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DEVELOPMENT OF TRIBO-TESTERS FOR PREDICTING METAL CUTTING FRICTION

This paper overviews some frequently used apparatus for determination of friction between the elements of tribo-pairs which represent the cutting tool and the workpiece materials. The three methods which utilize different measuring techniques are outlined and some construction details of tribotesters are presented. The main advantages and disadvantages of the closed and open tribosystems along with their practical applications in machining are highlighted.

1. INTRODUCTION

The experimental and numerically-based investigation of the performance of the cutting process is strongly focused on the two fundamental physical phenomena involving intensive plastic deformation of the removed material and associated friction at the contact surfaces of the cutting tool. As a result, reliable friction is of key importance in the FEM modeling of the cutting process. In general, the characterization of friction behavior in the secondary shear zone and in the rubbing zone (Fig. 1 from [1]) is based on three different methods [2, 3]:

- measurements of the components of the resultant cutting force using piezo- or strain-gauge dynamometers (1st type),
- conventional tribometers (2nd type) which are typically used for evaluating the friction coefficient of construction materials, as for instance hard alloys and bearing steels,
- specially-designed tribometers (3rd type) which are better adopted for the mechanical, thermal and tribological conditions in the cutting zone.

The first method, described in [2], is usually used for the orthogonal cutting arrangement typical for turning and milling and broaching operations [3]. During cutting

tests, normal and tangential forces are continuously recorded and the macroscopic equivalent friction coefficients are calculated.

This method does not consider the variations of the local contact conditions along the tool-workmaterial interface [3, 4] due to the changes of local sliding velocity, contact pressure and temperature (Fig. 2). As a consequence, this approach ignore the presence of the sticking and sliding zone on the rake and flank faces. In order to overcome this situation, some authors use either split tools whereas other authors develop an analytical post-treatment. In order to overcome these disadvantages it is proposed to combine an interrupted turning with the deep analysis of the layer formation using several experimental techniques.
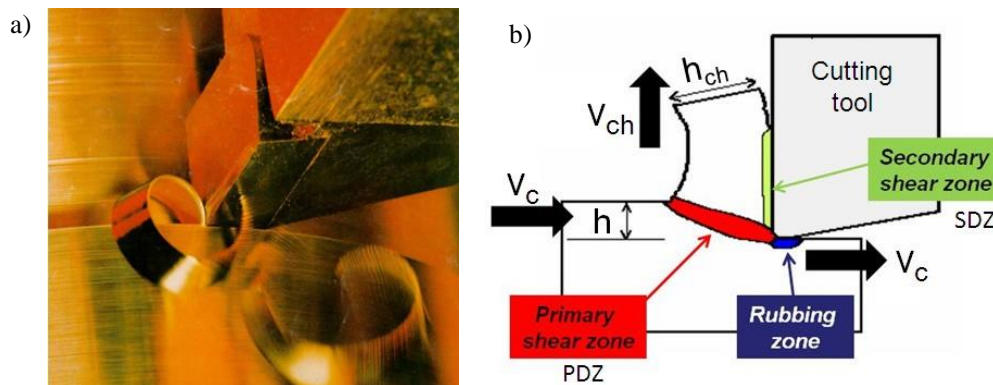

Fig. 1. Chip formation mechanisms: (a) image recorded by high-speed camera, (b) model of the cutting zone [1]
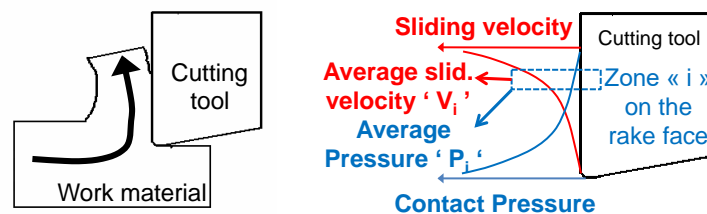

Fig. 2. Variation of the tribological conditions along the tool-workmaterial interface [4]

The second method uses either standard or special tribometers. The most common tribometers use the pin-on-disc or pin-on-ball arrangements as shown in Fig. 3. In particular, the disc (counterspecimen) is made of the workmaterial, whereas the pin is made of the cutting tool material (optionally the substrate (uncoated) material or additionally coated similar as cutting tool inserts). This approach can be used to classify tool coatings in terms of frictional behaviour.

In order to avoid special specimens in the form of pins, commercial cutting tool inserts are often applied [3, 5] (Fig. 4). Unfortunately, such tribometers hardly provide relevant tribological conditions occurring along the tool-work material interface in the cutting process. They quantify the frictional behavior without surface refreshment, which corresponds to a so-called "closed tribosystem". This is weak point of this method compared to the tribosystem along the tool-workmaterial interface in which a fresh workmaterial rubs the cutting tool (open tribosystem) [3].
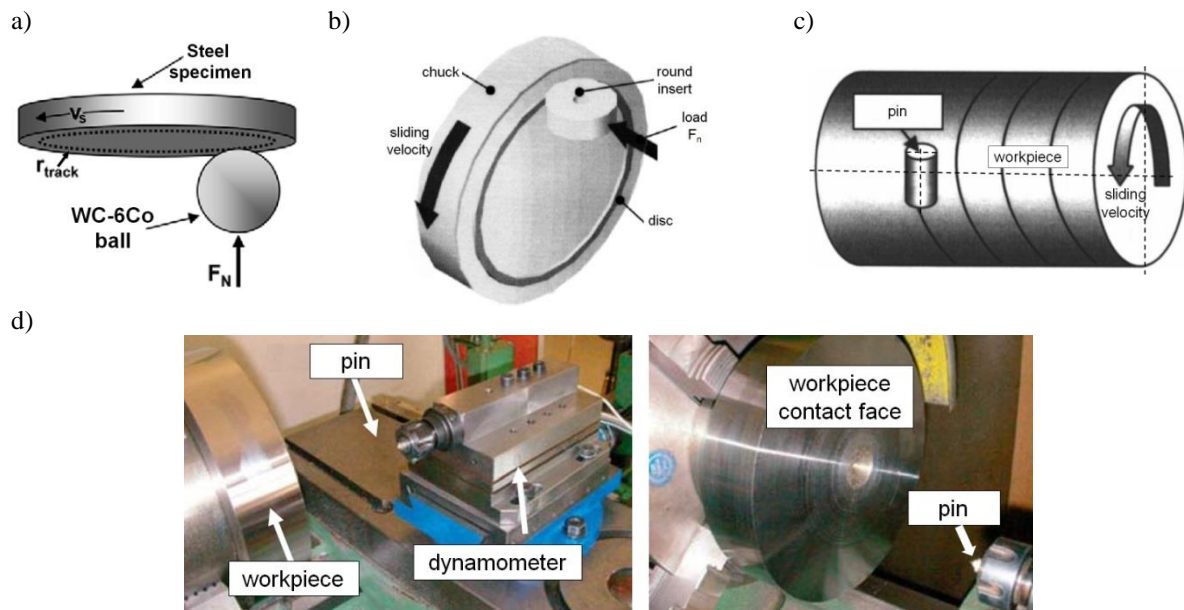
Fig. 3. Closed tribosystems: (a) ball-on-disc, (b) pin-on-disc and (c) pin-on-ring systems, (d) tribometer integrated with piezoelectric measuring platform [3, 5–9]

The third approach is based on special tribometers that simulate open tribo-conditions with different sliding velocity and contact pressure. One of the most popular configuration (Fig. 6) introduces a ball-ended pin which is placed just after a cutting tool during the machining of a tube's flat face [3].

2. A SURVEY OF CONSTRUCTIONS OF ADOPTED TRIBOMETERS (2nd TYPE)

Three typical constructions of closed (adopted) tribometers are shown in Fig. 3. In case of the ball-on-disc tribotester shown in Fig. 3a, a hard sphere made of hardened bearing steel or sintered carbide is pressed with the load F_n against a rotating specimen flat surface with the defined sliding track radius r_{track}. For the defined sliding speed v_s, the tangential (friction) force F_t is measured and the friction coefficient is determined as the ratio F_t/F_n. Specimens are specially manufactured in the form of pins (balls or cylinders) which are localized perpendicular or tangential to the flat disc surface (as presented in Fig. 3b). This method is frequently used to test coatings with respect to the sliding friction.

So as to avoid the manufacturing of special pins, some authors use commercial cutting tool inserts. The cylindrical corner of the insert rubs on the surface as shown in Fig. 4. The sliding track is a narrow flat or concave cog (also a series of cogs as in Fig. 4c). In Fig. 4a a rounded insert of 1 in. diameter was used and the maximum (Hertzian) contact normal stresses are estimated at the level of 1.2 GPa [6]. This method is effectively used to determine the friction coefficient values for variable load and sliding velocity to support FEM-based modelling [11], as shown in Fig. 5. The countermaterial is mounted as the workpiece in the chuck in the lathe and the pin in the tool holder integrated with the dynamometer. A spring-loading system is utilized to apply the normal force.
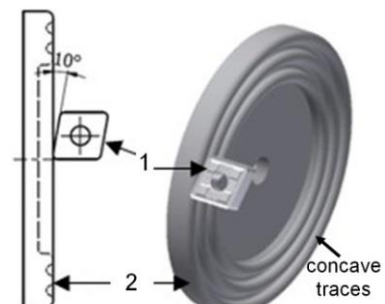
a)
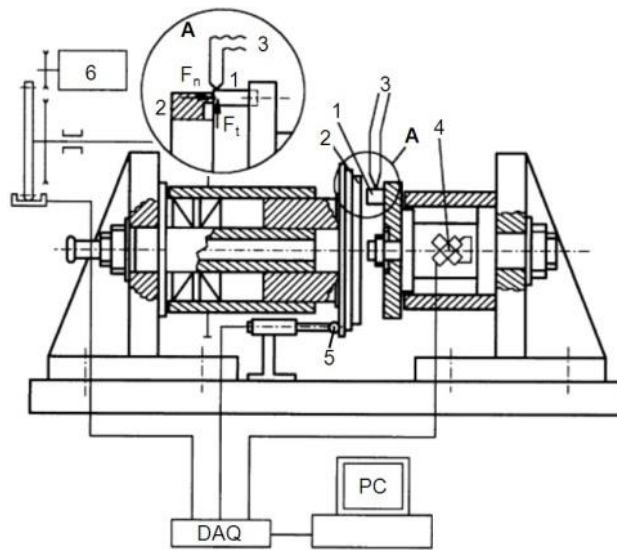
A-tribo-contact with attached thermocouple: 1 – pin, 2 – disc, 3 – *K*-type thermocouple,
4 – dynamometer, 5 – inductive sensor, 6 – motor with stepless speed control

b)
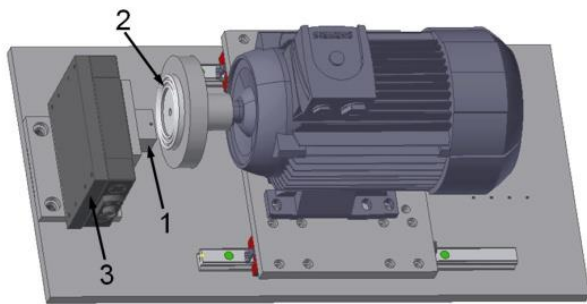
1 – specimen, 2 – disc, 3 – dynamometer with specimen fixture

c)

1 – specimen, 2 – profiled disc

Fig. 4. A scheme (a) and a model (b) of the cylinder-on-disc tribotester from Fig. 3b with the load and temperature control systems; (c) location of the specimen against the disc [5, 6, 10]
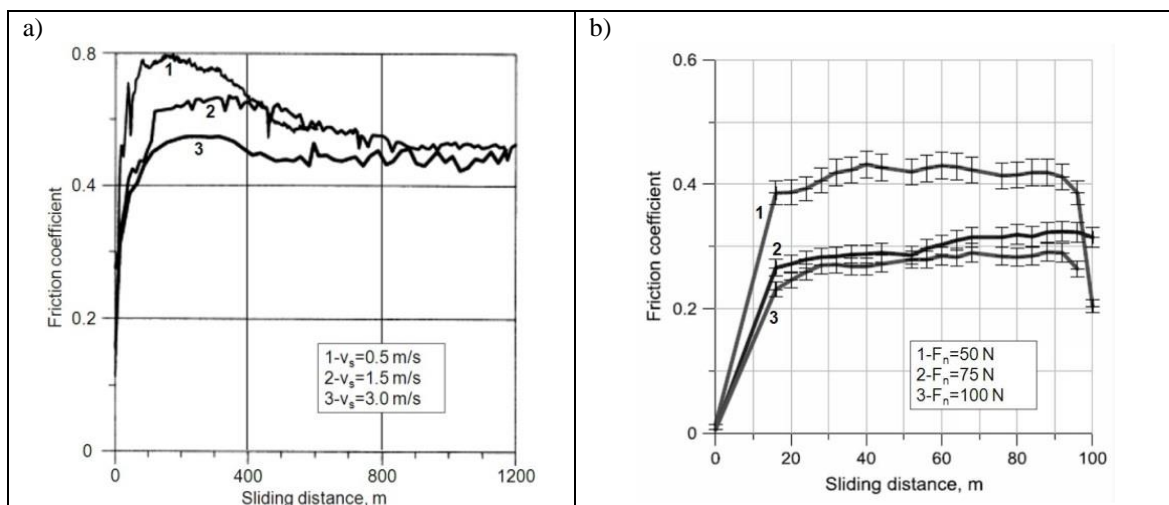

Fig. 5. Changes of the friction coefficient for $TiC/Al_2O_3/TiN$ coated carbide-AISI 1045 steel pair for variable sliding velocity (a) [5], and Si_3N_4 nitride ceramic-SCI (spheroidal cast iron) tribo-pair for variable normal load (b) [12]

3. A SURVEY OF CONSTRUCTION OF SPECIAL TRIBOMETERS (3nd TYPE)

Figure 6 presents several tribometers developed especially to characterize friction coefficients for cutting applications. They are all based on an open tribosystem principle. A cutting tool refreshes a surface either before the friction test (Figs. 6c, 6d, 7a, 7b). When preparing the surface before the friction test, the surface of the sample may be oxidized or contaminated which may disturb the identification of the friction coefficient. So other authors prefer refreshing the surface during the friction test it-self (Figs. 6a, 6b, 6e). In order to minimize the reactions with air, the distance between the cutting edge and pin is kept as low as possible. The pin is placed some millimeters behind the orthogonal cutting contact zone to ensure the time interval between the surface generation by the cutting tool and the measurement of the friction coefficient as low as possible. Additionally, some authors have embedded their tribometers in a chamber with argon gas flowing at high rate which protects the sliding contact (Fig. 6a). However this strategy of continuous refreshing induces a pre-heating of the surface. Moreover this pre-heating depends on the sliding velocity. So all these tribometers are disturbed by an initial surface temperature that is not controlled. For this reason, some authors use a pyrometer to take into account the initial temperature in their post-treatment (Fig. 6e).
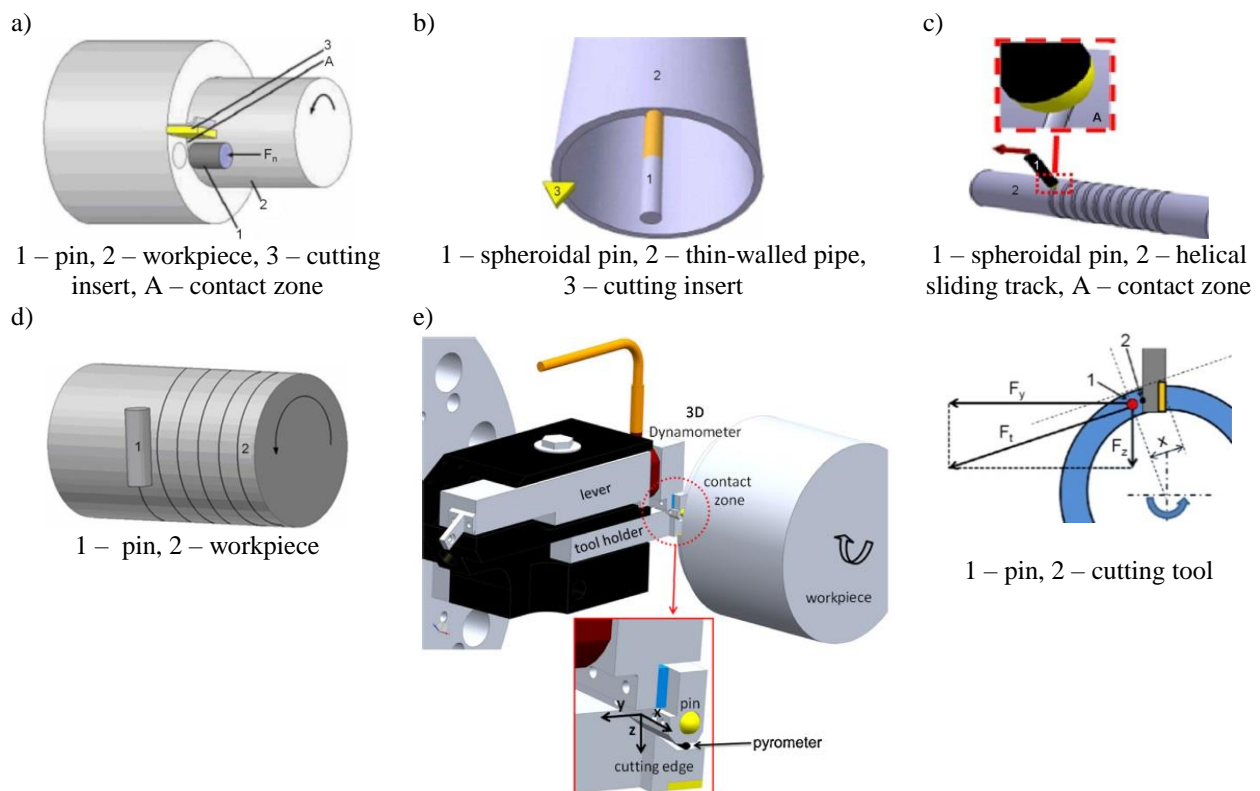

a)

1 – pin, 2 – workpiece, 3 – cutting insert, A – contact zone

b)

1 – spheroidal pin, 2 – thin-walled pipe, 3 – cutting insert

c)

1 – spheroidal pin, 2 – helical sliding track, A – contact zone

d)

1 – pin, 2 – workpiece

e)

1 – pin, 2 – cutting tool

Fig. 6. Schemes of open tribometers of the 3rd type developed to characterize friction in cutting:
(a) modified pin-on-disc method using flat-ended pin [3], (b) pin-on-disc method using ball-ended pin [15],
(c) pin-on-ring method using ball-ended pin [13], (d) pin-on-ring method using cylindrical pin [8],
(e) pin-on-disc method using ball-ended pin [16]

Regarding the preparation of the samples, some authors use specially manufactured pins (Fig. 6a => 6e), whereas others prefer to use cutting tool inserts (Fig. 7a, 7b). However all of them use pins with a curvature (Fig 6b => 6e) or a chamfer (Fig. 6a) or an inclination (Fig. 7a, 7b) at the extremity in order to prevent the pin from removing chips. Whereas the tribometers, presented in Fig. 6, enable long duration tests that lead to a steady state and allow to evaluate wear, tribometers presented in Fig. 7 can only rub during some millisecond (one single revolution for Fig. 7a other it becomes a closed tribosystem) or some tenth of seconds for Fig. 7b. Due to the elasticity of the machines, it becomes hard to stabilize the normal force within a so short duration.

a)

b)

1 – disc, 2 – cutting tool, A – contact zone,
CL – contact length, α – inclination angle,
t – engagement depth

1 – workpiece, 2 – cutting tool, 3 – fixture,
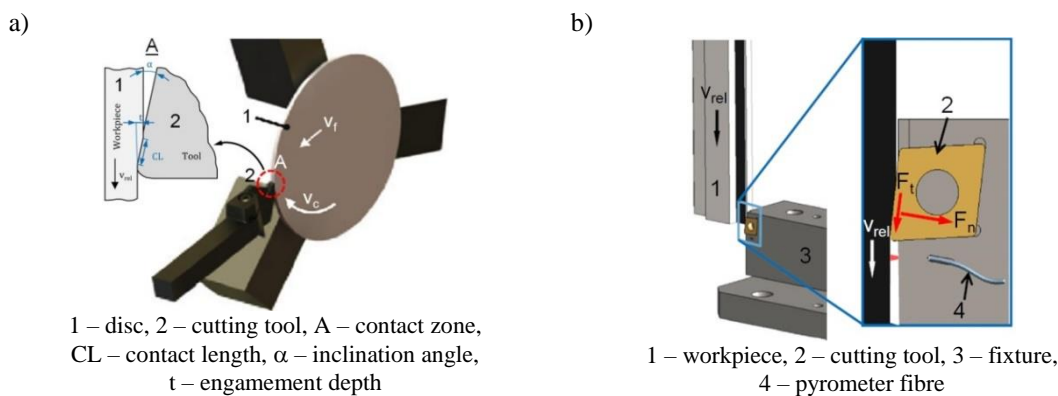4 – pyrometer fibre

Fig. 7. Scheme of open tribometer of the 3rd type based on the use of: (a) grooving tool rubbing a disc rotating in a reverse direction in relation to the cutting and rubbing on its clearance face [17], (b) turning insert clamped on a broaching machine and rubbing on its clearance face [18]
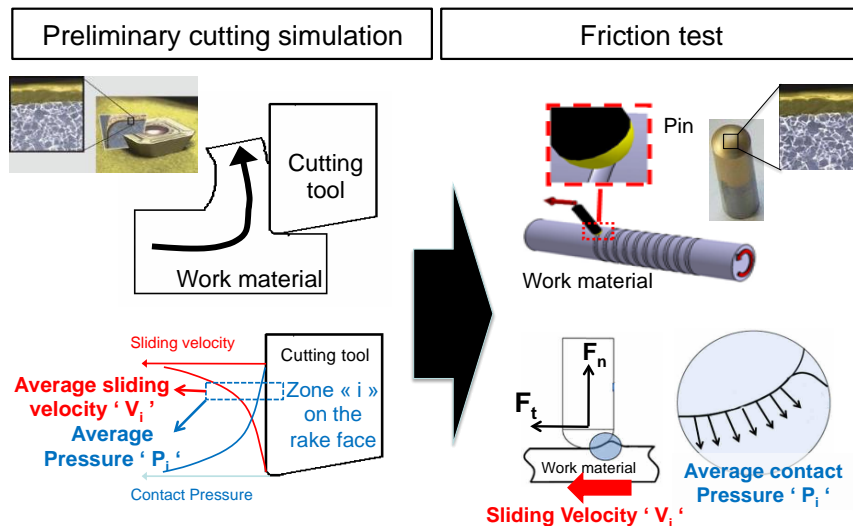
Fig. 8. Procedure to identify friction conditions in the cutting zone from laboratory tests using ball-ended pin (see scheme # 6c) [13, 14]

The normal and friction forces are measured using a piezoelectric dynamometer or strain gauges. It is well known that in a real cutting process, as shown in Fig. 8, the sliding

velocity varies along the tool-workmaterial contact. So the friction coefficient varies also along the contact [4, 13]. Moreover, the contact pressure, along the tool rake face of a cutting tool, varies considerably. For instance, its maximum value is close to the cutting edge and easily reaches 3.5 GPa for Inconel cutting as documented in Ref. [14].

So as to modify sliding velocity and contact pressure, various technical solutions are used. Most of the tribometers are developed in a lathe so as to use its ability to rotate at high speed (high sliding velocity) and to take benefit of its stiffness (Figs. 6a => 6e, 7a). Figure 11 illustrates one of this group of tribometers.
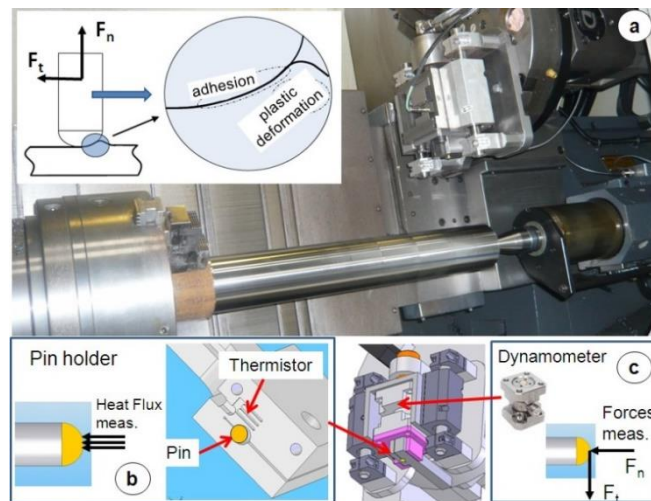

Fig. 9. Structure and functional elements of the open tribometer based on the scheme from Fig. 5c:
a) general view, b) heat flux measurement, c) force measurement [4, 13, 15]

Only a single tribometer is based on a broaching machine which limits its velocity to some m/min (Fig. 7b). Regarding the modification of the contact pressure, most of them use a pneumatic of hydraulic jack to control the normal force. However any of them is able to predict the contact pressure due to the severe plastic deformation. The effective average
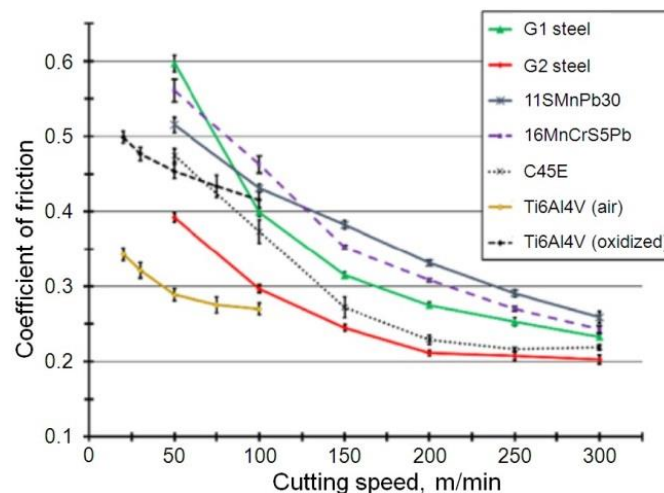

Fig. 10. Evolution of friction coefficient for different cutting speeds and machined materials [16]

contact pressure has to be post-treated thanks to experimental observations on the tracks and on the effective normal force applied on pins [1, 4, 13, 14]. Figure 11 illustrates that an analytical or a numerical model has to be used so as to identify the couple pressure vs. sliding velocity that should be tested. Figure 10 highlights the evolution of friction coefficient versus sliding velocity for various workmaterials using the open tribotester shown in Fig. 7a.

As mentioned before, due to the high contact pressures applied by these tribometers, severe plastic deformation occurs on the contact in a similar way as along the tool-workmaterial interface. However, the macroscopic force measured by the tribometer is the consequence of the friction at the interface and the plastic deformation. So any of these tribometers necessitates a post-treatment so as to extract the adhesive friction component and the plastic deformation component from the macroscopic friction coefficient (Fig. 11). Several others have developed simplified analytical methods such as [4], whereas the most efficient and complex ones necessitate thermo-mechanical numerical simulations [1].
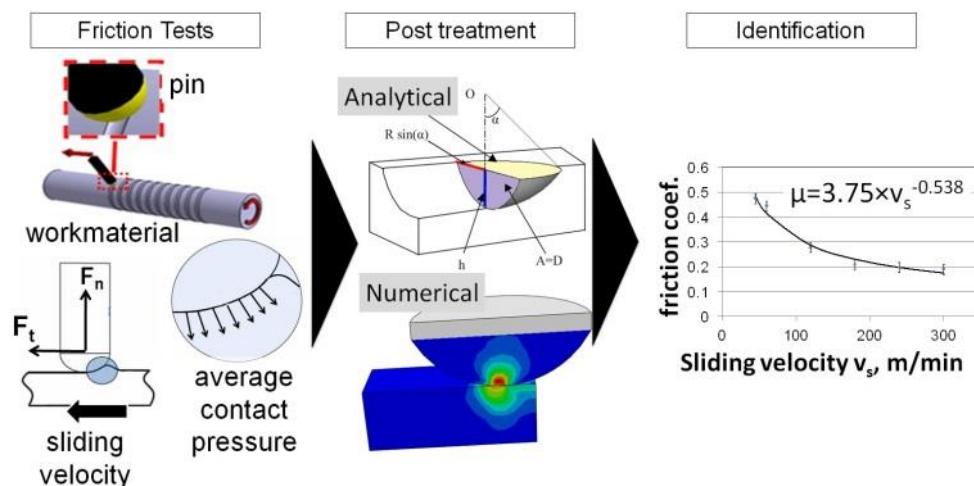

Fig. 11. Post-treatment methods to identify adhesive friction coefficients [3]

4. CONCLUSIONS

In general, it is not possible to obtain fully reliable friction data for metal cutting process due to very complex mechanical, thermodynamical and tribological interactions existing in the cutting zone and especially in the secondary deformation zone. For this purpose a number of tribotesters selected in this case-study into three characteristic groups which use different measurement techniques are designed. The most promising seems to be the 3rd group which better reproduce the tribological conditions producing in the secondary cutting zone. Moreover, apart from the cutting pressure also cutting temperature is controlled during tribo-tests performed. In order to improve the prediction accuracy some analytical and simulation post-treatment methods are necessary. Tribo-testers can also be applied for predicting functional properties of machined surfaces [19].

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