Advanced Materials Research Vol. 223 (2011) pp 257-266
© (2011) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/AMR.223.257

Input Data for the Numerical Simulation of Metal Cutting

P.A.R. Rosa[1,a], V.A.M. Cristino[1,b], C.M.A. Silva[1,c] and P.A.F. Martins[1,d]

[1]IDMEC, Instituto Superior Técnico, Tec.Uni. Lisbon, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

[a]pedro.rosa@ist.utl.pt, [b]valentino.anok@ist.utl.pt, [c]carlos.alves.silva@ist.utl.pt, [d]pmartins@ist.utl.pt

Keywords: Metal cutting; Experimentation; Finite element method; Material characterization, Tribology; Ductile fracture.

Abstract. This paper is focused on the fundamentals of metal cutting and is aimed at enabling the readers to recognize the validity of test calibration procedures, to identify the possible sources of modelling errors and to understand the routes to improve the overall accuracy and reliability of physical, tribological and mechanical input data for the numerical simulation of metal cutting processes. Innovative testing equipments, experimental methodologies and numerical procedures developed by the authors give support to the presentation.

Introduction

Taking a general view of the state-of-the-art in terms of numerical modelling it appears that the finite element method is the most widespread technique for the analysis of metal cutting processes.

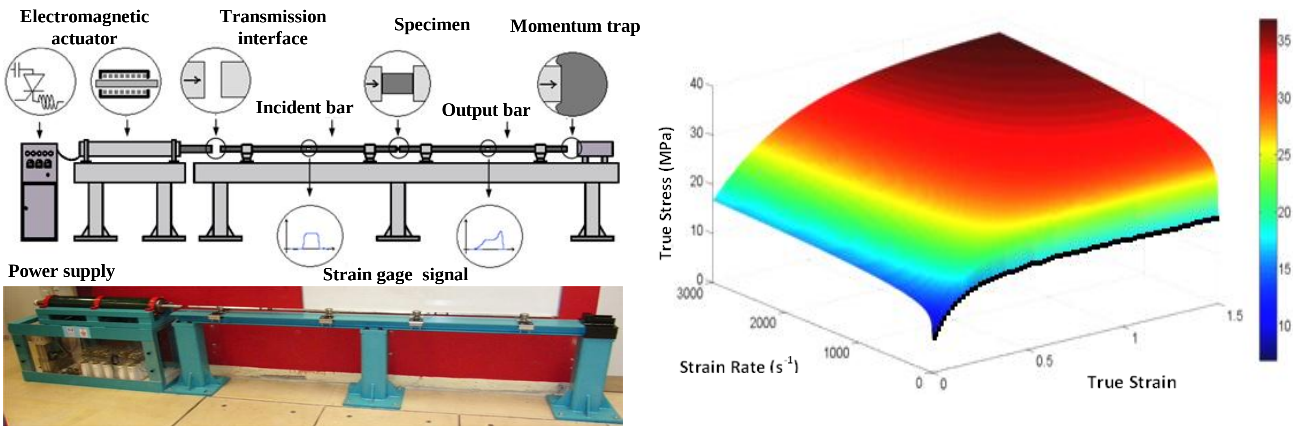
The finite element method is capable of providing very efficient computer programs that can easily take into account the practical non-linearities in the geometry and material properties as well as the contact change typical of chip flow to produce accurate predictions of chip curling, chip compression factor, temperature distribution, cutting forces and residual stresses, among others [1, 2]. However, the widespread utilization of finite elements is being accomplished with a growing evidence that most of the users are currently utilizing commercial programs as 'black-boxes'. As a result of this, users are growingly being confronted with the need to properly understand the key topics that significantly influence the accuracy, reliability and validity of their numerical estimates provided by commercial computer programs.

Besides, the need of users being educated or refreshed with fundamental knowledge on theory of continuum mechanics and finite element methodologies that will allow them to recognize the pitfalls of the existing formulations that give support to available computer programs, it is also very important for the users to be able to identify the basic sources of modelling and numerical errors. Awareness and understanding of all these issues is the key ingredient for improving the overall accuracy and reliability of the finite element estimates of metal cutting processes.

Authors are concerned with the aforementioned problem [3] and this paper is exclusively focused in the modelling errors that can be directly related to the physics of the process and to the mechanical and tribological behaviour of materials. The objective is accomplished by presenting innovative testing equipments, experimental methodologies and numerical procedures that help identifying a new level of understanding for the construction of flow curves, for accounting the influence of surface roughness and surrounding medium in the coefficient of friction and for analysing the formation of new freshly cut surfaces in the light of modern ductile fracture mechanics.

Mechanical Testing of Materials

Contrary to other traditional and well-established manufacturing processes, where the rates of loading are within the range of universal testing machines, metal cutting processes are known to operate under high levels of strain-rate. This requires mechanical testing of materials to be performed in other equipments than universal testing machines in order to ensure loading rates similar to those found in real metal cutting conditions.



(a) (b)

Figure 1: (a) The electromagnetic compressive split Hopkinson bar; (b) True stress (MPa) as a function of strain and strain-rate for technically-pure lead.

Unfortunately, this is not only constrained by a reduced and costly offer of equipments as the alternative of digging up material data in the open literature is regularly not a solution because, in most cases, the information available is scarce or simply non-existent. The above mentioned difficulties often give rise to a wide-spread practice of extrapolating quasi-static material data to applications that involve high strain-rates of loading or to perform the identification of flow curves by means of inverse analysis. These procedures often lead to important sources of errors.

One of the most widespread laboratory equipment for mechanical testing of materials at high strain-rates is the Hopkinson bar. However, major disadvantages of commonly available compressive split Hopkinson bar systems can be summarized as the need for very-high air pressures for reaching high strain-rates, the lack of repeatability of the firing pressure, the high operation noise due to the instantaneous expansion of the air and the large overall length of the apparatus.

In the past years authors, developed an innovative design for the compressive split Hopkinson bar that makes use of the intense pressure created in a transient magnetic field formed by the passage of a pulse of electric current through a series of coils [4] (Fig. 1a). The magnetic field behaves like air being relief from a high pressure vessel and is capable of properly accelerating the striker bar against the incident bar. However, because the propulsion is purely electromagnetic, its overall performance can be easily controlled and nearly infinitely adjustable.

In order to show the influence of strain-rate in the mechanical response of metallic materials, the stress-strain curve of technically-pure lead was obtained by means of compression tests performed on the innovative electromagnetic Hopkinson bar system and on a universal testing machine. The Hopkinson bar enabled reaching values of strain-rate in the range of 200 to 3000 s^{-1} while the testing machine worked under quasi-static kinematic conditions (that is, under very low values of strain-rate). The experimental data for technically-pure lead (Fig. 1b) presents significant strain-rate sensitivity and, therefore, substantial modeling errors will be introduced if quasi-static material data (refer to the black line in Fig. 1b) is extrapolated to model real metal cutting conditions.

Roughness, Medium and Friction

Evaluation of friction in pin-on-disc tests.

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]. However, the alternative solutions to pin-on-disc testing that are claimed to be more successful in reproducing real metal cutting conditions, are more expensive, more time consuming and demand a more accurate control of the operating parameters [6].

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 needed 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 paragraph, authors developed a new design for the pin-on-disc tribometer (Fig. 2a) and compared the friction coefficient obtained by means of pin-on-disc simulative testing with that acquired in a specially designed metal cutting apparatus installed on a CNC machining centre.

Since the pin-on-disc tests that were performed in the investigation were designed for testing friction in metal cutting it follows that the pin is simulating the workpiece material (for example, technically-pure lead) whereas the disc is replicating the rake face of the cutting tool (for example, AISI 316L stainless steel).

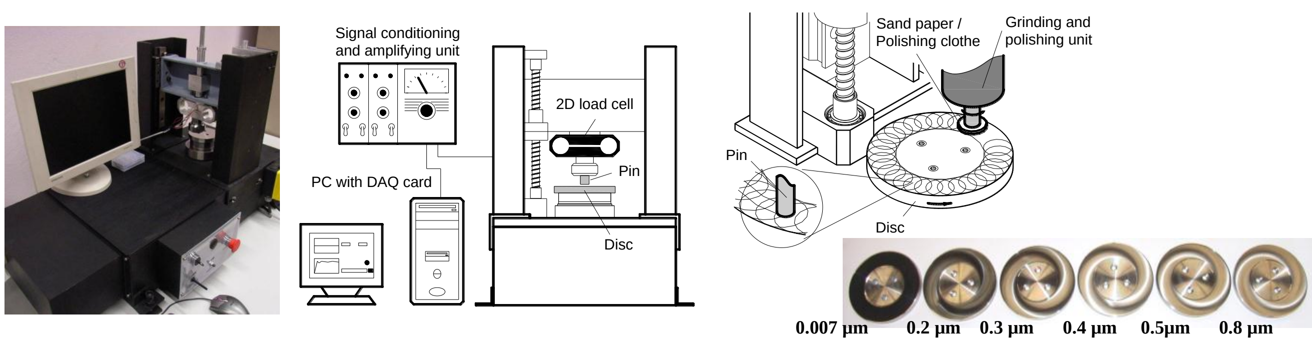
The design of the pin holder deviates from traditional architecture of commercial pin-on-disc machines in order to increase stiffness and reduce the deformation caused by weight and applied loads. The new design also eliminates the need for a counter-weight. A precision ball screw driven by a motor and 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, fixed to the pin holder, a multifunction data acquisition system and a personal computer (PC).

The pin-on-disc tester is further equipped with a grinding and polishing custom built unit that serves the purpose of producing and regenerating the desired texture and roughness in the surface of the discs after completion of each test (Fig. 2b).

As seen in the Fig. 2b, 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 (Ra) in the range 0.007 to 0.8 μm. These values were measured by a roughness tester and an atomic force microscope along a direction perpendicular to the rotation of the discs.

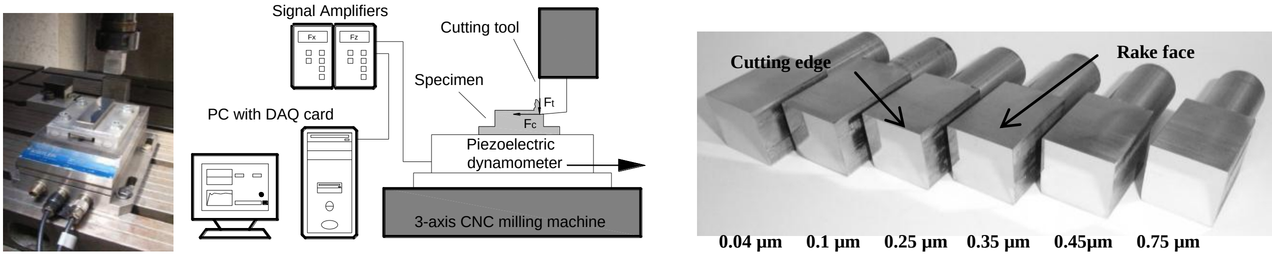
The metal cutting testing apparatus that was built for assessing the validity of the pin-on-disc estimates of the friction coefficient is shown in Fig. 3a. The cutting specimen is made of the same material as the pin of the pin-on-disc tests and is fixed directly on the three-dimensional piezoelectric dynamometer. The cutting tools have a rake face angle $\alpha = 0^{\circ}$ and a clearance angle $\sigma = 5^{\circ}$ and were manufactured from the same material as the rotating discs of the pin-on-disc tests (Fig. 3b).

Grinding and polishing of the cutting tools was performed in order to ensure the directionality of the predominant surface pattern to be identical to that of the rotating discs of the pin-on-disc tests because patterns aligned in different directions will inevitably influence the friction coefficient and the average surface roughness $R_a = 0.04\,\mu\text{m}$ on the relief surface was maintained throughout the experiments.



(a) (b)

Figure 2: (a) The innovative pin-on-disc tester; (b) Grinding and polishing the discs prepared with different values of surface roughness (Ra).



(a) (b)

Figure 3: (a) Metal cutting testing apparatus and (b) cutting tools prepared with different values of surface roughness (Ra).

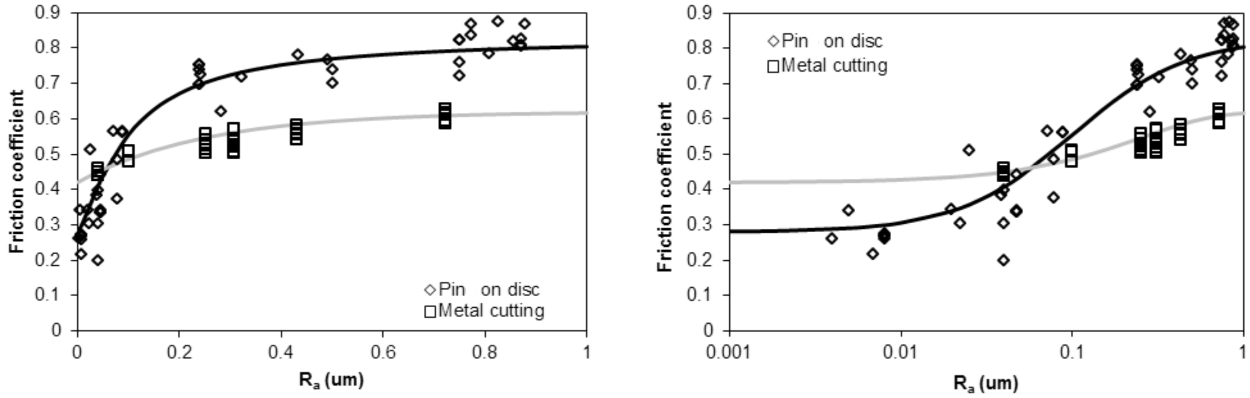
Fig. 4a shows the variation of friction coefficient with surface roughness for the lead-stainless steel tribo-tests. The main differences between Fig. 4a and 4b are due to the fact that the latter employs a logarithmic scale in-stead of the usual linear one on the horizontal axis in order to facilitate reading of the results obtained for the discs with smoother surfaces.

The combined analysis of both Fig. 4a and 4b allows the identification of three different regions; (i) a leftmost region (Ra<0.1) where the friction coefficient is constant and takes the smallest value among all the test cases, (ii) a rightmost region (Ra>0.5) where the friction coefficient is constant and reaches the largest value among all the test cases and (iii) a region in between where the friction coefficient progressively grows from the smallest to the largest measured values.

In the leftmost region of the Fig. 4 the surface roughness of the stainless steel discs is very small and, for that reason, 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 Fig. 4 (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. 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.

As seen in Fig. 4b there is a general acceptable agreement between pin-on-disc and metal cutting measurements of the friction coefficient. Major differences are found at the extreme regions of the FIG. 4 and may be attributed to the freshly cut surfaces of metal cutting that are not capable of being reproduced in pin-on-disc simulative tests.



(a) (b)

Figure 4: (a) Friction coefficient as a function of surface roughness for the lead-stainless steel tribo-tests; (b) Same as in (a) but showing a detail of the leftmost region of the graphic.

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

Friction and surrounding medium.

Although the experimental work of Poletica referred in the book by Astakhov [7] claims no influence of the surrounding medium in metal cutting after cutting copper and armco iron in the presence of air and under an inert argon atmosphere, there is a common believe among researchers and practitioners that active gases may significantly influence the mechanics of chip flow.

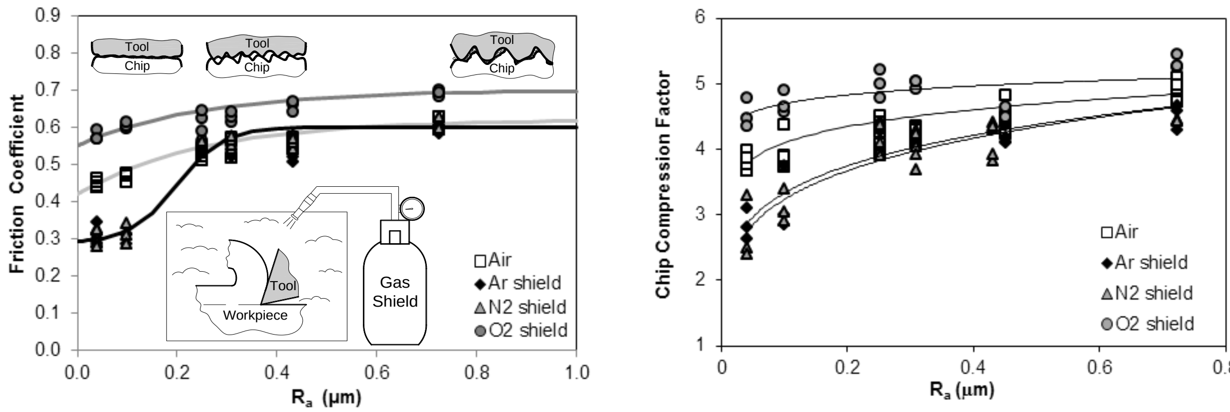
Under these circumstances, the investigation performed by the authors and reported in this section of the paper draws from metal cutting experimentation under active and inert gas shields to demonstrate that oxygen acting on the freshly cut surfaces of lead may change friction, chip compression factor, chip curling and forces to a level that goes significantly beyond what has been said and written in the context of metal cutting fundamentals [8].

The experiments were performed in the metal cutting testing apparatus shown in Fig. 3a. Cutting material and tools were similar to those of previous section. The influence of the surrounding medium was analysed by cutting in the presence of air and by shielding the cutting region by means of active and inert gases (oxygen, nitrogen or argon). The gases were supplied from an external source and applied at a rate of approximately 5 l/min through a nozzle on to the cutting region (Fig. 5a).

The Fig. 5a shows the friction coefficient as a function of the surface roughness of the cutting tool for different gas shields. In the leftmost region of the Fig. 5a the basic source of friction is adhesion ($\mu \cong \mu_{adh}$) because surface roughness is very small (refer to previous section) and because the low affinity of lead for nitrogen and the inert characteristics of argon avoid the formation of surface films, allowing the chip to slide smoothly along the rake surface of the cutting tool.

On the contrary, in the rightmost region of the Fig. 5a there is a more pronounced interaction between the asperities, in close agreement with what had been previously mentioned in previous section. The results obtained from the orthogonal cutting tests in the presence of argon or nitrogen shifts the intermediate region of the Fig. 5a, where friction progressively grows from the smallest to the largest measured values, to the right side in comparison to what had been previously depicted in Fig. 4.

In fact, cutting in the presence of air or under an oxygen-rich atmosphere shows a monotonic increase of the friction coefficient from smaller to larger values of surface roughness. This is attributed to the oxide films of PbO formed in the upper and lower surface boundaries of the chips, which do not allow material to slide smoothly along the rake surface of the cutting tools, even when roughness is very small.



(a) (b)

Figure 5: (a) Friction coefficient as a function of surface roughness and surrounding medium; (b) Chip-compression factor as a function of surface roughness and surrounding medium.

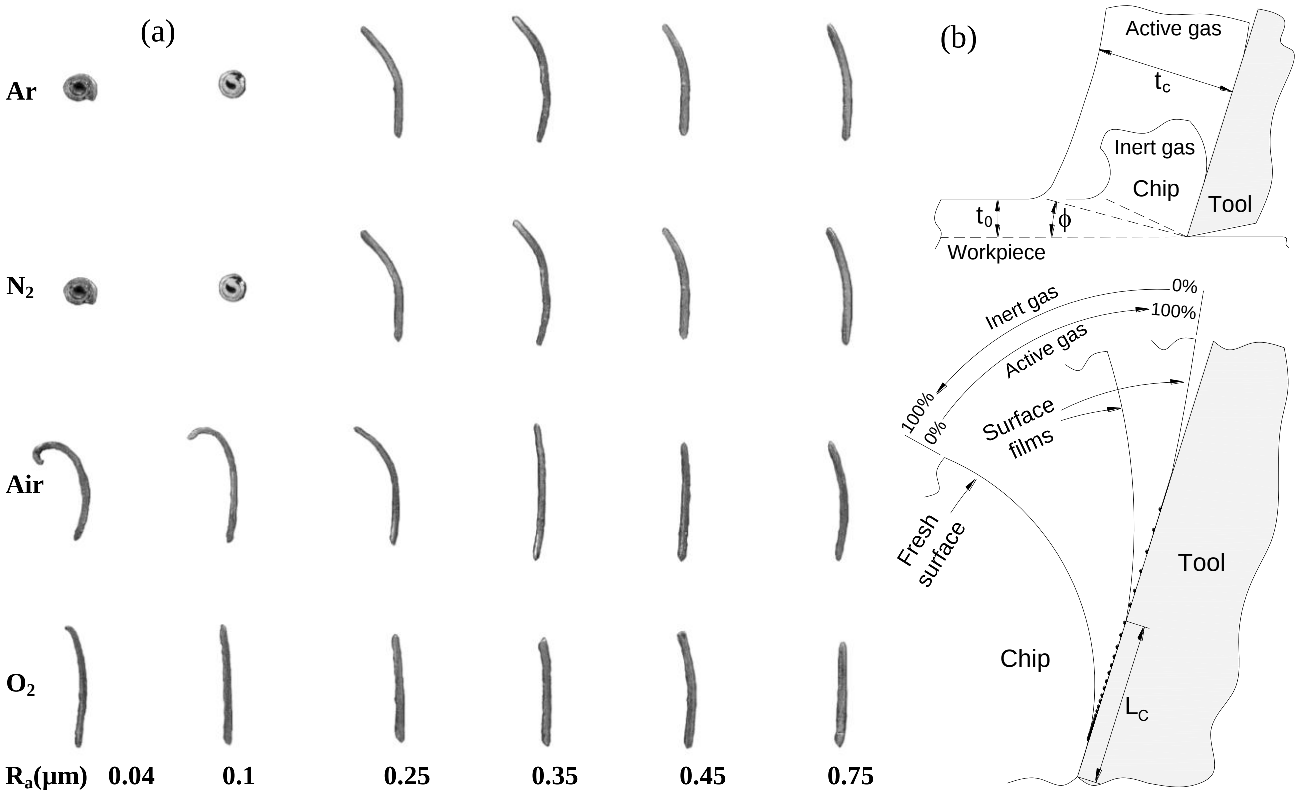


Figure 6: (a) Chip cross sections obtained with different surface roughness and surrounding medium and (b) basic types of chip flow as a function of the surrounding medium.

Although the influence of the surrounding medium in metal cutting is often resumed to its primary function of cooling and lubricating, one important aspect of the cutting medium on the tribological conditions at the tool–chip contact interface is the protection against active gases in air.

As seen in Fig. 6a cutting of lead under nitrogen or argon atmospheres allow chips to curl naturally within the normal range of surface roughness currently found in cutting tools whereas the exposure to oxygen causes the chip curl radius to become larger. In fact, the exposure to oxygen causes the chips to flow along the rake surface of the cutting tools, increasing the contact length L_c (Fig. 6b), and promoting its curvature away from the cutting edge.

The contact length L_c in steady-state cutting conditions (Fig. 6b) is due to an energy compromise between the plastic work, a quantity inversely proportional to the radius of curvature of the chip, and the amount of frictional work which is directly proportional to the contact length and, therefore, to the radius of curvature of the chip. Because, cutting in the presence of oxygen increases the friction coefficient (Fig. 5a), it follows that frictional work will also increase with the formation of oxide films on the new freshly cut surfaces of lead. The exposure of lead to oxygen also results in larger chip curl radius (Fig. 6b).

The influence of the surrounding medium in the mechanics of chip flow can be further understood by analysing the evolution of the chip-compression factor t_c / t_0 as a function of the initial surface roughness R_a of the cutting tools (Fig. 5b).

Fracture and Chip Formation

In what concerns chip formation, the commonly accepted view considers (i) that new surfaces in metal cutting are formed by plastic flow around the tool edge, (ii) that the energy required for cutting is overwhelmingly due to plasticity and friction and (iii) that any energy required for the formation of new surfaces is negligible. This view is referred as the 'plasticity and friction only'

(PFO) approach and is inherent in the most significant contributions to the understanding of metal cutting fundamentals made by Zorev [9], Shaw [10] and Oxley [11], among others.

A recent breakthrough in the mechanics of chip formation was made by Atkins [12] by extending traditional analysis to include the work involved in the formation of new surfaces at the tip of the tool. The combination of plasticity and friction with ductile fracture mechanics proves effective for obtaining good estimates of the cutting forces and to solve a longstanding incompatibility problem of the metal cutting theory between the specific cutting pressure and the state-of-stress resulting from flow curve of the materials [13].

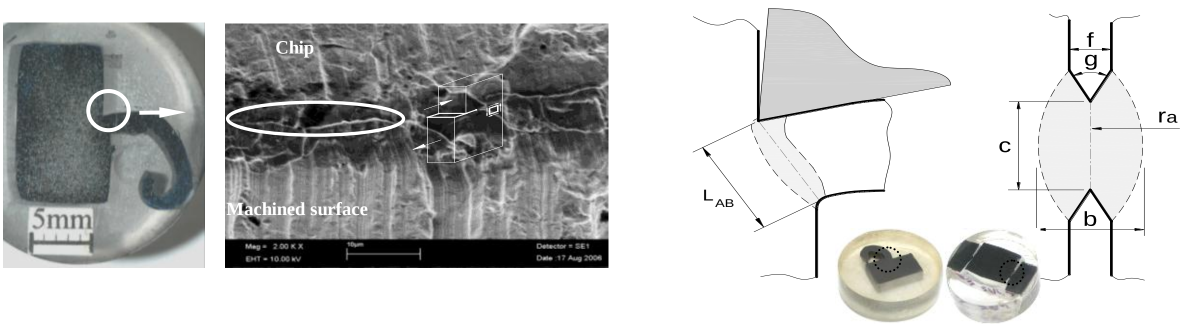
Fracture toughness.

The characterization of fracture toughness can be performed by means of experimental tests carried out on double-notched cylindrical specimens loaded in shear (Fig. 7b). The choice of this particular test specimen, which suggested that the separation process at the tip of the tool occurs in shear, is experimentally corroborated by means of scanning electron microscope observations of the material adjacent to the tip of the tool showing a kink perpendicular to the plane of the figure, a clear indication that the crack formed ahead of the cutting edge is closed and growth occurs in shear [14] (Fig. 7a).

The double-notched cylindrical tests were performed with specimens where started cracks have been introduced to various depths before loading and the experiments consist on determining the punch shearing load-displacement evolution from which fracture toughness of the material may be deduced. The maximum length of the ligament between notches was limited to $a = 2.5\,\text{mm}$ so that plastic deformation is confined to a small region in between the notches. If $a > 2.5\,\text{mm}$ the plastic deformation extends outside this zone and the experimental measurements are no longer adequate for calibrating fracture toughness.

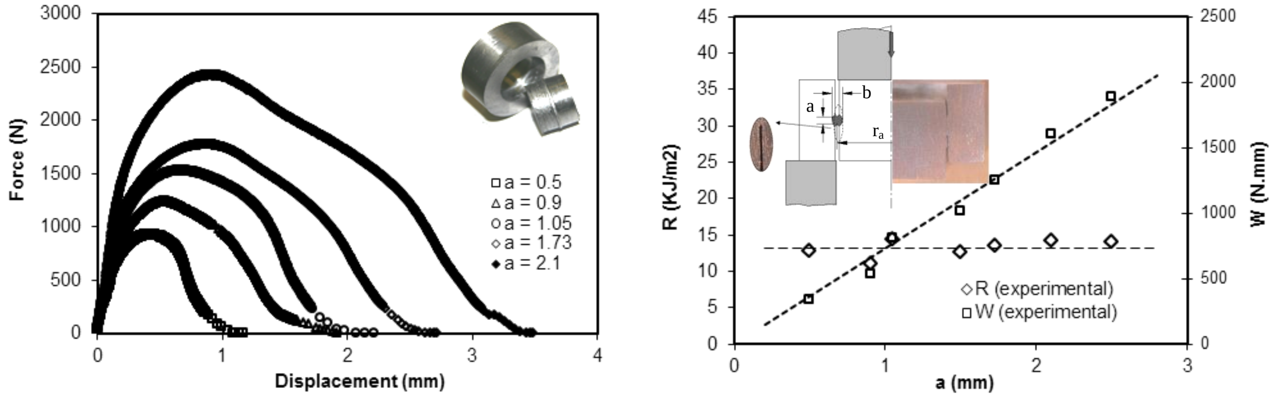
The energy   to initiate crack propagation is calculated by direct integration of each curve up to the maximum punch shearing load (at which cracking begins, Fig. 8a) and the specific work of surface formation (fracture toughness) R is obtained from Eq. 1 where, r_a is defined in Fig. 7b. The shear load depends directly on the length of the ligament a between notches and fracture toughness $R \cong 13.3$ kJ/m^2 is taken from the intercept with vertical axis in Fig. 8b.

Accountability of the fracture work involved in the formation of new surfaces in metal cutting can be achieved by means a ‘decoupled approach’ that neglects the influence of fracture work in the yield surface of the material being cut. Material is assumed to be continuous and isotropic throughout the cutting process and the conventional constitutive equations for elastic-plastic and/or rigid-plastic/viscoplastic material behaviour are utilised. In other words, the major field variables such as strain, stress and strain-rate are to be directly calculated from a PFO finite element computations, while the cutting force F_c is to be determined by summing up afterwards the contribution of finite elements with that of ductile fracture associated with the formation of new surfaces [13].



(a) (b)

Figure 7: (a) SEM observation showing a crack formed by shear at the tip of the tool; (b) Comparison between the plastic deformation zone of the double-notched cylindrical test specimens and the primary shear zone of metal cutting.



(a) (b)

Figure 8: (a) Load vs. displacement for the double-notched test specimens fracture and (b) fracture toughness R and energy W to initiate crack propagation.

$$R = \frac{W}{2\pi r_a a} \quad (1)$$

The decoupled approach proposed by the authors is based on a simple but physical meaningfully analogy between resistance to crack propagation offered by the plastically deforming region placed in between the notches of the fracture test specimen and by the plastically deforming region induced by crack formation at the tip of the cutting tool. It is further assumed that the primary shear zone of metal cutting results from PFO material shearing as well as from resistance to crack propagation (Fig. 7b). The computer implementation of the decoupled approach combining finite element modelling with ductile fracture mechanics was performed in the in-house finite element computer program I-Form. The program is built upon the flow formulation and has been utilized and extensively validated against experimental measurements of PFO metal forming processes since the end of the 80's [15].

The Fig. 9 presents the steady-state cutting forces F_c for different values of the uncut chip thickness t_0 obtained from finite element modelling and experimental testing on technically-pure lead with a rake angle $\alpha = 10^{\circ}$. As shown, PFO finite element estimates, of the cutting forces vs. uncut chip thickness, pass through the origin and considerably underestimates the experimental measurements The failure of finite element modelling seems to suggest that PFO analysis of orthogonal metal cutting is not adequate for calculating the forces in actual cutting processes.

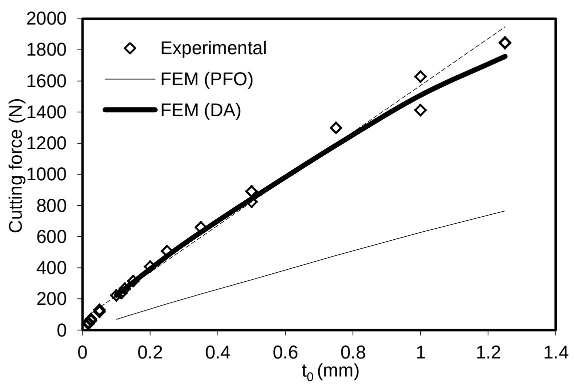


Figure 9: Variation of the theoretical and experimental cutting force with the undeformed chip thickness.

The missing value in the cutting force is related to the fracture work involved in the formation of new cut surfaces. Confirmation of this conclusion is given by the results supplied by the proposed decoupled finite element-fracture mechanics approach, where the effect of fracture work on the cutting force F_c is added on afterwards (refer to the FEM (DA) in Fig. 9).

The proposed decoupled approach is capable of providing very good correlations between theory and experimentation and it is interesting to notice that the trend curves containing the numerical estimates 'bend down' at small values of the uncut chip thickness t_0 in agreement with the experimental measurements.

Conclusions

In the past decade numerical simulation of metal cutting processes has evolved from simple two-dimensional plane strain cases to complex three-dimensional processes. Computer programs increased in sophistication, robustness and computational efficiency and, nowadays the biggest problem related with its utilization is whether the conceptualized models and associated results are correct or wrong.

This paper revisited finite element input data related to mechanical, fracture and tribological response of materials and discussed the physics behind material separation and chip formation at the tip of the tool in order to help users increasing their critical thinking assessment of the appropriateness and correctness of their models and sources of input data.

The presentation includes a brief overview of innovative testing equipments that were specifically designed for obtaining input data in operative conditions similar to those of real metal cutting processes.

Acknowledgements

The authors acknowledge the support of POCI-2011 and FCT SFRH/BD/46798/2008.

References

[1] J. Mackerle: Finite-element analysis and simulation of machining: a bibliography (1976–1996), J. Mater. Process. Tec., 86, (1999), 17–44.

[2] J. Mackerle: Finite element analysis and simulation of machining: an addendum: A bibliography (1996–2002), Int. J. Mach. Tools Manuf., 43, (2003), 103-114.

[3] A. E. Tekkaya and P. A. F. Martins: Accuracy, reliability and validity of finite element analysis in metal forming: a user's perspective, Eng. Comput., 26, (2009), 1026-1055.

[4] C. M. Silva, P. A. R. Rosa and P. A. F. Martins: An innovative electromagnetic compressive split Hopkinson bar, Int. J. Mech. Mater. Des., 5, (2009), 281-288.

[5] W. Grzesik, Z. Zalisz, P. Nieslony: Friction and wear testing of multilayer coatings on carbide substrates for dry machining applications, Surf. Coat. Tech., 155, (2002), 37–45.

[6] V. A. M. Cristino, P. A. R. Rosa and P. A. F. Martins: On the utilization of pin-on-disc simulative tests for the calibration of friction in metal cutting, J. Eng. Tribol., 224, (2010), 169-177.

[7] V. P. Astakhov: Tribology of metal cutting, Elsevier, (2006), Oxford.

[8] V. A. M. Cristino, P. A. R. Rosa and P. A. F. Martins: Cutting under active and inert gas shields: a contribution to the mechanics of chip flow, Int. J. Mach. Tools Manuf., 50, (2010), 892-900.

[9] N. Zorev: Metal cutting mechanics, Pergamon Press, (1966), Oxford.

[10] M. C. Shaw: Metal cutting principles, Clarendon Press, (1984), Oxford.

[11] P. L. Oxley: Mechanics of machining: An analytical approach to assessing machinability, John Wiley & Sons, (1989), New York.

[12] A. G. Atkins: Modelling metal cutting using modern ductile fracture mechanics: quantitative explanations for some longstanding problems, Int. J. Mech. Sci., 45, (2003), 373-396.

[13] P. A. R. Rosa, P. A. F. Martins and A. G. Atkins: Revisiting the fundamentals of metal cutting by means of finite elements and ductile fracture mechanics, Int. J. Mach. Tools Manuf., 47, (2007), 607–617.

[14] P. A. R. Rosa, O. Kolednik, P. A. F. Martins and A. G. Atkins: The transient beginning to machining and the transition to steady-state cutting, Int. J. Mach. Tools Manuf., 47, (2007), 1904–1915.

[15] M. L. Alves, J. M. C. Rodrigues and P. A. F. Martins: Simulation of three-dimensional bulk forming processes by the finite element flow formulation, Model. Simul. Mater. Sci. Eng. – Inst. Phys., 11, (2003), 803-821