Dry Metal Forming Open Access Journal

Fast Manuscript Track

Edited by Frank Vollertsen
Available online at elib.suub.uni-bremen.de
www.drymetalforming.de

Dry Met. Forming OAJ FMT 1 (2015) 91–95
Received 25 September 2015; published 04 November 2015

Numerical Modelling of the Tribology of a Selective Oxidised 1.2379 Tool Steel Surface Developed for Dry Metal Forming

Amer Almohallami*[1], Deniz Yilkiran[1], Daniel Wulff [2], Sven Hübner[1], Milan Vucetic[1], Hans Jürgen Maier[2], Bernd-Arno Behrens[1]

[1]Institut für Umformtechnik und Umformmaschinen, Leibniz Universität Hannover, An der Universität 2, 30823 Garbsen, Germany
[2]Institut für Werkstoffkunde (Materials Science), Leibniz Universität Hannover, An der Universität 2, 30823 Garbsen, Germany

Abstract

An oxidative heat treatment of a hardened conventional tool steel surface (EU alloy grade 1.2379 X153CrMoV12) at controlled oxygen partial pressures and temperatures was carried out to condition the surface of a forming tool for deep drawing processes in order to minimise the wear on this tool without adding lubricants. By means of this method an oxide layer of α-Fe_2O_3 with advantageous tribological properties suitable for the aimed application was generated.
The subject of this paper is to numerically investigate the tribological behaviour of the created surface and to parameterise and validate a numerical model in order to predict the wear development on this surface in practice. To realise the intended investigation the approach of Sarkar, which is based on the wear model of Archard, was used in a finite-element-model of a strip-drawing experiment of a DP600+Z sheet metal strip on a wear-specimen of 1.2379 steel coated with α-Fe_2O_3. This model was validated with experimental continuous strip-drawing tests and shows good results. The mathematical approach was parameterised through experimental tests to determine the coating hardness using a Nanoindenter and the friction coefficient determined by strip-drawing tests with a strip of DP600+Z formed around a steel cylinder coated with the same α-Fe_2O_3 layer as generated on the wear-specimen.

Keywords: Strip drawing test, Friction, Wear modelling, Nanoindenter, Hardness

1 Introduction

The production of metallic components requires tool surfaces which meet special mechanical and other demands since the tribological properties of the boundary layer are decisive [1]. The most important tribological properties of a surface are frictional behavior and wear resistance. Wear and friction are among the most critical physical phenomena affecting the life of tools used in the mechanical forming industry. They are responsible for component damage and failures in machines and devices [2]. It is estimated that wear is responsible for direct losses of 7 % of the gross national product in the industrialised countries. In Germany alone, wear causes a total loss of about 35 billion euros per year [3, 4]. Thus, it is very important to reduce friction and wear between the moving tools, especially forming tools involved in a production process of metallic parts. In sheet metal forming, such as deep drawing, hardening the tools by heat treatments is a common procedure to protect these tools from high dynamic load changes as well as to support their resistance against wear. Besides that, the most convenient way to reduce friction and wear is to apply lubricants to the blank surfaces before the forming process. The use of suitable lubricants is essential to increase tool life and to avoid wear damages [4, 5].

However lubricants have their own disadvantages. They have to be removed from the blank after forming, which is being done by costly and polluting procedures. Moreover, the remaining oil particles affect the following joining or coating procedures negatively [6, 7].

In order to reduce production cost, shorten the process chain and avoid the disadvantages of lubricants without reducing product quality or tool life, a new technology was proposed at the Institute of Forming Technology and Machines in cooperation with the Institute of Materials Science in Hannover, Germany to develop a new friction-reducing tool coating [8]. This

*E-mail address of corresponding author: almohallami@ifum.uni-hannover.de

coating is based on metal-oxides generated from alloy elements of the tool steel itself.

By means of heat treatments an oxide layer of α-Fe_2O_3 was created on a hardened tool of the working steel (X153CrMoV12) under controlled atmospheres. Its tribological behaviour was analysed by a continuous strip drawing test to determine the friction as a function of the contact pressure. This paper presents a numerical model to investigate the tribological behaviour of this layer based on the approach of Archard [9]. Archard et al. [10] have studied the non-lubricated sliding wear between different material contact pairs. They found that the wear is proportional to the load and sliding distance and inverse to the material hardness. The following equation (1) shows Archard’s wear formula:

$$W = k \cdot \frac{F_N}{H} \cdot s \qquad (1)$$

In this formula W describes the wear volume, k the wear factor, F_N the normal contact force, H the hardness of the material and s the sliding distance. Archard’s wear equation has been continually used and extended by different research groups to quantify the wear rate between sliding surfaces in different processes [11-13]. Based on this equation a more complex approach describing the tribology of oxidised metal surfaces was proposed by Quinn et al. [14-18] taking into account oxidation activity factor, temperature and oxidation energy.

Sarkar (1980) suggested a modification of Archard’s equation to illustrate the effect of the friction coefficient μ on the wear calculation under unlubricated surface conditions [19]. His modification is shown in the following equation (2):

$$W = k \cdot \frac{F_N}{H} \cdot s \cdot (1 + 3\mu^2)^{0.5} \qquad (2)$$

This formula is used in this work to numerically investigate and anticipate the wear behaviour of the newly developed oxidised layer while continuously strip drawing a high-strength steel strip of DP600+Z.

2 Creating and characterising the wear model

A numerical model using the Abaqus CAE 6-13.1 software was created in order to simulate the strip drawing process of a high-strength steel blank over a wear-specimen made of tool working steel of EU alloy grade 1.2379 (X153CrMoV12). The following Fig. 1 illustrates the work bench.

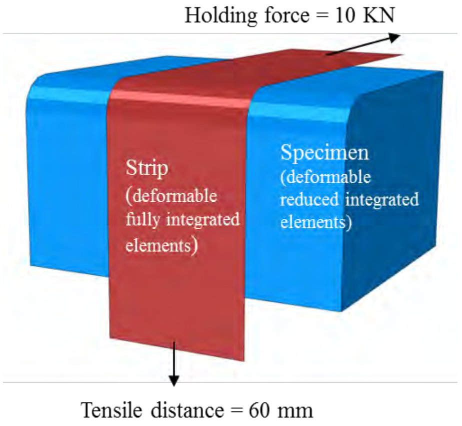

Fig. 1: Geometry of the wear-specimen and the strip for the wear tests

To model a deformable (elastic) wear-specimen, hexahedra solid elements were used. In order to minimise the simulation time and since no deformation is assumed to take place, a reduced integrated element’s formulation was employed. Contrary to this, the strip is formed around the corner of the wear-specimen and thus was modeled using deformable (elastoplastic) fully integrated quadrilateral shell elements with a thickness of 0.98 mm. With 5 integration points over the thickness of the shell elements the mechanical bending of the strip around the corner of the wear-specimen can be modeled. The numerical model simulates a continuous strip drawing test with a constant drawing velocity of 20 mm/s. The holding force was set to be constant and has a value of 10 KN during the drawing process. To assure a realistic representation of the experimental tests, a timetable was implemented in the FE system which realises an ascending holding force from 0 to 10 KN and a drawing velocity from 0 to 20 mm/s in 0.14 seconds. In order to characterise the plastic flow DP600+Z of the strip material, tensile tests were carried out with the quench and deformation dilatometer DIL 805 A/D + T of TA Instruments at 80°C which is assumed as the steady-state blank temperature during the forming procedure for the used high-strength steel. The flow curve was measured until uniform elongation was reached and then extrapolated using the approach of Hocket-Sherby to an equivalent plastic strain value of 0.5 which is presented in the following equation (3):

$$k_f = \mathrm{b} - (\mathrm{b} - \mathrm{a}) \cdot EXP(-m \cdot \varphi^n) \qquad (3)$$

with b = 0.752, a = 0.368, m = 7.64 and n = 0.709. The following diagram (Fig. 2) shows the measured flow curve of the strip material.

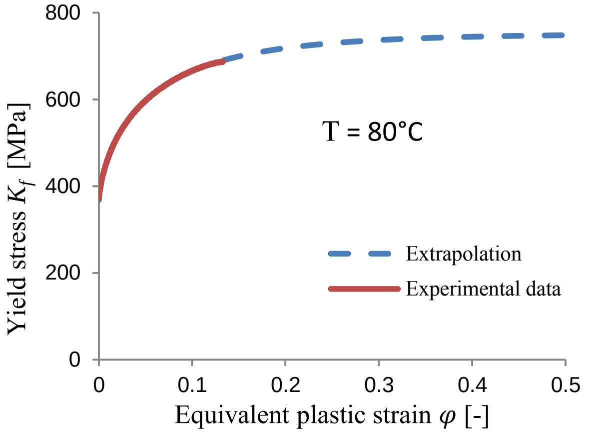

Fig. 2: Measured and extrapolated flow curves of the material DP600+Z

In order to determine a value for the friction coefficient between the sliding surfaces of the strip and the wear-specimen, experiments had to be carried out. The experiment bench is illustrated representatively in the following Fig. 3. Here cylindrical wear-specimens of 1.2379 (X153CrMoV12) covered with its oxidised layer (showed in Fig. 3) were used to determine the friction coefficient. In this case the contact partner was a tensioned high-strength steel strip of DP600+Z which slides around the wear-specimen, covering 90° of its surface. The test was carried out realising a drawing speed of 20 mm/s and an analytically calculated contact pressure of 10 MPa.

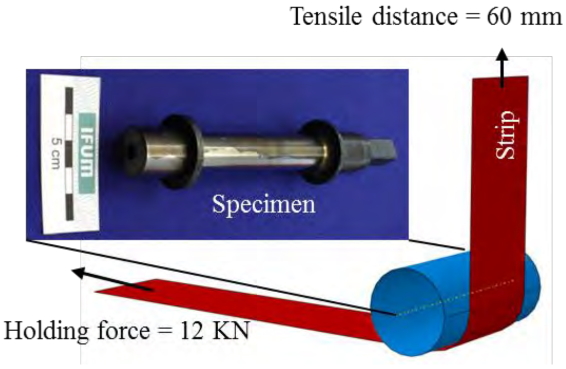

Fig. 3: Testing concept to determine the friction coefficient with cylindrical wear-specimens (strip drawing with redirection)

In order to simplify the model the friction coefficient μ has been constant over the entire simulation, but it would be considered as a function of the contact pressure in further investigations within this project.

The hardness of the oxidised α-Fe_2O_3 steel layer with a thickness between 100 and 300 nm was measured by using the nanomechanical testing system Triboindenter, TI 950 – Hysitron. The surfaces were tested using this system with its nano pins with a pressing force of 300 µN to avoid destroying the layer and to merely characterise it while preventing an affection by the mechanical properties of the basic material. Two types of pins were used in this analysis. The Berkovich pin and the ball pin and both delivered the same results.

Archard's wear factor k describes the wear rate and its relation to the number of forming cycles when Archard's approach is used for wear investigations on a forming tool. Many other factors affect the value of k such as the sliding direction, the roughness of the contact surfaces and their other mechanical properties. Due to this, it is very important to carry out the wear test cycles under reproducible constant conditions and to evaluate the material removal at defined time intervals in order to determine the factor k and its relation to the number of cycles. Our research group is still working on a way to measure the thickness of the extraordinarily thin oxidised steel layer at different time intervals. However, after 4000 cycles (stroke) it was determined that the oxidised layer on the surface of the basic tool no longer existed. Thus, it is estimated that the material removal amounts to 300 nm after 4000 cycles. This estimation is essential in defining the value of k.

In order to implement the common wear equation of Archard in the FE system, the wear volume change of an element at a certain time step $\Delta W_{(t)}$ is expressed by the following equation:

$$\Delta W_{(t)} = (1+3\mu^2)^{0.5} \cdot k \cdot \frac{F_{N(t)}}{H} \cdot v_{(t)} \qquad (4)$$

where $v_{(t)}$ is the sliding velocity and equals $\frac{\Delta s}{\Delta t}$ and $F_{N(t)}$ is the normal force at the time step t. The one-dimensional wear depth is more important than the wear volume for studying the layer thickness during a wear process. Thus, both equation terms are divided by the area of the element. Archard's equation now reads:

$$\Delta W_{(x,t)} = (1+3\mu^2)^{0.5} \cdot k \cdot \frac{P_{(x,t)}}{H} \cdot v_{(x,t)} \qquad (5)$$

where w_x is the wear depth in the x position and P_x is the normal contact pressure on the x position. To determine the numerical wear at the end of the strip drawing cycle the incremental wear should be accumulated over all time intervals of the numerical simulation with the following equation:

$$w_x = \frac{(1+3\mu^2)^{0.5} \cdot k}{H} \cdot \sum_{t=1}^{t=n} P_{(x,t)} \cdot v_{(x,t)} \qquad (6)$$

where n is the total number of time intervals at the end of the calculation. This formula (6) is integrated in the numerical simulation system of Abaqus with the help of the subroutine UVARM providing access to the calculated values of the incremental velocity and contact pressure at the end of each increment.

3 Results and Discussion

The strip drawing tests with redirection to determine the friction coefficient illustrated in figure 3 have shown that it is possible to reduce the friction coefficient between the used high-strength steel sheet DP600+Z and the wear-specimens with selective oxidised α-Fe_2O_3 surfaces. Within the scope of determining the friction coefficient µ in the strip drawing tests under a contact pressure of 10 MPa one wear-specimen coated with α-Fe_2O_3 (SD1) and two reference wear-specimens all made of hardened tool working steel of 1.2379 (X153CrMoV12) were investigated. The first reference without oxide layer was tested dry and without any lubrication (R1). The second reference was tested with the use of a lubricating mineral oil that is developed for deep drawing tasks (Wisura AK3080) (R2). The amount of the oil used in the experiments was 2 g/m². It can be seen in the diagram in figure 4 that the average friction coefficient (5 retries for statistical backup) of the wear-specimen SD1 shows better results than both references R1 and R2 with a value of µ = 0.15.

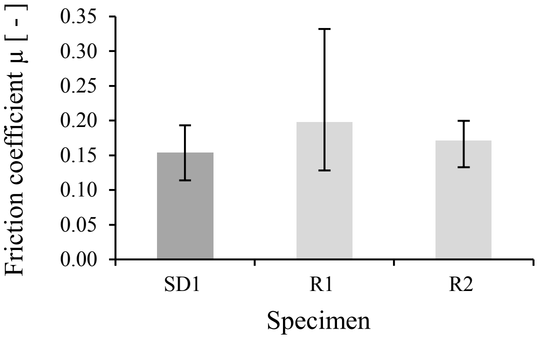

Fig. 4: Results of the strip drawing tests with deflection at a surface pressure of 10 MPa

Concerning the analysis of the surface hardness using the Triboindenter, the maximum penetration depth reached was 31 nm. The following figure 5 shows a test carried out on the very rough layer surface of α-Fe_2O_3 with the ball pin. The marked area of the post-test image illustrates the location of the pin imprint on the analysed surface. The accuracy of this imaging is within the range of a few nanometres. The mean measured hardness value is 5.6 ± 0.6 GPa. The analysed values were registered for the test, with a penetration depth of the nano pin between 10 and 30 nm, which equals 10 % of the layer thickness. This value is used to parameterise the wear approach used in the simulation.

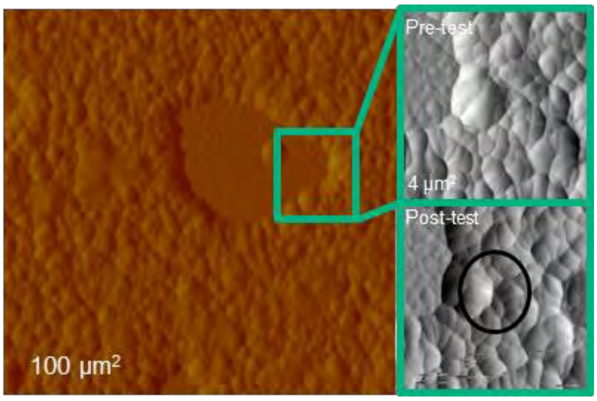

Fig. 5: Surface scanning using the Triboindenter for the analysed area illustrating the pin imprint after the hardness measurement.

The high error value for the measured hardness (± 0.6) was calculated based on a confidence interval of 90 % with a standard deviation of 1.7. This indicates a high scattering of the data, based on which the mean value was estimated. The following figure 6 shows a 0.64 mm^2 scanning of the surface which reveals different structures existing on this surface. The variation of the microstructures within this layer may explain the high deviation of the measured hardness.

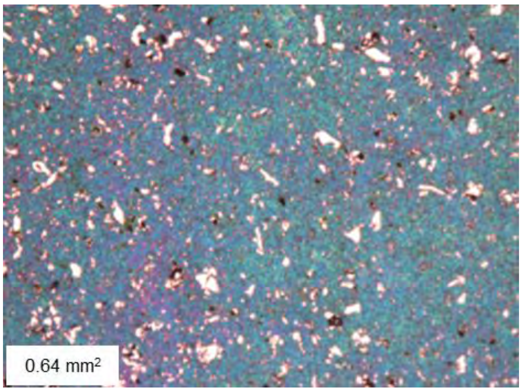

Fig. 6: Microstructure of the surface of the oxide-coating layer

To validate the mechanical behaviour of the virtual model the calculated tensile (drawing) force was compared with the measured force. The following diagram in figure 7 shows both, calculated and measured drawing forces and emphasizes the validity of the numerical model. The deviation is to be explained by the fact that the velocity could not be maintained perfectly constant during the experiment.

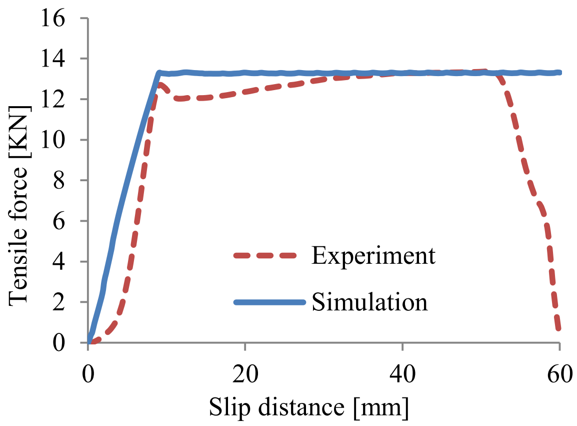

Fig. 7: Comparison between the measured and the calculated drawing force

Figure 8 depicts a comparison between the calculated and the tested wear-specimen illustrating the local wear on the surface after 4000 drawing cycles. Here a linear correlation was assumed between the depth of the wear and the number of the strip drawing cycles. Furthermore, a homogeneous coating layer thickness of 300 nm was considered for this numerical investigation. Based on this assumption a value of 5.3×10^{-3} was estimated for the friction coefficient k for the equation (6) with w in µm. The localisation of the calculated wear confirms the qualitative validity of the wear model and shows that the material removal occurred mostly at the bending surface. Here it has to be mentioned that the scale in figure 8 is logarithmically defined. Particularly noticeable is the high substance wear at both ends of this surface.

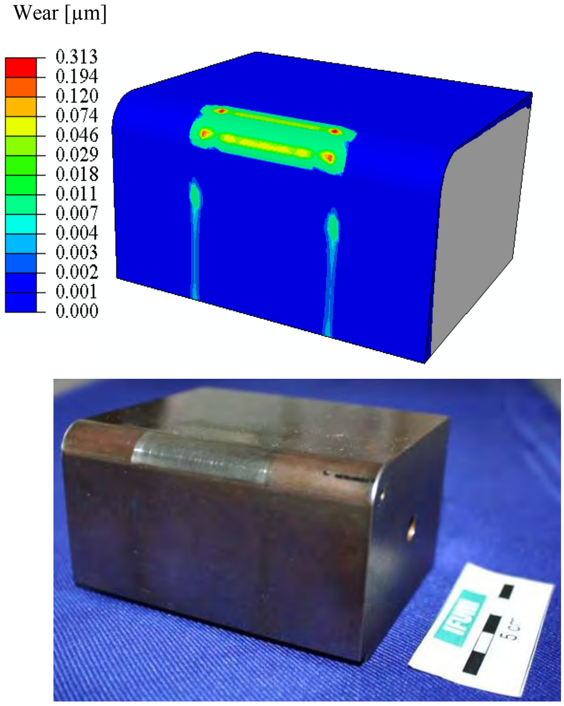

Fig. 8: Numerical investigation results of material removal at the wear-specimen

The numerical calculation of the contact pressure (figure 9) during the test between the strip (blank) and the wear-specimen explains the results of the wear calculation. The simulation shows high local pressure distributed over the curved (bending) surface. On both edges of this surface the strip presses the wear-specimen with a load up to 150 MPa while between the edges the pressing force reaches a maximum of 90 MPa.

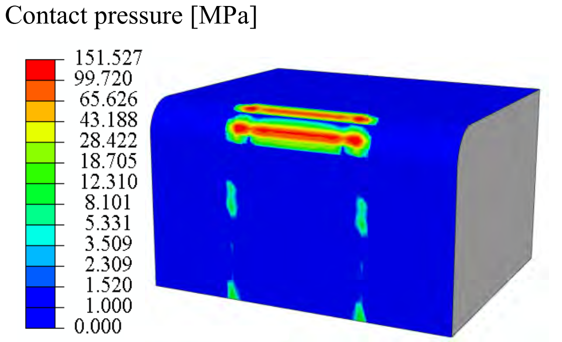

Fig. 9: Numerical calculation of the contact pressure between strip and wear-specimen

4 Conclusion and Outlook

Despite the simplified wear rate assumption the proposed numerical modelling of the wear test was successfully validated. This emphasises the compatibility and the relevance of using Archard's wear approach to investigate material removal in sheet metal forming processes. Furthermore, Archard's approach was experimentally parameterised and prepared to be used for wear estimations on the oxide layer of the steel (X153CrMoV12) in more complex forming processes.

The developed model will be optimised to take into account the influence of the contact pressure on the friction coefficient and thus on the wear results. In addition, previous investigations confirmed the increase in blank temperature during the forming process, which might affect the contact conditions and the friction coefficient. The model will be improved to estimate the rising temperatures during the strip-drawing process and implement these changes in contact conditions into the wear calculation. For this purpose the influence of the elevated temperatures on the friction will be experimentally determined.

The relationship between the oxide-layer wear rate and the strip-drawing cycles was assumed to be linear, which must be described more accurately. The research group is working on a way to analyse the thickness of the layer in respect to the drawing cycles. This would define a function to describe the changes in wear rate in accordance with the drawing cycles which will be implemented into the wear model. This would provide a more accurate prediction of the total material removal as a function of the forming cycles.

Acknowledgements

This work was financially supported by the DFG (reference numbers BE1690/170-1 and MA1175/41-1). In particular, the authors appreciate the support of the company Tata Steel Europe Limited and are grateful for the provision of the required sheet material.

References

[1] K. Sommer, R. Heinz, J. Schöfer: Verschleiß metallischer Werkstoffe, Viehweg + Teubner Verlag Wiesbaden (2010)
[2] V. Popov: Contact Mechanics and Friction: Pyhsical principles and applications. Springer Verlag Berling (2010)
[3] Gesellschaft für Tribologie: Online resource of the "Gesellschaft für Tribologie", www.gft-ev.de, (2015) last visit 24.01.15.
[4] H. Czichos, K.-H. Habig: Tribologie-Handbuch - Tribologie, Tribomaterialien, Tribotechnik, 3., überarbeitete und erweiterte Auflage, Viehweg + Teubner Verlag Wiesbaden (2010) 6.
[5] E. Doege, B.-A. Behrens: Handbuch Umformtechnik - Grundlagen, Technologien, Maschinen, Springer-Verlag Berlin Heidelberg (2007) 412-417, 808.
[6] S. Itasse: Umformen ohne Öl schützt die Umwelt, Vogel Business Media, maschinenmarkt.vogel.de, (2013).
[7] D. Schulz: Richtig angepasster Reinigungsprozess erhöht Qualität und Wirtschaftlichkeit, Vogel Business Media, maschinenmarkt.vogel.de, (2013).
[8] D. Wulff, D. Yilkiran, U. Holländer, D. Lützenkirchen-Hecht, R. Wagner, S. Hübner, K. Möhwald, H. J. Maier, B.-A. Behrens: Selective oxidation of 1.2379 tool steel surfaces – an approach for Dry Metal Forming, Dry Met. Forming OAJ FMT 1 (2015).
[9] J.F. Archard: Contact Rubbing of Flat Surfaces. J. appl. Phys. (1953) 8: 981-988
[10] J.F. Archard, W. Hirst: The Wear of Metals under Unlubricated Conditions. Proc Roy Soc (London) (1956), A: 236-397.
[11] F.S. Qureshi, A.K. Sheikh: A Probabilistic Characterization of Adhesive Wear in Metals. IEEE Transactions on Reliability (1997) 46: 38–44.
[12] X. Yin, K. Komvopoulos: An Adhesive Wear Model of Fractal Surfaces in Normal Contact, International Journal of Solids and Structures (2010) 47: 912–921
[13] H. Hoffmann, G. Nürnberg, K. Ersoy-Nürnberg, G. Herrmann: A New Approach to Determine the Wear Coefficient for Wear Prediction of Sheet Metal Forming Tools, Prod. Eng. Res. Devel. (2007) 1:357–363
[14] T.F.J. Quinn: Review of Oxidational Wear: Part I: The Origins of Oxidational Wear. Tribol Int (1983) 16: 257–71.
[15] T.F.J. Quinn, D. M. Rowson, J. L. Sullivan: Application of the Oxidational Theory of Mild Wear to the Sliding Wear of Low Alloy Steel. Wear (1980) 65: 1–20
[16] T.F.J. Quinn: Oxidational Wear Modelling: Part II. The General Theory of Oxidational Wear. Wear (1994) 175: 199–208.
[17] T.F.J. Quinn: Oxidational Wear Modelling Part III. The Effects of Speed and Elevated Temperatures. Wear (1998) 216: 262–75.
[18] T.F.J. Quinn The Oxidational Wear of Low Alloy Steels. Tribol Int (2002) 35: 691–715
]19[A. D. Sarkar: Friction and Wear Academic Press, London U.K. 1980