Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 58 (2017) 163 – 168

www.elsevier.com/locate/procedia

16th CIRP Conference on Modelling of Machining Operations

In-process measurement of the coefficient of friction on titanium

Linus Meier[a]*, Nikolas Schaal[a,b], Konrad Wegener[a]

[a]*Institute of Machine Tools and Manufacturing (IWF), ETH Zurich, Switzerland*
[b]*Oerlikon Surface Solutions AG, Balzers, Liechtenstein*

* Corresponding author. Tel.: +41 44 632 54 88; fax: +41 44 632 11 25. *E-mail address:* meier@iwf.mavt.ethz.ch

Abstract

The coefficient of friction between a freshly cut titanium surface and a coated tungsten carbide pin is measured in-process with a cutting tribometer to emulate the tribological conditions between a titanium chip and the cutting tool. The sliding speed and the normal force are varied over the large range which is prevailing in conventional cutting. Large deviations from the Amonton friction model are observed and a new model is proposed. The complex influence of the velocity in lubricated contacts under medium loads is studied with respect to the coefficient of friction. The results are compared to results from pin-on-disk tests and spiral pin-on-disk tests.

Keywords: Friction; cutting tribometer; Titanium

1. Introduction

Friction plays an important role in metal cutting. It is responsible for the chip compression and therefore for the cutting forces as well as generated heat which has in turn a strong influence on the tool wear. Different pressures and gliding speeds are acting on the rake and clearance face, causing frictional phenomena.

Classical methods how to quantify the coefficient of friction are based on pin-on-disk tests, where a pin is pressed against a rotating disk. This method has limits regarding gliding speed, normal force and temperature. Deviations from real cutting processes are further caused by oxidation of the material and by the closed tribosystem, always reintroducing the same contact points again into contact with the pin. With the increasing need to improve manufacturing, simulations of cutting processes are used. They demand for new methods to determine the coefficient of friction close to the cutting conditions. Light metals like titanium are especially prone to surface oxidation and thus friction cannot be measured simply with pin-on-disk tests.

Another approach is to use Merchants model [1] and its refinments to estimate the coefficient of friction from the cutting forces. However, only an overall coefficient of friction can be calculated, which does not reflect the diversity of tribological conditions which prevail between tool, chip and workpiece. Furthermore, the condition of the cutting edge has a large influence in those methods.

Various tribometers measuring the friction close to the cutting process under defined conditions are known from literature. Olsson [2], Zemzemi [3], Rech [4] Smolenicki [5], and Puls [6] integrate friction measurements on machine tools with high cutting speeds and high normal forces. In addition, Olsson, Zemzemi and Smolenicki [2,3,5] added a cutting process creating a fresh unoxidized surface. All publications are showing a drop of the coefficient of friction with rising cutting speeds. The normal forces employed in literature lie between 430 N and 5000 N, resulting in very high contact pressures far above the yield point of the material. This leads to a shearing of the material, but does not reflect all the conditions occurring on rake and clearance face. On the rake face, a chip is first plastically deformed until the contact pressure is gradually dropping. This work focusses on the conditions between tool and chip further away from the cutting edge, where the contact pressures is sufficiently low to allow the penetration of cutting fluids. Similar conditions

doi:10.1016/j.procir.2017.03.212

concerning plastic and elastic deformation occur on the clearance face between the tool and the machined surface as well [7].

Especially titanium is known to cause elastic deformation on the clearance face [8], leading to higher cutting forces and tool wear. Titanium is also known to cause segmented chip formation, has a high oxidation-affinity and leads to material adhesion. To simulate titanium cutting, friction data are required to achieve realistic results.

While the need of cooling lubricant in titanium cutting is well known in industry, cutting simulation is lacking data points for lubricated contact. Little is known about the influence of cooling lubricant on the coefficient of friction with high cutting speeds. Claudin [9] performed a first study on the influence of commercial cutting oil, proving its ability to lower the coefficient of friction even at high contact pressures in a pin-on-disk configuration.

This paper covers the influence of the normal force, respectively the contact pressure between the workpiece and the tool, on the coefficient of friction of titanium. A cutting tribometer combines a cutting process with industrially viable cutting speeds together with a friction measurement comprising a carbide pin. Additionally, effects of cooling fluid are displayed, proving a velocity-dependent reduction of the coefficient of friction.

2. Experimental Setup

2.1. In-Process Measurements

A new cutting tribometer has been designed according to the principle of Smolenicki et al. [5] (Figure 1A), which was in turn based on an original design from Olsson [2]. The components of the tribometers have been miniaturized and a high stiffness has been achieved. Thus, in contrast to the earlier cutting tribometers [3,5], a cylindrical billet with no need for preparation can be used as workpiece. Although the cutting tribometer is designed primarily for in-process measurements, pin-on-disk and spiral pin-on-disk measurements can be performed as well, mainly for the comparison with other tribometers.

The tribometer is designed for the use on a standard lathe and consists of a cutting tool, a pin which is pressed against the freshly cut surface by a preload mechanism, and a force sensor to measure the forces acting on the pin. The tool has an entering angle κ = 90° and is used in cylindrical turning to provide a flat surface for the pin to glide on. The distance between the cutting edge and the pin is set to 14 mm as a result of an engineering decision between a short time delay between cutting and the friction measurements and the stiffness of the assembly. Time delays are in the range from 8.4 ms at the highest speed to 84 ms at the lowest speed. Previous experiments [5] showed that those time delays do not lead to a significant oxidation which would change the tribological effects of the surface.

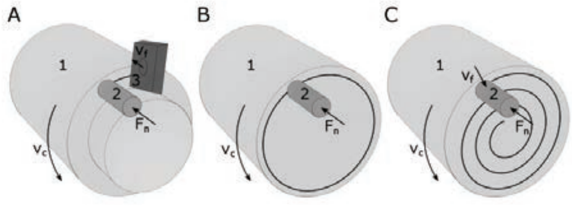

Figure 1. Schemes of the three tribometer setups used: (A) in-process measurement (B) pin-on-disk measurement and (C) spiral pin-on-disk measurement. (1) titanium workpiece, (2) coated carbide pin mounted on a 3D force sensor (not shown) and (3) cutting tool. The upcoming path of the contact point is shown.

The pin preloading mechanism assures a stiff guidance of the pin in the transversal directions and allows movement in the longitudinal direction. The preload force can be chosen from $F_n = 5\ N$ to $F_n = 400\ N$ and is applied by a coil spring. Assuming elastic deformations only and using the pin geometry given below, these forces lead to maximal contact pressures in the range between 1083 MPa and 4667 MPa according to the Hertzian theory. These pressures are in the range of the contact pressure predicted for titanium cutting by Bahi et al. [10].

A piezo-electric sensor measures the forces acting on the pin. The mass carried by the sensor is 56 g including the pin to enable highly dynamic measurements. The whole moving assembly has a mass of 380g which allows it to follow the surface contour with constant preload force even at low preload forces.

The pins have an outer diameter of 3 mm and a tip with a spherical diameter of 6mm. The base material is K40-UF, a tungsten carbide substrate with a grain size of 0.6 μm and a cobalt content of 10%. The tip is ground to a roughness $Ra = 0.4\ \mu m$ and coated with an AlTiN-based layer.

The workpiece material is Ti6Al4V, the alloy most frequently used in industry. It is used as billet with a diameter of 300 mm.

A copper tube delivers oil to the space behind the cutting tool and floods the pin. The oil used is ester-based, contains no additives and has a viscosity of 10.2 cSt.

All measurements take place on a NC-lathe with large slideways and thus a good damping. A depth of cut $a_p = 2.5\ mm$ is chosen to provide a track of sufficient width for the pin to glide on. The pin does not produce a measurable groove at the investigated light to medium preload forces. A small feed of $f = 0.05\ mm/rev$ proved to be sufficient to produce a uniform chip and remove the chemically altered surface. The new surface is strain hardened by the flank of the cutting tool which changes its properties closer to the heavily deformed chip to be emulated. A simplified two dimensional heat conduction simulation confirms that the heat generated by the cutting operation causes the surface temperature at the given offset of 14 mm to rise less than 5°C due to the rapid self-quenching effect even at the highest velocity of 100 m/min. The temperature at the interface between pin and workpiece is therefore predominantly determined by the local frictional heat. The gliding speed is ramped up from the lowest cutting speed to the highest and vice versa with the same pin. Preliminary tests confirm that the run-in behavior of the pins takes place in less than 1 s and therefore occurs before the in-process-measurements starts. Other preliminary tests confirm that the pin wear during one of the tests presented below is negligible.

2.2. Pin-on-Disk

Pin-on-disk measurements are well established tests in the field of tribology research. They make use of a closed tribosystem, bringing the same workpiece surface in contact with the pin over and over, leading to a feedback loop from the pin to the alteration of the surface and back to friction measurement over one revolution. Pin-on-disk measurements are performed with the newly developed cutting tribometer as well, but with cutting deactivated (Figure 2B). Prior to the tests, a planar surface is machined with a depth of cut $a_p = 0.1\,mm$, a feed $f = 0.2\,mm/rev$, a corner radius $R = 1.2\,mm$ and a cutting speed $v_c = 100\,m/min$. The surface is then cleaned from cutting fluid residues with acetone. Each test takes place on an unused region of the planar face, lying in the region between 290 mm and 270 mm in diameter.

2.3. Spiral Pin-on-Disk

The configuration of the tribometer for the spiral pin-on-disk measurements is the same as in the conventional pin-on-disk tests. The surface is prepared in the same way as well. The pin is sliding across the surface on an Archimedean spiral (Figure 2C). The width of the contact zone is 0.6 mm, which is derived from microscopic images of used pins. A spiral pitch of 1 mm therefore guarantees that the pin glides on an oxidized but unused surface. Special attention has to be paid to surface contaminants, e.g. sources of oil mist. As one test uses a range from 290 mm to 140 mm in diameter, a large surface area is covered by the glide track, increasing the potential for deviations through contaminants. The gliding speed is kept constant in correlation to the gliding radius by the machine control.

2.4. Data Processing

The force signal in longitudinal direction F_z is corrected for temperature drift influences. Together with the two other force signals in in the plane of cutting F_x and F_y, the apparent coefficient of friction is calculated:

$$\mu(t) = \frac{\sqrt{F_x(t)^2 + F_y(t)^2}}{F_z(t)} \quad (1)$$

The coefficient of friction is then averaged over time for one experiment.

3. Results

3.1. Variation of the Normal Force

The coefficient of friction is measured with the cutting tribometer. The normal force is varied between $F_n = 5\,N$ and $F_n = 400\,N$. A cutting speed $v_c = 60 m/min$ is chosen, resulting in the same gliding speed for the pin. This experiment is valid for the tool-chip interaction in conventional cutting at slightly higher speeds, as the chip speed is always lowered by chip compression. The test is performed three times at each normal force (Figure 2).

Even at the lowest normal force $F_n = 5\,N$, a titanium built-up layer forms on the pin before the first data samples are acquired. As the contact area at lower normal forces is smaller as well, the geometry of the built-up material has a higher relative influence, leading to a bigger variance in the coefficient of friction at low normal forces.

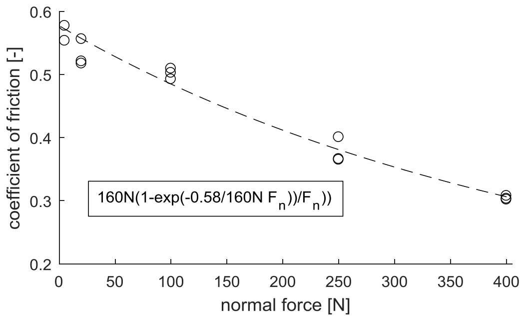

Figure 2. Coefficient of friction in relation to the normal force at 60 m/min, measured with the cutting tribometer

Amonton's law is often used in simulations and predicts a coefficient of friction that is independent of the normal force. This holds true, as long as the real contact area is much smaller than the apparent contact area. However, in this case, contact stresses lead to plastic deformation of the titanium workpiece. The shear force may only increase to the point of the shear yield force, therefore leading to a decrease in coefficient of friction at higher normal forces. This behavior may be described by a simple saturation function for the tangential force F_{tan} as function of the normal force F_n as it has been similarly proposed by Levanov [11]:

$$F_{tan}(F_n) = F_{max} \cdot (1 - exp(-\mu_0/F_{max} \cdot F_n)) \quad (2)$$

with F_{max} as the maximum tangential force and μ_0 as the coefficient of friction at low normal forces. Using the definition of the coefficient of friction, the following relation is retrieved:

$$\mu(F_n) = F_{max} \cdot (1 - exp(-\mu_0/F_{max} \cdot F_n))/F_n \quad (3)$$

In this case, $F_{max} = 160\,N$ and $\mu_0 = 0.58$ are obtained least-squares fit for a speed of 60 m/min (Figure 2).

3.2. Use of Lubricant

The normal force is set to $F_n = 100\ N$ in order to represent the tool-chip-interface und the rake face apart from the extreme pressure region at the cutting edge. The speed is stepped up from 10 m/min to 100 m/min in steps of 10 m/min and the coefficient of friction is measured with the cutting tribometer. The tests are performed five times with ascending speeds and four times with descending speeds. As a reference, measurements with a preload force of $F_n = 400\ N$ were performed at 20 m/min, 60 m/min and 100 m/min.

Ascending speeds and descending speeds do not show systematic differences in the coefficient of friction, proofing that pin wear has a negligible influence.

The coefficient of friction slightly increases with higher velocities in dry tests at medium preload forces of $F_n = 100\ N$ as shown in Figure 3. This may be attributed to higher shear forces at higher relative speeds and a stronger adhesion between the built-up layer and workpiece material at higher local temperatures. A negative slope of the coefficient of friction as function of speed as shown for high loads in [3,4,5], can be observed with the presented tribometer as well at higher loads, e.g. at $F_n = 400\ N$, when workpiece material deformation plays a significant role and temperatures rise enough to soften the titanium (Figure 3).

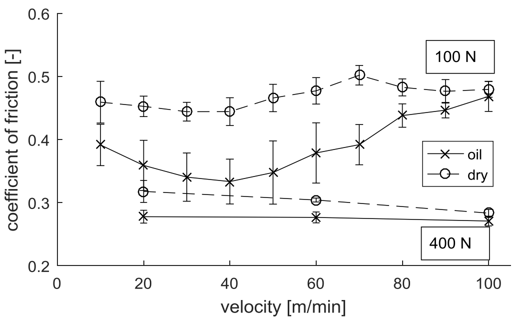

Figure 3. Coefficient of friction in relation to the gliding speed, measured with the cutting tribometer

In tests with a lubricated pin, the coefficient of friction is decreasing with increasing velocity in a range from 10 m/min to 40 m/min, before increasing again and nearly reaching the level of the dry tests. Ester oil is well known as a friction modifier, possibly building an adsorption layer on workpiece and pin at medium velocities. The effect of the adsorption layer is outweighed at the highest velocities by the increased adhesion strength at raised temperatures. The bigger variation in the measured coefficient of friction in lubricated tests is to some extent governed by the stochastic geometry of the built-up, leading to different lubrication conditions. The region of mixed lubrication is not yet left at 100 m/min, as can be derived from the observation of a built-up layer forming at this speed.

3.3. Pin-on-Disk

The normal force is set to $F_n = 100\ N$ as well and tests at 20 m/min, 60 m/min and 100 m/min are performed. A built-up layer is formed in a similar manner than in the in-process measurements. After three to five revolutions, the built-up layer adheres to the surface, leaving a hardened bump of titanium on the workpiece surface. With each subsequent revolution, the built-up layer is scraped from the pin at this position, causing a periodic change in the coefficient of friction (Figure 4).

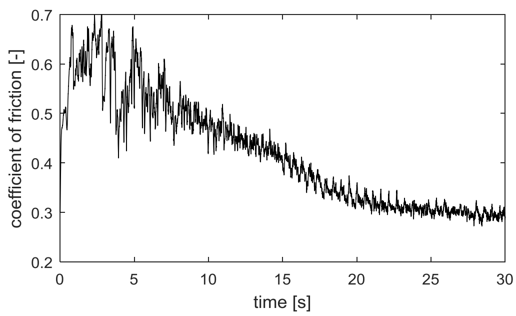

Figure 4. Raw signal of a dry measurement in pin-on-disk configuration at 100 m/min.

The mean coefficient of friction is not constant but slowly decreasing with time. The surface of the track is continuously getting rougher, eventually causing the pin to vibrate and intermittently leave the surface. This behavior is not comparable with the interaction between tool and chip. Therefore, the coefficient of friction is measured before bump formation.

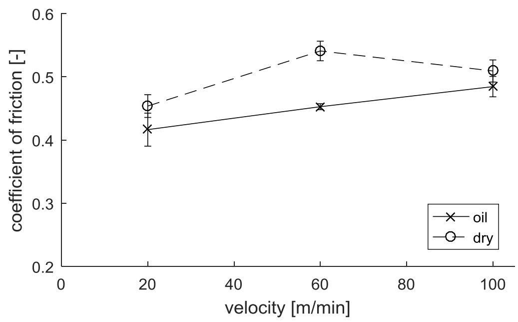

Figure 5. Coefficient of friction in pin-on-disk configuration

The mean coefficient of friction from dry pin-on-disk tests is slightly above the coefficient of friction measured in-process with the cutting tribometer. This may be attributed to the partial reveal of fresh, strain hardened workpiece material without an oxygen layer after the first revolution.

3.4. Spiral Pin-on-Disk

The normal force is set to $F_n = 100\ N$ and tests at 20 m/min, 60 m/min and 100 m/min are performed. There is a low tendency of vibrations of the pin and the run of the coefficient of friction is very smooth, leading to a low variance in the measurements. The pin is mainly gliding on the oxide layer, which has weaker adhesive forces than bare titanium. The built-up layer is significantly smaller than in in-process measurements with the cutting tribometer or missing completely.

The coefficient of friction is lower than in in-process measurements, especially at higher speeds, where the adhesion strength is increasing otherwise through a rise in temperature. The influence of lubrication is not significant.

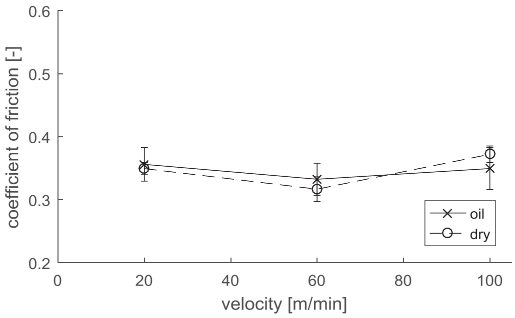

Figure 6. Coefficient of friction in spiral pin on-disk configuration

3.5. Friction Mode

All tests except for some spiral pin-on-disk tests exhibit a built-up layer of titanium on the pin, indicating the presence of shear friction. Roughing cutting tests with coated carbide inserts, at a cutting speed of 50 m/min, show a distinct crater wear with a nearly complete built-up layer of titanium (Figure 7), indicating a similar friction mode in cutting processes.

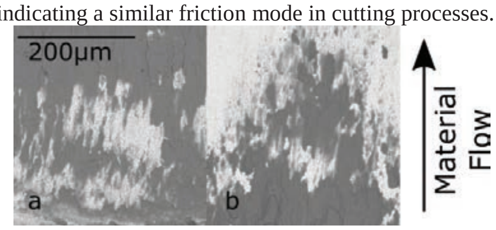

Figure 7. Backscattered electron close up image of crater wear on a cutting tool (a) and a pin after a dry test (b). Titanium shows as dark grey, tungsten carbide as light grey

4. Conclusions

The coefficient of friction measured with conventional tribometers is reported to be 0.55 for dry titanium on titanium [12] and 0.17-0.6 for lubricated contact between titanium and steel [13]. The coefficients of friction presented in this work are all lower than 0.55, as medium instead of low contact forces, as in literature, were investigated. The coefficient of friction between coated carbide and titanium is not a constant. The biggest influence is the contact pressure, followed by the speed and lubrication. In a lubricated contact at medium contact forces, the coefficient of friction exhibits a complex dependence on the velocity, strongly influenced by the chemical properties of the cutting fluid. Furthermore, the coefficient of friction strongly depends on the method used for measuring. Three methods are compared:

Pin-on-disk measurements are well established but are found not to reach a steady-state value at high speeds and high normal forces. They use a closed tribosystem, which is not comparable to the situation in metal cutting.

Spiral pin-on-disk measurements are very reproducible and proven for steels, but require time to prepare a large defined surface. They are prone to surface contaminations. In fast oxidizing metals such as titanium, the results at low to medium contact forces are strongly influenced by the oxide layer.

The in-process measurement requires the biggest effort in terms of cutting tribometer design. In terms of the measured coefficient of friction, similar results are obtained in dry in-process measurements and in dry pin-on-disk tests (Figure 8), with the values measured in-process being slightly lower than the values from pin-on-disk tests.

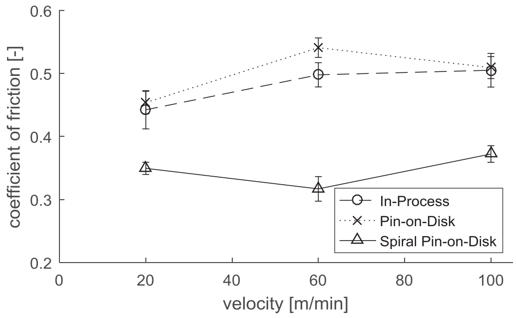

Figure 8. Comparison of the coefficient of friction measured dry with different methods

However, in case of a lubricated contact, all three methods show different results (Figure 9), with the values measured in-process again lying between the two other methods.

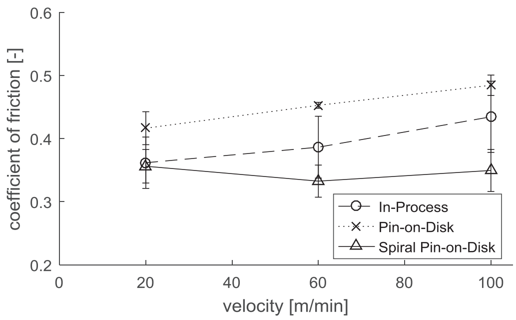

Figure 9. Comparison of the coefficient of friction measured lubricated with oil with different methods

In-process measurements are not prone to surface contamination and tests do not require preparation of the workpiece. Data processing can be easily automated. Most importantly, the results do represent the conditions between a cutting tool and the workpiece. A similar built-up layer in the tribometer tests as in cutting tests indicates the usability of the cutting tribometer measurement for simulation, coating and cutting fluid tests and wear predictions.

Acknowledgements

The authors thank the Commission for Technology and Innovation (CTI) of Switzerland for promoting this research and the companies Blaser Swisslube and Oerlikon Balzers for the support.

References

[1] M.E. Merchant, Mechanics of the metal cutting process. I. Orthogonal cutting and a type 2 chip, 1945, Journal of Applied Physics, 16/5:267-275
[2] M. Olsson, S. Söderberg, S. Jacobson, S. Hogmark, Simulation of cutting tool wear by a modified pin-on-disc test, International Journal of Machine Tools and Manufacture, 1989, 29/3:377-390
[3] F. Zemzemi, J. Rech, W. Ben Salem, A. Dogui, P. Kapsa, Identification of a friction model at tool/chip/workpiece interfaces in dry machining of AISI4142 treated steels, Journal of Materials Processing Technology, 2009, 209/8:3978-3990
[4] J. Rech, P.J. Arrazola, C. Claudin, C. Courbon, F. Pusavec, J. Kopac, Characterisation of friction and heat partition coefficients at the tool-work material interface in cutting, 2013, CIRP Annals - Manufacturing Technology, 62/1:79-82
[5] D. Smolenicki, J. Boos, F. Kuster, H. Roelofs, C.F. Wyen, In-process measurement of friction coefficient in orthogonal cutting, 2014, CIRP Annals - Manufacturing Technology, 63/1:97-100
[6] H. Puls, F. Klocke, D. Lung, Experimental investigation on friction under metal cutting conditions, 2014, Wear, 310/1–2:63-71
[7] R. Neugebauer, K.-D. Bouzakis, B. Denkena, F. Klocke, A. Sterzing, A.E. Tekkaya, R. Wertheim, Velocity effects in metal forming and machining processes, 2011, CIRP Annals - Manufacturing Technology, 60/2:627-650
[8] N. Schaal, F. Kuster, K. Wegener, Springback in Metal Cutting with High Cutting Speeds, 2015, Procedia CIRP, 31:24-28
[9] C. Claudin, A. Mondelin, J. Rech, G. Fromentin, Effects of a straight oil on friction at the tool–workmaterial interface in machining, 2010, International Journal of Machine Tools and Manufacture, 50/8:681-688
[10] S. Bahi, M. Nouari, A. Moufki, M. El Mansori, A. Molinari, A new friction law for sticking and sliding contacts in machining, 2011, Tribology International, 44/7–8:764-771
[11] A.N Levanov, Improvement of metal forming processes by means of useful effects of plastic friction, 1997, Journal of Materials Processing Technology, 72/2:314-316
[12] E. Rabinowicz, ASLE Trans., 1971, 14:198
[13] H. Tian , N. Saka, N.P. Suh, Boundary Lubrication Studies on Undulated Titanium Surfaces, 1989, Tribology Transactions, 32:3:289-296