Influence of machining conditions on friction in metal cutting process – A review

Wpływ warunków obróbki na tarcie w procesie skrawania metali – przegląd literatury

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This paper presents a range of variable machining factors which **influence substantially friction directly or by the tool wear developed in the cutting zone. The group of direct factors include the workpiece and cutting tool materials coupled, the cutting/ /sliding velocity, cooling media supplied to the tool-chip contact zone, modification of the tool contact faces by micro-texturing. Special attention was paid to the tool wear evolution and its pronounced effect on changes of the contact conditions.**
KEYWORDS: metal cutting, friction, contact conditions, wear

Przedstawiono wiele zmiennych czynników procesowych, które istotnie wpływają – bezpośrednio lub pośrednio przez zużycie ostrza – na tarcie występujące w strefie skrawania. Grupa czynników bezpośrednich obejmuje: materiał obrabianego przedmiotu i narzędzia skrawającego, prędkość skrawania/ /poślizgu, media chłodzące dostarczane do strefy kontaktu oraz modyfikację powierzchni kontaktowych ostrza narzędzia przez mikroteksturyzowanie. Specjalną uwagę zwrócono na ewolucję zużycia narzędzia i jej dominujące oddziaływanie na zmiany warunków kontaktowych.
SŁOWA KLUCZOWE: skrawanie metali, tarcie, warunki kontaktowe, zużycie

The validation of the friction models by means of the tribo-tests presented in Ref. [1] needs a deep sensivity analysis which allows to select the most important factors influencing the behaviour of frictional interactions between the tool and the work material machined. Based on the metal cutting the following groups of factors influencing friction can be distinguished:

- work material: composition and microstructure,
- cutting tool: substrate, deposited coating, surface texture, i.e. micro-texture,
- cooling/lubrication: cooling medium, supplying technique,
- contact conditions in sliding coupling.

Influence of variable factors on friction

Effect of work material and its microstructure

Regarding the influence of work material, Fig. 1 provides an overview on the frictional behaviour with a TiN coated carbide tool. Fig. 1 shows that apparent friction coefficients μ_{app} can vary significantly in the range from 0.1 to about 0.7. In particular, the difference resulting from the grade of work materials and its physical and mechanical properties is very significant for low sliding velocities in dry friction conditions.

For instance, it was documented [2] that both ferritic-pearlitic and austenitic steels produce much higher friction coefficients compared to martensitic steels. It has also highlighted there is the variation of friction between an austenitic stainless steel and a ferritic-pearlitic grade. On the contrary, friction coefficients of metallic work materials converge toward 0.2 in dry conditions, which corresponds to a semi-solid frictional regime.

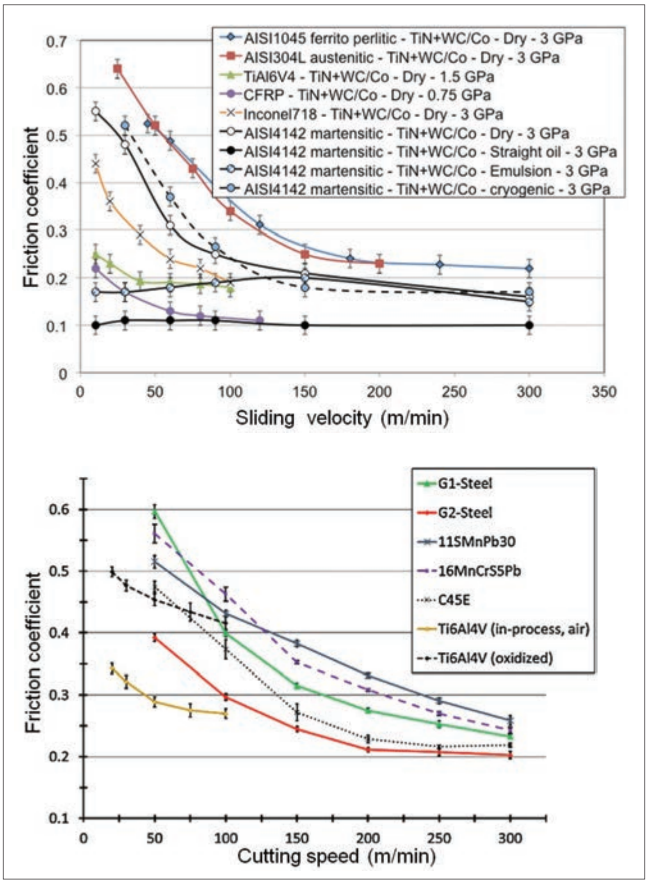

Fig. 1. Evolution of apparent friction coefficient vs. sliding velocity for various material pairs [5, 6]

However, all work materials with a similar microstructure cannot be considered as representing a similar friction model. For instance, it has been shown that a small percentage of CaMnS or Pb inclusions decreases significantly friction at low sliding speeds, whereas similar inclusions do modify the frictional behaviour on austenitic grades [3].

More recently, it has been shown [4] that, as far as ferritic-pearlitic grades are concerned, ferrite increases significantly friction on the contrary to pearlite (Fig. 2). This trend is more intensive for low sliding velocity; i.e. for such processes as broaching or tapping with low cutting speed.

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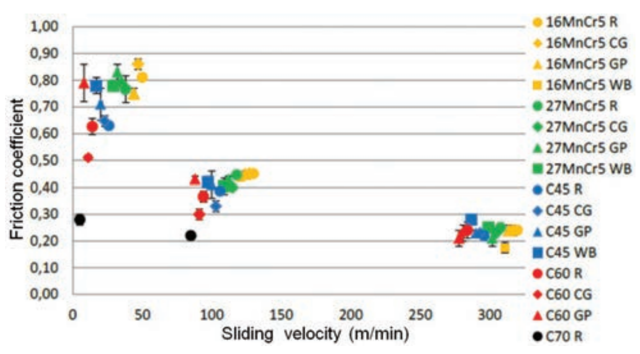

Fig. 2. Evolution of macroscopic friction coefficient vs. sliding velocity for a range of steels vs. TiN/WC-Co pin, pin diameter d_p = 17 = mm, normal load F_n = 1000 N [4]. Symbols: *R* – standard, *CG* – coarse grain, *GP* – globular pearlitic, *WB* – with band

Effect of cooling media

Regarding the influence of cutting fluids, Fig. 3 evidently reveals that the application of an emulsion leads to a large decrease of friction coefficient in comparison to a dry sliding contact performed with low sliding velocities. On the contrary, for high sliding velocities emulsion is not able to lubricate the contact effectively and the values of friction coefficients can be similar to the ones obtained for a dry contact. The application of a straight oil influences the friction much more, since the friction coefficient remains constant around 0.1 irrespective of the value of sliding velocity. Once again, these friction coefficients cannot be generalized, since it strongly depends on the amount of lubricant present at the tool-workmaterial interface, on the duration of the contact.

In fact, it has shown [6] that when oil is present in the contact before friction, it is eliminated within some tenth of seconds due the high contact pressure and the sliding velocity. So it is questionable if oil is able to penetrate in the tool-workpiece material interface during cutting operations such as turning, drilling, etc., longer than the first second. In case of interrupted cutting processes such as milling, the contact is lubricated before each cutting period. However, even if the cutting duration is very short, the friction coefficient cannot be assumed as equal to the one obtained for a fully lubricated regime [7].

Moreover, it have shown in Fig. 3 that the amount of oil deposited at the interface (before cutting) between the tool and the workpiece material depends strongly on the cutting speed. For high cutting speeds, there is an oil starvation due to the lack of time to depose a sufficient amount of oil, which, in turn, leads to a dry sliding. On the contrary, for low cutting speeds, the contact is fully lubricated. A similar observation has been reported in [8]. Moreover, this observation includes the fact that oil viscosity strongly influences friction under MQL by modifying the generation of oil mist irrespective of its composition.

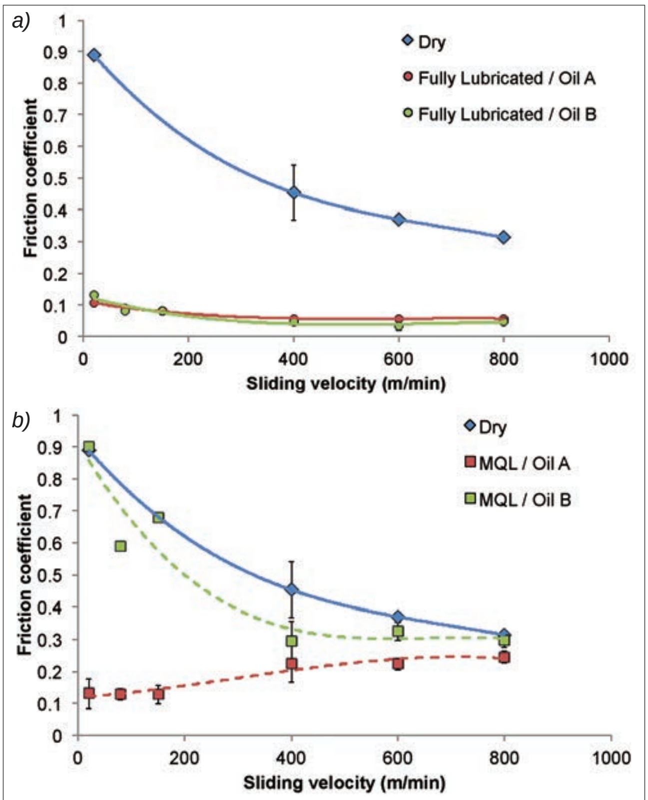

Fig. 3. Influence of lubrication mode and oil viscosity on friction coefficient: *a*) full lubricated, *b*) MQL [8]

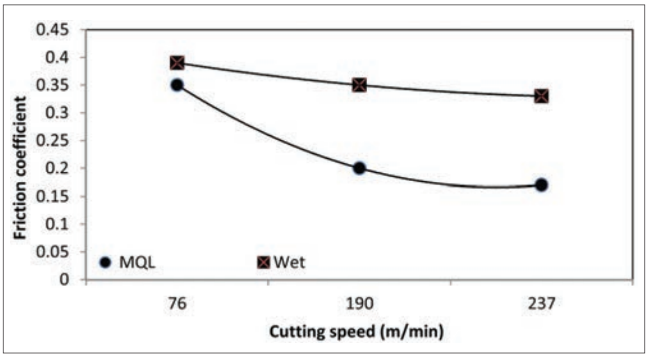

Fig. 4. Comparison of cooling supply method on friction coefficient [9]

The effect of the cutting speed and feed rate on the effectiveness of MQL supply in the machining of AISI1045 steel was investigated and modelled by Banerjee and Sharma [9]. As a result a non-linear empirical equation (see below) which represents the influence of these machining parameters on the friction coefficient when MQL was supplied is proposed.

$$\mu = 3{,}32 v_c^{-0{,}45} - 0{,}24 f$$

where: v_c – cutting speed; f – feed rate.

Fig. 4 shows that MQL supply results in a two-fold reduction of the friction coefficient (below 0.15) at the cutting speed above 200 m/min.

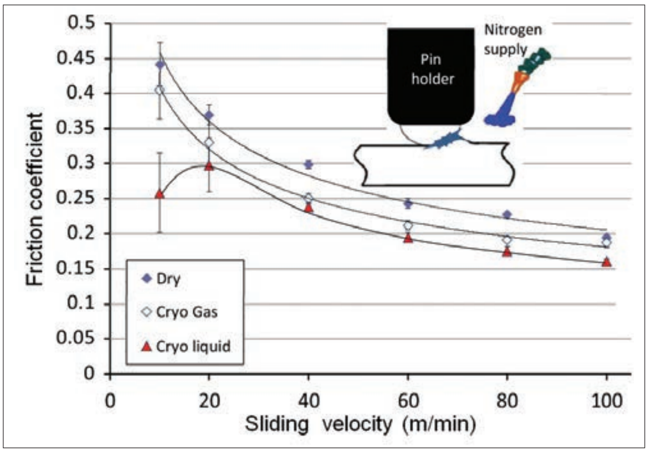

Fig. 5. Influence of sliding velocity and cooling medium on apparent friction coefficient in the tribo-test of Inconel 718 against TiN/WC-Co pin, d_p = 9 mm, F_n = 1000 N [10]

The application of liquid or gas nitrogen or solid CO_2 is also under development in industry. Neither is considered as lubricant. So it can be assumed that they do not influence friction. However, it have shown [5, 10] that liquid nitrogen is able to decrease significantly friction when machining Inconel 718 (Fig. 5) whereas it does modify friction when machining TiAl6V alloy or AISI4142 steel. It is not clear if nitrogen can remain in its liquid state at the tool-workpiece material interface or if it is transformed into gas. However, some authors have shown that the application of nitrogen lead to oxygen starvation, which modifies fully friction phenomena [11]. On the contrary, an oxidized surface modifies also strongly the identification of friction coefficients [6].

In particular, high performance metallic materials, such as nickel alloys, titanium alloys and intermetallics, stainless steels, represent classes of materials that have seen an expansion in use in the last years due to their elevated performance in many areas of application, such as the aerospace, biomedical, marine or automotive industry. However, they are characterized by poor machinability, due to abrasiveness, poor thermal conductivity, which leads to high cutting temperatures on the rake face, chemical affinity with many cutting tool materials, leading to adhesive welding of the contacted irregularities and an intensive diffusion wear [12].

These negative tribo-effects are typically limited by the use of lubricant, or lubro-coolant, but the current quest for dry or minimum quantity lubrication (MQL) machining, aimed at control of pollution and part surface contamination, further compounds the severe conditions at the interface. In fact, various researchers have examined the benefits, drawbacks, and conditions necessary for machining a range of materials with dedicated cooling methods such as flood-cooling, dry, and MQL machining. Several conscious cooling approaches, including cryogenic cooling [13], have been widely investigated in recent times, especially for difficult-to-cut materials.

Effect of high cutting/sliding speeds

Nowadays, high speed machining (HSM) is a leading machining technology and modelling of machining processes performed at high or very high cutting speeds, in general higher than 1000 m/min [14] needs a new input data which are substantially modified by strain rate, temperature and friction [15].

The relevant trends observed in Fig. 6 were also reported for the machining of Inconel 718. According to Fig. 6 the friction coefficient drops rapidly from about 1 for low

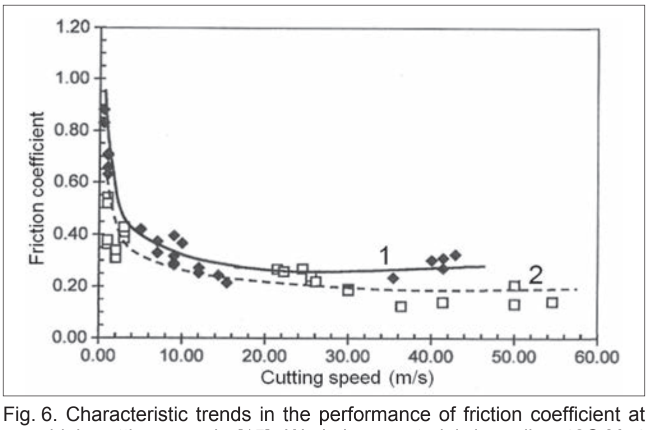

Fig. 6. Characteristic trends in the performance of friction coefficient at very high cutting speeds [15]. Workpiece material: low alloy 42CrMo4 steel, *1* – a_p = 0.2 mm; *2* – a_p = 0.5 mm (a_p – depth of cut)

cutting speeds to about 0.2 to high and ultra high cutting speeds, which corresponds to a semi-solid frictional regime. It should be noticed that due to intensive thermal softening of the chip material friction condition stabilizes for cutting speeds higher than 1000 (1200) m/min. In addition, a critical cutting speed in the range of 15÷25 m/s at which the minimum cutting force appears is recorded.

Effect of tool coatings

The influence of cutting tool materials (substrate, coating) has to be discussed due to a huge number of recommended cutting tool materials. In particular, it is evident that cutting tool coatings can very significantly modify the friction properties at the tool/work material interface (Fig. 7) [16].

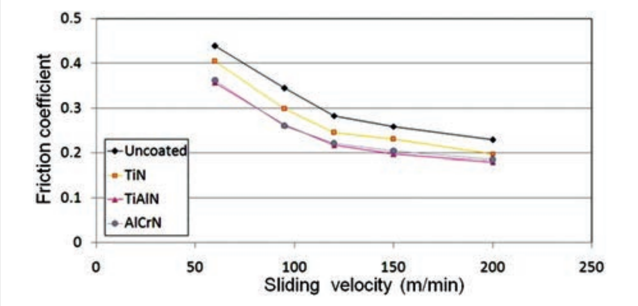

Fig. 7. Influence of cutting tool coatings on friction coefficient when dry machining 42CrMo4 steel (AISI4140, 300 HB), WC-Co pin, d_p = 9 mm, F_n = 1000 N, contact pressure $p \approx$ 2600 MPa [16]

The influence of substrate is also very significant. As shown in [17] a CBN substrate leads to a very low friction coefficient (μ = 0.1÷0.2) when machining Inconel 718, whereas TiAlN coated carbide tools exhibit higher values of μ = 0.2÷0.4. On the other hand, HSS and sintered carbides lead to severe adhesion and high friction coefficient whereas PCD exhibits a self-lubricated contact when machining aluminium + silicon alloys [18].

An extensive characterization of tool coatings is performed in Refs. [19, 20]. This approach was based on mechanical, thermal and energy-based considerations according to complex friction models overviewed in Section 1.2. It has been noted the identification of an accurate friction model has to be conducted by carefully preparing samples, tools/pins and lubrication in close accordance with the application concerned by the modelling. This is due to the obviously known fact that the interface between cutting tool and workpiece material has always been characterized by complex phenomena including abrasive friction, high relative velocity, high temperature, high pressures, chemical interaction.

In the machining of difficult-to-cut alloys, metal cutting operations that require the engineering of tools with elevated surface properties in terms of wear resistance, hardness, strength, toughness, and thermal stability at high temperature, correlation between chemical, physical and mechanical characteristics of cutting tools' surfaces and their performances in cutting operations becomes a key issue for both tools manufacturers and users [21]. To this purpose, mainly for economic reasons, such coating systems are always previously deposited on samples, on which an extensive list of laboratory tests are performed, prior to depositing on actual cutting tools to perform the cutting tests. Therefore, correlation models between the outcomes of the laboratory tests and the results of the cutting tests are of uttermost utility to limit the time- and money-consuming cutting tests and to forecast functional cutting tool coating performance.

Some methodologies for classifying cutting tool coatings' performance according to the outcome of laboratory tests are developed and reported in Refs. [12, 21, 22]. Indicators such as friction coefficient, sample wear depth, ball wear area measured with a ball-on-disc test, nano-hardness, coatings adhesion and toughness, obtained at different temperatures and with different lubro-cooling conditions, have been successively correlated with the cutting performance of the coatings, giving a useful tool for the design of advanced coating systems.

As an representative example, the ratio between ball wear area and sample trace depth it has been used to rank nanostructured TiN+AlTiN (coating *A*), TiN+AlTiN+MoS_2 (coating *B*) and CrN+CrN:C+C (coating *C*), deposited on WC-Co inserts, in terms of their cutting performance, as shown in Fig. 8.

In these wear tests, tool life was examined in a comprehensive series of turning tests performed in the range of cutting speed of 35 to 140 m/min, taking as the end-life criterion the maximum width of flank wear VB_B = 0.15 mm, according to ISO 3685. Final ranking of the tested coatings in terms of increasing tool life was *C*, *A*, *B*, in agreement with the outcome of tribological tests, is shown in Fig. 8.

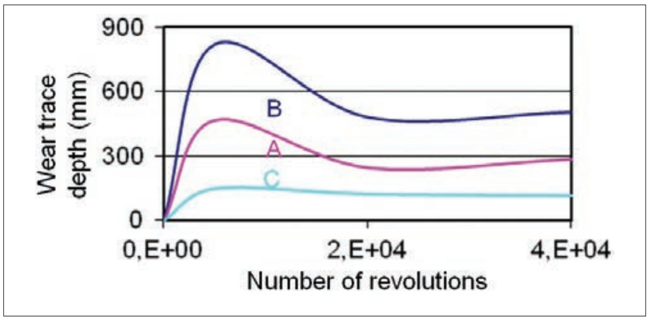

Fig. 8. Ratio between ball wear area and sample trace depth vs. number of revolutions. Wear tests performed at 800°C [22]

Effect of texturing of tool working faces

At present, active surfaces on cutting tools are specially engineered by means of laser texturing in order to reduce adhesion between the rake face and the chip, improve cutting fluid retaining (Fig. 9*b* vs. Fig. 9*a*) and enhanced cutting performance by reducing friction [23].

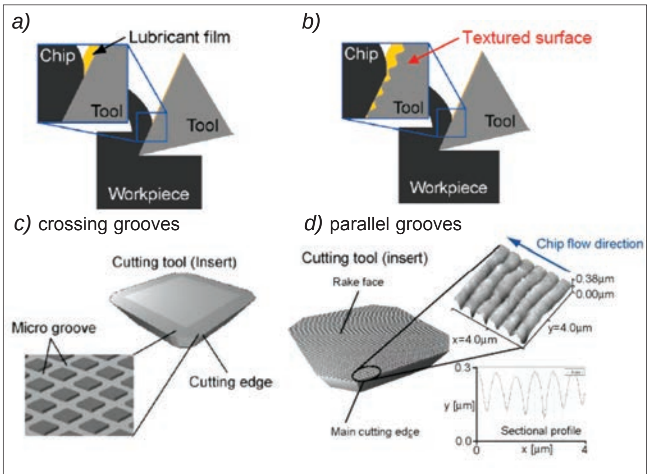

Fig. 9. Schematic illustration of lubrication action for cutting tools with smooth (*a*) and textured (*b*) rake face; *c*) and *d*) examples of nano-/micro-textures performed on milling inserts [23]

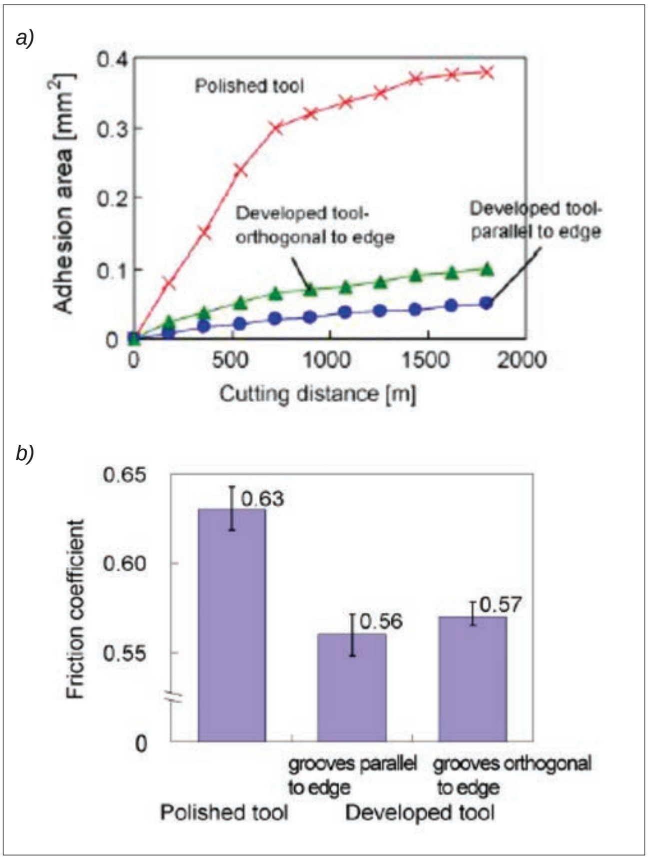

Fig. 10. Changes of adhesion evolution (*a*) and friction coefficient (*b*) for textured rake faces from Fig. 9*c* in aluminium milling [21, 23]

Different textures including micro-grooves, dimples or holes with different orientation (parallel, perpendicular or inclined) in relation to the cutting edges are producing on the rake face of the cutting tools as those exemplarily presented in Fig. 9*c* and Fig. 9*d*.

It was revealed that the textured surfaces filled with solid lubricants exhibited an enhanced tribological performance as compared to the textured and smooth surfaces under dry friction conditions.

For instance, micro-textures in the form of grid presented in Fig. 9*c* and Fig. 9*d* are generated on DLC coatings deposited on tungsten carbide inserts using special tungsten mesh wire as a mask to create a regular grid. The effects of using textured cutting inserts related to the reduction of adhesion area and friction coefficient are illustrated in Fig. 10*a* and Fig. 10*b* respectively. Both the anti-adhesive properties and lubricity of the rake face surface are improved. In this case study the texturized structure consisting of parallel groves is the most effective. In addition, surface quality was improved by substantial reduction of BUE formation.

Influence of tool wear on friction

Determination of friction in tribo-tests

One of the basic tribological assumption is that friction and wear are two kinds of interactive responses from the tribo-system and, as a result, a comprehensive relationship between these tribological characteristics should be established.

It should be noticed that these tribo-phenomena are simultaneously the effects of the same tribological contact process that occurs between two moving surfaces, e.g. between the chip material and the tool. In particular, they

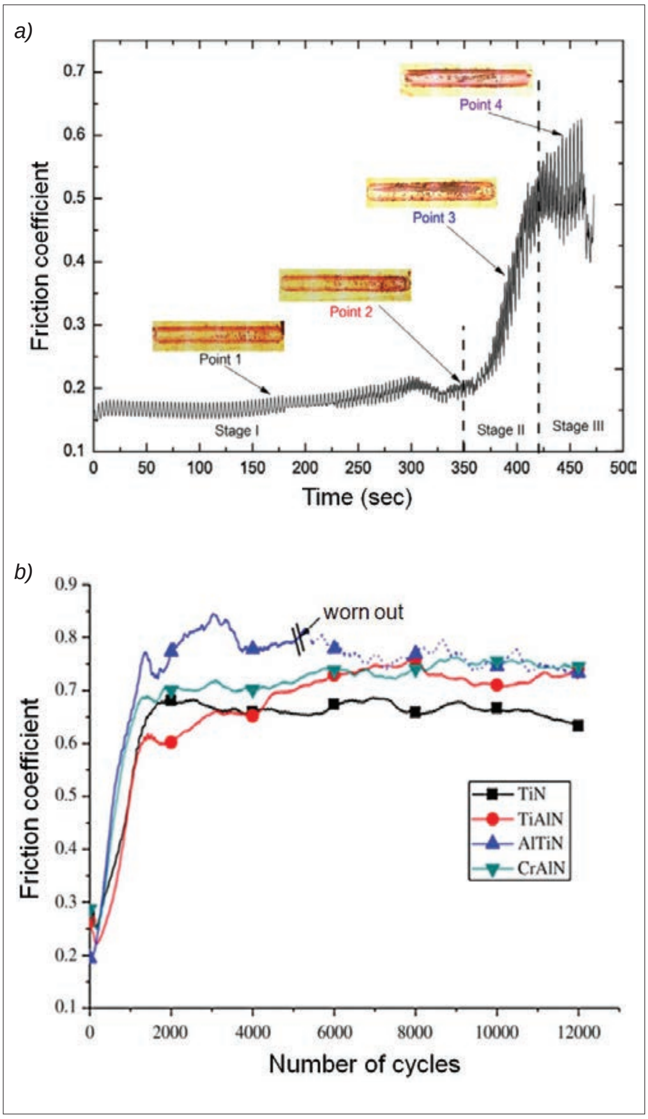

Fig. 11. Friction coefficient evolution of the TiN coated sample under load 200 N (*a*) and TiN, TiAlN, AlTiN and CrAlN PVD nitride coatings as function of number of cycles after [24, 25]

are always reasonably related with each other when the desired functions of the tribo-system are taken into consideration. It is well known and practically proven that low friction corresponds to low wear and consequently high friction to higher wear. Unfortunately, the relation between friction and wear in metal cutting was not sufficiently investigated because typically so-called "fresh tool" and the average value of friction coefficient are assumed in the orthogonal model of metal cutting. In the case of practical aspects of metal cutting a special focus should be placed on coated cutting tools with deposited hard, soft of soft/ /hard layers [24].

Fig. 11*a* shows the evolution curves of friction coefficient (COF) for TiN coated samples under a normal load of 200 N using a ball-on-disc tribo-testing device. It can be seen in Fig. 11*a* that three characteristic stages are distinguished: low friction stage (I), ploughing friction stage (II) and coating breakdown stage (III). The friction coefficient in stage (I) ranges from 0.15 to 0.2. Moreover, Fig. 11*b* shows the evolution of friction coefficient vs. number of cycles up to 12,000 cycles for a group of nitride coatings against a SiC ball. The evolution curves contain the rapid running-in period and a visible steady-state stage with the values of μ ranging between 0.65 and 0.8.

Determination of friction in real machining processes

The second group of investigations of friction evolution during wear tests concern real machining processes, including orthogonal and oblique machining of a spheroidal cast iron using ceramic Si_3N_4 and CBN cutting tools [26] and hard machining of a case-hardened alloy steel using CBN tools [27].

The local values of friction coefficient corresponding to measured values of VB_c tool flank wear were determined based of mechanistic friction model for which the friction and normal forces were computed using three componential cutting forces. In addition, the worn rake angle was dimensioned based on 3D images obtained using a laser confocal technique [26]. Moreover, the equivalent rake angle for the worn rake face was determined graphically as shown in Fig. 12*b*. The obtained changes of friction coefficient at the rake and flank faces are presented in Fig. 13.

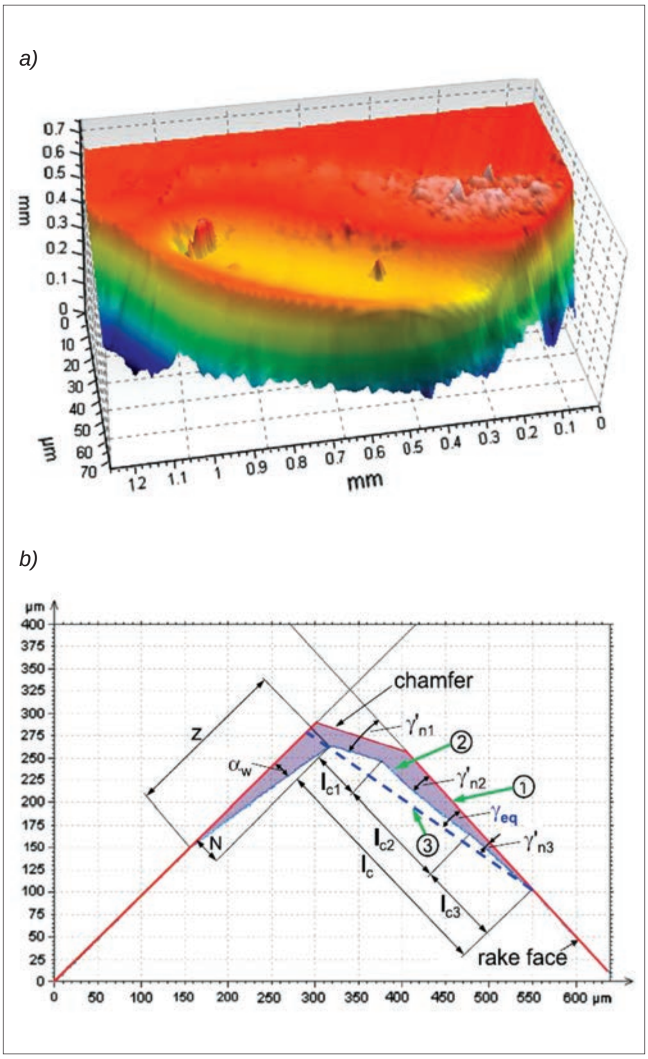

Fig. 12. Confocal image of worn cutting tool (*a*) determination of the equivalent rake angle (*b*) after [26]. *1* – the shape of fresh tool, *2* – the shape of worn tool, *3* – planar equivalent rake face

As shown in Fig. 13*a* the friction coefficient for the rake face $\mu_{\gamma o}$ changes from about 0.15 to 0.75 depending on the wear intensity (cutting speed used). On the other hand, relevant changes the friction coefficient for the flank face μ_α are distinctly higher and increase from 0.55 to about 2. Such exceptionally high values of μ_α are caused by adhesion between the tool and the chemically fresh surface of

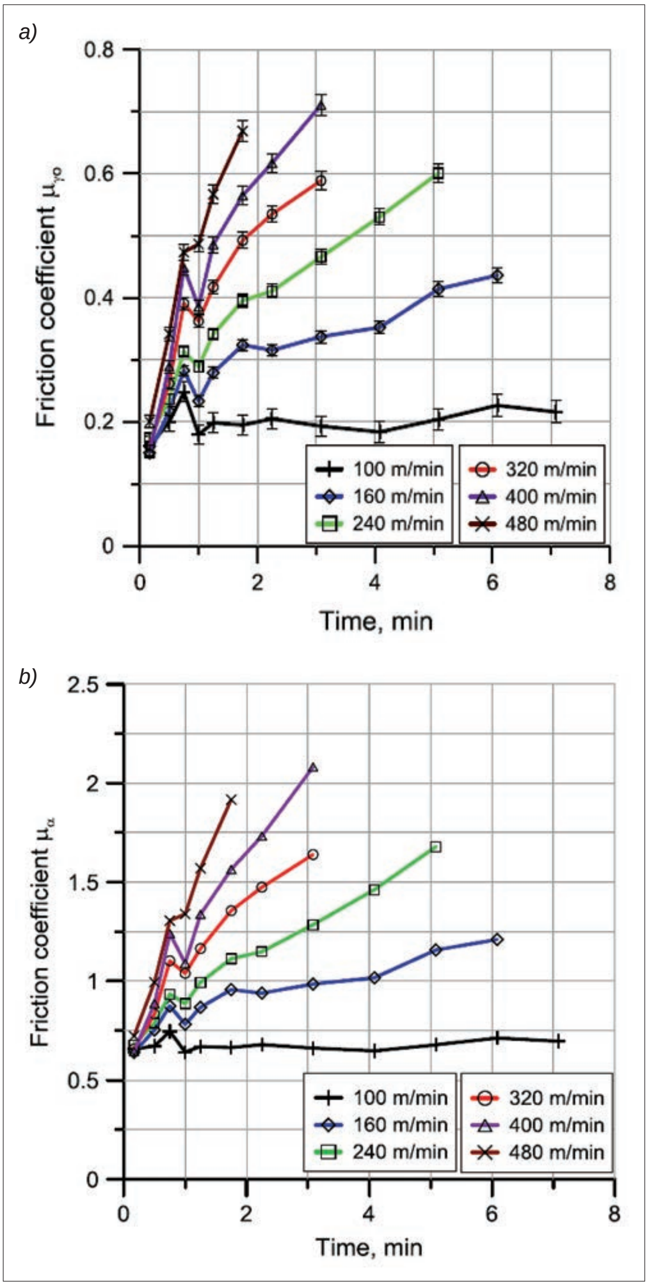

Fig. 13. Changes of friction coefficient at rake and flank faces after [26]

the workpiece, which is intensified when the cutting speed increases. A good agreement between values of μ_{α} for machining and tribo-tests was observed.

The energy-based investigation of precision hard machining using CBN cutting tools revealed that the ploughing component of friction coefficient dominates in precision hard machining with extremely low uncut chip thickness of the minimum value of 2.5 μm [27]. As shown in Fig. 14 an excessive increase of the friction coefficient is observed for higher feed (*a*), larger tool nose (*b*) and the smallest depth of cut (*c*) which cause that the ploughing and lateral material flow is intensify. Abnormal values of friction coefficient of about 4 are determined but such high values are documented in tribology [25].

The main conclusion from these studies is that tool wear influences differently friction and different components such as adhesion or ploughing components, which can dominate as the predominant friction mechanisms (see: "Effect of work material and its microstructure").

Summary

The following important conclusions can be formulated:

- Friction in metal cutting depends on a number of factors including machining parameters (mainly cutting speed), work material properties and its microstructure, cutting tool material and deposited coatings, cooling media.
- Such physical phenomena as plastic deformation, thermal softening and adhesion and oxidization control the frictional behaviour. Also modification of the tool contact faces by micro-texturing reduces adhesive interaction between the tool and the chip and, as a result, overall friction. Examine these relationships can support the selection of optimal cutting conditions in terms of reduction of friction and associated wear.
- Friction should be considered in a strong conjunction with tool wear evolution.
- It is important to develop more effective tribo-testers and computing procedures.
- For more scientific inside into the metal cutting friction it is necessary to develop experimental procedures for separating mechanical, adhesion and ploughing components in the friction models for different tribo-pairs. In particular, the ploughing action is extremely intensive in precision hard machining operation.

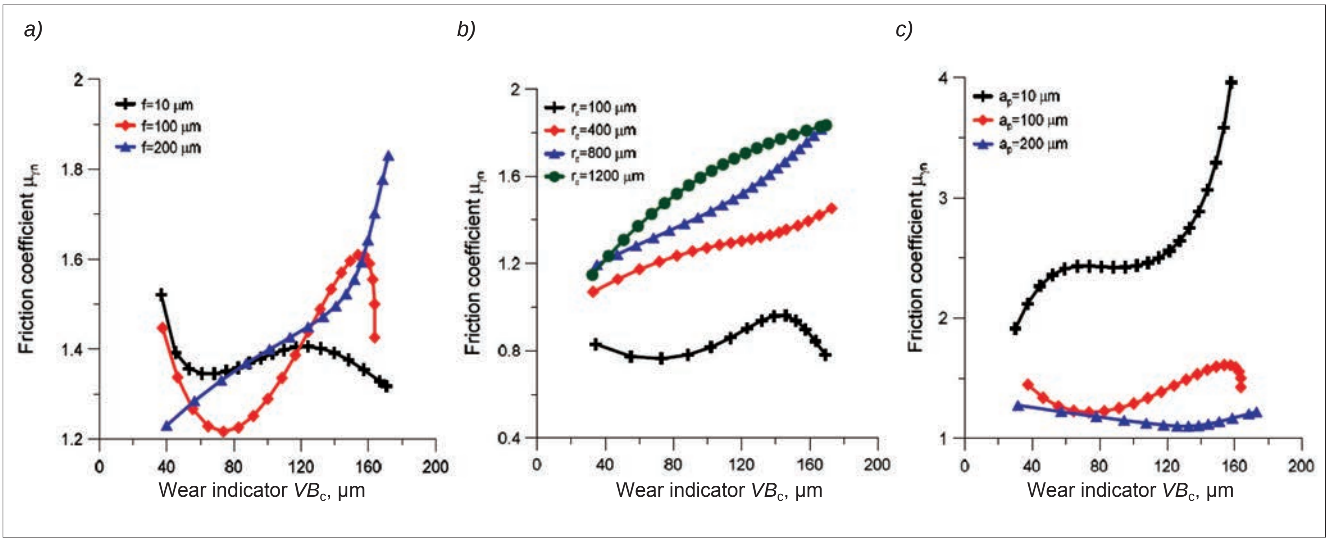

Fig. 14. Changes of friction coefficient on the rake face with tool wear resulting from variations of feed rate (*a*), tool nose radius (*b*) and depth of cut (*c*) after [27]

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