Journal of Materials Processing Technology 214 (2014) 1787–1797

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Complementary tribometers for the analysis of contact phenomena in grinding

E. García[a,*], J.A. Sánchez[a], D. Méresse[b], I. Pombo[a], L. Dubar[b]

[a] Dpt. Mechanical Engineering UPV/EHU, Almeda de Urkijo s/n, 48013 Bilbao, Spain
[b] TEMPO EA 4542 Laboratory, UVHC Carnot Arts Institute, 59300 Valenciennes, France

ARTICLE INFO

Article history:
Received 25 February 2014
Accepted 16 March 2014
Available online 23 March 2014

Keywords:
Grinding
Friction coefficient
Specific energy
Abrasive wear
Cutting mechanisms

ABSTRACT

The characterization of friction and tribological phenomena occurring in grinding requires reliable experimental input data. Up to now, existing test benches exhibit important limitations. Steep thermal gradients and elastic deformations of both machine structure, and rubbing elements are the main sources of inaccuracy cited in the literature. In this paper, an alternative approach is presented for the study and characterization of contact phenomena in grinding. It consists of two complementary test benches: the On-Machine Test Bench and the High Speed Tribometer. They are designed to overcome the limitations of current grinding experimental studies.

On the one hand, the On-Machine Test Bench enables accurate control of process parameters. This allows assessing the effect of the different grinding mechanisms on process forces, and specific energy. In addition, its configuration avoids steep thermal gradients; consequently, it is possible to obtain stable and accurate temperature measurements that can be directly related to process variables. On the other hand, the High Speed Tribometer enables to isolate adhesive effect because of its predominance. This test bench allows an accurate control of contact pressure and contact area. Then, adhesive phenomena can be characterized and related to process parameters using force and temperature measurements.

Experimental results obtained in both test benches are presented. A wide range of data (forces, specific energy, temperatures, wear...) concerning contact conditions in grinding can be obtained from this complementary approach.

1. Introduction

Grinding is an abrasive material removal process which despite of the advances in performance and accuracy of other manufacturing processes, such as turning or milling, is a key technology in modern manufacturing. It is due to its capacity for producing parts of high precision and high surface quality in difficult-to-machine materials that grinding is widely used in motor industry, aerospace and precision cutting tool manufacturers (Oliveira et al., 2009) amongst others. This fact easily explains why grinding has been the object of extensive research during the past 40 years and it is still nowadays.

Studying frictional characteristics of abrasive machining yields useful information for industrial process optimization. Friction and thermal phenomena are related to aspects such as surface finish and thermal damage of the ground components, which are usually main constraints in process optimization Malkin and Guo (2000). Improvements in the scientific understanding of friction and heat conduction phenomena are directly translated into industry in the form of software for process optimization Malkin and Guo (2000).

The analysis of friction conditions in material removal processes is a topic of large interest in scientific literature. A study of the friction coefficient at high sliding velocities can be found in Philippon et al. (2004). At low sliding velocities (below 1 m/s, this is not the case of grinding) friction coefficient depends strongly on the roughness of the contacting surfaces. At higher velocities (over 1 m/s) the friction coefficient, μ, depends on both relative velocity and normal force. For a constant sliding velocity μ decreases with the increasing normal force. And in the same way, μ decreases also with increasing relative sliding speed too. This behavior is usually found in research literature about the friction factor in grinding as it is shown in the work of Cai et al. (2002) and in the conclusion of Patnaik Durgumahanti et al. (2010). Finally, at very high speeds and normal forces, the sliding surfaces are separated by a lubricating film of melted material, reducing thus μ.

* Corresponding author. Tel.: +34 94 601 73 47.
E-mail addresses: eduardojose.garcia@ehu.es, edugarcia.g@gmail.com (E. García).

http://dx.doi.org/10.1016/j.jmatprotec.2014.03.026

Nomenclature

Parameter

a	depth of cut (mm)
A_c	contact area (m^2)
b	workpiece thickness (mm)
e_c	specific grinding energy (J/mm^3)
e_{pl}	specific ploughing energy (J/mm^3)
e_{rb}	specific rubbing energy (J/mm^3)
e_{sh}	specific shearing energy (J/mm^3)
F	force (N)
F_t	tangential force (N)
F_n	normal force (N)
h	chip thickness (nm)
h_{eq}	equivalent chip thickness(mm)
l_c	contact length (mm)
P	grinding power (W)
Q_w	material removal rate (mm^3/s)
Q'_w	specific material removal rate ($mm^3/mm\,s$)
R_w	heat partition ratio to the workpiece
t	time (s)
T	temperature (K)
v_f	infeed speed (mm/min)
v_s	grinding wheel speed (m/s)
v_w	workpiece speed (mm/min)
V'_w	specific volume of part material removed (mm^3/mm)
μ	friction coefficient
μ_a	adhesion friction coefficient
μ_p	ploughing friction coefficient

Although the above-mentioned facts are well known in tribology, as recognized in Patnaik Durgumahanti et al. (2010), a significant number of models of the grinding process use a constant value of the friction coefficient, adducing a negligible influence on the final results Aurich and Kirsch (2012). The study of the interaction single grain-part material provides an interesting approach to this discussion. It is accepted Hahn (1966) that during contact, three different mechanisms are activated depending on the chip thickness h. These three phenomena, namely rubbing, ploughing and shearing contribute to the necessary material removal of grinding. Due to the random nature of the topography of the grinding wheel, during a given grinding operation some grits can be rubbing while others are ploughing and others are actually cutting material. A detailed explanation of the factors affecting the contact modes can be found in Nguyen and Butler (2005).

A further step is to consider a variable friction coefficient. In this case, such models suggest studying the behavior of a single grit. Results are then extrapolated to the whole wheel from the surface topography experimentally obtained. Nevertheless this approach is a hard task. Hamdi et al. (2003) developed a characterization of abrasive grain behavior using a high speed scratch test, and also a standard scratch test. Although they obtained interesting results it was not possible to extrapolate from one test to another and, even more difficult, to the whole grinding process. Badger and Torrance (2000) compared different models one of Challen and Oxley (1978) and other of Xie and Williams (1996) that used a variable formulation of the friction coefficient. In this work it is acknowledged that one of the priorities is to develop a suitable method for the independent determination of the friction factor. More recently Patnaik Durgumahanti et al. (2010) developed a grinding force prediction model incorporating the effects of variable friction coefficient and ploughing force.

In a later work Tang et al. (2009) developed a mathematic model for predicting grinding forces. For the development of the formulation they divided grinding force into two parts: chip formation force, and sliding force. The final model that was completed with experimental work calculated the friction coefficient as well. According to their results friction coefficient must be variable with process parameter since different contact conditions are found during the cutting process: elastic contact, elasto-plastic contact and plastic contact.

Subhash and Zhang (2002) also separated frictional effects for the assessment of forces and friction coefficient. In this case, the force ratios of scratch tests were evaluated as the addition of adhesion friction μ_a and ploughing friction μ_p. Adhesion friction is a result of the tool sticking to the workpiece and is commonly known as Coulomb friction, while ploughing friction is due to the resistance of the workpiece material ahead of the moving tool. Authors separated both coefficients and showed that while adhesion friction decreased with cutting speed, the ploughing friction remained mainly constant with varying speed.

Traditionally, two approaches to the experimental study of the interaction between abrasive and workpiece have been used. On the one hand, the study and characterization of abrasive friction and wear phenomena based on tests developed directly in grinding machines; on the other, the use of classical tribology concepts and experimental methods for the characterization of contact in controlled laboratory conditions. Both approaches present advantages and limitations.

Tests developed directly in grinding machines are obviously capable of reproducing industrial grinding conditions, but obtaining reliable measurements from the test becomes very difficult. Accessibility to the contact zone is very limited, and industrial conditions are far from being exactly controlled. Experimental determination of temperatures and contact pressures is still a research issue. Extremely high temperature gradients (as much as of 10,000 K/s Kohli et al. (1995)) are observed in grinding due to the reduced contact time (order of microseconds) and the high temperatures reached (up to 900 K in some cases). The use of infrared systems Batako et al. (2005) and different configurations of thermocouples can be found in specialized literature Xu and Malkin (2001). As far as to contact pressure refers, uncertainty in the actual contact area Malkin and Guo (2008) due to deformations in machine components and grinding wheel have to be considered.

Classical tribology tests serve as a starting point to understand the phenomena occurring during abrasive machining as it shown in the work of Torrance (2005). However, the relative speeds and contact pressures of tribometer tests are far from those actually involved in a grinding operation (30–50 m/s and 2–5 MPa). Common Pin-on-disk configurations are not suitable to simulate grinding conditions. In the work of Montgomery (1976) a sophisticated high-speed-pin-on-disk test was designed to investigate friction of barrel guns which allowed contact pressures from 20 to 140 MPa and high velocities (from 40 to 183 m/s). The Split-Hopkinson bar allows pressures in the range of 20–100 MPa and speeds up to 10 m/s, with a limitation in the slip distance of about 10 mm, as it is explained in Hartley et al. (1985). More recently, Philippon et al. (2004) proposed a new set-up of friction experiment capable of testing sliding conditions in the range of velocities from 0.01 m/s to 60 m/s and with variable pressure up to 230 MPa.

At the sight of the above facts, it is clear that advances in characterization of frictional effects during the grinding process are welcomed both by academia and industry. Under this context, this paper presents an alternative experimental configuration specifically designed for the study of contact conditions in grinding operations. It consists of two complementary test benches: the On-Machine Test Bench and the High-Speed Pin-On-Disk Tribometer that are described in Section 2. The On-Machine Test Bench is