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IDENTIFICATION OF FRICTION AND HEAT PARTITION MODEL AT THE TOOL-CHIP-WORKPIECE INTERFACES IN DRY CUTTING OF AN INCONEL 718 ALLOY WITH CBN AND COATED CARBIDE TOOLS

F. Zemzemi , J. Rech, W. Ben Salem, A. Dogui, Ph. Kapsa

S u m m a r y

This paper aims at characterizing the frictional behaviour at the cutting tool-workmaterial interface during the dry machining of a Inconel 718 in its aged state with various coated carbide tools and c-BN tools. A specially designed open tribometer has been used to characterize friction coefficient, heat partition coefficient under extreme conditions corresponding to the ones occurring in cutting. The tribometer provides the evolution of the apparent friction coefficient and of the heat partition coefficient for a large range of sliding velocity and contact pressure. It has been shown that friction coefficient as well as heat partition coefficient decrease with sliding velocity or contact pressure. A threshold effect of the contact pressure has been highlighted. On the contrary, any sensitivity to coatings deposited on carbide has been observed, whereas c-BN leads to very low friction coefficients.

Keywords: Inconel 718, cutting, friction, heat partition coefficient, cubic boron nitride, coatings, carbide

Identyfikacja tarcia i model podziału ciepła w strefie kontaktu wiór-ostrze-materiał obrabiany w toczeniu na sucho nadstopu Inconel 718 narzędziami z CBN i węglików spiekanych z naniesionymi powłokami

S t r e s z c z e n i e

W pracy określono charakterystykę tarciowego zachowania się strefy kontaktu wiór-ostrze obrabianego w toczeniu na sucho nadstopu Inconel 718 po starzeniu narzędziami wykonanymi z różnych gatunków węglików spiekanych z naniesionymi powłokami i polikrystalicznego CBN. Zaprojektowano i wykonano tribometr do wyznaczania wartości współczynnika tarcia i współczynnika podziału ciepła. Badania prowadzono w warunkach ekstremalnych zbliżonych do występujących w procesie skrawania na sucho. Tribometr umożliwia pomiary w czasie wartości pozornego współczynnika tarcia i przepływ ciepła dla dużego zakresu wartości prędkości skrawania i nacisku normalnego. Wykazano, że zarówno współczynnik tarcia, jak i podziału ciepła zmniejszają się przy wzroście prędkości i siły normalnej skrawania. Określono graniczny efekt nacisku kontaktowego. Nie stwierdzono wpływu rodzaju powłoki

Address: F. ZAMZENI, PhD, Université de Monastir, Ecole Nationale d'Ingénieurs de Monastir, Laboratoire de Génie Mécanique, Monastir, Tunisia, J. RECH, Prof. DSc. [c] Université de Lyon, ENISE, LTDS, CNRS UMR 5513, 58 Rue Jean Parot, 42000 Saint-Etienne, France, W. BEN SALEM, PhD, Université de Monastir, Ecole Nationale d'Ingénieurs de Monastir, Laboratoire de Génie Mécanique, Monastir, A. DOGUI, PhD, Université de Monastir, Ecole Nationale d'Ingénieurs de Monastir, Laboratoire de Génie Mécanique, Monastir, Ph. KAPSA, PhD, Université de Lyon, Ecole Centrale de Lyon, LTDS, CNRS UMR 5513, Ecully, Tel.: +33 6 77 09 81 23; fax: +33 4 77 43 75 39, e-mail: joel.rech@enise.fr

na ostrzu z węglika spiekanego na wartość współczynnika tarcia. Natomiast skrawanie narzędziami z ostrzem p-CBN prowadzi do uzyskania bardzo małej wartości współczynnika tarcia.

Słowa kluczowe: Inconel 718, skrawanie, tarcie, współczynnik podziału ciepła, regularny azotek boru, powłoki, węgliki spiekane

1. Introduction

Inconel 718 alloy is a nickel based alloy, which is widely used in the aircraft industry. The primary uses of these alloys are in aircraft gas turbines (disks, combustion chambers, shaft exhaust systems, blades, etc.) and steam turbine power plants (bolts, blades, stack gas reheaters, etc.) due to their exceptional thermal resistance and ability to retain their mechanical properties at high temperatures. However, many authors, such as Javaid et al [1], have reported their difficulties to cut this material in its aged state due to its high shear strength, work hardened tendency, highly abrasive carbide particles in the microstructure, strong tendency to weld and form built-up-edge and low thermal conductivity. These characteristics of the alloys cause high temperature (>1000°C) and stresses (>3450 MPa) in the cutting zone leading to accelerated flank wear, cratering and notching, depending on the tool material and cutting conditions super alloys [2]. Nickel-base are normally machined with uncoated carbide tools (WC–Co grades) or TiN coated carbide tools with cutting speeds in the order of 20-30 m/min [3]. Turbine engines manufacturers are willing to increase the productivity of their cutting processes. In order to achieve this aim, industry is willing to adopt high cutting speeds. With the introduction of TiAlN coatings on carbide tools, it is possible to apply cutting speed close to 50 m/min [4] due to their high chemical resistance at high temperature. More recently the application of c-BN materials enables to increase the cutting speed in the range 120 to 240 m/min due to their high hardness [2]. Considering the cost of each part made of Inconel 718 (ex: a forged ring in its aged state costs ~ 60.000 € before any machining operations – diameter 900 mm – thickness 120 mm), it is highly necessary to develop models in order to predict the best cutting conditions and/or the best cutting tool design, which can provide the greatest improvement without destroying a part. Several scientific papers have proposed important contributions to the analytical modeling [5-7] or to the numerical modeling (Finite Element Analysis) of Inconel 718 cutting [8, 9].

These models enable to estimate cutting tool wear based on the thermo-mechanical conditions occurring at the tool-workmaterial interface, or to predict the segmentation of chips (saw tooth chips).

The development of a cutting model necessitates a large number of parameters:

- The mechanical properties of the workmaterial: flow stress model, damage model,

• The thermal properties of the workmaterial and of the cutting tool material,

• The heat exchange coefficient of the material with environment,

• The friction model of the couple workmaterial/cutting tool material,

• The heat partition coefficient at the interface between the workmaterial and the cutting tool material (secondary shear zone and rubbing zone in Fig. 1) due to the frictional heat.

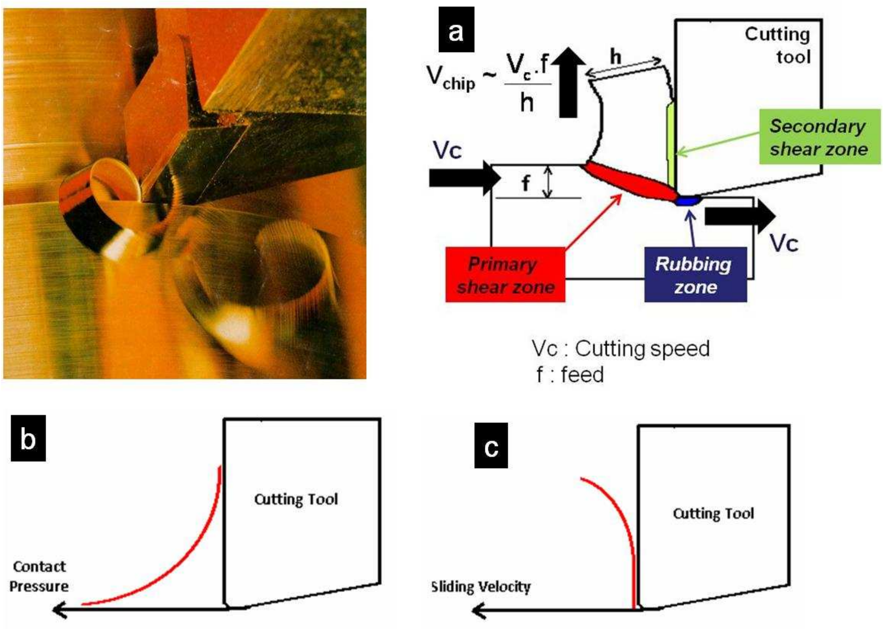


Fig. 1. Chip formation mechanisms (a) – typical shape of normal stress distribution (b) and sliding velocity distribution on the tool rake face (c)

Among these data, the scientific community regrets an important lack of knowledge on friction and heat partition models at the tool-workmaterial interface [10]. In the context of Inconel 718 alloy machining, this lack is even worse due to the narrow range of applications and to the price of this alloy, which limits practical investigations as pointed out by [7]. As an example, some authors [6, 8, 9] do not mention the values of friction coefficient in their model. Other authors [5], consider that friction coefficient is constant all around the cutting tool, but do not provide its value. Finally some authors [7], consider two regions in the contact: a sliding region modeled by a Coulomb’s friction law, and a sticking region defined by a critical shear stress, but they do not provide any quantitative value of these parameters. Anyway, soo et al. [7] reports that the discrepancies of his model is largely influenced by the over-simplification of the friction model, whereas Monaghau [5] indicates that his model is not able to predict the built-up-edge effect, that is largely dependent on the friction model. One explanation for these discrepancies is probably due to the absence of any specific tribological set-up to identify these data. Friction coefficient are either assumed, or adjusted by iteration by means of the numerical cutting model itself in order to fit numerical and experimental macroscopic cutting and feed forces and/or the shear angle in the primary shear zone [7]. Due to the large uncertainty for each input data, it is questionable if this methodology could provide relevant friction coefficient. Especially, Ozel [10] has shown, that a large variation in friction modeling has little influence on macroscopic forces, but is has a huge influence on contact temperature. So it is difficult and dangerous to use macroscopic forces to fit friction parameters.

Moreover, many papers do not mention the existence of a heat partition coefficient at the tool-workmaterial interface, even if several authors, such as Bonnet et al [11], have shown its strategic influence on contact temperature. As an example, in the context of Inconel 718 cutting, Sonawane et al [9] has neglected the heat transfer at the tool-chip interface, whereas Montaghau et al [5] has included this parameter in theirs model without providing its value.

This literature review proves that the knowledge on the frictional properties during the machining of Inconel 718 alloy requires great improvement. So there is a deep necessity to discuss the way to obtain relevant friction and heat partition coefficients. Fig. 1 proposes a schematic view of the various tribological situations observed along the tool-chip contact area. The contact pressure, along the tool rake face of a cutting tool, varies considerably [12]. Its maximum value is close to the cutting edge and easily reaches 3.5 GPa for Inconel cutting as shown by [2]. On the contrary, its minimum value (0 MPa) occurs at the end of the contact between the cutting tool and the chip (Fig. 1b). Additionally, [13] and [11] reported that sliding velocity varies along the tool rake face (Fig. 1c). The sliding velocity is about zero close to the cutting edge and increases slowly until it reaches its maximum value at the end of the tool-chip contact area (close to V_{chip} as defined in Fig. 1). On the other side, in the rubbing zone, the friction velocity is almost equal to the sliding velocity *Vc*.

As a consequence, it is clear to any expert in tribology that, due to the variable sliding velocity along the tool-workmaterial contact, the friction coefficient and the heat partition coefficient vary also along the contact [14] in the case of steel and stainless steel machining. As plotted in Fig. 2, in zone “i” at the tool-workmaterial interface, the local contact pressure “P_i” and the local sliding velocity “V_i” will lead to a local friction coefficient “μ_i” and to a local heat partition coefficient “α_i”. So there is a need to perform a friction test on a tribometer independent from the cutting process itself, with the same contact pressure “P_i” and the same sliding velocity “V_i” in order to identify this local friction coefficient “μ_i” and this local heat partition coefficient “α_i”.

Additionally, in order to identify the evolution of the local friction coefficient in any zone “i” along the contact, it becomes necessary to perform friction tests with a large range of sliding velocities (from 0 m/min up to the desired cutting speed *Vc*).

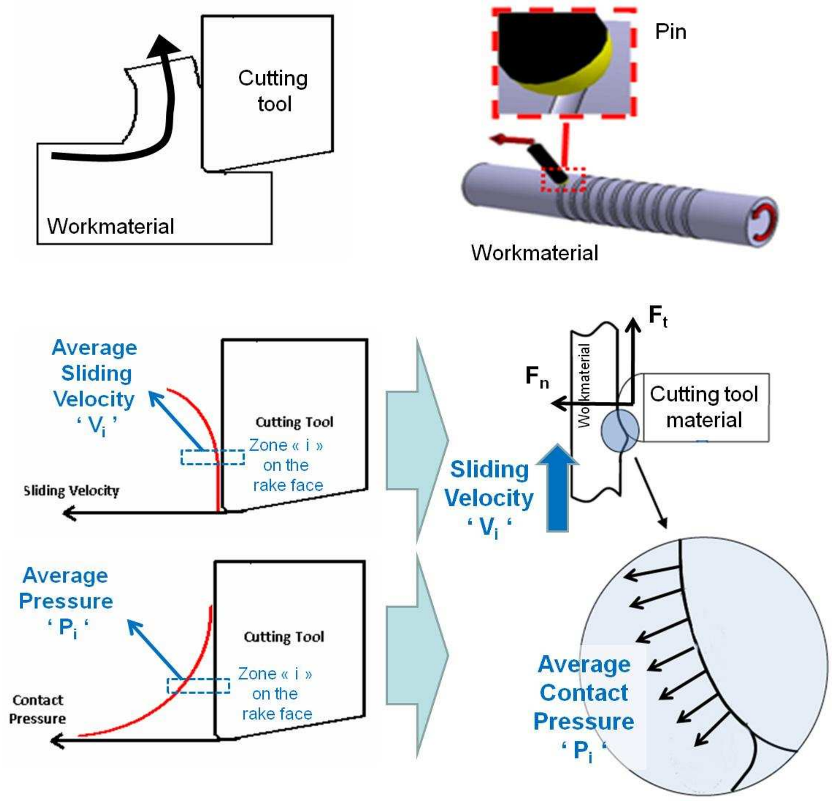


Fig. 2. Specification of the tribo-contact to simulate a cutting operation

As mentioned previously, many authors use the cutting process itself to evaluate an average macroscopic value of friction coefficient on the rake face, without considering the influence of the edge radius (ploughing effect) or without considering the contact with the flank face. This method has been used by several authors for Inconel 718 alloy [7], but also for other workmaterials [15, 16]. The main limitation of this approach is due to the fact that the estimated friction coefficient is obtained from cutting tests and not from friction tests. The limitation of cutting tests comes from the fact that they are only able to provide macroscopic data. For example, from macroscopic cutting force and feed force, it is very difficult to discriminate the role of the primary shear zone and of the secondary shear zone and of the rubbing zone. As a consequence, the estimation of the friction coefficient is difficult as well. Moreover, it has been shown previously that such tests can only estimate an average friction coefficient on the rake face, whereas the friction coefficient varies a lot along the contact. Additionally most of them are not able to estimate the heat partition coefficient, since they are not able to measure the heat flux transmitted to cutting tools or the temperature in the cutting tool.

Hence, it becomes clear that a better understanding of the frictional phenomena at the tool-workmaterial interface can only be done by means of a special tribometer, independent of any cutting process, able to simulate similar tribological conditions (pressure, temperature, velocity) as the one occurring along the tool-workmaterial interface, as shown in Fig. 2. A specially designed tribometer (Fig. 2) has been developed to simulate any tribological conditions occurring at the tool-workmaterial interface in terms of contact pressure “Pi” and sliding velocity “Vi”. This tribometer involves a pin (made of the same material as the one of the cutting tool) rubbing a surface (made of the same material as the one of the investigated workmaterial), in order to simulate the friction in cutting. Due to the helical movement of the pin around the bar, this tribometer can be classified as a so called ‘open tribometer’, since the pin rubs against a continuously regenerated surface on the bar. This configuration is highly necessary in order to simulate the friction of the workmaterial around the cutting tool. Indeed, Fig. 1 reminds that the workmaterial is only once in contact with the cutting tool, either on the rake face or on the flank face, which explains the necessity to use only open tribometers instead of commonly used pin-on-disc tribometer.

This system, based on the principle proposed by Hedenquist et al. [17], was developed by Zemzemi et al. [14]. The instrumentation provides the friction coefficient, as well as the heat flux transmitted to the pin, which enables to estimate the heat partition coefficient.

As mentioned previously, Inconel 718 alloy is commonly machined on the one hand with TiN or TiAlN coated carbide tools, and on the other hand with c-BN tools. So, this paper aims at characterizing the friction coefficient and heat partition coefficient of TiN or TiAlN coated carbide pins and c-BN pins against a bar made of Inconel 718 in its aged state. Moreover, considering the variety of cutting conditions used in industry and considering that friction conditions vary very significantly on the rake face and on the flank face, this paper aims at characterizing these friction properties in a large range of sliding velocity and contact pressure.

2. Experimental set-up

The principle of this open tribometer has already been applied and validated in several previous works [11, 14, 18] published in various scientific journal, including International Journal for Machine Tool and Manufacture. The tribometer is based on a lathe as shown in Fig. 3. The workmaterial is simulated through a cylindrical bar of a Inconel 718 alloy.

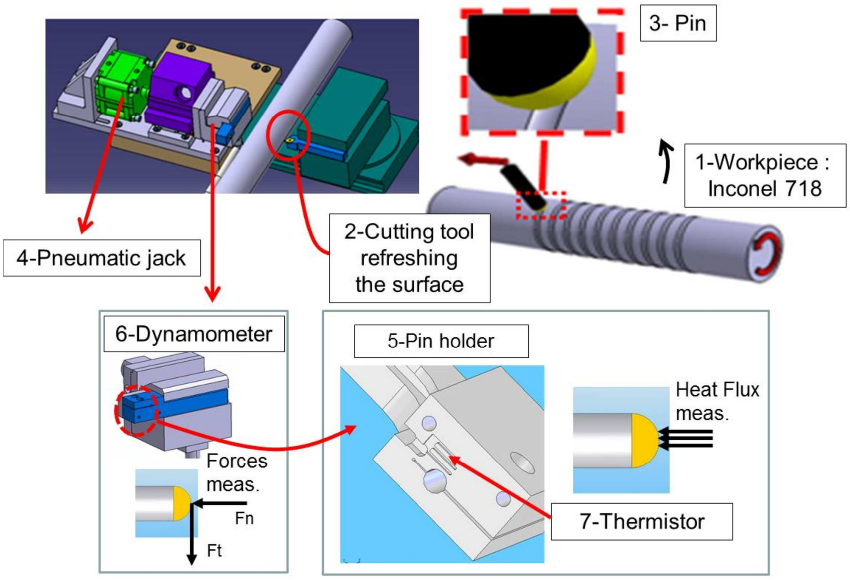


Fig. 3. Description of the tribometer

Cutting tools are simulated through pins having a spherical geometry. They are either made of carbide (grade H10F from Sandvik) or made of c-BN (grade DCC500 from Element Six) which are similar grades to the ones used for cutting tools designed for Inconel 718 alloys. In order to eliminate the potential influence of surface roughness, pins have been polished to reach a low surface roughness (Ra < 0.3 µm) which is coherent with a typical surface roughness on a finely ground carbide cutting tool. Then carbide pins either remains uncoated, or have been coated with TiN layer or a TiAlN layer deposited by the PVD method.

Concerning the bar, after each friction test, a cutting tool refreshes the surface ploughed by the pin. A belt finishing operation is also performed in order to obtain a very low surface roughness (Ra ~ 0.1 µm) and a constant surface for each test.

Each friction test has 10 seconds duration approximately and it has been replicated 3 times in order to estimate the uncertainty.

Each pin is maintained by an instrumented pin-holder. The pin-holder is fixed onto a dynamometer in order to provide the apparent normal F_n and tangential force F_t (macroscopic forces). The apparent friction coefficient is provided by the ratio between the tangential and the normal forces.

$$\mu_{app} = \frac{F_t}{F_n} \tag{1}$$

The term ‘apparent friction coefficient’ or ‘macroscopic friction coefficient’ is used since it differs significantly from the ‘local friction coefficient’ induced by adhesion at the pin-workmaterial interface (Fig. 2). Indeed the macroscopic forces measured by the tribometer include on the one hand adhesive phenomena, that is affected by properties such as hardness, chemical reactivity, asperities, and on the other hand plastic deformation of the workmaterial, which cannot be neglected under such severe contact conditions (up to $F_n \approx 1000$ N). Bonnet et al and Zemzemi [11, 14] have used a simple decomposition of these macroscopic forces:

$$\mu_{app} = \mu_{adh} + \mu_{plast} \tag{2}$$

Where, μ_{app} is the apparent friction coefficient, μ_{adh} the adhesive part and μ_{plast} the deformation part. Of course, the major hypothesis of this model is that a relative movement exists between two materials. No static adhesive layer should be present at a smaller scale in the interface.

Based on this assumption, it becomes possible to extract the part of adhesion and deformation from the apparent friction coefficient, based on an analytical model [19] or a numerical model [14].

Each pin is maintained by an instrumented pin-holder which, in dry sliding situation, is able to provide data on the instantaneous heat flow entering into the pin (φ_{pin}). [20]. It should be underlined that only a percentage of the total energy φ_{tot}, dissipated during tests, is transmitted to pins. A large amount of heat remains in the workmaterial $\varphi_{workmaterial}$ [14].

It is possible to estimate the total energy dissipated during the test by:

$$\varphi_{tot} = F_t \, . \, V \tag{3}$$

By assuming that all the energy is transformed into heat, and by assuming that the thermal conductivity of the interface remains constant, the heat partition coefficient α can be estimated by:

$$\alpha = \frac{\varphi_{pin}}{F_t \cdot V} \tag{4}$$

This means that a heat flux equal to $\alpha \cdot \varphi_{tot}$ is transmitted to pins, whereas the workmaterial supports $(1 - \alpha) \cdot \varphi_{tot}$.

By neglecting the heat dissipated by the plastic deformation of the workmaterial and by assuming that a relative movement at the interface exists, it becomes possible to estimate the theoretical heat partition coefficient α_{theo} for sliding contacts. A commonly used model is based on the ratio of effusivity ε of the two materials [5], as shown in equ. 5. This model has also been validated for several materials (steels, stainless steels) [11, 21], when sliding velocity is very low (quasi-static contact).

$$\alpha_{theo} = \frac{\varepsilon_{pin}}{\varepsilon_{pin} + \varepsilon_{wm}} = \frac{\sqrt{\lambda_{pin}.\rho_{pin}.C_{pin}}}{\sqrt{\lambda_{pin}.\rho_{pin}.C_{pin}} + \sqrt{\lambda_{wm}.\rho_{wm}.C_{wm}}} \tag{5}$$

with :

λ_{pin} = 44.6 ($W.K^{-1}.m^{-1}$) at 20°C

ρ_{pin} = 12800 ($kg.m^{-3}$) at 20°C

C_{pin} = 226 ($J.kg^{-1}.K^{-1}$) at 20°C

λ_{wm} = 6.6 ($W.K^{-1}.m^{-1}$) at 20°C

ρ_{wm} = 4430 ($kg.m^{-3}$) at 20°C

C_{wm} = 565 ($J.kg^{-1}.K^{-1}$) at 20°C

Thus α_{theo} is close to 64% at 20°C.

As mentioned previously, this equation is only valid for very quasi-static contacts and not for dynamic sliding interfaces [13, 22]. So an experimental estimation of the heat partition coefficient α is necessary for high sliding velocity. This point is an important originality of this experimental set-up.

Concerning the friction conditions that have to be tested, they depend on the cutting conditions. As mentioned previously, Inconel 718 alloy is commonly machined on with TiN or TiAlN coated carbide cutting tools with cutting speed in the range 20-50 m/min, and with c-BN cutting tools up to 250 m/min. So, this paper aims at characterizing the friction coefficient and heat partition coefficient of uncoated or TiN or TiAlN coated carbide pins in a range of sliding velocity between 20 and 50 m/min, and of c-BN pins in a range of sliding velocity between 80 and 250 m/min in order to explore the frictional phenomena along the tool-chip interface (secondary shear zone and rubbing zone – Fig. 1).

Carbide pins have been manufactured with three pins spherical diameter of 9, 13 and 17 mm. A normal force of 1000 N has been applied for all pins in order to obtain average contact pressure of approximately 3.4, 2.6 and 1.8 GPa [14]. This range of contact pressure is in accordance with the contact pressure estimated along the tool-Inconel 718 interface [2].

C-BN pins have been manufactured with a 9 mm diameter only. A normal force of 1000 N has been applied in order to obtain an average contact pressure of approximately 3.4 GPa.

All tests have been performed in dry conditions.

3. Experimental results

3.1. Influence of sliding velocity

Figure 4 plots the evolution of the apparent friction coefficient μ_{app} versus sliding velocity *Vs* for TiAlN coated pins. It is shown that friction coefficient decreases as sliding velocity increases. Apparent friction coefficients are in range from 0.2 to 0.6. This trend corresponds to a standard behaviour already observed for several metallic materials, such as AISI1045 steels [21] or AISI316L [11] or AISI4142 [14]. This decrease is due to a combined effect of the decrease of the interfacial friction coefficient μ_{adh} and of the loss of the mechanical properties due to heating of the Inconel 718.

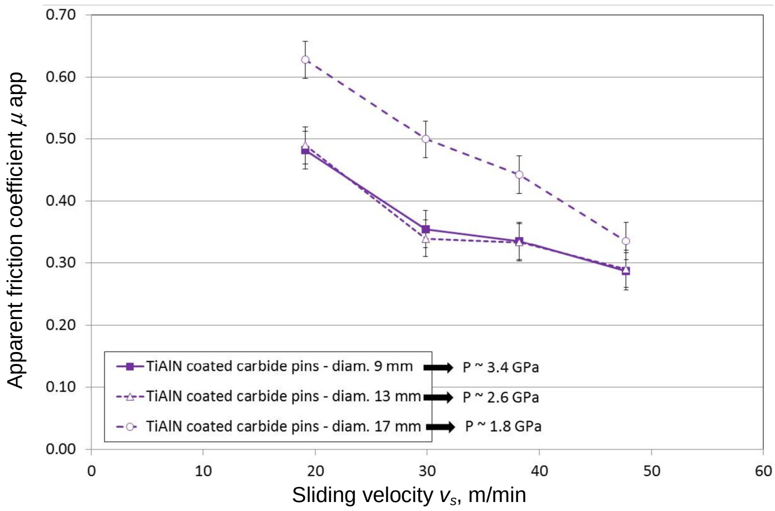


Fig. 4. Evolution of the apparent friction coefficient versus sliding velocity for three contact pressures

Figure 4 plots also the evolution of apparent friction coefficients for three average contact pressures from 1.8 GPa to 3.4 GPa. It appears the lowest level of contact pressure (1.8 GPa) leads to high apparent friction coefficient, whereas the two highest level of contact pressure (2.6 and 3.4 GPa) lead to lower and equivalent values. This shows that the couple of materials "TiAlN coated carbide / Inconel 718" is sensitive to contact pressure.

Moreover, it shows that a threshold effect exists. Apparent friction seems to decrease with contact pressure to a critical pressure. Beyond this limit, apparent friction coefficient seems to remain constant. Of course, additional contact pressures have to be investigated in order to define more precisely this critical value, as well as the rate of decrease for the apparent friction coefficient versus contact pressure. This behaviour has already been observed during the machining of TiAl6V4 alloy with carbide tools [23], whereas steels do not reveal any sensitivity to contact pressure [14, 24].

3.2. Influence of coatings

Figure 5 plots the evolution of apparent friction coefficient versus sliding velocity for three types of carbide pins having a diameter of 9 mm: uncoated, TiN coated and TiAlN coated carbide pins. It reveals clearly that the tribological behavior of Inconel 718 is almost not sensitive to coatings. However, this does not mean that coatings are not beneficial for cutting tools. Indeed, several authors, [4] have shown that TiAlN enables to increase significantly the wear resistance during the machining of Inconel 718. These results only show that

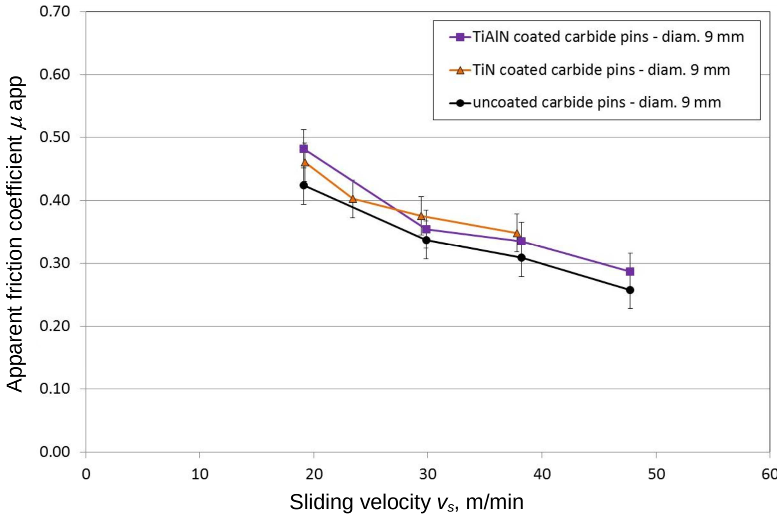


Fig. 5. Evolution of apparent friction coefficient versus sliding velocity for two various coatings deposited on carbide, and an uncoated carbide

these coatings do not influence the interfacial friction coefficient μ_{adh}. It can influence the chemical reactivity and improve its resistance to carbide particles included into the Inconel 718. Of course, this has to be investigated further, but it is not the topic of this paper, that only aims at providing quantitative data to sustain the development of numerical cutting models.

3.3. Influence of c-BN substrate

Figure 6 plots the evolution of apparent friction coefficient versus sliding velocity for TiAlN carbide pins and c-BN pins. Of course, it does not make sense to perform friction tests under the same sliding velocity since the range of cutting speeds are fully different (~50 m/min for carbide tools and ~250 m/min for c-BN tools). Considering the chip compression ratio illustrated in Fig. 1, the sliding velocity is approximately 2 to 3 times smaller on the rake face compared to the cutting speed. So, for TiAlN carbide pins, it makes sense to perform friction tests in the range of 20-50 m/min, whereas for c-BN pins, it makes sense to perform tests in the range 80 to 250 m/min.

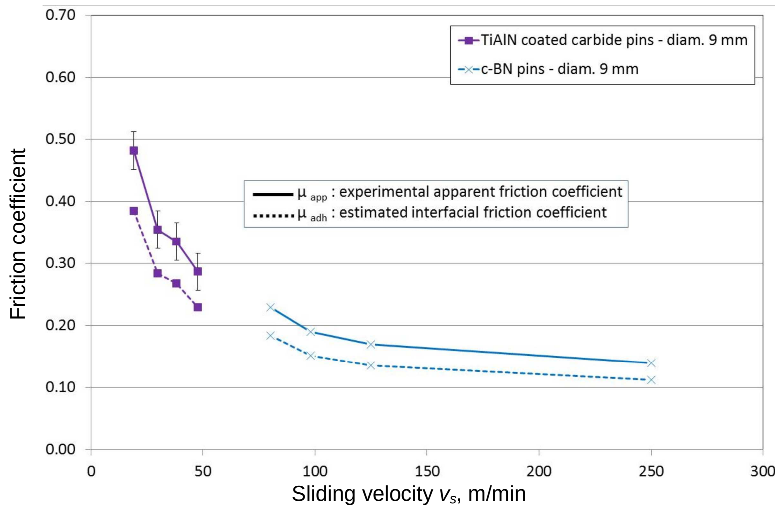


Fig. 6. Evolution of apparent friction coefficient and of estimated interfacial friction coefficient versus the macroscopic sliding velocity for TiAlN coated carbide pins and c-BN pins

Figure 6 shows that the c-BN substrate leads to very small values of apparent friction coefficient (0.1 – 0.22). Additionally, the values decreases versus sliding velocity as for TiAlN coated carbide pins. This very low level of apparent friction coefficient is never obtained in dry conditions with any other metallic materials such as steels against TiN coated pins (lowest value ~ 0.2 for AISI1045 [24]). These values are comparable to the ones obtained with steel using mineral oil lubrication [18]. This seems to indicate that c-BN exhibits very low interfacial friction coefficient. The detailed estimation of the interfacial friction coefficient has not been presented in this paper since it is a tough work [14]. However, the application of the analytical model developed by Mondelin [19] shows, that for Inconel718, μ_{adh} can be estimated by:

$$\mu_{adh} \sim 0.8\, \mu_{app} \tag{6}$$

So, based on the experimental apparent friction coefficients plotted in Fig. 6, it is possible to plot the evolution of the estimated interfacial friction coefficient versus macroscopic sliding velocity Vs. Authors would like to catch the attention on the following aspect: The macroscopic sliding velocity Vs is not the average local sliding velocity V_{ls}. Indeed, due to friction, the sliding velocity of workmaterial at the interface is limited [11, 14]. In order to identify a model of the evolution of the interfacial friction velocity μ_{adh} against the average local sliding velocity V_{ls}, it is necessary to perform a post-treatment with a numerical model of the friction test as the one developed by [14]. This work will be the topic of an additional paper.

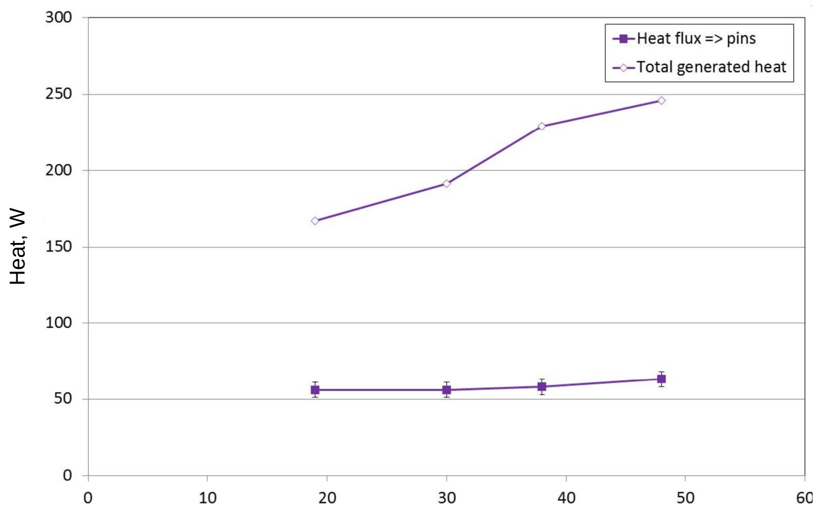
3.4. Evolution of the heat partition coefficient

By means of the original instrumentation of pin’s holder, the evolution of the heat flux transmitted to pins versus sliding velocity in dry conditions can be obtained (see Fig. 7). It has been applied only for the couple of materials. TiAlN coated carbide / Inconel 718 since the calibration of this system is very costly. In addition, the total heat generated at the interface is also plotted in Fig. 7 based on eq. 3.

Based on Fig. 7 and on eq. 4, it is possible to estimate the experimental heat partition coefficient α. Fig. 8 plots the evolution of the experimental heat partition coefficient α versus sliding velocity.

Figure 7. reveals that the heat flux transmitted to pins remains almost constant or increases with sliding velocity. This tendency is surprising compared to previous observations made for steels [24] or titanium alloys [23] in this range of the sliding velocity. Indeed, it was expected that the heat flux transmitted to pins increases significantly with sliding velocity. Theoretically, the total heat generated at the interface is supposed to increase linearly with the sliding velocity if the friction coefficient remains constant. But the interfacial friction coefficient decreases also exceptionally rapidly as shown in Fig. 6. So the increase of sliding velocity is partially compensated by the decrease of apparent friction coefficient. So the total heat flux generated in the contact increases much slower than expected.

In parallel, Fig. 8 plots the evolution of the experimental heat partition coefficient versus sliding velocity. It is observed, that the heat partition



Sliding velocity v_s, m/min

Fig. 7. Evolution of heat flux transmitted to pins versus sliding velocity for TiAlN coated carbide pins

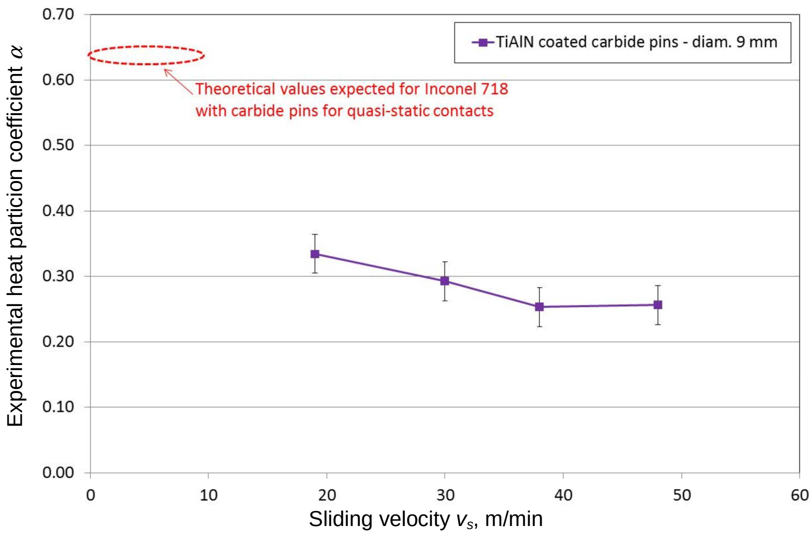


Fig. 8. Evolution of experimental heat partition coefficient versus sliding velocity for TiAlN coated carbide pins

coefficient decreases with sliding velocity, which is a standard behavior already observed for all metallic alloys. However the level of this heat partition coefficient is exceptionally low compared to the theoretical values estimated from the ratio of effusivity as presented in the eq. 5. It shows that the application of this model is not valid for the couple of materials. TiAlN coated carbide / Inconel 718. It is difficult to explain the reason for this result. Additional investigations have to be contact at a much smaller scale at the interface between pins and bars. This work has not been performed. However it shows that the assumption made by Monaghan [5], considering any heat transfer at the interface, is not appropriate to model heat exchanges at the tool-chip interface.

As discussed previously, it is not possible to identify a model reporting the evolution of the heat partition coefficient versus sliding velocity, since it is necessary to estimate, for each test, the average local sliding velocity by means of a numerical model. This work will be presented in a future paper.

4. Conclusions

This paper was concerned by the characterization of the frictional properties at the tool-workmaterial interface during the machining of an Inconel 718 alloy with various coated carbide tools or c-BN tools in dry conditions. A specially designed tribometer has been applied in order to simulate an open tribosystem as well as sliding velocity and contact pressure similar to the ones occurring at the cutting tool-workmaterial interface. A design of experiment has been conducted in order to explore a large range of sliding velocity from 20 to 50 m/min for carbide tools and from 80 to 250 m/min for c-BN tools. A range of contact pressures has also been investigated from 1.8 to 3.4 GPa.

This work has provided the evolution of apparent friction coefficient and of the adhesive friction coefficient versus sliding velocity. It has been revealed that friction coefficient decreases with sliding velocity and contact pressure. A threshold effect has also been highlighted, i.e. beyond a critical value of contact pressure, friction coefficients are no more sensitive to contact pressure.

It has been shown that TiN and TiAlN coatings are not able to modify the frictional behavior compared to an uncoated tools. On the contrary, c-BN tools lead to very low friction coefficients.

Finally, an investigation on the heat flux transmitted to pins has shown that experimental values of heat partition coefficient are very low compared to theoretical values. Additionally, it has been shown that heat partition coefficient decreases with sliding velocity.

Finally this work provides original data of friction coefficient and heat partition coefficient for several couples of cutting tool material / Inconel 718, and for a spectrum of sliding velocity and contact pressure. The next step of this work will be to make a post-treatment with a numerical model of the friction test, in order to provide local parameters such as local sliding velocity and temperature and then to identify a friction model and a heat partition model depending on these local parameters. Finally these models will be implemented in a numerical cutting model.

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References

[1] A. JAWAID, S. KOKSAL, S. SHARIF: Cutting performance and wear characteristics of PVD coated and uncoated carbide tools in face milling Inconel 718 aerospace alloy. *Journal of Materials Processing Technology*, **116**(2001), 2-9.

[2] I.A. CHOUDHURY, M.A. El-BARADIE: Machinability of nickel-base super alloys: a general review. *Journal of Materials Processing Technology*, **77**(1998), 278-284.

[3] E.O. EZUGWU, D.A. FADARE, J. BONNEY, R.B. Da SILVA, W.F. SALES: Modelling the correlation between cutting and process parameters in high-speed machining of Inconel 718 alloy using an artificial neural network. *International Journal of Machine Tools & Manufacture*, **45**(2005), 1375-1385.
[4] P.C. JINDAL, A.T. SANTHANAM, U. SCHLEINKOFER, A.F SHUSTER: Performance of PVD TiN, TiCN, and TiAlN coated cemented carbide tools in turning. *International Journal of Refractory Metals and Hard Materials*, **17**(1999)1-3, 163-170.
[5] J. MONAGHAN, T. MacGINLEY: Modelling the orthogonal machining process using coated carbide cutting tools. *Computational Materials Science*, **16**(1999)1-4, 275-284.
[6] E. UHLMANN, M. GRAF von der SCHULENBURG, R. ZETTIER: Finite element modeling and cutting simulation of Inconel 718. *CIRP Annals – Manufacturing Technology*, **56**(2007)1, 61-64.
[7] S.L. SOO, D.K. ASPINWALL, R.C. DEWES: 3D FE modelling of the cutting of Inconel 718. *Journal of Materials Processing Technology*, **150**(2004)1-2, 116-123.
[8] G. DONG, H. ZHAOPENG, H. RONGDI, C. YANLI, J.N. MUGUTHU: Study of cutting deformation in machining nickel-based alloy Inconel 718. *International Journal of Machine Tools and Manufacture*, **51**(2011)6, 520-527.
[9] H.A. SONAWANE, S.S. JOSHI: Analytical modeling of chip geometry and cutting forces in helical ball end milling of superalloy Inconel 718. *CIRP Journal of Manufacturing Science and Technology*, **3**(2010)3, 204-217.
[10] T. OZEL: The influence of friction models on finite element simulations of machining. *International Journal of Machine Tools and Manufacture*, **46**(2006)5, 518-530.
[11] C. BONNET, F. VALIORGUE, J. RECH, C. CLAUDIN, H. HAMDI, J.M. BERGHEAU, P. GILLES: Identification of a friction model – Application to the context of dry cutting of an AISI 316L austenitic stainless steel with a TiN coated carbide tool. *Journal of Materials Processing Technology*, **48**(2008), 1211-1223.
[12] T.H.C. CHILDS: Friction modelling in metal cutting. *Wear*, **260**(2006), 310-318.
[13] P.J. ARRAZOLA, D. UGARTE, D.X. DOMINGUEZ: A new approach for the friction identification machining through the use of finite element modelling. *International Journal of Machine Tools and Manufacture*, **48**(2008), 173-183.
[14] F. ZEMZEMI, J. RECH, W. BEN SALEM, A. DOGUI, P. KAPSA: Identification of a friction model at tool/chip/workpiece interfaces in dry machining of AIS14142 treated steels. *Journal of Materials Processing Technology*, **209**(2009), 3978-3990.
[15] W. GRZESIK, P. NIESLONY: A computational approach to evaluate temperature and heat partition in machining with multilayer coated tools. *International Journal of Machine Tool and Manufacture*, **43**(2003), 1311-1317.
[16] P.J. ARRAZOLA, T. OZEL: Investigations on the effect of friction modeling in finite element simulation of machining. *International Journal of Mechanical Sciences*, **52**(2010), 31-42.
[17] P. HEDENQUIST, M. OLSSON: Sliding wear testing of coated cutting tool materials. *Tribology International*, **23**(1991)3, 143-150.

[18] C. CLAUDIN, A. MONDELIN, J. RECH, G. FROMENTIN: Effects of a straight oil on friction at the tool-workmaterial interface in machining. *International Journal of Machine Tools and Manufacture*, **50**(2010), 681-688.

[19] A. MONDELIN, C. CLAUDIN, J. RECH, F. DUMONT: Effects of lubrication mode on friction and heat partition coefficients at the tool-workmaterial interface in machining. *Tribology Transactions*, **54**(2011), 247-255.

[20] F. ZEMZEMI, W. BENSALEM, J. RECH, A. DOGUI, P. KAPSA: New tribometer designed for the characterisation of the friction properties at the tool/chip/workpiece interfaces in machining. *Tribo Test*, **14**(2008), 11-25.

[21] J. RECH, C. CLAUDIN, E. D'ERAMO: Identification of a friction model – Application to the context of dry cutting of an AISI 1045 annealed steel with a TiN-coated carbide tool. *Tribology International*, **42**(2008), 738-744.

[22] W. GRZESIK, P. NIESLONY: Prediction of friction and heat flow in machining incorporating thermophysical properties of the coating–chip interface. *Wear,* **256**(2004), 108-177.

[23] A. EGAÑA, J. RECH, P.J. ARRAZOLA: Characterization of friction coefficient and heat partition coefficient during machining of a TiAl6V4 titanium alloy and a cemented carbide. Submitted to *Tribology Transactions*.

[24] H. Ben ABDELALI, C. CLAUDIN, J. RECH, W. BEN SALEM, P. KAPSA, A. DOGUI: Experimental characterization of friction coefficient at the tool-chip-workpiece interface during dry cutting of AISI 1045. *Wear*, doi:10.1016/j.wear.20.11.05.030.

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