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Characterization of Friction Properties During Machining of Various Stainless Steels

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Many issues in machining are related to interface characteristics, such as the friction coefficient, adhesive layer, or heat transfer coefficient. A specially designed tribometer is used to quantify these contact parameters in the case of four stainless steels (three austenite grade with controlled composition and an austenito-ferritic one). The sensitivity to sliding velocity and coatings is investigated. It is highlighted that the contact pressure effect is limited compared with the influence of sliding speed. Moreover, tool damage can also be explained by local phenomena exhibited by the tribometer, such as adhesion layer or thermal aspects, which are critical in case of stainless steels.

Key words: friction, tribometer, stainless steels.

1. Introduction

Stainless steels are extensively used in industry, for a large range of applications such as medical, nuclear, or aeronautics. In the field of machining processes, a major objective consists in predicting cutting tools performance. Some authors have proposed analytical or numerical predictive models for material removal mechanisms. However, friction modelling at the tool/work-material interface remains an issue. Indeed, scientific literature [1, 2] reports that machining stainless steel induces intensive thermal and mechanical loads (temperatures 500 to 1000°C, contact pressures up to 3 GPa, and friction velocity from 0 to 400 m·min^{-1}) which makes it difficult to simulate by a tribological test. Moreover, it is obvious that cutting operations can be considered as "open tribo-systems", as defined by Zambelli in [3], i.e. cutting tools rub continuously against a refreshed surface.

There are two main ways to investigate friction in cutting. The first approach consists in comparing forces during elementary cutting operations. Fromentin propose in [4] to use a tap test to measure influence of lubricants on friction and diffusive properties. Harris [5] used drilling tests to understand wear behaviour of multi-layer coatings, while Ezugwu [6] use intermittent cutting test of TiN coated inserts for tool life prediction. These methods ensure relevant friction conditions. Unfortunately, macroscopic forces do not provide quantitative value of local friction coefficients and heat partition coefficient along the interface.

Moreover, Bonnet *et al.* [7] have shown that friction properties vary continuously along this interface during the machining of an AISI316L stainless steel depending on local sliding velocity and pressure (Fig. 1). There is a need for a dedicated friction test simulating relevant conditions (pressure, velocity and open tribo-system). Thus, Zemzemi developed a special tribometer [8] providing friction coefficient, heat flux, and adhesion. This system has been improved by Claudin [9] to characterize the frictional properties of various steel grades in machining under a larger range of sliding velocity, like Claudin [10] or Rech [11].

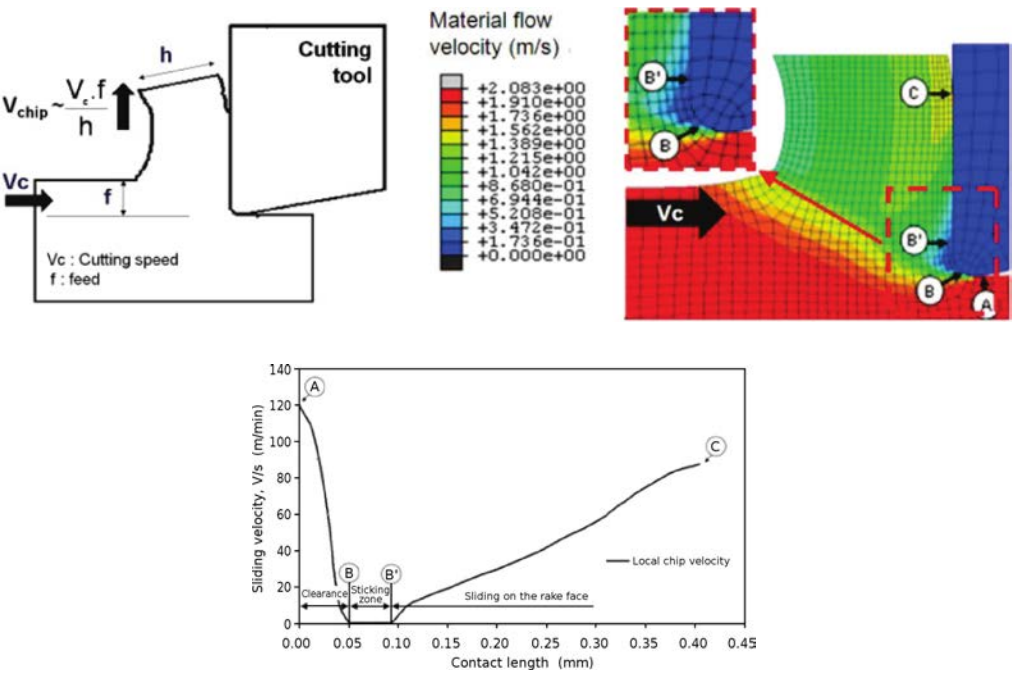

Fig. 1. Illustration of strategic zones in orthogonal cutting [7].

The present paper aims at applying this tribometer to quantify the frictional properties in machining of stainless steel grades for a large range of sliding velocities. The 4404HM (i.e. AISI316L) and 4305HM (i.e. AISI303) are austenitic grade, both with a special heat and chemical treatment improving their machinability. The 4441 is an austenitic grade with a highly controlled composition designed for medical application. This material is well known as a difficult one to machine, as is the 4362, which is a duplex austenite ferrite grade. In addition, the sensitivity of one of these work-material to cutting tool coatings is also evaluated.

2. Experimental setup

The tribometer (Fig. 2) has been used already in various published work [7, 10, 12]. The work-material is a cylindrical bar of stainless steel, and cutting tool is a cemented carbide pin, with a 10% Co and grain size closed to 0.8 μm. The sliding area of the pin is polished to reach a roughness Ra lower than 0.3 μm. Three different sliding speeds of 20, 60, and 180 $m\cdot min^{-1}$ have been chosen, in order to simulate a large range of cutting conditions. A refreshing procedure is applied before each friction test, consisting in a turning phase followed by a belt finishing phase, to ensure a relative stability in mechanical state of the material.

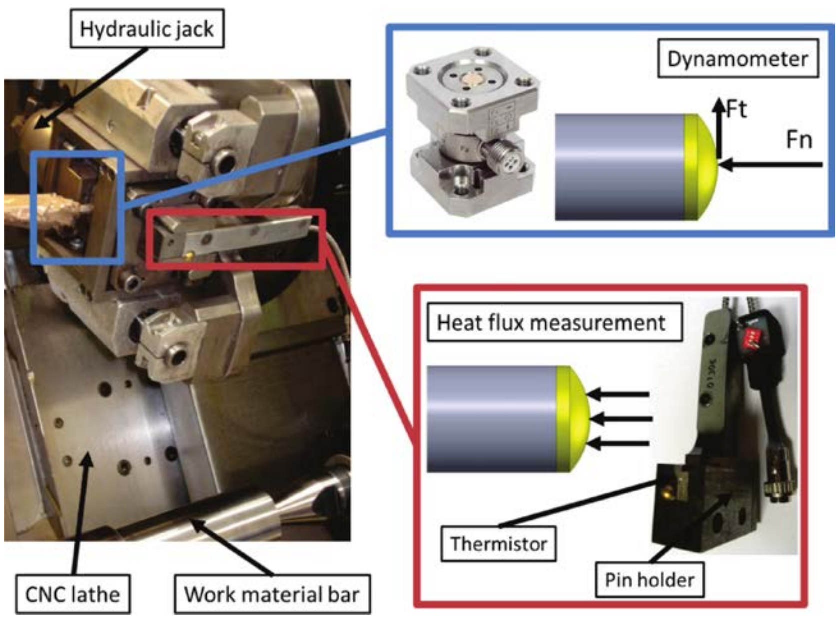

Fig. 2. Design of the tribometer used.

For each test, the tribometer provides normal and tangential forces through a dynamometer, while the pin holder is instrumented to estimate the heat flow transmitted to the pin. From two force components in the stabilized phase, it's possible to calculate apparent friction coefficient (2.1). As presented in [13], the apparent friction coefficient can be divided into an adhesive friction coefficient μ_{adh} and a plastic deformation coefficient μ_{def}.

$$\mu_{\text{app}} = \frac{F_t}{F_n} = \mu_{\text{def}} + \mu_{\text{adh}}\,. \tag{2.1}$$

An analytical method has been developed in [13] to identify adhesive friction coefficient μ_{adh} from the apparent friction coefficient μ_{app}. Bonnet *et al.* have shown in [7] that the adhesive part μ_{adh} is close to 90% of the apparent friction coefficient μ_{app} in the case of a 316L austenitic stainless steel (which is close to 4404HM in term of composition and work-material characteristics). Claudin has arrived at [10] the same conclusion in the case of AISI 1045 steel with TiN coated pins. This model will not be presented in this paper because similar qualitative conclusions can be announced with μ_{app} or with μ_{adh}.

The tribometer also provides the heat flux transmitted to pin ϕ_{pin}. This heat flux is only part of the total heat flux generated at the interface. The fraction β of heat transmitted to pins, also called heat partition coefficient, is provided by Eq. (2.2), with V_g the sliding velocity (m/s).

$$\beta = \frac{\phi_{\text{pin}}}{F_t \times V_g}\,. \tag{2.2}$$

The work-material in this study is stainless steel. Four different steels have been chosen in order to measure influence of composition or microstructure over frictional behaviour. Table 1 give chemical composition (percentage of volume) and grade type.

Table 1. Chemical composition of the stainless steels tested.

Name	Structure	C	Si	Mn	Ni	Cr	Mo	Cu	P	S
4404HM	Austenitic	≤ 0.03	≤ 1	≤ 2	11	17	2.2	≤ 0.75	≤ 0.04	0.025
4441	Austenitic, electro-slag-remelted	0.03	1.00	2.00	14	18	2.9	–	0.025	0.01
4362	Duplex austenitic / ferritic	≤ 0.03	≤ 1	≤ 2	4.5	23	0.35	0.4	≤ 0.04	≤ 0.02
4305HM	Austenitic + resulphurised	< 0.07	< 0.75	1.8	9	17.5	< 0.5	< 0.75	< 0.04	0.3

3. Friction parameters analysis

3.1. *Influence of contact pressure and sliding velocity*

The tribometer allows adjusting both pin diameter and normal force in order to influence the contact pressure. Three pin diameters (9, 13 and 17 mm) and two normal forces (1000 N and 650 N in case of 17 mm diameter pin) have been chosen with TiN coated pins. The following graphs (Fig. 3) show the evolution of friction parameters *versus* sliding speeds for a 4441 stainless steel grade.

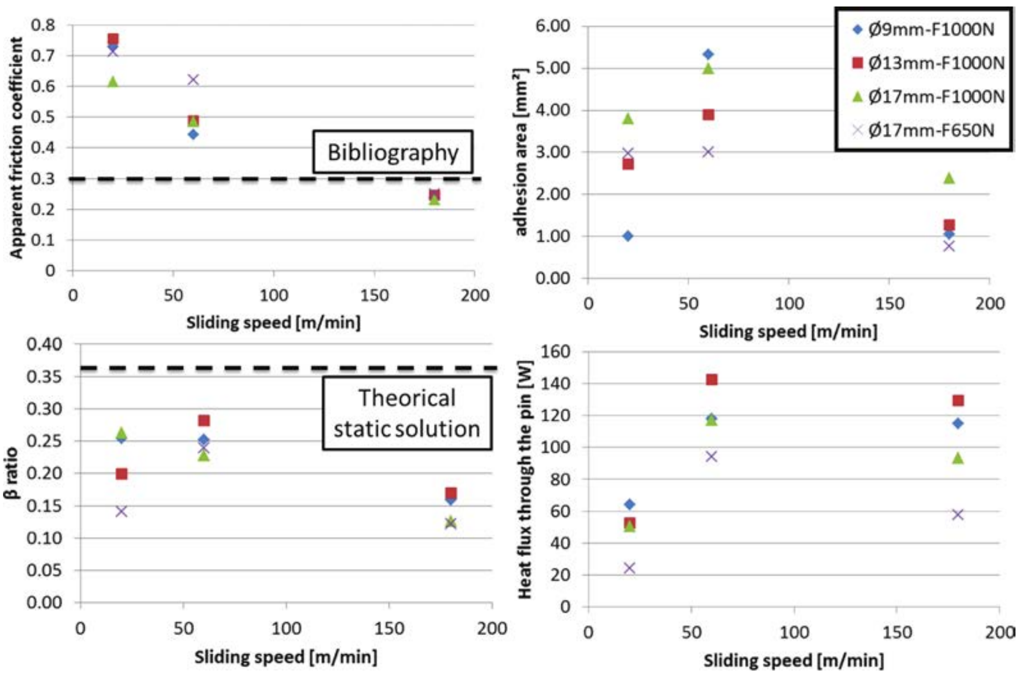

Fig. 3. Influence of contact pressure and sliding velocity on friction properties.

One can observe that both the friction coefficient and the heat partition ratio depend on sliding speed, which is not mentioned in literature (with disc/pin method in one hand [7], or static effusivity ratio on other hand [14]). It shows that sliding velocity has much more influence than contact pressure on the friction coefficient and heat partition coefficient. When increasing sliding velocity, the friction coefficient decreases. This trend has already been observed in several previous papers [7, 10, 12], including a similar grade. On the contrary, the heat partition coefficient exhibits an unusual behaviour. Heat partition coefficient commonly decreases with increasing sliding speed. In the case of stainless steels however, the fraction β is significantly lower at low speed which is very different from the tribological properties of conventional steels leading to a continuous decrease.

However, it is obvious that contact pressure increases when normal force increases or when pins diameter decreases. Despite the variation of contact pressure, friction coefficient and heat partition ratio (β) are influenced under low sliding velocities whereas they remain almost constant under high siding velocities. It appears that a higher contact pressure leads to a lower friction coefficient under low sliding velocities. On the contrary, a higher heat partition ratio is obtained for high contact pressure.

3.2. Sensitivity to cutting tool coatings

In this test, only the 4441 austenitic steel grade (highly controlled composition grade) is involved since it is considered as a difficult to cut material due to its thermal properties and to its capacity to induce adhesion on cutting tools. For a defined contact pressure configuration ($F_n = 1000$ N, $d = 17$ mm), TiN and AlTiN coatings are investigated. As shown in Fig. 4, TiN coating exhibits the lowest friction coefficient under low sliding velocities. On the contrary, both coatings lead to similar friction coefficients under high sliding velocities. Deviations in measurement are not plotted here because they are not significant.

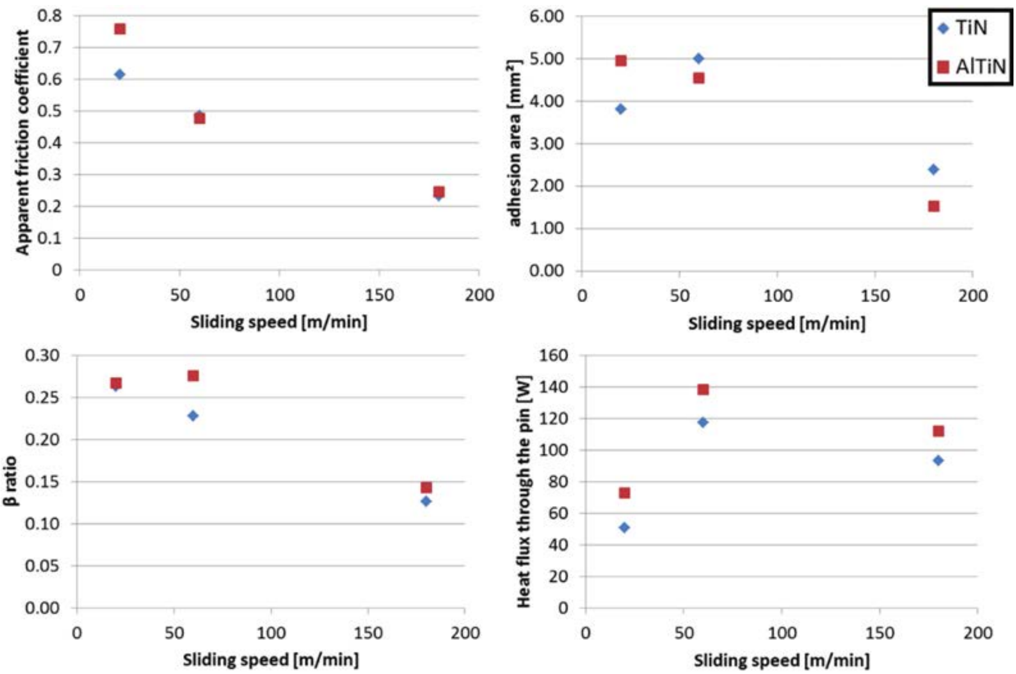

FIG. 4. Influence of coatings on friction coefficient and heat partition ratio.

Concerning the affect on thermal properties, TiN coating leads to smaller heat partition coefficient. As a consequence these two properties of TiN coatings enable to decrease the amount of heat transmitted to pins as shown in Fig. 5. Moreover, adhesion at low speed is greater for AlTiN. So, TiN coating seems to be more appropriate for austenitic steel machining. This observation has now to be correlated with wear tests in order to investigate the chemical wear resistance of both coatings which cannot be estimated through such rapid friction tests.

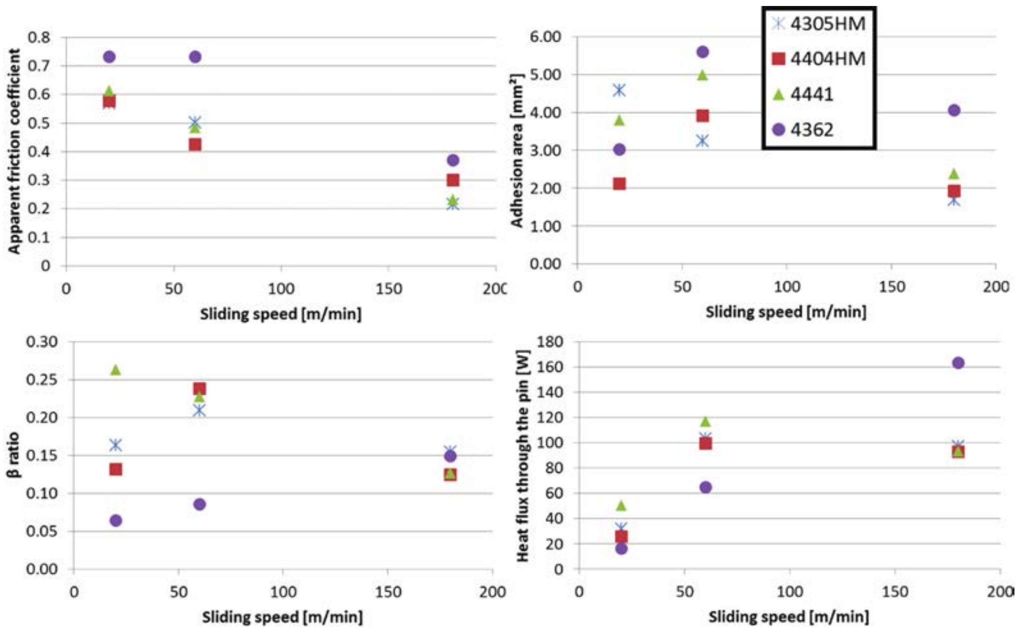

FIG. 5. Friction properties of various stainless steel.

3.3. Influence of work-material

In this section, only TiN coated pins are considered to investigate the influence of the work-material. Pins with a 9 mm diameter are used under a normal force of 1000 N. Concerning the evolution of friction coefficient; Fig. 5 reveals that the duplex austenito-ferritic grade (4362) leads to much higher friction coefficients than other grades. On the contrary, the heat partition ratio is very small in this case. As a consequence, a stronger adhesion occurs, especially at high speed and, at the same time, this adhesion induces a thermal insulation effect.

From a productivity point of view, end users are interested in high cutting speeds. When machining austenito-ferritic grades, they will face higher friction coefficient and about three time higher thermal conductivity compared to austenitic grades. While conductivity trends to a faster evacuation of heat generated at the interface in the work-material, the higher friction coefficient leads to about 30% more energy production in contact zone. Finally, at low speed, 4362 absorbs most part of energy, while at higher speeds, the tool have to resist to a significantly higher amount of energy.

Austenito-ferritic grades will induce both higher mechanical strength and higher thermal loads on cutting tools. More precisely, they will induce higher thermo-mechanical loads in some tool/work-material interface where sliding speeds will be high (see Fig. 1). As an example at the end of the flank face and at the end of the rake face. So there is a higher risk of crater wear in such zones. This result is in accordance to the well-known poor machinability of such grades, and is represented by adhesion on the pin, as one can observe in Fig. 6 (contour of adhesion area is highlighted).

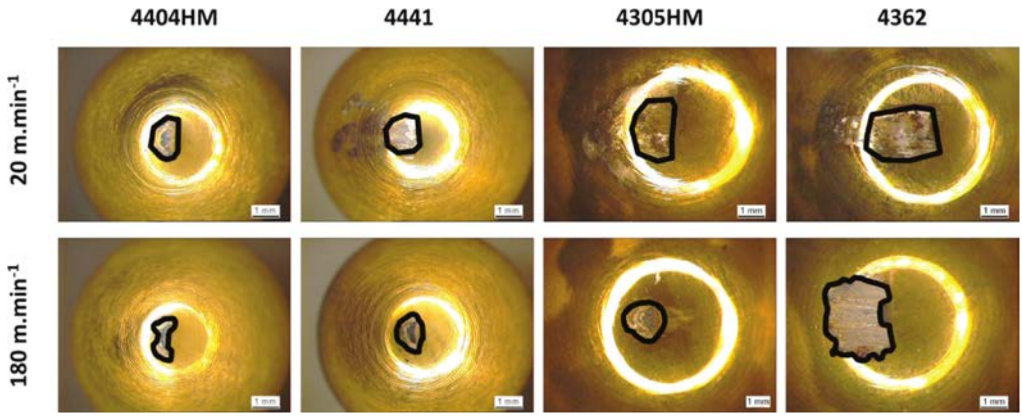

Fig. 6. Adhesion phenomenon for TiN coated pin at 20 m·min^{-1} (top) and 180 m·min^{-1} (bottom).

By comparing the austenitic grades 4404HM and 4305HM, it seems that they lead to similar friction coefficient and heat partition coefficient. In this case, the tribometer is not able to discriminate a variation of machinability induce by resulphurising process. On the contrary the low machinability austenitic grade 4441 leads to higher friction coefficient under low sliding velocities, whereas no difference are observable under high sliding velocities compared to the same material but in its high machinability grade 4404HM. Concerning the thermal behaviour, it appears that the heat partition ratio of the low machinability grade is higher than the high machinability grade. As a consequence, a larger amount of heat is transmitted to pins under low sliding velocities. The consequence of these observations is that 4441 grade will lead to higher adhesion at the tool/work-material interface where sliding velocity is low. This is especially observed around the cutting tool edge. As a consequence, a higher sensitivity to built-up edge can be expected with such grades. These tribological observations are in accordance with experimental observations in cutting.

4. Conclusion

The present work has presented the application of a tribometer dedicated to the characterization of the frictional properties at the tool/work-material interface for four various stainless steel grades. It has been shown that sliding velocity is the major parameter influencing friction coefficient and heat partition coefficient in any cases. The higher the sliding velocity is, the lower the friction coefficient and the heat partition coefficient are. But at low speed, stainless steel grades present a significantly lower heat partition ratio, which is quite different from usual steel material.

In the case of austenitic stainless steels, the TiN coating seems to lead to lower friction coefficients and heat partition ratio compared to AlTiN coatings. Concerning the influence of work-material, it seems that austenito-ferritic grades exhibits higher friction coefficient and at the same time a lower heat partition coefficient compared to other grades, which make cutting tools sensitive to crater wear.

The tribometer does not allow one to discriminate any large difference between austenitic high machinability grades, whereas high purity controlled austenitic grade have exhibited higher friction coefficient and heat partition coefficient under low sliding velocities which confirms its ability to built-up edge creation.

In order to compare machinability of stainless steels, and influence of composition and micro-structure, tool wear tests have to be conducted. Observation and measure of built-up or crater wear can confirmed our conclusions on the influence of work-material composition and structure over tribological phenomenon.

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References

1. Trent E.M., Wright P.K., *Metal Cutting*, 4th ed., Butterworth-Heinemann, 2000, ISBN 075067069X.
2. Stephenson D.A., Agapiou, J.S., *Metal Cutting Theory and Practice*, 2nd ed., Taylor and Francis CRC Press, 2005, ISBN 9780824758882.
3. Zambelli G., Vincent L., *Matériaux et contacts*, Presses polytechniques et universitaires romandes, 1998, ISBN 9782880743383.
4. Fromentin G., Bierla A., Minfray C., Poulachon G., *An experimental study on the effects of lubrication in form tapping*, Tribology International, **43**, 9, 1726–1734, 2010.
5. Harris S.G., Doyle E.D., Vlasveld A.C., Audy J., Quick, D., *A study of the wear mechanisms of Ti1-xAlxN and Ti1-x-yAlxCryN coated high-speed steel twist drills under dry machining conditions*, Wear, **254**, 7-8, 723–734, 2003.
6. Ezugwu E.O., Okeke C.I., *Tool life and wear mechanisms of TiN coated tools in an intermittent cutting operation*, Journal of Materials Processing Technology, **116**, 1, 10–15, 2001.
7. Bonnet C., Valiorgue F., Rech J., Claudin C., Hamdi H., Bergheau J.M., Gilles P., *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*, International Journal of Machine Tools and Manufacture, **48**, 11, 1211–1223, 2008.
8. Zemzemi F., Rech J., Salem W.B., Dogui A., Kapsa P., *Development of a friction model for the tool-chip-workpiece interfaces during dry machining of AISI4142 steel with TiN coated carbide cutting tools*, International Journal of Machining and Machinability of Materials, **2**, 3/4, 361–377, 2007.
9. Claudin C., Rech J., Grzesik W., *"Development of a new tribometer to identify the effects of coatings and lubricants during machining processes*, 2nd International Conference "Innovative Cutting Processes and Smart Machining", Cluny, 2008.
10. Claudin C., Mondelin A., Rech, J., Fromentin G., *Effects of a straight oil on friction at the tool-workmaterial interface in machining*, International Journal of Machine Tools and Manufacture, **50**, 8, 681–688, 2010.
11. Rech J., Claudin C., D'Eramo E., *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**, 5, 738–744, 2009.
12. Zemzemi F., Rech J., Salem W.B., Dogui A., Kapsa P., *Identification of a friction model at tool/chip/workpiece interfaces in dry machining of AISI4142 treated steels*, Journal of Materials Processing Technology, **209**, 8, 3978–3990, 2009.
13. Challen J.M., Oxley P.L.B., *An explanation of the different regimes of friction*, Wear, pp. 229–243, 1979.
14. ThermiLyon, *Documentation technique des revȩtements*, 2007.

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