On the utilization of pin-on-disc simulative tests for the calibration of friction in metal cutting

V A M Cristino, P A R Rosa, and **P A F Martins***
IDMEC, Instituto Superior Técnico, TULisbon, Lisboa, Portugal

The manuscript was received on 10 March 2009 and was accepted after revision for publication on 26 May 2009.

DOI: 10.1243/13506501JET639

Abstract: This article proposes a new design for pin-on-disc machines and introduces a research methodology that aims at providing a new level of understanding for the influence of surface texture and roughness on the average value of the friction coefficient.

The new design for pin-on-disc machines increases the overall stiffness, eliminates the need for counter weights, and allows tests to be carried out under variable loading conditions and includes a unit for producing and regenerating the desired texture and roughness in the surface of the discs after completion of each test.

The comparison between the friction coefficient obtained with pin-on-disc tests and that acquired in metal cutting laboratory conditions allows concluding that pin-on-disc tests, when performed with an adequate control of texture and surface roughness, are capable of providing a good estimate of the average value of the friction coefficient in metal cutting applications.

Keywords: pin-on-disc, friction coefficient, metal cutting, surface texture, roughness

1 INTRODUCTION

Metal cutting is one of the oldest manufacturing processes but, despite its economic and technical importance, remains one of the least understood because of low predictive ability of its analytical and numerical simulation models.

In a recent study, Bil *et al.* [**1**] compared the estimates provided by three different finite-element computer programs with experimental data and concluded that although individual parameters (such as the cutting force, the thrust force, and the shear angle) may be made to match experimental results, none of the numerical simulation models was able to achieve a satisfactory correlation with all the measured process parameters all the time. Mismatches between numerical simulation and experimentation were attributed to lack of information about the flow stress and friction at the rates and temperatures of the real metal cutting processes.

In line with the aforementioned observations, Astakhov [**2**] noticed that finite-element modelling of metal cutting available in the open literature always seemed to be in good agreement with the experimental results regardless of the particular value of the friction coefficient that had been utilized in the simulation. As the friction coefficient, in most cases, was not predetermined by means of experimental testing, it is tempting to agree with Zemzemi *et al.* [**3**] who consider friction to be commonly utilized as a variable allowing the adjustment of the numerical estimates in order to fit the experimental results, namely the cutting force.

From what was mentioned before, it follows that prediction and control of friction is one of the most critical problems emerging in the simulation of metal cutting. This is the main reason why researchers are growingly being confronted with the following questions that need to be properly addressed; is it possible to perform independent determinations of the friction coefficient under testing conditions similar to those of real metal cutting processes? If so, which are the essential features of the tests that need to be carefully controlled? and, how accurate and reliable are the independently determined values of the friction coefficient?

**Corresponding author: Departamento de Engenharia Mecanica, Instituto Superior Tecnico, Seccao de Tecnologia Mecanica, Avenida Rovisco Pais, Lisboa 1049-001, Portugal.*
email: pmartins@ist.utl.pt

As regards the first question, there are two possible experimental approaches. The first makes use of the cutting process itself and determines the friction coefficient directly from the ratio $\mu = F_t/F_c$ between the experimental values of the thrust F_t and cutting F_c forces in benchmark cutting conditions. For example performing turning tests on a large diameter tube made of the material under investigation in order to ensure orthogonal metal cutting conditions. Although the general accuracy and reliability of the friction coefficient determined in such benchmark cutting conditions are generally good, there are several reasons for considering the approach as inadequate. In fact, benchmark cutting tests require the availability of machine tools (preferentially not enrolled in production), are greatly influenced by operating variables (which may be difficult to control), and fail to provide quantitative local information about the friction coefficient [**3**]. Moreover, benchmark cutting tests cannot be classified either as independent calibration techniques or laboratory tests for the determination of the friction coefficient.

The second approach for determining the friction coefficient consists of using simulative tests under laboratory controlled conditions. The aim is to employ laboratory tests that are cheaper than benchmark cutting tests while providing accurate control of the operating variables and easy quantitative measurement of friction without losing relevance to real metal cutting applications.

Resort to friction simulative tests commonly utilized in bulk metal forming (for example upset compression, plane strain compression, and ring compression, among others [**4**]) proves inadequate because the generation of new surfaces in such tests results from plastic material flow throughout the entire work material, while in metal cutting formation of new surfaces and plastic deformation is limited to the tip of the tool and adjacent regions of the shear plane. Moreover, plastic deformation in metal cutting is always combined with sliding of the new surfaces along the rake and relief faces of the cutting tools.

One of the most commonly utilized simulative tests for evaluating friction in local plastic or elastic deformation is the pin-on-disc test. The pin-on-disc tribometer consists essentially of a pin in contact with a rotating disc and the friction coefficient is determined by measuring the tangential and normal forces acting on the pin with a dynamometer. In case of analysing friction characteristics of sliding contacts in metal cutting, the pin is made of the work material to be machined and the disc is made of the material and coating of the cutting tool, or vice-versa.

In recent years, several authors have been arguing that pin-on-disc testing is not adequate for analysing friction in metal cutting because it is not capable of reproducing the contact pressure, temperature, and material flow conditions that are commonly found in real metal cutting applications [**5**]. In case of material flow it is being claimed that chip flows on the rake face and never comes back again, whereas the pin always rubs the disc on the same track during pin-on-disc testing. As a result of this, several alternatives to pin-on-disc have been proposed by Olsson *et al.* [**6**], Hedenquist and Olsson [**7**], and Zemzemi *et al.* [**8**], among others.

However, although the alternative tests are successful in reproducing real metal cutting conditions, they are more expensive, more time consuming, and demand a more accurate control of the operating parameters than conventional pin-on-disc tests. It is further worth noticing that very often pin-on-disc tribometers work under exaggerating contact pressures and sliding speeds in order to deliberately increase or accelerate the wear rate of a test in order to speed up the overall evaluation. This is not necessary for evaluating the friction coefficient as well as the test can be performed in a single turn of the rotating disc in order to avoid pin rubbing on the same track.

Taking into account what has been said in the previous paragraphs it can be concluded that pin-on-disc needs revisiting in order to identify which technical modifications may be included and what operating parameters need to be carefully controlled in order to successfully employ this easy, quick, and cheap simulative test (available in the vast majority of manufacturing laboratories worldwide) for the independent determination of the friction coefficient in metal cutting applications.

This article proposes a new design for the pin-on-disc tribometer and introduces a testing methodology that aims at providing a new level of understanding for the influence of surface texture and roughness on the friction coefficient. The comparison between the results obtained with the new pin-on-disc tribometer and those acquired in metal cutting tests specifically designed for assessment purposes allows concluding on the validity of the pin-on-disc simulative test for evaluating friction in metal cutting applications. The experimental work on the correlation between surface roughness and friction helps solving existing gaps of knowledge that have been reported by several researchers [**9**, **10**].

2 EXPERIMENTAL BACKGROUND

This section introduces the new proposed design for the pin-on-disc tribometer and follows with the presentation of a laboratory metal cutting apparatus that was specifically designed and fabricated for assessing the friction coefficients determined by means of pin-on-disc simulative testing. The last part of the section is focused on the experimental workplan.

2.1 A new pin-on-disc tribometer

Figure 1 presents the new pin-on-disc tribometer that was developed and fabricated by the authors. The main components of the equipment can be divided into four different groups:

(a) basic structural parts;
(b) specific electrical and mechanical parts;
(c) control and measurement appliances;
(d) grinding and polishing unit.

Basic structural parts provide support to electrical and mechanical components, to control and measurement appliances, as well as to the grinding and polishing unit. They are independent of the type of testing (e.g. wear or friction), operation conditions and materials, coatings, and lubricants to be analysed.

Specific electrical and mechanical parts comprise the electrical motor, the disc holder, the pin holder, the position and guiding systems, the pins, and the discs. The electrical motor is equipped with a frequency inverter for a precise control of the rotational velocity of the disc. The disc holder is mounted to the rotating shaft of the electrical motor by means of a tapered roller bearing that takes radial and axial combined loadings resulting from the interaction between the pin and the disc. Since the pin-on-disc tests that were performed in this investigation were specially designed for testing friction in metal cutting, it follows that the pin is simulating the workpiece material whereas the disc is replicating the rake face of the cutting tool.

The design of the pin holder deviates from traditional architecture of commercial pin-on-disc machines in order to increase stiffness and to reduce the deformation caused by weight and applied loads. The new design also eliminates the need for a counterweight.

A precision ball screw driven by a motor and coupled with a linear guiding system is utilized for controlling the position of the pin holder. The utilization of linear guides reduces the axial gaps of the screw, improves the parallelism of the overall positioning system, and allows the applied loads to reach maximum values up to 15 kN. Pins and discs are dependent on the type of testing, operation conditions and materials, coatings and lubricants to be analysed.

Control and measurement appliances include a two-dimensional load cell, a multifunction data acquisition (DAQ) system, and a personal computer. The load cell (designed and fabricated by the authors) is fixed to the pin holder and connected to a signal amplifier unit (Vishay 2100). A personal computer data logging system based on a DAQ card (National Instruments, PCI-6025E) combined with a special purpose LabView software controls testing and acquires/stores the experimental values of the normal and tangential loads.

The grinding and polishing unit is a custom built piece of equipment that serves the purpose of producing and regenerating the desired texture and roughness in the surface of the discs after completion of each test. As seen in Fig. 2, the unit combines the rotational velocity of the sand paper or polishing clothes with the rotation of the disc in order to ensure average values of surface roughness (R_a) in the range 0.007–0.8 μm. These values are measured by a roughness tester and an atomic force microscope along a direction perpendicular to the rotation of the discs.

Resort to the grinding and polishing unit at the end of each test followed by roughness measurements guarantees repeatability and analogy of the surface topography of the discs irrespective of the friction test case. Table 1 provides surface micrographs of the discs pictured in Fig. 2 and correlates texture (in terms of the predominant surface pattern, irregularities, and waviness) and average surface roughness R_a with the final grade of grinding and polishing that was utilized in the unit.

To conclude the presentation of the new proposed architecture for the pin-on-disc tribometer, it is worth

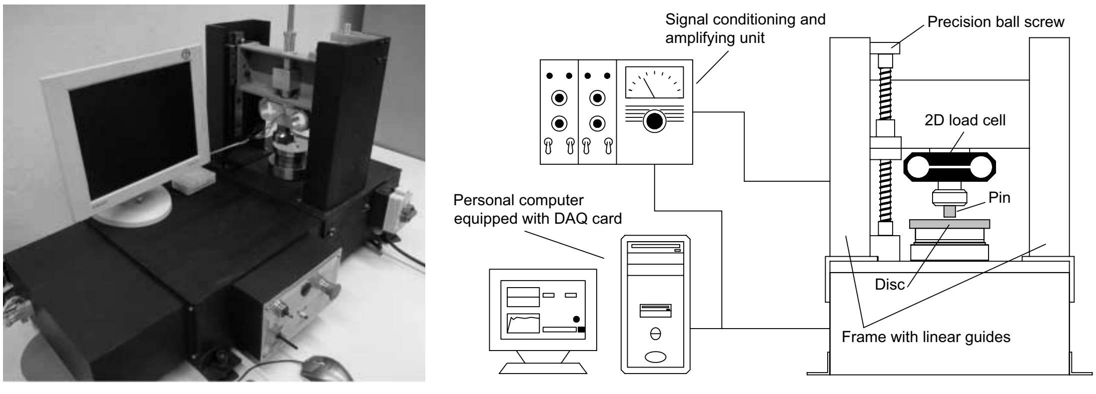


Fig. 1 Picture and schematic representation of the new pin-on-disc tester that was designed and fabricated by the authors

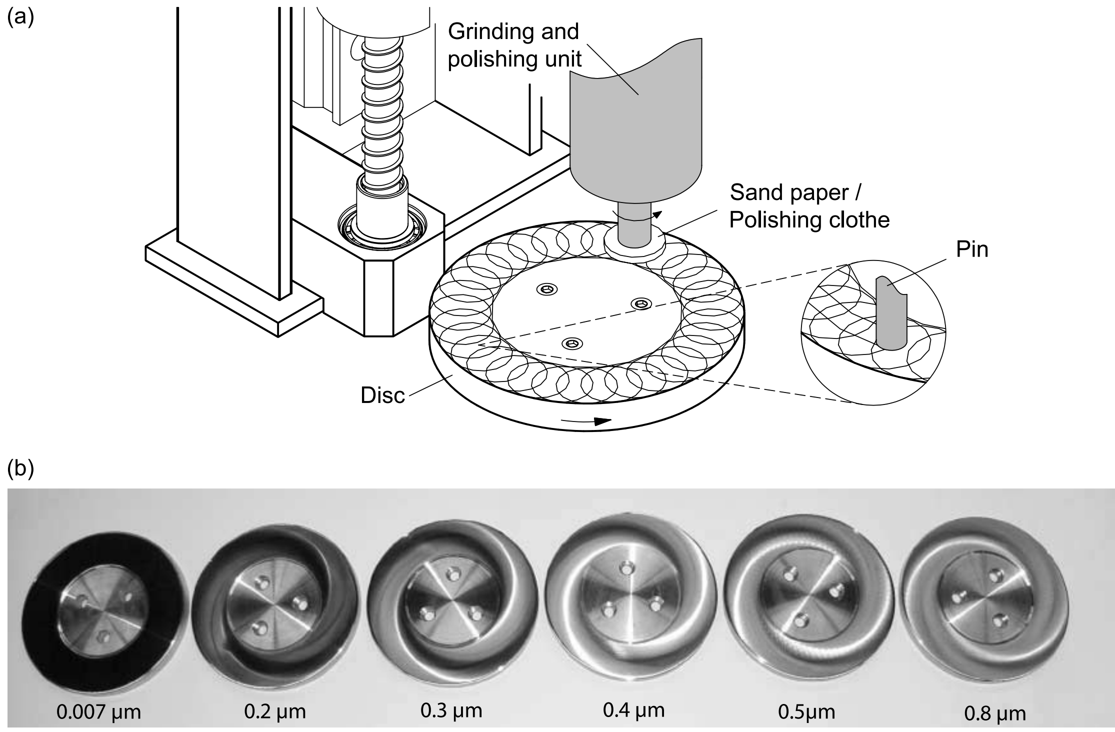


Fig. 2 Pin-on-disc tester: (a) schematic representation of the grinding and polishing unit and (b) picture showing discs prepared with different values of average surface roughness (R_a)(the pin was removed from the schematic representation for better visualization of the grinding and polishing unit)

noticing that its design allows two different methods of applying loads in the pin: (a) the standard procedure of loading calibrated weights on a slot and (b) an innovative procedure that makes use of the precision ball screw (driven by a motor) for controlling both position and load applied on the pin. This new procedure of applying loads is different from what is commonly found in commercial pin-on-disc machines and allows simulative testings to be carried out under variable loading conditions.

2.2 Special purpose metal cutting testing apparatus

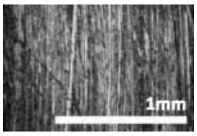
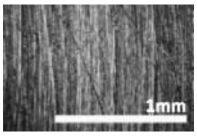
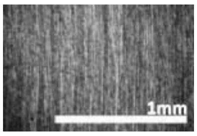
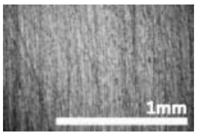
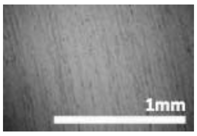
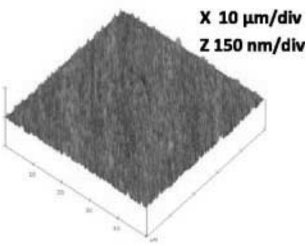
Assessing the friction coefficient determined by means of simulative pin-on-disc tests requires independent measurements to be performed in real metal cutting applications. This involves measuring the cutting forces in several metal cutting processes (turning, milling, and drilling, among others) and, if put into practice, would turn out to be difficult and very time consuming. Moreover, the operating variables of each cutting process would have to be individually controlled in order to ensure that surface roughness and wear of the cutting tool inserts would be identical in all testing cases.

Because the aforementioned requirements would be very difficult to ensure (making impossible to guarantee that all tests were performed under comparative conditions), authors decided to develop and fabricate a special purpose metal cutting testing apparatus for measuring the forces (and, therefore, the friction coefficient) in laboratory controlled conditions. The set-up was installed in a CNC milling machine (Fig. 3) and is essentially composed by a cutting tool, a three-dimensional (3D) piezoelectric dynamometer, a cutting specimen, and a self-grinding and polishing unit (Fig. 4).

The cutting tool has a rake face angle of $\alpha = 0^{\circ}$ and a clearance angle of $\sigma = 5^{\circ}$ and was manufactured from the same material as the rotating discs of the pin-on-disc machine. The cutting specimen is made of the same material as the pin of the pin-on-disc machine and is fixed directly on the 3D piezoelectric dynamometer. The metal cutting experiments were performed in orthogonal conditions, i.e. the cutting edge of the tool was straight and perpendicular to the direction of motion.

The 3D piezoelectric dynamometer (Kistler 9257B) is attached to a signal amplifier (Kistler 5011B) and allows measuring the cutting forces during testing. The system is linear across its entire range, measures forces with an accuracy of 1 per cent, and its resolution allows measuring almost any dynamic changes in the forces of great amplitude. A personal computer data logging system based on a multifunction DAQ card (National Instruments, PCI-6025E) combined with a

Table 1 Relationship between texture, average surface roughness R_a, and final grade of grinding that was utilized in the preparation of the discs

Disc surface texture	R_a (μm)	Sand paper/polishing suspension grade
	0.8	100
	0.5	180
	0.4	240
	0.3	600
	0.2	1200
	0.007	0.3 μm (Aluminium oxide suspension)

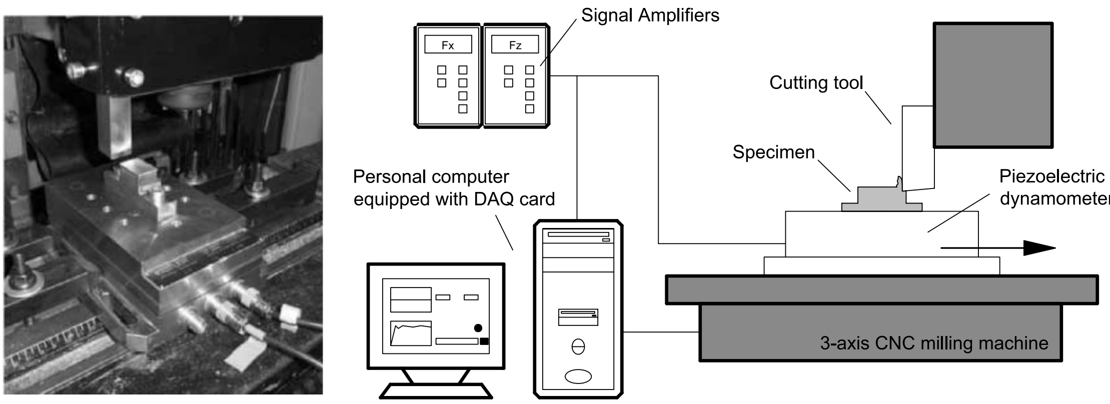


Fig. 3 Picture and schematic representation of the metal cutting testing apparatus that was specifically designed and fabricated for assessing the results provided by the pin-on-disc simulative tests

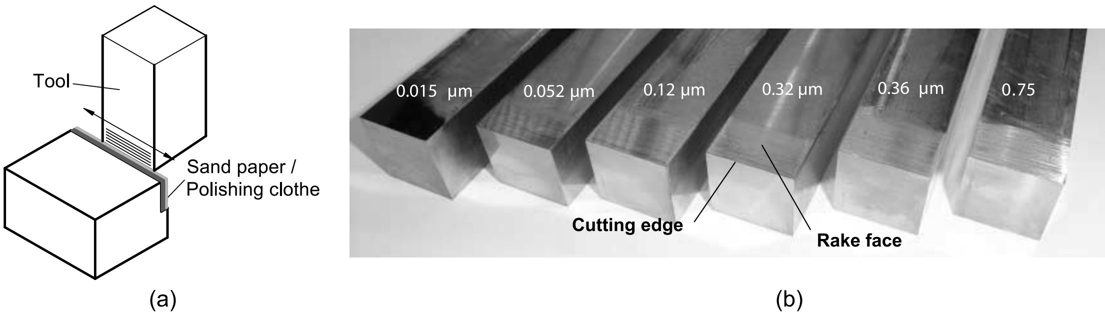


Fig. 4 Special purpose metal cutting testing apparatus: (a) schematic representation of the self-grinding and polishing unit and (b) picture showing cutting tools prepared with different values of surface roughness(the movement of the cutting tool during self-grinding and polishing operations is ensured by the CNC milling machine)

special purpose LabView software controls testing, acquires and stores the experimental data.

The self-grinding and polishing unit removes pick-up material and produces a texture in the cutting tool that closely matches that of the rotating disc under comparative evaluation. Figure 4 shows a schematic detail of the self-grinding and polishing unit together with pictures of the cutting tools that were self-prepared with different types of textures and surface roughness.

In connection with what was mentioned before, it is important to notice that the self-grinding and polishing unit is designed to ensure the directionality of the predominant surface pattern to be identical to that of the rotating discs of the pin-on-disc tribometer because patterns aligned in different directions will inevitably influence the friction coefficient [**10**, **11**].

2.3 Experimental workplan

The pin is a cylinder with 8 mm diameter made of technically pure lead (99.9 per cent). The mechanical behaviour of this material is very close to the ideal rigid–plastic material model that is assumed by the generality of the analytical models of metal cutting because of the almost absence of strain hardening. In addition, the choice of technically pure lead makes possible to simulate at room temperature and at low strain rates the material flow behaviour of conventional steels at the usual machining temperatures [**12**]. The rotating discs were manufactured from AISI 316L stainless steel.

Table 2 presents the experimental workplan for the pin-on-disc simulative tests. The experiments were designed in order to isolate the influence of the process parameters that are considered more relevant for the frictional behaviour in metal cutting; (a) the applied forces, (b) the velocity, and (c) the texture and surface roughness of the tools. No lubricants were utilized during the tests. The discs were degreased with acetone in order to ensure clean surface conditions in all the test cases.

Table 2 The experimental workplan

Case	R_a (μm)	Velocity (m/s)	Load (N)
1–4	0.007	0.072, 0.216, 0.432, and 0.72	200–600
5–8	0.2		
9–12	0.3		
13–16	0.4		
17–20	0.5		
21–24	0.8		

The elimination of lubrication (dry cutting conditions), temperature, and strain hardening from the experimental workplan is crucial for reducing the number of parameters that influence friction. The same applies to the undeformed chip thickness that was kept constant and equal to 0.2 mm for all testing conditions. Otherwise, the number of possible combinations of variables would become quite large. The experiments were performed in a random order and at least two replicates were produced for each test configuration in order to provide statistical meaning.

The workplan for the benchmark metal cutting tests was designed to match pin-on-disc experiments in order to ensure that comparison between the two types of tests was performed in the same conditions.

3 RESULTS AND DISCUSSION

This section of the article is structured in two parts. The first part is focused on the frictional response of the pin-on-disc simulative tests, while the second part is centred in assessing the friction coefficient determined by pin-on-disc with data collected from benchmark metal cutting experiments. Special emphasis is placed on the influence of surface texture and roughness in the friction coefficient.

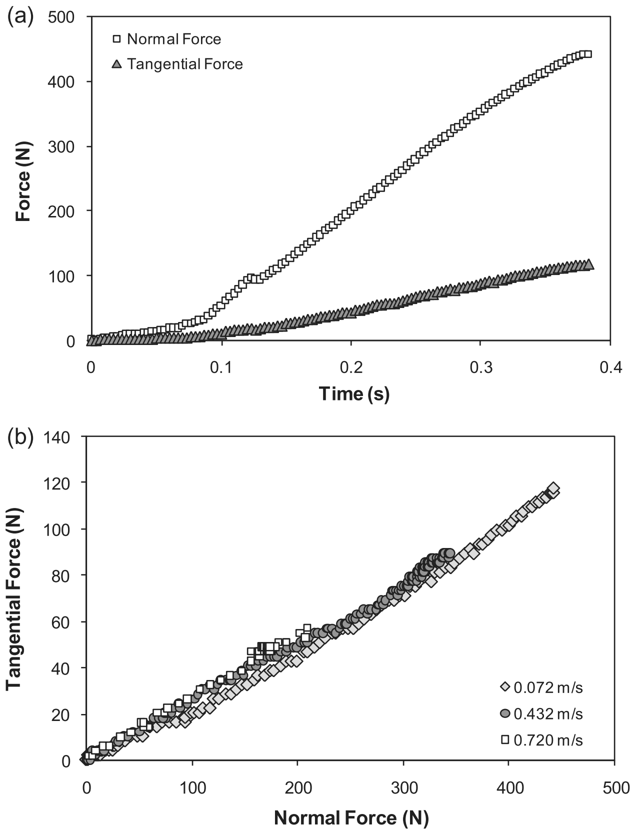


Fig. 5 Pin-on-disc tests for case 1 of Table 2. (a) Normal and tangential forces as a function of time for a test velocity of $v = 0.072$ m/s. (b) Typical friction coefficient graphic showing the tangential force as a function of the normal force for different test velocities

3.1 Friction in the pin-on-disc simulative tests

The pin-on-disc simulative tests took full advantage of the innovative features that were incorporated in the design of the equipment (section 2.1), which allow tests to be performed under variable loading conditions. Figure 5(a) shows a typical plot of the normal F_n and tangential (friction) F_t forces as a function of the test time retrieved from case 1 of Table 2. The forces were measured by the 2D load cell with a frequency rate of 300 Hz.

By extending the analysis to the entire set of velocities included in the experimental workplan, it is possible to obtain the result depicted in Fig. 5(b). This figure allows two different types of conclusions to be drawn. First, it shows the friction force to be directly proportional to the normal force applied on the pin and the friction coefficient not being affected by the contact pressure. Second, it reveals friction to be not significantly influenced by the sliding velocity. In fact, the deviation of the friction coefficient observed in the whole range of velocity testing conditions is very small.

The first conclusion is in close agreement with the fundamental laws of friction. The second conclusion may be surprising when analysed in the light of previous works in tribology but falls right in-line with the experimental results that were recently published by Sedlacek *et al.* [**10**]. It may, however, be argued that the range of velocities employed in the pin-on-disc tests is not sufficient enough to support the aforementioned conclusion but, for the testing conditions under investigation, it seems that surface texture and roughness play the key role in the frictional behaviour of the lead–stainless steel tribo-pair. This will be comprehensively analysed in the following section of the article.

3.2 Friction and surface roughness

Figure 6 shows the variation of friction coefficient with surface roughness for the lead–stainless steel tribo-tests described in section 2.3 (Table 2). The main differences between Figs 6(a) and (b) are due to the fact that the latter employs a logarithmic scale instead

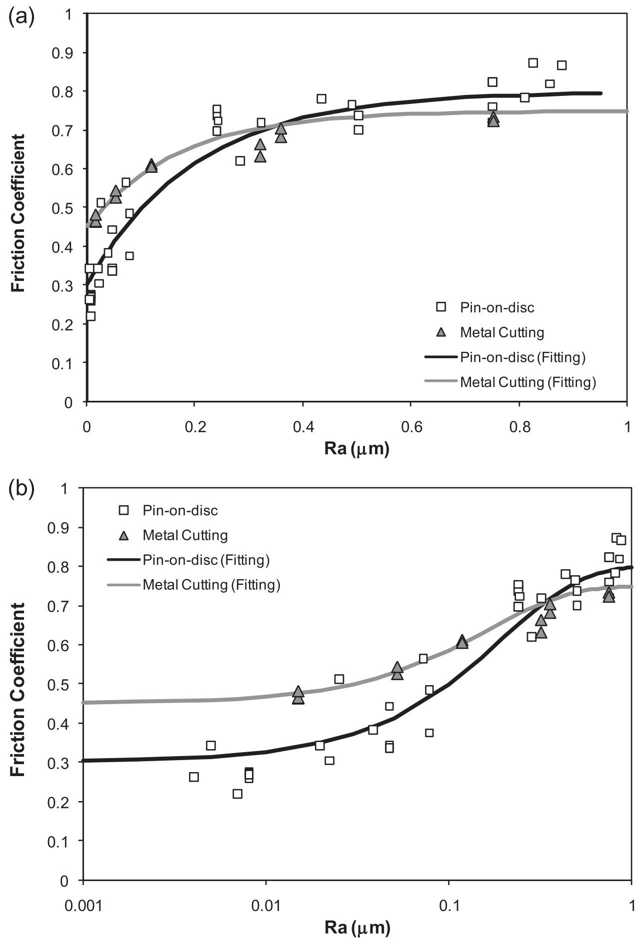


Fig. 6 Friction coefficient as a function of surface roughness. (a) Comparison between results obtained from pin-on-disc and metal cutting experiments. (b) Same as in (a) but showing the leftmost region of the graphic in greater detail

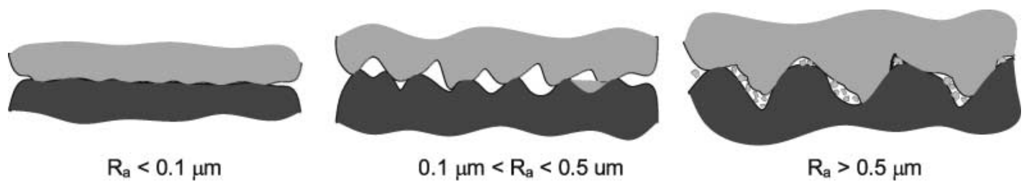


Fig. 7 Illustration showing the interaction between the pin and the disc for different values of surface roughness

of the usual linear one on the horizontal axis in order to facilitate reading of the results obtained for the discs with smoother surfaces.

The combined analysis of both graphics allows the identification of three different regions: (a) a leftmost region ($R_a < 0.1$), where the friction coefficient is constant and takes the smallest value among all the test cases, (b) a rightmost region ($R_a > 0.5$), where the friction coefficient is constant and reaches the largest value among all the test cases, and (c) a region in between where the friction coefficient progressively grows from the smallest to the largest measured values.

In the leftmost region of the graphics the surface roughness of the stainless-steel discs is very small and, for that reason, the sliding between the pin and the discs is smooth. The basic source of friction is adhesion ($\mu \cong \mu_{adh}$) and the friction force resulting from the relative movement between the pin and the disc should be roughly equal to the force that is needed for shearing the junctions formed by localized pressure welding (cold welding) at the asperities.

On the contrary, in the rightmost region of the graphics (where the surface roughness of the discs is very large) there is a more pronounced interaction between the asperities. The tips of the asperities on the discs will penetrate and plastically deform the surfaces of the pins, and in some cases debris may also be produced from micro-cutting in the asperity level (Fig. (7)). The increase of ploughing and the extra resistance to sliding caused by loose debris at the interface will raise the friction force. As a consequence, the friction coefficient for rough discs is larger than for smooth discs (Fig. (6)).

The accuracy and reliability of the friction coefficients that were independently determined by means of pin-on-disc simulative tests were assessed by metal cutting experiments performed in laboratory controlled conditions (section 2.2). Special attention was taken in choosing velocities and surface preparation of the cutting tools in accordance with those utilized in the pin-on-disc tests in order to guarantee comparative experimental conditions. In case of the cutting tools this required not only to ensure similar values of surface roughness but also to make certain that predominant patterns of surface texture were aligned in the same working direction as that employed in the pin-on-disc tests. This is very important because the friction coefficient depends on the texture of the harder counter surface as recently shown by Menezes *et al.* [**11**].

The comparison between pin-on-disc and metal cutting measurements of the friction coefficient shows a general good agreement (Fig. (6)). Major differences are found at the extreme regions of the graphics and may be attributed to the freshly cut surfaces of metal cutting that are not capable of being reproduced in the pin-on-disc simulative tests.

However, the overall quality of the results is very encouraging and allows concluding that the pin-on-disc simulative test, when performed with an adequate control of texture and surface roughness, is capable of providing a good average value of the friction coefficient in metal cutting applications.

4 CONCLUSIONS

Evaluation of the friction coefficient by direct testing in real metal cutting processes is difficult and very time consuming. Simulative testing performed on pin-on-disc machines is faster and cheaper, and provides a better control of the operation variables but is often considered inadequate for determining the friction coefficient in real applications.

This article shows that pin-on-disc is feasible to evaluate frictional conditions in metal cutting when combined with experimental procedures to guarantee an adequate control of texture and surface roughness and to allow acquisition of data to be performed in a single turn in order to avoid any rubbing of the pin on the same track of the disc.

The new proposed architecture for pin-on-disc machines that allow tests to be carried out under variable loading conditions and include an accessory for producing and regenerating the desired texture and roughness on the surface of the discs after completion of each test is in-line with the aforementioned experimental needs.

The remaining drawback in the evaluation of the friction coefficient seems to be related with the inadequacy to generate freshly cut surfaces on pin-on-disc machines. This problem is presently being investigated and a new patent on a device that is capable of producing a new freshly cut surface on the pin at the beginning of each turn was recently registered by the authors [**13**].

ACKNOWLEDGEMENTS

The authors would like to acknowledge PTDC/EME-TME/64575/2006, FCT-Portugal for the financial support.

REFERENCES

1 **Bil, H., Kiliç, S. E.,** and **Tekkaya, A. E.** A comparison of orthogonal cutting data from experiments with three different finite element models. *Int. J. Mach. Tools Manuf.*, 2004, **44**, 933–944.
2 **Astakhov, V.** On the inadequacy of the single-shear plane model of chip formation. *Int. J. Mech. Sci.*, 2005, **47**, 1649–1672.
3 **Zemzemi, F., Rech, J., Ben Salem, W., Dogui, A.,** and **Kapsa, P.** Identification of a friction model at tool/chip/workpiece interfaces in dry machining of AISI4142 treated steels. *J. Mater. Process. Technol.*, 2008
Q1 (in press).
4 **Bay, N., Wibom, O.,** and **Martins, P. A. F.** Testing of friction and lubrication in bulk metal forming. In Proceedings of the IMECE98 – International Mechanical Engineering Conference and Exhibition, Anaheim, USA, 1998.
5 **Grzesik, W., Zalisz, Z.,** and **Nieslony, P.** Friction and wear testing of multilayer coatings on carbide substrates for dry machining applications. *Surf. Coat. Technol.*, 2002, **155**, 37–45.
6 **Olsson, M., Soderberg, S., Jacobson, S.,** and **Hogmark, S.** Simulation of cutting pin-on-disc test. *Int. J. Mach. Tools Manuf.*, 1989, **29**, 377–390.
7 **Hedenquist, P.** and **Olsson, M.** Sliding wear testing of coated cutting tool materials. *Tribol. Int.*, 1991, **23**, 143–150.
8 **Zemzemi, F., Rech, J., Ben Salem, W., Kapsa, P.,** and **Dogui, A.** Development of a friction model for the tool–chip–workpiece interface during dry machining of AISI4142 steel with TiN coated carbide cutting tools. *Int. J. Mach. Machinability Mater.*, 2007, **2**, 361–367.
9 **Svahn, F., Kassaman-Rudolphi, A.,** and **Wallen, E.** The influence of surface roughness on friction and wear of machine element coatings. *Wear*, 2003, **254**, 1092–1098.
10 **Sedlacek, M., Podgornik, B.,** and **Vizintin, J.** Influence of surface preparation on roughness parameters, friction and wear. *Wear*, 2009, **266**, 482–487.
11 **Menezes, P. L., Kishore,** and **Kailas, S. V.** Role of surface Q2
texture of harder surface on subsurface deformation. *Wear*, 2009, **266**, 103–109.
12 **Altan, T., Henning, H. J.,** and **Sabroff, A. M.** The use of model materials in predicting forming loads in metalworking. *Trans. ASME, J. Eng. Ind.*, 1970, **92**, 444–452.
13 **Cristino, V. A. M., Rosa, P. A. R.,** and **Martins, P. A. F.** *Método e aparelho para a determinação do coeficiente de atrito em interfaces de contacto com superfícies recém-geradas*. Patent request no. PT103935, INPI, Portugal, 2008.

JET639

Queries

V A M Cristino, P A R Rosa, and P A F Martins

Q1 Please update Ref. [3].

Q2 Please check and provide initial for author "Kishore"in Ref. [11].