSÉN[6]

[1]Swerea IVF,Argongatan 30, SE-431 53 Mölndal, Sweden
[2]Olofström School of Automotive StampingVällaregatan 30, SE-293 38, Olofström, Sweden
[3]Sandvik Tooling R & D Center, Olofström, Vällaregatan 30,29338 Olofström, Sweden
[4]Techn. University of Denmark, Dep. of Mech. Eng., Build. 425, DK-2800 Kgs. Lyngby, Denmark
[5]Manufacturing Engineering, Die Development, Volvo Car Corp., SE-293 80 Olofström, Sweden
[6]Halmstad University, School of Business and En.g, P.O. Box 823, SE-301 18 Halmstad, Sweden,

Abstract

The evolvement of product requirements in the automotive industry, e.g. reduced weight, means that the use of Advanced High Strength Steels (AHSS) in automotive applications is continuously increasing. The introduction of high strength steels in production implies increased tool wear and calls for functional tool surfaces that are durable in these severe tribological conditions. In this study the influence of tool surface topography on friction has been investigated. The frictional response was studied in a Bending Under Tension test. The results did show that a low frictional response was generated by low slope of roughness profiles combined with a strong anisotropy applied perpendicularly to the sliding direction. An improved machining strategy has a high potential to significantly reduce the need for manually polished surfaces.

Keywords: Sheet metal forming, Die surface topography, Finish milling, Friction model

1 INTRODUCTION

Higher product requirements such as reduced weight, increased safety and lower emissions mean that the use of Advanced High Strength Steels (AHSS) is continuously increasing. Reporting from Japan indicates that 16% of the total body-in-white weight is now made of AHSS [1]. The use of these materials has significantly increased the abrasive and adhesive tool wear in production. The challenge is to develop tool surfaces which are durable in these severe tribological conditions. Besides, there is a strive to reduce costs and lead times in die manufacturing as well. The aim is to machine functional tool surfaces and thereby eliminate the step of manual polishing.

Several studies have discussed the influence of tool surface topography on friction and galling in sheet metal forming. The approach of the studies has been theoretical [2-3] or experimental with the emphasis on dry [4-5] or lubricated contact [6-9]. The purpose of the present research work is to generate functional die surfaces by milling, and to study the frictional response of these in comparison to manually polished surfaces.

2 EXPERIMENTS

2.1 BENDING UNDER TENSION TEST

The BUT test represents mild tribological conditions with medium normal pressure, low sliding length and no surface expansion comparable to the conditions at the die radius in deep drawing [10]. Figure 1 shows the test design developed by Andreasen et al. [11]. The sheet strip is bent around a non-rotating tool-pin, while it is clamped in two claws. Pulling the strip with the front claw while breaking the back claw with a controlled force ensures sliding of the strip around the pin under controlled back tension. Front and back tension are delivered by hydraulic cylinders and measured by strain gauges mounted on the thin webs of the two tool frames. Placing the tool-pin in a holder mounted with needle bearings in the tool frames ensures minimum friction loss. Friction on the tool pin is measured directly by the piezoelectric torque transducer shown in Figure 1c. Applying this direct measurement technique instead of the normal friction determination by subtracting the back tension from the front tension force ensures very accurate results with low scatter [11].

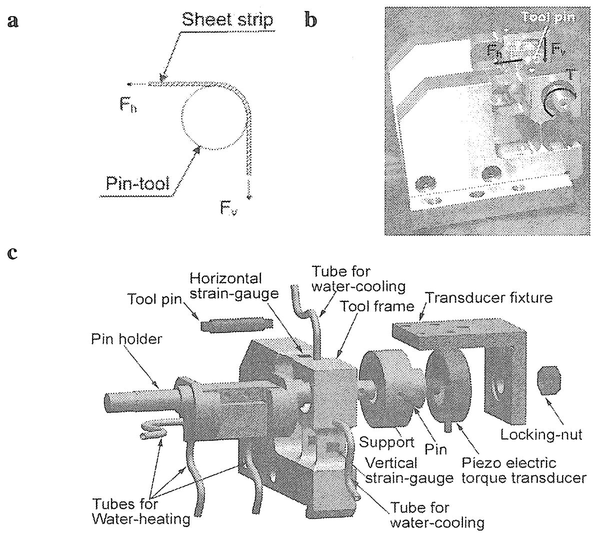


Figure 1: (a) Schematic outline of BUT test, (b) exploded view of the BUT equipment, (c) forces and torque acting on the tool-pin during testing

The lubricant was applied on the cleaned sheet material with a roller. The lubricant Ensis PQ144 is a mineral oil without additives and has a kinematic viscosity of 32 mm^2/s at 40°. The amount was measured and documented with a "Fuchs oil film thickness sensor". The applied amount was 0.85±0.1 g/m^2 (95% confidence level). The sliding speed in the test was 120 mm/s and the die mean contact pressure was 60 MPa.

2.2 MATERIALS

The tool material (Sleipner) used this investigation are frequently used within the automotive sector and is designed with universal properties to handle wear, chipping etc. in a cutting or forming operation. The tool material was produced and delivered by Uddeholm Tooling AB. The surfaces were laser hardened to 769±109 HV100.

The sheet material used in this investigation was a Docol 600 DP, t=1.2mm which is an Extra High Strength Steel (EHSS). The texture was Shot-Blasted and had a roughness of Sa=1.5 μm. The sheet material was produced and delivered by Swedish Steel (SSAB).

2.3 POLISHING OF TOOL SURFACES

A round ground surface was the delivery condition of the draw radii pins. The active working surface was manually polished with emery cloths to design a surface with a specific anisotropy and roughness. Manual polishing of the tools was performed with emery cloths 320, 800, 1200 and finally 1200 with oil to obtain low roughness. The procedure for high roughness was emery cloths 320, 600 and finally 600 with oil. The obtained surface roughness for the different surfaces is listed in Table 2. See Figure 2 for an example.

2.4 MILLING OF TOOL SURFACES

The surfaces m1 – m11 were machined using a 5 axis machining centre, a Hermle C40U Dynamic, with a Capto C5 spindle interface and a spindle capable of 24000 RPM. The surfaces were machined with ball-nose end mills using different strategies to produce different surface textures. Surfaces m1 – m6 were machined to have a lay perpendicular to the sliding direction using two different strategies and with different cutting data to produce slightly different surface textures. Surfaces m7 – m9 were machined using the same cutting data as with m2 but with different angles. Surfaces m10 and m11 were machined to have a lay along the sliding direction and to have different height of the texture. The obtained surface roughness for the different surfaces is listed in Table 2. See Figure 2 for some examples.

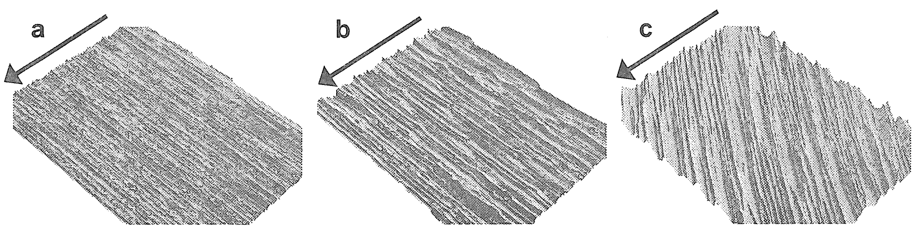


Figure 2: (a) Surface p4, polished surface with a lay perpendicular to the sliding direction. (b) Surface m1, machined surface with a lay perpendicular to the sliding direction (c) Surface m8, machined surface with a 35° angle. Arrows indicate sliding direction

3 MEASURING AND CALCULATION METHODS OF SURFACES

The tool surfaces were measured with a white light interferometer instrument, Wyko RST plus. The measured area was 0.58x0.43 mm with 10 times magnification. The utilized x- and y- sampling was 1.57x1.52 μm when calculating the surface parameters. Each surface was analysed and measured in three positions. The calculation was made by the software Mountainsmap Premium version 5.1.1.5450 from Digital Surf. The surfaces were filtered with a polynomial of order 2 and a Robust Gaussian filter with cut-off 0.08 mm.

3.1 MULTI-SCALE ROUGHNESS ANALYSIS

As a complement to the surface roughness analysis using traditional surface parameters the multi scale method, scale-sensitive fractal analysis and the parameter relative area, available in the software Sfrax, was used. Multi-scale surface analysis is based on the principle that the apparent area of a rough surface depends on the scale of observation. A complete account of scale-sensitive fractal analysis is given in the ASME standard [12] and illustrative demonstrations of the method are available in the literature [13, 14]. Relative area is calculated using a tiling algorithm where the topography of the surface measurement is modelled using triangular tiles. At each scale all tiles have the same area. The relative area at each scale is the calculated area at that scale divided by the nominal area. The calculated area at each scale is found by multiplying the number of tiles by the area of the tile at that scale. The area of the tile is also used to represent the scale [13]. Relative areas were calculated for all surfaces at 471 scales ranging from 1.2 μm^2 to 68285 μm^2. The relative areas for all surfaces were correlated with friction at each scale using linear regression.

Unfiltered surface data was used for the multi-scale analysis. The surface data was divided into two groups based on the difference in surface lay angle, 90 degrees (sliding along the lay) and 0 degrees (sliding perpendicular to the lay). The surfaces m7, m8 and m9 were excluded from this analysis.

4 MODELLING THE FRICTIONAL RESPONSE

In a previous study the influence of anisotropical surface textures on friction was investigated [9]. The result did show a linear increase of friction when sliding along the lay. Pure boundary condition was the present regime and friction was generated by tool surface asperities ploughing through the sheet material. This state is modelled by the first parenthesis in equation 1. Friction is thereby a linear correlation to the Rdq parameter [15], here represented by the RMS-slope in the sliding direction.

$$\mu = (\mu_0 + C_1 Rdq)\left(1 - C_2\left(1 - \frac{\alpha}{90}(1 - Str) - \frac{Str}{2}\right)\right) \tag{1}$$

However, the previous study did also show that a perpendicular lay reduced the friction. A perpendicular lay restrained the flow of lubricant in the sliding direction. A pressure was built up and the lubricant was partly carrying the load. The hydrodynamic influence is here modelled in the second parenthesis in Equation (1). The strength of the lay affects the ability to restrain the flow of lubricant and thereby the load carrying capacity [16].

This effect is modelled by the *Str*-parameter ("the texture-aspect ratio") [17, 18]. The *Str*-parameter approaches 0 when the strength is increasing and when the surface resembles an isotropic surface it approaches 1. Further, the angle of the lay is also expected to influence the leakage phenomena. The angle of lay (α), here represented by the first angle, is 0 degrees when the lay is perpendicular to sliding direction and 90 degrees when it is sliding along the lay. The model is exemplified in table 1.

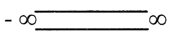
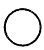
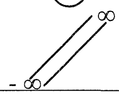
	Str	Angle α	Correction factor A	L/W	Correction factor B
	0	0	1	∞	1
	0.25	0	0.875	4	0.85
	0.25	90	0.125	0.25	0.07
	1	-	0.5	1	0.45
	0	45	0.5	∞	-

Table 1. Sliding direction is vertical in reference to the illustrations in the leftmost column. The expression (1-α/90(1-str)-str/2) is denoted as correction factor A in the table. The factor compensates for leakage effects in Equation 1 and is a function of the texture-aspect ratio (Str) and the angle (α) of lay. Frene [16] has calculated a correction factor for the load capacity of infinite pad bearings when leakage effects have to be considered. A mean value is here presented as correction factor B and is a function of the length (L) and Width (W) of the pad bearing.

5 RESULTS

Table 2 shows the results of the Bending-Under-Tension tests. In Figure 3 are the results from the friction model evaluated versus the experimental data. The boundary friction, μ_0 and the constant C_1, was evaluated by fitting a linear regression to the surfaces which have the lay in the sliding direction, i.e. an angle of 86-88 degrees. The constant C_2 was calculated from the results of m1, since it had a low angle and a strong anisotropy, and thereby hydrodynamic effects were expected. The results show that the frictional response for machined surfaces and manually polished surfaces can be described by the friction model except for the surface p3, encircled in Figure 3, which is a strong outlier. The correlation is significant at the 1 % level if the outlier is excluded (R^2=0.64).

Surface	Sq [µm]	Std Sq	Ssk [-]	Rdq [°]	Str [%]	Angle [°]	Friction [-]	Std Fric.
m1	0.32	0.009	-0.01	5.81	1.84	0.25	0.139	0.003
m2	0.33	0.017	0.09	5.30	3.90	0.19	0.133	0.001
m3	0.32	0.003	-0.35	6.01	5.12	0.31	0.136	0.004
m4	0.38	0.005	0.25	6.05	2.22	0.30	0.135	0.001
m5	0.49	0.014	-0.42	8.21	1.65	0.30	0.138	0.001
m6	0.40	0.007	0.38	6.29	2.22	0.21	0.143	0.000
m7	0.33	0.018	-0.03	5.79	4.71	15.42	0.138	0.002
m8	0.37	0.006	0.00	5.39	7.30	35.77	0.147	0.005
m9	0.40	0.020	0.09	4.86	6.29	49.99	0.154	0.002
m10	0.48	0.024	-1.57	6.50	9.88	88.41	0.161	0.003
m11	0.36	0.011	-0.59	4.56	12.59	86.20	0.137	0.001
p1	0.10	0.003	-0.45	0.84	4.22	88.82	0.132	0.002
p2	0.09	0.010	-0.55	2.94	3.03	7.15	0.124	0.002
p3	0.50	0.134	-1.62	10.21	5.42	12.35	0.124	0.006
p4	0.25	0.057	-0.57	8.03	1.41	0.32	0.138	0.002
p5	0.10	0.011	-0.59	4.23	6.62	0.93	0.127	0.001

Table 2. Surface parameters of the tools and the obtained frictional response in the Bending-Under-Tension test. The milled surfaces are numbered with 'm', the hand polished ones with 'p'.

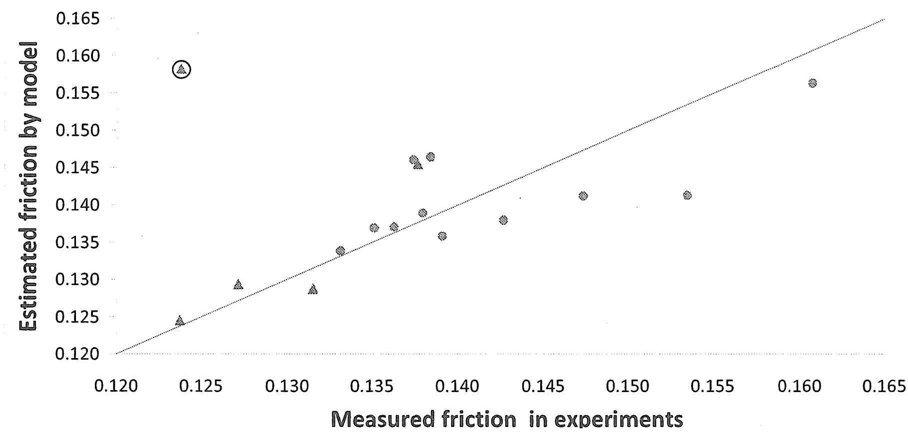


Figure 3. The measured frictional response from the Bending-Under-Tension test vs. the theoretical results of the friction model. The correlation is significant at the 1 % level if the outlier (encircled) is excluded (R^2=0.64). Triangular markers represent the hand polished tools, circular markers the milled tools.

5.1 CONSIDERING THE MULTI-SCALE ROUGHNESS ANALYSIS

The results from the scale-sensitive fractal analysis are presented in Figure 4 as correlation coefficients, R^2 values, on the y-axis and scale of observation on the x-axis.

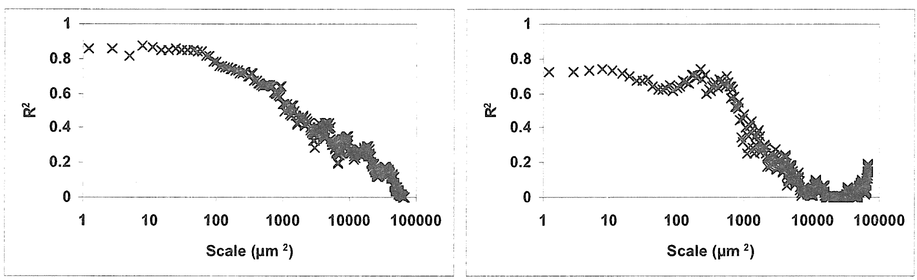


Figure 4. Correlation coefficients (R^2) for correlation between relative area and friction at 471 scales for the two groups: lay along sliding direction (left), lay perpendicular to sliding direction (right).

6 DISCUSSION

The results did show a significant correlation between the frictional response predicted by the model and the results obtained in the BUT-test. Only one surface diverges significantly from the model. This means, for low friction, it is beneficial to have a strong anisotropical surface lay applied perpendicular to the sliding direction and that a low slope of roughness profile in the sliding direction also reduce the friction.

Consequently, when lay is applied along the sliding direction the hydrodynamic effect is negligible. Pure boundary condition is the present regime and friction is generated by tool surface asperities ploughing through the sheet material. In this state, only a molecular film of the lubricant is separating the two mating surfaces, and the friction is increasing dramatically (linearly) with the slope of the asperities. This is very severe tribological conditions with a high risk of a breakdown of lubricant. A break down will quickly generate pick-up and galling implying deteriorated tool and work piece surfaces [9, 10]. However, when a hydrodynamic pressure is built up friction and the risk of galling is reduced [9]. The tool asperities are still causing elastic and plastic deformations in the sheet surface but the hydrodynamic effects of lubricant facilitate the separation of surfaces.

The observed importance of the roughness profile slope is in good agreement with studies on influence of pocket geometry on microhydrodynamic lubrication in surface structured blanks for sheet metal forming, [19, 20] and in surface structured tools for cold forging, [21].

Still, the friction model was not able to describe correctly the response of the manually polished surface p3. However, this surface has a divergent surface topography. Comparing the surfaces with a perpendicular lay p3 is the only one with a high negative skewness. The excursion of its distribution creates deep valleys. This could imply at least two effects which the relatively simple friction model (Equation 1) does not cover. Firstly, the deep valleys can introduce hydrodynamic effects which increase the load capacity of the lubricant and thereby reduce the friction [22]. Secondly, the high slope could possibly be derived from deeper parts of the surface which do not contribute to the deformation work. The latter effect could also have influenced the surface m10 since it has a strong skewness, but this surface fits quite well into the model. This argues for the hydrodynamic influence. Consequently it would be very interesting to apply the same surface topography as the m10 possess with a low angle of the anisotropy. These effects will be investigated in future research work.

The results of the multi-scale analysis show a higher correlation between relative area and friction when sliding along the lay than when sliding perpendicular to the lay. Also, considering the group of surfaces "0 deg" (sliding perpendicular to the lay) there is a peak in the R^2 coefficients at the scales around 220 μm^2. This area corresponds to a length of about 21 μm since triangular tiles are used in the analysis and $\sqrt{(2*220)} \approx 21$. This corresponds well to range of widths of the ridges and narrow dales produced by the polishing and machining processes. The results imply, in the case of sliding perpendicular to the lay, that the lubricant pressure is built up by features of this size.

The results show clearly that the machining strategy influence the frictional response, e.g. m10 has 21% higher friction values than m2. The importance is emphasized by comparing m10 with m5. Both surfaces have about 0.5 μm (Sq) roughness but still the frictional response is significantly lower for m5. Thereby the strategy for generating functional surfaces should not just focus on lowering the roughness only, the angle and strength of the anisotropy must be considered as well. The texture created by the machining process can be designed through careful selection of cutting tools and cutting data.

The results are also very interesting when comparing the machined with the manually polished surfaces. For example, the manually polished surface p5 has only 4.7% lower friction than the machined m2, but at the same time the roughness is markedly lower. The roughness (Sq) of p5 is about 0.1 μm and 0.3 for m2. However, the cost and lead time can increase considerably for large dies if the lower roughness is specified since the surfaces needs to be manually polished. These results indicate that an improved machining strategy has a very high potential for generating functional die surfaces and thereby to reduce or eliminate the manual work. Consequently, the cost and lead time would be reduced as well. Still, to really establish the functionality of the machined surfaces comparable wear tests needs to be performed in the future research work.

7 CONCLUSIONS

- The slope of roughness profile, strength and angle of anisotropy influenced the frictional response.
- Low frictional response was generated by low slope of roughness profile combined with strong anisotropy applied perpendicularly to the sliding direction.
- A friction model described the response for 15 out of 16 surfaces with a significant level of 1 % (R^2=0.64).
- For machined surfaces, the machining strategy clearly influenced the frictional response.
- An improved machining strategy has a high potential to significantly reduce the need for manually polished surfaces.

8 REFERENCES

[1] K. Mori personal communication with N. Bay (2009)

[2] S. Zhang et al., *"A finite element simulation of micro-mechanical frictional behaviour in metal forming"*, J. Mater. Process. Technol. 134 (2003) 81-91

[3] S.L. Wang, K.P. Rao, *"Upper-bound analysis of friction in metal forming"*, Int. J. Mech. Sci. 39 (1997) 201-209

[4] K. Osakada, R. Matsumoto, *"Fundamental study of dry metal forming with coated tools"*, CIRP Ann. 49 (2000) 161-164

[5] A. Maatta, P. Vuoristo, T. Mantyla, *"Friction and adhesion of stainless steel strip against tool steels in unlubricated sliding with high contact load"*, Tribol. Int. 34 (2001) 779-786

[6] E. van der Heide, D.J. Schipper, *"Galling initiation due to frictional heating"*, Wear 254 (2003) 1127-1133

[7] E. van der Heide, D.J. Schipper, *"On the frictional heating in single summit contacts: Towards failure at asperity level in lubricated systems"*, J. Tribol. 126 (2004) 275-280

[8] D. Wiklund, B.-G. Rosén, A. Wihlborg, *"A friction model evaluated with results from a bending-under-tension test"*, Tribol. Int. 42 (2009) 1448-1452

[9] D. Wiklund et al., *"Effects of tool die surface topography on friction and galling in sheet metal forming"*, Proc. of Int. 3rd Swedish Production Symposium, B.-G. Rosén (Ed.) The Swedish Production Academy, Göteborg, Sweden, 2-3 Dec. 2009, 178-183

[10] N. Bay, D.D. Olsson, J.L. Andreasen, *"Lubricant test methods for sheet metal forming"*, Tribol. Int. 41 (2008) 844–853

[11] J. Andreasen, D.D. Olsson, C. Chodnikiewicz, N. Bay, *"Bending Under Tension Test With Direct Friction Measurement"*, Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. 220 (2006) 73-80

[12] US National Standard ASME B46.1, *"Surface Texture (Surface Roughness, Waviness, and Lay)"*, The American Society of Mechanical Engineers, New York (2002)

[13] G.J. Cantor, C.A. Brown, *"Scale-based correlations of relative areas with fracture of chocolate"*, Wear 266 (2009) 609-612

[14] C.A. Brown, S. Siegmann, *"Fundamental scales of adhesion and area–scale fractal analysis"*, Int. J. Mach. Tool. Manu. 41 (2001) 1927–1933

[15] ISO 4287:1997, *"Geometrical Product Specifications (GPS) – Surface texture: Profile method – Terms, definitions and surface texture parameters"*, International Organization for Standardization (1997)

[16] J. Frene et al., *"Hydrodynamic lubrication; Bearings and Thrust bearings"*, Tribology Series 33, D. Dowson (Ed.) Elsevier Science, Amsterdam, New York (1997) p. 470

[17] ISO/DIS 25178-2. *"Geometrical product specifications (GPS) - Surface texture: Areal - Part 2: Terms, definitions and surface texture parameters"*, International Organization for Standardization

[18] N. Patir, H.S. Cheng, *"Average Flow Model for Determining Effects of Three-Dimenional Roughness on Partial Hydrodynamic Lubrication"*, J. Lubr. Technol. 100 (1978) 12-17

[19] C.G. Soerensen, J.L. Andreasen, J. Bech, N. Bay, U. Engel, T. Neudecker, *"A basic study of the influence of surface topography on mechanisms of liquid lubrication in metal forming"*, CIRP Ann. 48 (1999) 203-208

[20] K. Steinhoff, *"Neues zur Strukturierung von Feinblechoberflächen"*, Umformtechnik im Spannungsfeld zwischen Plastomechanik und Werkstofftechnik, K. Steinhoff, R. Kopp, (Eds.) Bad Harzburg, Germany 2008, 239-260 (In German)

[21] A. Otto, S. Weidel, U. Engel, M. Geiger, *"Laser in metal forming – benefits for tribology"*, Proc. 6th Int. Conf. The Coatings,. F.-W. Bach, K.-D. Bouzakis, B. Denkena, M. Geiger (Eds.) Hannover, Germany, 2007, 13-22

[22] B. Nilsson, *"Finite Element Procedures for Virtual Triboloy"*, PhD dissertation, Chalmers University of Technology (2009)