Tribology in Manufacturing Processes and Joining by Plastic Deformation II

8th International Conference on Tribology in Manufacturing Processes and Joining by Plastic Deformation

ICTMP 2018

Edited by
Niels Bay and Chris V Nielsen

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Preface

The present book contains the papers presented at The International Conference on Tribology in Manufacturing Processes & Joining by Plastic Deformation (ICTMP2018) held in Elsinore, Denmark 24th -26th of June 2018. The ICTMP was originally established by Professors K. Dohda, W.R.D. Wilson, S.R. Schmid and N. Bay. The series of conferences includes:

1997 – 1st ICTMP in Gifu, Japan

2004 – 2nd ICTMP in Nyborg, Denmark

2007 – 3rd ICTMP in Yokohama, Japan

2010 – 4th ICTMP in Nice, France

2012 – 5th ICTMP in Notre Dame, USA

2014 – 6th ICTMP in Darmstadt, Germany

2016 – 7th ICTMP in Phuket, Thailand

2018 – 8th ICTMP in Elsinore, Denmark

The aim of the conference is to present the latest research and development on tribology in manufacturing processes. Subjects like friction, lubrication and wear as well as surface engineering of both workpiece and tool are scopes of interest. As in the last two ICTMP conferences, the conference also includes joining by forming as a theme of interest.

The book contains three keynote papers and 49 session papers. The chapters in the book correspond to the sessions and include the following topics:

1. Surface Engineering
2. Galling
3. Lubrication
4. Simulative Testing
5. Tribology of Metal Forming Processes
6. Tribology of Machining Processes & Wear
7. Solid Phase Welding I
8. Solid Phase Welding II & Mechanical Joining I
9. Mechanical Joining II
10. Unconventional Joining Processes.

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Tribological Effects in and by Metal Cutting

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Abstract. In metal cutting, a severe thermo-mechanical load collective determines the friction and wear behavior at the tool-chip interface. The inaccessibility of this interface complicates studies and thus the understanding of tribological effects in metal cutting. During a tool's lifetime, local friction conditions change drastically as coatings and tool geometry wear down. This paper shall provide a comprehensive overview of current methods to understand and describe friction conditions in metal cutting and how cutting induced surface layer states may influence the friction and wear behavior of the finished workpiece.

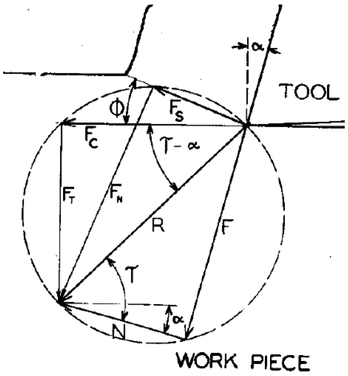
Introduction

Most moving parts rely either on low friction contacts allowing for relative movement with low wear or on high friction contacts ensuring the cohesive assembly. Either way, cut metal surfaces carry the main load of today's frictional wear and tear in most man-made machines. They are either in direct contact or in coated or lubricated contact, carrying variable or constant loads encompassing large or small relative displacements and pressures at various temperatures. Even though cut metal surfaces are usually looked at in terms of topography, wear mechanisms of metal parts depend on and change most surface layer states. Machining processes used to manufacture these surfaces in turn can be seen as extreme tribological contacts. The cutting process as tribological system thus sets the boundaries of tribological part performance by creating the near-entirety of surface layer states. Because cutting processes such as drilling, milling or turning are highly inaccessible to observation, frictional conditions at the tool-workpiece interface are generally hard to analyze and to model, which complicates systematic manufacturing of metal surfaces optimized for tribological applications.

The interdependent nature of tribology and cutting induced surface layer states requires large-scale investigations for any two surfaces in contact, making thorough investigations a time and resource consuming undertaking. Consequently, smaller scale investigations are prevalent and comprehensive approaches do not currently exist. Tribology therefore remains one of the more obscure sciences insofar as the true potential of controlling tribological aspects of contacts remains untapped beyond topographies, lubrication, and coatings. This paper focuses on the current state of knowledge with regard to analyzing and modelling friction in metal cutting, and friction of cut metal surfaces with regard to cutting induced surface layer states when using defined cutting edges. In section 2, tribological effects in metal cutting will be described considering the tool-chip interface, tool wear and stick-slip phenomena. Subsequently, section 3 depicts the current state of tribological test setups and direct tribological analyses of cutting experiments. Section 4 reviews the modelling techniques for friction in metal cutting including finite element modelling (FEM) of chip formation. Section 5 then focuses on friction on cut metal surfaces with regard to topography and structuring as well as cutting induced surface layer states primarily in sliding contacts. In section 6, future needs and opportunities for further research are composed. Finally, section 7 concludes this paper with a short summary.

Tribological Effects in Metal Cutting

Metal cutting as a tribological system. The removal of material using a defined tool geometry encompasses classic processes as for instance turning, drilling and milling as well as less known processes like broaching, whirling and skiving. Usually, the cutting tool needs to be significantly harder than the workpiece, and concurrent high relative speeds and cutting forces ensure high normal pressures in the contact area resulting in frictional force components in addition to the forces necessary to cut the metal. The endeavor to understand this friction in metal cutting started with analytical and experimental means, which were reviewed by Bailey in 1975 [1]. It was apparent, that the tribological system of metal cutting could not be described in its entirety by classical means, even though it was later proven that the classical mechanisms of friction (adhesion, ploughing and plastic deformation) do apply [2]. This is due to complex interaction of tool and workpiece along the tool-chip interface influenced by material behavior under high stresses, strains and temperatures as well as phenomena such as varying stick-slip zones along the edge radius, ploughing beneath the flank/clearance face and built-up edges (BUE), built-up layers (BUL) or material transfer layers (MTL). In some cases this is complicated further through diffusional processes as demonstrated by [3, 4] for machining of Ti alloys with WC/Co tools and nano-scale machining of copper with diamond like carbon tools respectively. For simplification, orthogonal cutting experiments, analytics, and simulations are widely used to this day [5] with most of the analytical methods still based on early considerations like refined shear plane models considering friction forces or contact stress distribution models as shown exemplary in Fig. 1 for Merchant’s shear plane model and Zorev’s stress distribution model.



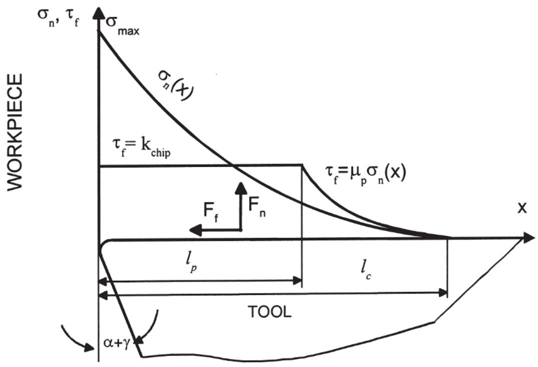


Fig. 1. (left): Merchant’s shear plane model of forces [6];
(right): Zorev’s contact stress distribution model [7].

Most real metal cutting processes are governed by extreme maxima and gradients of strain (1-10 [-]), strain rates (up to $1 \cdot 10^6 s^{-1}$), and temperatures (in the excess of 1000°C) which cannot always be measured accurately [8, 9], and thus pose an uncertainty for any modelling attempt. Through these boundary conditions, the tool-chip interface constitutes an extreme tribological contact featuring high relative speeds depending on cutting speed and tool geometry as well as pressures up to the current yield strength of the cut material. This also determines the contact area (or length l_c in simplifications), wear, and stagnation zone or built-up edges along the edge radius.

Machining in any form can thus be defined as an extreme tribological system, which is subject of numerous disturbances and may exhibit stable or instable behavior depending on the cutting boundary conditions (CBC). Besides the machining parameters, they are comprised of tool/tool coating, workpiece material and lubrication or custom strategies like preheating the workpiece.

Tool-chip interface. The tribological contact between tool and workpiece is subject of many phenomena, which have been analyzed in a large number of research projects over the years. The more severe occurrences at the tool-chip interface completely change local conditions of friction and wear. For instance, the formation of a BUL or MTL relocates the cutting interface into the workpiece material which can either lower or increase wear [10, 11]. The mechanism governing frictional forces changes from asperity-asperity deformation and sliding/shearing contact towards bulk workpiece material shearing, inducing forces not describable by ordinary sliding conditions. In most real cutting processes, these effects may occur temporarily or consistently depending on cutting conditions and chemical composition of tool/tool coating and workpiece material. In general, higher speeds tend to change conditions at the tool-chip interface from sliding conditions towards complete or temporal sticking, promoting chip segmentation through shear localization [12, 13].

Many different coating techniques and coating compositions exist to reduce wear of cutting tools, as was compiled for (Ti,Al)N based coatings by PalDey and Deevi [14]. These coatings naturally exhibit different interface properties such as friction and heat partition coefficients depending on the workpiece material. This renders the choice of coating a complex technical task, since few works truly focus on optimizing the choice of coating like Grzesik and Nieslony [15] or Rech et al. [16]. The multitude of coating types and possibilities of layering different types of coatings to be combined with lubrication strategies lead to a dependency on manufacturers recommendations and room for scientific investigations of coating-workpiece material interfaces under different lubrication conditions.

Tool surface texturing (e.g. through laser ablation) represents another method to influence the tool-chip interface, as was demonstrated in [17, 18] for Ti6Al4V (turning and drilling), [19] for turning of AISI 316 steel and [20] for turning of AISI 1045. Depending on the structure applied as well as the tool and workpiece material, frictional forces and process temperatures were reduced, leading to reduced contact length and tool wear either directly or through built-up edge stabilization.

Since frictional contacts constitute the transformation of kinetic into heat energy, a correlation between frictional conditions and thermal conditions at the tool-chip interface is obvious. Due to the inaccessibility of the interface, analytical models enhanced by experiments and simulations provide an insight into how the heat partition coefficient influences local conditions. This was analyzed in [21] for dry cutting of Inconel 718 with coated and uncoated tools, concluding that CBN coatings reduce the friction force more than TiAlN coatings. Additionally, the heat partition coefficient for TiAlN is less than half of what was expected from theoretical calculations. This implies that coatings may influence the heat fluxes present during cutting, leading to more heat energy conducted into chip or workpiece. Even if friction reduction decreases the total heat energy dissipated, it may change surface layer quality in dry cutting if critical temperatures are surpassed in the workpiece (e.g. inducing unwanted phase transitions or influencing residual stresses). Also considering thermal conditions, Atlati et al. [22] analyzed dry cutting of aluminum alloy AA2024-T351 by correlating frictional conditions with the thermomechanical load in the primary shear zone by means of experiments and simulation. They reported that with increasing cutting speed, a smaller contact length and a localized thermally affected region lead to reduced cutting forces. Considering dry milling of Ti6Al4V with cemented carbide tools, Di et al. [23] created an analytical model for calculating the heat partition coefficient at the tool-chip interface which was quite consistent with their experimental data . In both, analysis and experiment, high feed leads to high temperatures irrespectively of cutting speed.

Analyses of the tool-chip interface allow insight into the thermo-mechanical load collective carried by both, tool and workpiece during cutting. Because of the analyses, understanding details as for instance heat partition or texturing of tools is crucial to set up the process to produce parts with surface layer states as desired.

Tool wear in metal cutting. Tool wear in metal cutting entails high cost in industrial use on account of workpiece quality (which degrades with tool wear) and changing time for worn tools. Recently, online tool condition monitoring has become a research priority aiming at alleviating these difficulties [24-31]. Most of these techniques require an extensive database and depend on the process, tool, and material. Furthermore, they do not offer insight into tool wear mechanisms. These mechanisms, while manifold, have been investigated thoroughly over the years. For instance, Gu et al. [32] systematically analyzed tool wear mechanisms of uncoated and coated cemented carbide inserts while milling AISI 4140 steel. By conducting a large number of experiments, the authors were able to create wear mechanism maps as shown exemplarily in Fig. 2 (uncoated inserts). They conclude that ZrN coated inserts do not offer a significant improvement of wear behavior over uncoated inserts when machining AISI 4140. This underlines the difficulty in analyzing the tool wear in metal cutting since any combination of coating, material and process parameters may behave differently. Consequently, many works focus on either different materials of cutting tools, coatings or workpiece materials. For instance, in [33] the wear mechanisms of cutting tools made of PCBN, TiN coated PCBN and mixed alumina ceramic were tested during turning of D2 tool steel. For the workpiece material state (medium hardness), the ceramic tools were found to be the most wear resistant. The effect resulting in this wear resistance is the formation of a Cr-O tribological layer on the ceramic tool surface (BUL), which reduces the severity of frictional conditions at the interface. In [34], CVD diamond and H-DLC coated tools were tested by drilling different cast AlSi alloys. These alloys pose a challenge to tool materials or coatings depending on their silicon content. The percentage of silicon in aluminum correlates to the formation of silicon inclusions, which can damage cutting tools during cutting. This study found that a high silicon content also raises the average friction coefficient at elevated temperatures, with CVD diamond offering the longest tool life. At lower silicon contents, H-DLC coated tools were on par with CVD-diamond coated tools. Similarly, Çalışkan and Küçükköse [35] also considered aCN/TiAlN coatings with regard to workpiece quality of milled Ti6Al4V, Grzesik et al. [36] analyzed CBN tools in precision hard machining of AISI 5115, and Boyd and Veldhuis [37] investigated PVD-coated carbide tools by turning AISI 1045. For difficult-to-cut materials, such as super duplex stainless steels, AlTiN-coated tools not only reduce friction and wear through BUL formation, but also enhance workpiece surface quality according to two recent, separate studies considering dry [38] and wet [39] cutting conditions. However, in dry cutting, mt-CVD-TiCN-Al_2O_3 coating ultimately showed a better performance. It is hard to say, if a cutting length of 0.45 m in dry condition [38] is comparable to 2500 m in wet condition [39].

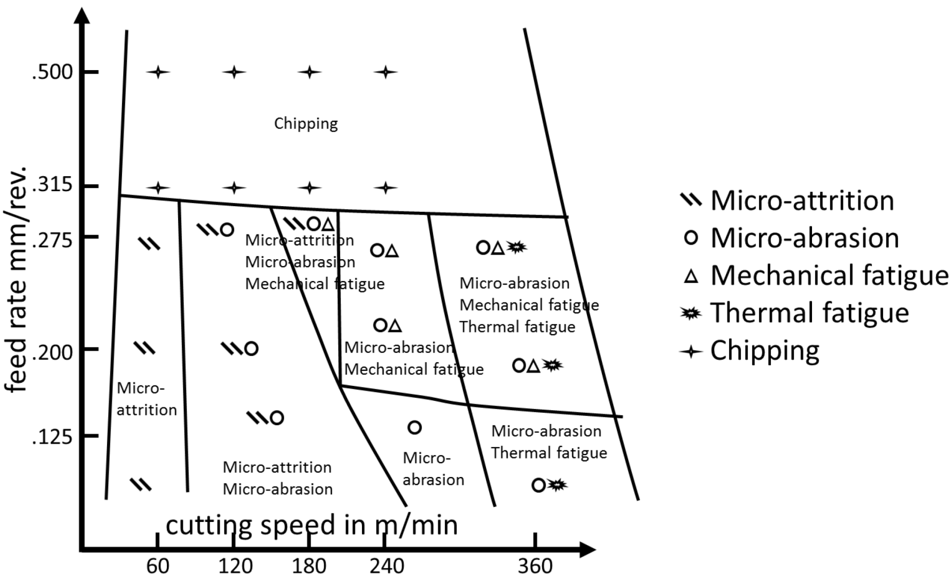


Fig. 2. Wear mechanism map when milling AISI 4140 with uncoated C5 cemented carbide inserts [32].

The influence of the cutting edge radius and its asymmetry on the thermo-mechanical load and wear was analyzed [40]: In continuous cutting of AISI 1045 with TiN-TiAlN coated tools, a larger cutting edge radius leads to higher thermal and mechanical loads. Nonetheless, it offers a minimum of wear compared to unprepared tools at medium sizes with a larger flank edge segment. This is in spite of two facts: First, the increase of the mean tool edge radius (comprised of flank and rake edge segment) generally increases friction on account of a longer contact length. Secondly, a longer flank edge segment significantly increases thermal loads on the cutting tool. For discontinuous cutting, this effect is reverse with a very large radius and the longest rake edge segment achieving the highest tool life increase compared to unprepared edges. The authors conclude that there is still untapped potential regarding cutting edge microgeometry and tool life.

Because lubrication strategies usually enhance metal cutting performance by lowering peak temperatures and friction, they are used widely and in many different forms. Recent works have been focusing on the performance of different lubricants [41], minimum quantity lubrication (MQL) [42], lubrication concurrent with coatings [43], cryogenic [44], and hybrid [45] cooling strategies. Because of the broad spectrum of available lubricants, the resulting possible combinations with cutting tool materials, coatings, and cut material, a multitude of lubrication solutions exist and are subject of past, current, and future research. The works cited here should thus be seen as a small excerpt of current efforts to enhance cutting performance and lower tool wear with lubrication strategies. Certainly, the afore mentioned structuring methods for cutting tools [18-20] also aim at reducing wear and achieve the same – to varying degrees – depending on cut material, coating, and process parameters.

Due to the relevance of tool wear in metal cutting, major effort is channeled into investigating methods to model wear. A few examples are: tool wear prediction using 2D FEM for cutting of Ti6Al4V [46], tool wear prediction using 3D FEM for complex tool geometries considering coatings when cutting ASISI 1045 [47, 48], tool wear prediction using 3D FEM for machining of AISI 4820 [49], and FEM-assisted analytical modelling of tool wear when machining AISI 1018 [50].

Even though, one of the industry's main interests rests on wear, its dependency on frictional conditions at the tool-chip interface renders investigations tedious and time consuming. This is mainly due to the nearly infinite number of combinations of CBC multiplied by processes and parameters thereof. Direct transfer of results considering different CBC or comprehensive approaches are therefore almost impossible.

Stick-slip phenomena in metal cutting. The transition from sliding to sticking friction occurs as the frictional force surpasses the shear flow stress of the workpiece material at the interface. Due to the high normal forces and relative speeds, this frequently happens at the tool-chip interface, leading to BUE, BUL or MTL relocating the relative motion into subsurface plastic flow inside the workpiece [1]. This in particular applies to cutting operations resulting in 'saw-tooth' chips characterized by localized shear bands. The formation of this type of chip, its mechanics and dependence on material hardness was analyzed in [51] for hard turning of AISI E52100. Limits for friction coefficients resulting in sticking vary with material of tool and workpiece as well as process parameters and special boundary conditions (like pre-heating workpieces). With [52] an analytic methodology to determine local tool friction conditions considering sticking and sliding zones was introduced and validated. Due to calibration requiring FEM simulations including a good material model, and the fit of 16 variables, the methodology is rather cumbersome in application. However, it offers a detailed analysis of local friction conditions including tool radii and flank wear for any system. The sticking of material to the surface of the cutting edge can also lead to tribological layers changing the wear mode of cutting tools, as has been demonstrated by [53] for wear mechanisms of TiN coatings during cutting of Ti6Al4V and Inconel 718. In the case of Ti6Al4V, a tribological layer is formed, inducing tool wear through cracks without plastic deformation. This way, the coating increases tool wear. The high fracture strain and lack of adhesion during cutting of alloy 718 instead leads to sliding wear including plastic deformation of the coating, which reduces the wear.

Governing friction mechanics at the tool-chip interface can change from sticking to sliding depending on CBC, the process and its parameters. Even though the effects of stick-slip phenomena are not necessarily beneficial, exploitation of said mechanisms can enhance process effectivity regarding various target variables considerably.

Analyzing Tribological Effects in Metal Cutting

Common test setups. A number of conventional tribological test-setups are used for analyzing tribological effects in metal cutting. Usually, these setups are ball, pin, or cylinder on disc experiments. All afore mentioned types of setups allow working with coated materials and at elevated temperatures. Results can then be transferred to the cutting process, as was done in [18] for surface texturing of tools, or in [54] for drilling and orthogonal cutting. With small adjustments to the test setup, conditions more similar to cutting can be obtained, as demonstrated in [55, 56] with "insert on disc" experiments, as shown exemplary in Fig. 3.

Common setups usually do not reach the typical relative speeds, pressures and temperatures of cutting processes and – being "closed systems" sliding on the same surface – do not reflect the continuous contact with new surfaces (chip and/or workpiece) during metal cutting. Run-in behavior as can be observed in closed tribological systems are possible only for the tool in metal cutting. Even if this does not render the test-setups ineffective, it does raise the question of applicability of data generated this way. Applied in simulations, the interaction of the material deformation and friction model makes this difficult to address, since good results can be obtained through fitting for set conditions regardless of the models used.

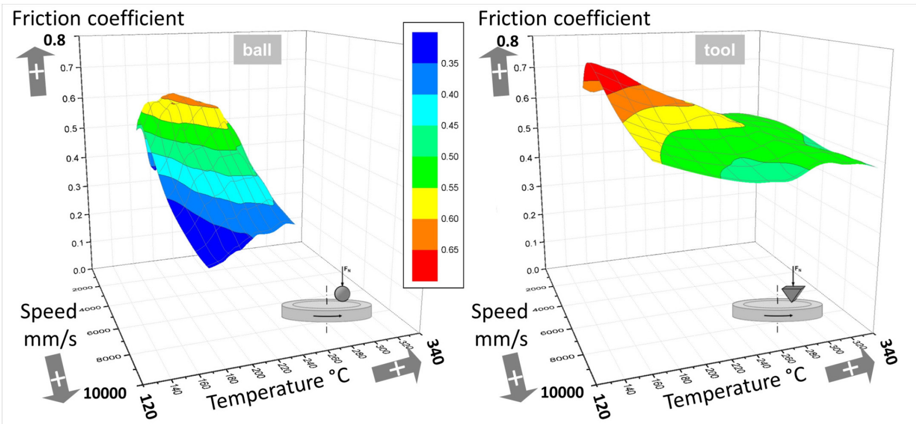


Fig. 3. Results from classic ball on disc (left) and insert on disc (right) tribo experiments [56].

Custom test setups. In order to create friction data with metal cutting conditions, various custom friction test setups were created across the globe. Hedenqvist and Olsson introduced a pin on ring sliding friction tribometer onto a lathe as shown in Fig. 4c [57]. The setup is an open tribological system, never measuring the same surface twice. While generating interesting results about friction coefficients at higher speeds (up to 120 m min^{-1}) and wear, this setup was unable to fully mirror metal cutting conditions due to inadequate magnitude of temperatures and pressures. Measuring friction on a newly generated surface right behind the cutting process can alleviate this issue. To this end, Olsson et al. developed a tribometer measuring directly behind a cutting process as shown in Fig. 4a [58]. Later Zemzemi et al. published a setup as shown in Fig. 4b [59], trying to alleviate issues from the Olsson et al. tribometer. Even though the setup was used by the authors in further works [60], they also developed a new method, which was published in [61] and subsequently used it for multiple publications [21, 62-66]. The more recent setup is an open system able to reach relative speeds of up to 300 m min^{-1} and pressures of approximately 3 GPa. It can be used on newly generated surfaces if desired. In [16], the authors studied friction and heat partition coefficients for different workpiece materials and lubrication conditions condensing earlier works while also adding more data.

Banerjee and Sharma used a Hedenqvist and Olsson tribometer to analyze frictional effects of MQL in cutting of Ti6Al4V [67]. Similarly, Outeiro et al. investigated air-flow cooling in cutting of copper [68]. Boyd et al. constructed a high pressure, high temperature pin-on disc tribometer to generate friction data under near-cutting conditions [69]. Apart from temperature (up to 1200 K) and pressure (in excess of 3 GPa), the closed setup also features a hemispherical imprint, isolating the adhesive component of friction from the ploughing component.

Using an enhanced tribometer based on the one by Olsson et al., Meier et al. investigated friction on newly generated surfaces (in-process) as well as in an open (spiral-on-disc) and closed (pin-on-disc) tribological system [70]. Main conclusions for lubricated sliding contact with Ti6Al4V include a lower friction coefficient at higher pressures and a high relevance of the chemical composition of the lubricant. Additionally, friction coefficients measured in-process were close to those from pin-on-disc experiments. However, spiral on disc data suggested significantly lower coefficients of friction than those measured by pin-on-disc or in-process. Smolenicki et al. also built a setup for an in-process measurement of friction with cutting speeds of up to 300 m min^{-1} [71]. The close proximity of tribometer and cutting tool allows analyses of non-oxidized newly generated surfaces. The authors were able to prove this through in-process experiments flushed with argon not yielding deviating results.

Brocail et al. built an upsetting-sliding test to analyze friction in forming processes. This setup was later fitted with an induction heating and used for various frictional experiments, including investigation of the interface sliding friction in orthogonal cutting of AISI 1045 [72]. The high temperatures (up to 1525 K) offer a good approximation of cutting conditions, even though the maximum relative velocity of 30 m min^{-1} is not fast enough for most cutting processes. Puls et al. also investigated orthogonal cutting conditions with an analogous setup using extremely negative rake angles applied to cutting tools without chip formation. While the first iteration was a closed tribological system [73], the authors later changed it to an open system analyzing various materials, tools, and coatings with a relative speed of up to 125 m min^{-1} [74-76].

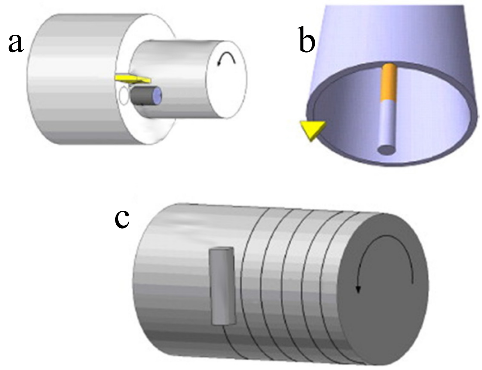


Fig. 4. Tribometers by (a) Olsson et al. [58]; (b) Zemzemi et al. [59]; (c) Hedenqvist-Olsson [57]; as shown in [77].

Custom tribometers should be considered as the best way to create friction data relevant for cutting. However, at least one study concluded that a modified traditional setup yielded nearly the same results as a setup measuring on a newly generated surface and thus implied redundancy of custom setups. Yet again, the multitude of CBC forbids leaping to conclusions. More studies comparing friction data created on different setups are direly needed for more CBC to address this issue.

Analyzing cutting experiments. Analyzing cutting experiments directly to identify the frictional conditions requires temperature and force measurements as well as analytics. Grzesik published comprehensive friction data in [78], regarding a wide range of workpiece materials and coatings. Together with various researches he later added in-depth analyses of the thermal interface of different coatings [15], progressing tool wear [79], and tool chamfers [80]. Hong et al. calculated frictional coefficients in cryogenic turning of Ti6Al4V [81]. Özel et al. determined material and friction data analytically by orthogonally cutting mold steels [82]. In [83], Ozlu et al. calculated sticking and sliding friction coefficients with pin-on-disc and orthogonal cutting tests. An in-depth analysis of orthogonal milling was conducted by San-Juan et al. in [84]. Tebassi et al. proposed a special workpiece geometry to characterize friction during turning [85]. The conus shaped workpiece causes a depth of cut, which continuously increases with feed. This leads to continuously changing CBC, which are not beneficial for friction analysis. However, a refined approach using a staggered geometry might lead to fast and reliable results. Franchi et al. performed an inverse fit of flow stress and friction models in [86]. Connecting exit burrs with friction effects, Niknam suggests analytics as a tool to predict burr formation [87]. Thus, choosing the right process parameters may help increasing workpiece quality after milling.

While promising the fastest results in friction analyses of metal cutting, analyzing cutting experiments directly requires in-depth knowledge of the CBC. Due to the fact that the system's boundary considered in this approach is far from the tool-chip interface, the transferability of results is even more difficult. However, fast and reliable results can be obtained by a direct analysis, even though it is only for one set of CBCs and just one process.

Modelling Tribological Effects in Metal Cutting

Analytical models. Analytical modelling of cutting processes has a long history. In some cases, the models consider frictional energy (usually heat and forces) in an advanced way. These models will be discussed here. In analytics, one problem constitutes in the complexity of the math involved when considering local friction conditions, especially due to the interdependence of friction conditions, forces, and temperatures involved. This problem can be alleviated through simplifications such as considering a mean temperature rather than local conditions as Moufki et al. did [88]. They argued that at high speeds, a coulomb friction law depending on said mean temperature is able to correctly depict the whole system due to the high speeds involved (≥ 1 ms^{-1} by their definition). Their model depends on the mean temperature, the melting temperature and a transition temperature. Later, they transformed their model into an analytical-numerical hybrid [89]. Another possible model postulates sole dependency on the shear angle, which allows considering local conditions as for instance sticking [90]. In [91], a measured, velocity dependent sliding friction coefficient was used to predict cutting forces considering sticking phenomena through calculation of contact length and sticking friction by analytical means. Zhou [92] presented an optimization of the oblique cutting and slip-line models proposed by Qi et al. [93], considering effective rake angle, shear angle and friction angle. Through the effective rake angle, this model is able to regard the cutting-edge geometry. In [94], the model was subsequently transferred to micro end milling also considering run-out and predicting uncut chip thickness. Speed-dependent models, like the one formulated in [95], also achieve good results when used to model process forces. More complex materials, as e.g. metal-matrix composites, require modified approaches, such as the one postulated in [96]. Whether or not similar approaches also apply to grain orientation and phases in micro cutting has not been addressed so far. Other special cases are dynamic processes, as for instance vibration assisted machining [97], or similarly the dynamics of frictional chatter [98, 99].

Even though machining has been subject of analyses for decades, analytical modeling of the tool-chip interface outside orthogonal cutting remains a challange, in particular with regard to the multitude of CBC in real metal cutting processes.

Common friction models. The Coulomb friction law is arguably one of the most widely used models in simulations of chip formation or forming operations. At its heart, it is also quite simple, calculating the frictional force (or shear stress) as the product of normal force (or normal stress) and a dimensionless frictional coefficient $\mu \leq 1$ ($\tau = \mu \cdot \sigma_N$). Combined with the Tresca shear friction model, a maximum frictional stress (sticking condition) is ensured through a second frictional coefficient m ($1 \geq m \geq \mu$) coming into effect if the shear stress reaches the material shear yield stress multiplied by m, depending on e.g. a von Mises yield criterion assumed for the material in contact. Modifying the Coulomb-Tresca model, Zorev suggested using a constant shear stress to consider sticking. This model assumes a maximum shear stress (k in his model) independent on material or further coefficients as the shear stress reaches a critical value [7]. Essentially, both models behave the same, with Zorev's sticking condition allowing for higher shear stresses at the interface. Zorev's model is usually applied differently to select regions of the interface, while the Coulomb-Tresca model can be applied to the whole interface. This also applies to the model proposed by Usui et al. [100], which offers the same functionality as Coulomb-Tresca but is more flexible regarding the transition between the sticking and the sliding condition. Childs et al. built on this model in order to further increase its capabilities in this regard [101].

Common friction models offer high value for the time invested if applied correctly. Still, they are not suited to provide in-depth analyses of surface layer states being induced by cutting operations on account of the disregard of influencing factors such as relative speed. Up to a point, dependencies on these factors can be added to common models by introducing state-dependent friction coefficients. Though ignoring many of the known effects of frictional contacts (as for instance asperity dynamics, roughness, tribolayers, and lubrication films), it is possible to achieve remarkably good results in chip-formation simulations regarding process forces or geometry changes using common friction models.

Custom friction models. For highly detailed analyses of e.g. phase transformation during metal cutting or resulting residual stresses after cutting, common friction models are not detailed enough. In these cases, models not just considering the material yield stress, but also considering stick-slip conditions, relative speeds, temperatures, or all the above, yield the best results. In 2006, Childs reviewed the state of friction models and mechanisms of friction in metal cutting covering lubrication, thermal softening, material inclusions, and solid lubrication as well as implementation into FEM simulations [102]. In his closing remarks, he proposes a friction model depending not on the normal pressure, but on the strain rate [102]. He did not follow up on this proposed model and instead built on the Coulomb model in [103]. Yang and Liu proposed a polynomial variant of the classical Coulomb model in [104]. Arrazola et al. proposed a model considering the local rake angle [105]. Examples for velocity-dependent models are proposed or used by [106-108]. Budak and Ozlu calculated local friction coefficients using observations about contact lengths and resulting forces [91]. Banerjee and Sharma proposed a friction model featuring MQL parameters [67, 109]. A temperature-dependent model was used by Puls et al. in [74]. Bahi et al. built on analytical work to propose a hybrid model in multiple works, e.g. investigating the friction conditions along the tool-workpiece interface during cutting of Ti6Al4V [110].

A selection of the mentioned custom-friction models is depicted in Table 1, stating the main formulation and the additionally addressed variable. The model proposed by Bahi et al. is far too complicated to be presented as a single equation.

Table 1. List of friction models used in literature, application may require additional equations or boundary conditions.

Friction-model formulation	Additional variables addressed	Authors Metal investigated	Publication
$\tau = \min\left(\mu \cdot \sigma_N, \frac{\sigma_f}{\sqrt{3}}\right)$	Flow stress σ_f	Childs steels	[103]
$\tau = \sum_0^n a_n \cdot \sigma_N^n$	/	Yang, Liu 304 stainless steel	[104]
$\mu = \tan\left[\arctan\left(\frac{dF_f}{dF_c}\right) + \gamma\right]$	Coulomb model considering rake angle γ	Arrazola, Ugarte, Domínguez AISI 4140	[105]
$\mu_{adh} = r \cdot V_{ls} + \mu_{max}$; $\mu_{max} = 0.39; r = -2 \cdot 10^{-3}$	Local sliding velocity v_{ls} influencing adhesive friction	Bonnet, et al. AISI 316L	[106]
$\mu_{adh} = c_1 + \frac{c_2}{1 + \left[{(v_{sl} - c_3)}/{c_3}\right]^2}$	Local sliding velocity v_{ls} influencing adhesive friction	Outeiro et al. OFHC copper	[107, 108]
$\mu_{app} = \frac{\tau_1}{P_0}\left[1 - \zeta \cdot \left(\frac{\tau_1}{P_0 \cdot \mu}\right)\right]$	Apparent friction coefficient related to sliding friction	Budak, Ozlu Ti6Al4V	[91]
$\mu = 3.32 \cdot V^{-0.45} - 0.24 \cdot f$	MQL-volume V and tool feed f	Banerjee, Sharma AISI 1045, Ti6Al4V	[67, 109]
$\mu = \mu_0 \cdot \left(1 - \frac{T - T_0}{T_m - T_0}\right)^m$	Temperature T and melting temperature T_m	Puls, Klocke, Lung AISI 1045, 4140, Inconel 718	[74]

Common variables addressed: τ: frictional shear stress; σ_N: normal stress; μ: sliding friction coefficient

Custom friction models enable in-depth analyses of surface layer states in simulations. Still, present models fall short of offering transferable, comprehensive solutions applicable to more than the process investigated under given CBC and can be rather complicated to understand, apply, and fit to the CBC investigated.

Chip-formation simulations. For some time, chip-formation simulations have been part of the international research effort. If executed correctly, a few select experiments empower simulations to predict forces, temperatures, and surface layer states across an area of process parameters. Friction models in use range from constant coefficient to the most complex hybrid models. Examples for Coulomb model usage in conjunction with various sticking conditions are [46, 111-117]. Reviews and comparisons of different models used in chip-formation simulations have been published by a number of authors [118-123]. Using the model proposed by Usui et al. or iterations thereof also yield good results if done properly [124]. Implementing friction data directly from experiments can enhance results considerably, if sliding velocity, temperature, pressure, and tool coating are considered [54, 125]. Velocity-based models, as applied in [47] for wear prediction, can also be quite accurate. Chen et al. used a regression of experimental data to determine friction conditions, allowing for cutting speed, feed and depth of cut [126]. The thusly calculated friction coefficient was applied for a constant Coulomb friction model in simulations. A few works also focused on inverse determination of friction coefficients, using the FEM for calibration [127, 128].
The works cited are a small part of the collective effort in empowering the simulation-based approach to be truly predictive. Steady progress is made and enhanced by continued achievements in measurement techniques, as critically reviewed in [5]. Besides future needs listed there, chip-formation simulations must assess current modelling techniques including software benchmarks for robustness, accuracy, and speed.

Tribology of Cut Metal Surfaces

Topography and surface structuring. Development of topography by cutting has been analyzed experimentally and analytically since the beginning of manufacturing science. Meanwhile, numerous methods which consider various influences have been elaborated. For example, Omar et al. proposed a model predicting topography and cutting forces in end milling [129], and Arizmendi et al. published a model predicting topography after peripheral milling considering tool vibration [130]. Maiss et al. experimentally analyzed the influence of cutting edge microgeometry on the resulting topography in [131]. Regarding the tribology of cut-metal surface topographies, Sedlaček et al. benchmarked ground, polished, turned, and milled AISI 52100 surfaces but were unable to draw definitive conclusions from their pin-on-disc experiments [132]. This might be because of the disregard for further surface layer states influenced by the manufacturing processes chosen. In a further study, the same authors correlated ground and polished samples with their respective roughness parameters to tribological properties [133]. Success in this case may be based on the similarity of grinding and polishing, isolating roughness from further surface layer states. Bruschi et al. investigated the wear behavior of differently machined, wrought and additively manufactured Ti6Al4V in reciprocal wear tests [134]. They concluded that even though cryogenic cooling did not improve topography over dry cutting, it significantly improved the wear behavior due to compressive residual stresses. The surface layer states before cutting exhibited little influence in their case. Considering experimental surface topographies, Albers at el. carried out wear simulations considering a mixed lubrication state [135]. When validated, the proposed model will be able to predict the flattening of the surface as well as the friction coefficient and the wear volume. Dzierwa carried out ball-on-disc tests on ground, milled and burnished AISI 4140 topographies [136]. Even though the author's analyses allowed for decisive conclusions correlating surface topography to wear behavior, further surface layer states were disregarded in the study. This adds an element of uncertainty to the results.

Surface structuring can be used to influence tribological performance of surfaces in sliding or rolling contacts [137-139]. This beneficial influence of structures, however, is highly dependent on the tribological system the structures are applied to as well as the anisotropy of the structures used. An example of investigations considering structure anisotropy is [140]. Due to changes in heat dissipation, textured surfaces were also found to reduce temperatures during sliding contacts as demonstrated by Wu et al. on wire cut textures [141], which may also explain the lowered friction coefficient measured. Apart from classical means of structuring, such as laser structuring,

structuring can also be achieved during machining using the cutting tool. This can be done using additional actuators as demonstrated by Denkena et al. [142], or using inclination angles of tool and workpiece as investigated by Resendiz et al. [143] and Hadad et al. [144]. Due to the kinematics involved, structuring is also possible in turn-milling as demonstrated by Karpuschewski et al. [145].

Surface structuring of metal surfaces can reduce friction and wear if applied correctly. In some cases, it is hard to separate the effects involved. Additionally, most investigations completely disregard the interaction of surface structure and surface layer states.

Residual stresses. Residual stresses of cut metal surfaces are induced through the combined effect of mechanical and thermal load. Recent works on cutting induced residual stresses include investigations into residual stresses after sequential cuts of AISI 1045 [146], of cutting parameters and residual stresses of AISI 1018 [147], and the dependency of residual stresses in hard turning of AISI 5115 [148] and AISI 52100 [149]. In [150], Jawahir et al. reviewed different cutting processes with regard to the resulting surface integrity. In [151], the influence of cutting edge geometry on resulting residual stresses was investigated. Geometries promoting a longer contact length were found to induce higher compressive stresses. Analytical [152] and empirical or numerical [153] predictions of residual stresses after metal cutting are also still being enhanced. A review by Saini et al. covered residual stresses, surface roughness and tool wear in hard turning up to the year 2012 [154].

While predicting residual stresses of cut-metal surfaces is widely practiced, as shown in the mentioned works, their relevance in tribological contacts has not yet been exhaustively analyzed with respect to sliding contacts. In rolling contacts, a number of works exists, as for instance by Pape et al., correlating bearing fatigue life with deep-rolling induced residual stresses [155]. In this application, residual stresses induced before rolling contacts increased fatigue life through suppression of crack initiation. In dry sliding contacts, studies from 1983 and 1991 concluded that residual stresses only influence part performance if they surpass the contact induced stresses [156, 157]. Simulating surface residual stresses with a four-point bending frame, Ryu et al. investigated the material removal rate during a single-asperity wear process of highly pure copper [158]. They concluded that the fatigue stress intensity was reduced by tensile stresses. The results agreed with earlier, similar works on ASTM F-75 [159]. Since numerous works demonstrated positive effects for compressive residual stresses, the applicability of these results for macroscopic contacts is doubtful.

Works on effects of residual stress states on sliding contacts are rare. In contrast, a myriad of investigations into processes and treatments concerning the evolution of residual stresses exist. New works considering cutting induced residual stresses and tribology of dry or lubricated sliding contacts are either non-existent or obscured by works covering other aspects of residual stresses.

Grain sizes. During cutting of metal, recrystallization of the surface layer can occur. Mechanisms of dynamic recrystallization of metals have recently been reviewed by Huang and Logé [160]. In cutting, the formation of nanocrystalline surface layers can be influenced by using the process parameters. Work in this field continues due to the interest in mechanical properties of nanocrystalline materials. Current works are considering effects during cutting [161, 162] as well as the formation of surface layers [163-166]. In general, nanocrystalline (av. grainsize ≤ 0.1 µm) or microcrystalline (av. grainsize ≤ 1 µm) metals tend to exhibit less wear due to not fully understood mechanics, as a review by Zhong et al. concluded ten years ago [167]. Recently, grain evolution during tribological load was analyzed by Wolff et al. [168]. Continued tribological load profoundly changes the surface layer microstructure over time. Investigations such as these combined with an enhanced understanding of the mechanical behavior of nanocrystalline metals during sliding contacts may provide insight into what grain size distribution are beneficial for tribological applications. Besides the surface structure, deeper surface layer states also seem to influence wear behavior. This was shown by Yao et al., who demonstrated higher wear with increasing grain size beneath the tribolayer [169].

Grain size effects in tribology remain only vaguely understood. This may well be due to the isolated perspective concentrating on different grain sizes or nanocrystalline surface layer depths and disregarding interactions with further surface layer states, as for instance residual stresses, phase composition or chemical composition, which may have been changed during manufacturing.

Phase composition and transition. During metal cutting, the combination of stress and temperature may lead to phase transformations. With regard to cooling strategies, this is either a problem or an opportunity for optimizations of surface layer states. The martensitic transformation of steels has been modelled and analyzed extensively [54, 56, 170, 171]. In principle, the impact of hardness and wear resistance has been known for a long time [172]. This makes the correlation between phase composition and wear resistance obvious, if a phase harder than the prevalent phase is involved. However, research on this topic revealed that the more stable phase exhibits less wear than the harder phase [173]. Stability in this case is measured versus the prevalent loads of the tribological contacts e.g. frictional heat, plastic deformation and crack initiation and propagation [173]. Frölich et al. demonstrated that martensitic transformation, induced by cryogenic cooling during cutting, can increase wear resistance of AISI 347 surfaces [171].

Surface-layer phase-composition may influence tribological and wear behavior in unexpected ways if disregarded in investigations. Literature offers insights into many observable effects regarding transition of phases during manufacture. The influence of these changes on tribological behavior are explainable through thermodynamics rather than mechanics. How a tribological system reacts may again not be predictable by isolated investigation of singular surface layer states.

Future Needs and Opportunities

As becomes apparent when weighting the works executed on different topics, friction during and after cutting remains of high relevance and offers much scope for improvement. Remaining questions can be ordered and summed up as follows:

Friction during metal cutting:

- Defining ways to transfer data from common setups to true metal cutting conditions
- Formulating new comprehensive approaches to friction in cutting able to cope with various speeds, pressures, temperatures, lubrication states, and materials/coatings
- Controlling local friction during cutting using process- and lubrication strategies or tool surface-structuring to improve workpiece quality or reduce wear

Friction on cut metal surfaces:

- Analyzing the true influence of topography through consideration of more surface layer states including residual stress states
- Combining knowledge of positive effects through all surface layer states to find ideal conditions for tribological contact of metal surfaces

Ongoing investigations, such as the CIRP working groups on material models by J. Outeiro and on friction by V. Schulze, may provide insight into solving some of the questions about friction during metal cutting and its influence on surface layer states in the near future.

Conclusions

The field of tribology in the context of metal cutting is wide and complex, requiring broad knowledge of advanced sciences in order to move forward. This paper laid out the state of knowledge and recent investigations into these matters. Many different approaches for investigating friction exist and are suited to produce coefficients of friction under various conditions. The large number of options for identifying frictional coefficients for cutting operations severely hampers unified approaches, as existing data may or may not be fitting for the friction model used. In practice, industry often uses very simple models in simulations to keep the process easily understandable. However, this hardly allows producing in-depth knowledge about metal processing, since advanced models are required for this application, as has been demonstrated in literature.

Analyses of friction and wear on cut metal surfaces must be intensified, in particular with regard to interdependence of different surface layer states from topography to phase composition.

Tribologists need to find a comprehensive approach to describing friction during cutting. Similar in complexity to constitutive material models, this approach must be able to depict all conditions during metal cutting. This includes the metal being cut and the material of the tool or coating. Influencing factors, such as speed, temperature, and pressure, should be considered separately in a conjoined formulation, making the model easy to use and applicable to a broad spectrum of processes. Workpiece and tool/coating material might be included through their respective surface/atomic-bond energy or similar, process-independent, material-specific values. This would ensure applicability across materials cut and tools used. To achieve this, more joint international and interdisciplinary works like those already in progress are needed to promote understanding of these matters. Thusly, predictive powers of simulation-based approaches in manufacturing science will be increased significantly.

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