

Theoretical Aspects of Tool and Surface Contact Friction during Metal Cutting

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Abstract – The modern terms of production dictate a necessity to produce details not only quickly, exactly and of high-quality, but also at minimum expenses. A thorough theoretical study of tool - surface contact friction is needed for this purpose. The following theoretical aspects of contact friction are considered in this article: tool - surface contact tribology characteristics, geometry of tools, influence of workpiece diameter, carrying ability of tool - surface tribological contact, part surface topology, and surface typology. These theoretical aspects create a base for understanding of the tool - surface system contact friction mechanism, and also enable to optimize this tribological process.

Keywords – tribological characteristics, surfaces topology, typology charts

I. INTRODUCTION

The tool - surface of the workpiece interface is the contact area that directly participates in the metal cutting process. Considerably different functions of the tool – surface interface in this process define the differences in the tribological processes occurring at this interface. Although there are a number of differences, there are also a number of similarities in the tribology of this interface such as high contact pressures and temperatures, contact with freshly formed (juvenile) counter-surfaces and high sliding velocities. There is also a correlation between the stresses at this interface as it is related to the same state of stress in the deformation zone.

The main objective of this article is to discuss the tribological conditions of the contact at the tool – surface of the workpiece interface. The understanding of these conditions and the proper utilization of this understanding in the design of the cutting process should result in the increased efficiency of the cutting system and in the reduction of tool wear. These results can be used in the meaningful selection of the machining regime, tool geometry and tool materials [1].

II. TOOL – SURFACE TRIBOLOGICAL CHARACTERISTICS

According to a generally accepted hypothesis, the contact between the tool flank and the workpiece machined surface occurs due to the elastic recovery (or spring back) caused by plastic deformation of this surface in cutting. Fig. 1 (a) shows an idealized case where the cutting tool is perfectly sharp as commonly assumed in the most known modeling of the metal cutting process. The radial cutting force F_T

causes the plastic deformation of the machined surface which, after the cutting edge passes over this surface, recovers by δ_1 causing the contact with the tool flank up to point A. The elastic recovery, therefore, should be proportional to this radial cutting force, which, in turn, depends to a large extent on the uncut chip thickness t_1 . The cutting edge of any real tool, however, is not perfectly sharp so a much real contact picture is shown in Fig. 1 (b). In this figure, the cutting edge radius forms the transition curve BD between the rake and the flank surfaces. This makes the position of point C uncertain, where the chip separates from the workpiece. The wear land DE is also present in any real cutting tool or, at least, it forms in the first few seconds of machining. Part EF represents the flank–workpiece contact surface. If the radius of the cutting edge is small, the normal F_{fN} and the friction F_{fF} forces acting on the flank are results of the interactions between the wear land DE and the machined surface of the workpiece [1].

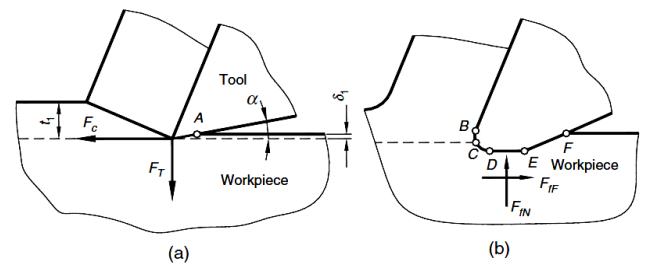


Fig. 1. Contact of the tool flank with the workpiece: (a) ideally sharp tool as assumed in modeling and (b) real contact with the tool–workpiece interface [1].

The basic tribological characteristics of the tool–surface of the workpiece interface are [1]:

- The sliding velocity which is normally equal to the cutting speed. In some special tools, where the feed velocity(ies) is significant, the magnitude of this velocity is equal to the magnitude of the resultant velocity of a considered point of the cutting edge.
- The contact length – the margin and then, after some time of cutting, the margin and flank wear length of the tool–chip contact, h_f .
- The friction force, F_{fF} .
- The specific frictional force which is the mean shear stress

$$\tau_{c-f} = \frac{F_{fF}}{h_f l_{ce-a}} \quad (1)$$

where l_{ce-a} is the active length of the cutting edge.

$$\text{Normally, } l_{ce-a} = \frac{d_w}{\sin k_r}$$

- The normal force at the tool–surface interface, F_{fN} .
- Mean contact stress at the tool–surface interface

$$\sigma_{c-f} = \frac{F_{fN}}{h_f l_{ce-a}} \quad (2)$$

- Mean contact temperature at the tool–surface interface, θ_{fl-av} .

III. TOOL GEOMETRY

The uncut chip thickness is an important parameter in metal cutting and it directly correlates with tool geometry. The influence of the tool nose radius on the uncut chip thickness and the shape of the uncut chip are correlated with this radius and other geometrical parameters of the cutting tool. The shape, mean uncut chip thickness and width as well as the cutting temperature are greatly affected by the tool nose radius, r_n . Therefore, this radius should significantly affect the shape of curves $h_{S-0} = f(v)$. Fig. 2 presents an experimental support to this point. For the considered case, the following empirical equation is valid [1, 2].

$$v_{opt} = 23.2r_n^{0.25} \quad (3)$$

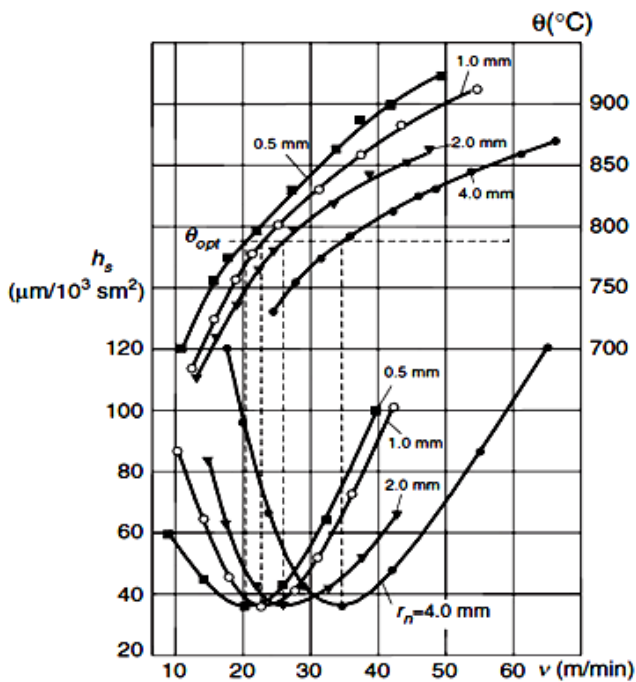


Fig. 2. Influence of the cutting speed on the tool wear rate and cutting temperature in turning for different tool nose radius. Work material – Haynes 263 alloy (29% Cr, 2.5% Ti), tool material – micrograin carbide M10 (94% WC, 6% Co) depth of cut $d_w = 1$ mm, cutting feed $f = 0.20$ mm/rev [1, 2].

When cutting at low cutting speeds ($v = 16$ m/min), tool wear rate increases significantly with the nose radius, as shown in Fig. 3. The change of this radius from $r_n = 0.5$ to 4 mm led to the increase of tool wear rate h_s from 32 to $120 \mu\text{m}/(10^3 \times \text{sm}^2)$, i.e. by four times. This is because the cutting temperature decreases with the nose radius, so it departs further from the optimal cutting temperature when the nose radius increases [1, 2].

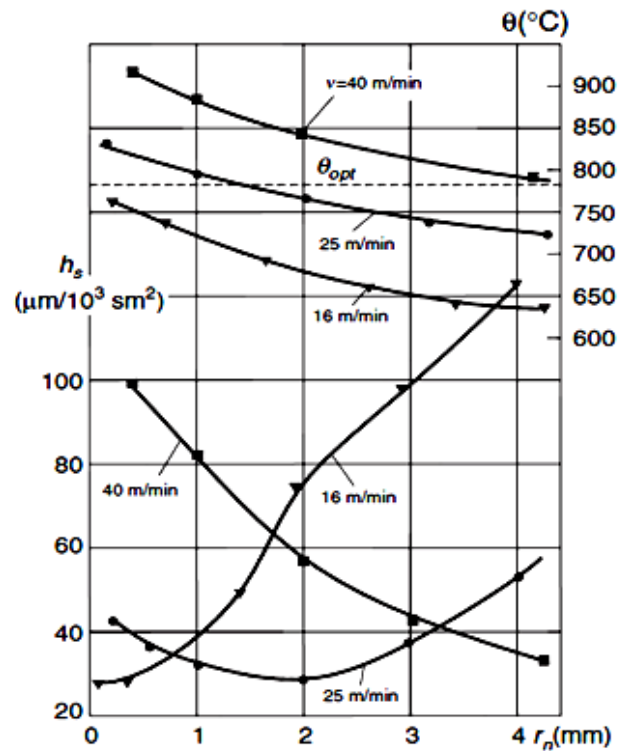


Fig. 3. Influence of the nose radius on the tool wear rate and cutting temperature in turning. Work material – Haynes 263 alloy (29% Cr, 2.5% Ti), tool material – micrograin carbide M10 (94% WC, 6% Co) depth of cut $d_w = 1$ mm, cutting feed $f = 0.20$ mm/rev [1, 2].

IV. WORKPIECE DIAMETER

The diameter of the workpiece affects the cutting process in various ways as [1]:

- The static rigidity of the machining system depends on the workpiece diameter. In boring, the diameter of the hole being bored often determines the diameter of the boring bar or the arbor and thus effects the static and dynamic stability of the machining system.

- The workpiece diameter affects the curvature on the surface being cut, that, in turn, affects the stressed-deformed state of the layer being removed. As a result, the final inclination angle and the total length of the surface of the maximum combined stress (often referred to as the shear angle and the length of the shear plane) change with the workpiece diameter.

- When the cutting speed is kept invariable, the rotational speed (r.p.m.) changes with the workpiece diameter that affects the dynamics of the process.

• The interaction of the thermal and deformation waves takes place in metal cutting. As such, if the cutting speed and feed are kept invariable, the time of one turn of the workpiece changes with its diameter that greatly affects the discussed interactions. In other words, less residual thermal energy left by the previous tool pass is available at the current pass when the diameter of the workpiece increases [1].

In practical testing, it is important to separate the influence of each factor. As cutting tests are conducted with different workpiece diameters, the workpiece diameter D_w and its length L_w should be selected accordingly to keep the ratio L_w^3 / D_w^4 invariable to exclude the influence of the workpiece diameter on the system rigidity [1].

Cutting tests were carried out where two diameters of the workpiece, 15 and 29 mm, were used. At first, the length of the workpiece was selected to keep the same rigidity ($51 \cdot 10^3$ N/mm), then the invariable workpiece diameter was used while the length (and thus rigidity) of the workpiece was varied. The test results are shown in Fig. 4. As shown, when the rigidity is kept invariable (by corresponding reduction in L), decreasing the workpiece diameters leads to a certain reduction in the tool wear rate as well in the roughness of the machined surface. However, if under the same conditions, L_w is not changed, the tool wear rate and surface roughness increase significantly [1].

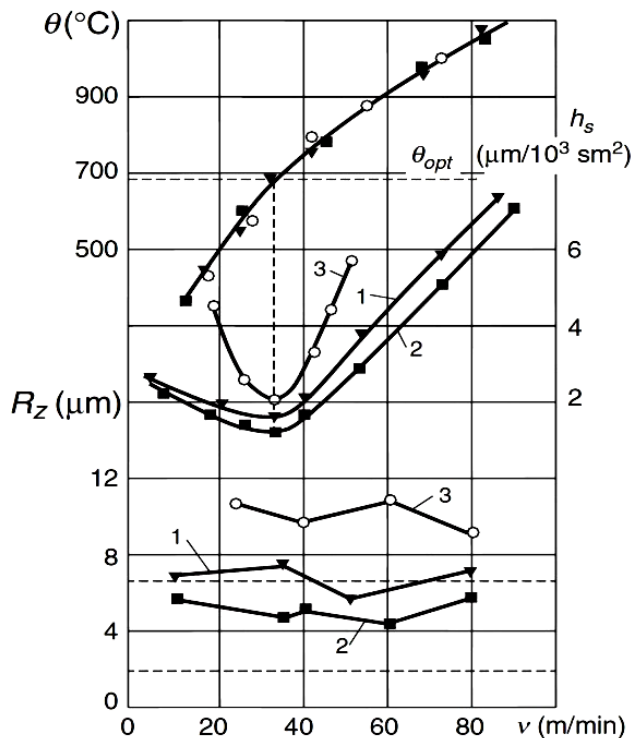


Fig. 4. Influence of the cutting speed and diameter of the workpiece in turning: on the cutting temperature, tool wear rate and roughness of the machined surface. Work material – custom-modified Haynes 263 alloy (0.02% C, 20% Cr, 2%Ti, 2%Al), tool material – micrograin carbide M10 (94% WC, 6% Co), depth of cut $d_w = 0.25$ mm, cutting feed $f = 0.09$ mm/rev: 1 – $D_w = 29$ mm, $L_w = 230$ mm, 2 – $D_w = 16$ mm, $L_w = 95$ mm, 3 – $D_w = 15$ mm, $L_w = 230$ mm [1].

V. TRIBOLOGICAL CONTACT OF TOOL-SURFACE LOADING CAPABILITY

Tool-surface contact can also be thought as tribocontact, which will have the following definitions: The total stress field on the tribocontact surface σ_{ij} can consist of mechanical (force) and thermal stress [3]:

$$\sigma_{ij} = \sigma_m [\bar{\sigma}_j^i(x, y, v, f) + \Phi_t \bar{\sigma}_{ij}^t(x, y, v, F_0)] \quad (4)$$

Dimensionless functions: σ_{ij} depending on the coordinates of the point x, y , Poisson's ratio ν , coefficient of sliding friction f ; σ_{ij} - from x, y, ν , and the number of Fourier F_0 , where

$$F_0 = \frac{2a_T}{\nu \cdot r_K} \quad (5)$$

a_T - Thermal diffusivity, ν - speed, r_K - the spot radius of the actual contact.

Dimensionless parameter:

$$\Phi_t = \frac{2(1+\nu)a_T G}{(1-\nu)\lambda} \gamma \cdot f \cdot \nu \cdot r_K \quad (6)$$

The mechanical and thermal stress action reduces the carrying capacity of tribocontact, causing the emergence of plastic deformation and the contacting bodies wear. The temperature factor Φ_t has been accepted as a thermomechanical criterion of early wear [3].

VI. PARTS SURFACES TOPOLOGY

Topographic features include the parameters that characterize the surface microgeometry, and not the individual section. However, a number of judgments about surface topography can be made by studying its profile. The surface geometry under machining results from the row of periodic factors effect superimposed with random perturbations. Systematic (periodic) component due to type of treatment, the kinematics of the flow, profile cutting edges and other permanent factors. Random component associated with the processes occurring during plastic deformation of the material during machining [4].

Depending on the technological factors ratio in the profile may predominate randomly or periodically arranged irregularities [4].

To characterize the part of random component, the profile randomness ratio is proposed:

$$\gamma_c = \frac{R^2 q_\gamma}{R^2 q} \quad (7)$$

where Rq_γ - RMS of the profile random component;

Rq - RMS of the whole profile.

The profile is at random if $\gamma_c = 1$, and if $\gamma_c = 0$ is perfectly periodic [4].

VII. SURFACE TYPOLOGY

The main goal of the numerous roughness parameters should be a proper texture shape classification with the aid of statistical or random process analysis, which has been called the typology of surfaces [6].

Contemporary evolutions like 3D profilometry and different mathematical approaches like fractal and Markov analysis give the opportunity to introduce new functionally oriented parameters that could be more successful for this task; but it is too early to appreciate their effectiveness. In conjunction with these developments, an exhaustive investigation must be carried out into the particular surface texture characteristics every individual machining process creates, taking into account, apart from the workpiece material, the different kinematic modes it possesses and covering a wide range of cutting factors employed in practice [6].

VIII. TYPOLOGY CHARTS

An effort on expanding these approaches was made with more data, systematically obtained in view of correlating turned profiles of different shapes with the cutting conditions applied [6]. The corresponding results are interpreted in the form of charts compared with the relevant "classical" charts. In Fig. 5 the kurtosis and skewness of the measured surfaces are shown. A cluster of points appears, as kurtosis and skewness are not interrelated but can fix the boundaries of surface textures in view of the shape for a wide range of cutting conditions employed. The area of high concentration of values located at the lower-right side of the diagram corresponds to regular chip formation. A chart comprising the parameters of the beta statistical function is illustrated in Fig. 6. The values are less scattered now and compared to the Whitehouse beta function typology (Fig. 6 (b)) the range is wider due to the fact explained before [5].

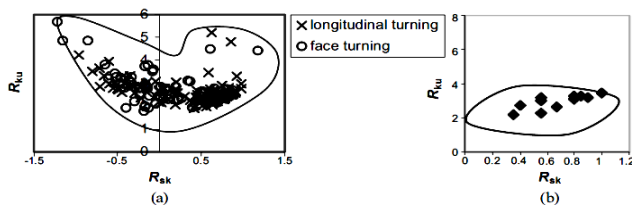


Fig. 5. Kurtosis against skewness chart (a) and the relevant chart (b) [8]

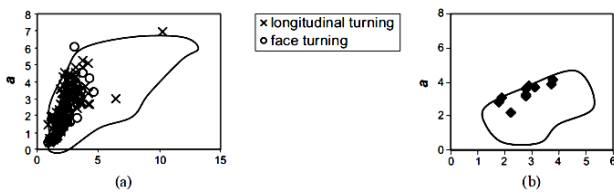


Fig. 6. Beta function parameters chart (a) and the relevant chart (b) [8]

An approach through the Fisher–Pearson parameters is proposed and the corresponding chart is shown in Fig. 7. It

has a resemblance to the beta function, as expected, but it may distinguish more explicitly between different texture shapes [7]; so it could be considered as a satisfactory method in the desired process identification.

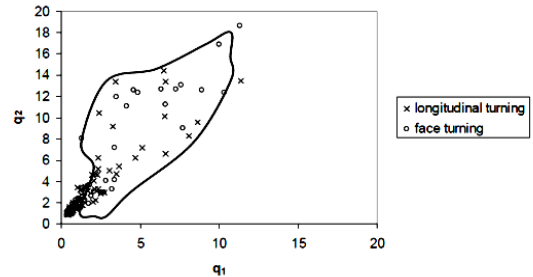


Fig. 7. Pearson parameters chart [6]

The presented data is representative of a wide range of turned metal surfaces encountered in practice but is certainly not exhaustive. A chance of modifying the charts again could be given if worn tools are used and considered at different stages of wear and special turning versions are performed [5].

IX. CONCLUSIONS

The theoretical aspects of the tool – surface system contact friction in metal cutting considered in the article give a picture of complexity and many-sided nature of this process. Comprehension of this theory gives possibility to optimize the major parameters of the process, which allow optimizing the followings indexes of the tribology process:

- *Reduction of the energy spent in cutting.* Because the efficiency of the cutting system is very low due to energy losses during tribological interactions, the optimization of the tribological processes improves the efficiency of the cutting system by reducing the energy spent by the cutting system.
- *Proper selection of application-specific tool material.* Considering the energy transmitted through the tribological interfaces in metal cutting, one can select a tool material for a given application to meet the chosen performance criterion such as tool life, quality of the machined surface, efficiency, etc.
- *Proper selection of tool geometry.* Because the tool geometry largely defines the state of stress in the deformation zone, stresses, temperatures and relative velocities at the tool–surface interface, the optimized tribological parameters can be directly used in the selection of proper tool geometry.
- *Control of machining residual stresses imposed in the machined surfaces.* The machining residual stresses are determined by the tribological process taking place at the tool–surface interface.
- *Proper selection of cooling and lubricating media as well as the method of its delivery and application technique.* The proper selection and application of a particular medium is only possible when the true tribological mechanism of its action is known.

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Dmitrijs Litvinovs, Andris Priževaitis. Instrumenta un kontaktvirsmas berzes teorētiskie aspekti metāla griešanas laikā

Rakstā ir atspoguļoti kontaktvirsmu berzes teorētiskie aspekti, kā: „instruments–virsmas” kontakta triboģiskie raksturlielumi. Tiem pieskaita: slīdes ātrumu, kontakta garumu, berzes spēku, trāšu berzes spēku - vidējo nobīdes spriegumu, normālo spēki instrumentam mijiedarbojoties ar apstrādājamo virsmu, vidējo nobīdes spriegumu instrumentam kontaktējoties ar apstrādājamo virsmu, vidējā temperatūra instrumentam kontaktējoties ar apstrādājamo virsmu.

Instrumenta ģeometrija, kas ir apskatīta rakstā, iekļauj ne tikai galvenos ģeometriskos instrumenta rādītājus, bet arī biežumu un nenogrieztu skaidu formu. Sagataves diametrs ietekmē darbgalda statisko stingumu, apstrādājamās virsmas izlieci, griešanas procesa dinamiku, siltuma un deformācijas viļņu mijiedarbību. Rakstā ir parādīta izteiksmes, kas nosaka tribokontakta nestspēju instrumentam ar virsmu. Detaļu virsmu topoloģijas raksturojumam, rakstā piedāvātas profila gadījuma komponentu attiecības. Virsmu tipoloģija ir nepieciešama, lai klasificētu tekstūras formas ar statistisko un gadījumu komponentu analīzi.

Дмитрий Литвинов, Андريس Прижевайтис. Теоретические аспекты трения контакта инструмента и поверхности во время резания металла

В данной статье освещены такие теоретические аспекты контактного трения, как: трибологические характеристики контакта инструмент – поверхность. К ним относятся: скорость скольжения, длина контакта, сила трения, особая сила трения – среднее напряжение сдвига, нормальная сила при взаимодействии инструмента с поверхностью, среднее напряжение сдвига при контакте инструмента с поверхностью, средняя температура при контакте инструмента с поверхностью.

Геометрия инструмента, рассмотренная в статье, включает не только основные геометрические параметры инструмента, но и толщину, а также форму не срезанной стружки. Диаметр заготовки влияет на статическую жесткость станков, на кривизну обрабатываемой поверхности, на динамику процесса резания, на взаимодействие тепловых и деформационных волн. В статье приводятся выражения для определения несущей способности трибоконтakta инструмент – поверхность. Для характеристики топологии поверхности деталей, в статье предлагается соотношение для случайных компонентов профиля. Типология поверхности необходима для классификации формы текстуры с помощью анализа статистических и случайных компонентов.