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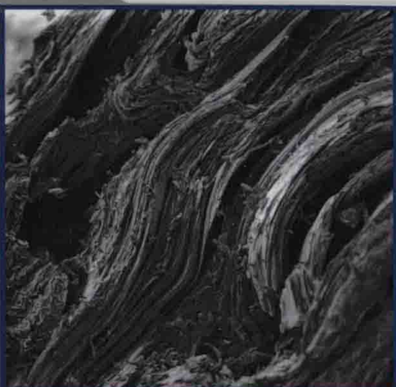

Handbook of Friction Materials and their Applications

Roberto C. Dante

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To my wife Georgette, my daughters Denisse and Birgit,
and my parents

Biography

Roberto C. Dante was born in Rivoli, Italy, on September 26, 1966. He majored in chemistry at the University of Turin (Italy) and graduated in 1990 in physical chemistry. Afterwards, he received a research fellowship and began to work as a researcher in the friction industry in Italy. In Mexico, where he has lived since 1998, he received a Ph.D. in materials science and engineering *cum laude* in 2006 at the National Autonomous University of Mexico (Universidad Nacional Autónoma de México, UNAM) which is widely regarded as one of the best universities in the world. In 2008 he received the Alfonso Caso Medal from UNAM. He also served as professor of chemistry in a well-recognized Mexican university, ITESM, in Mexico City. He has consulted in the friction industry around the world, including for companies such as Feno Resinas Fritec, Automanufactura Brake (Mexico), Ross, Galfer (Italy), Masu Brake (India), and others. Since 2005 his base has been in Piedmont, northwestern Italy, and he currently manages his own consultancy company 2D to 3D S.r.l.s (2dto3d.info@gmail.com). Dr. Dante has continued to actively carry out research work and has published many papers not only on friction materials and tribology but also on new materials such as carbon nitride nanosheets and related materials, with close attention to their applications, collaborating with several universities around the world. He settled with his family at the farm "Gabriella" in San Firmino (Revello), Italy, between the ancient Abbey of Staffarda and the River Po.

Preface

In the past few decades, friction materials engineering has become more sophisticated with many tests and techniques to investigate the properties of materials and their counterparts before, during, and after friction has occurred. Many research techniques are currently used in the field of material science, such as X-ray diffractometry, scanning and transmission electron microscopies, infrared spectroscopy, just to give a few examples. Moreover, the real scale dynamometric benches have become even more complete, including static friction, inertia, noise, weather and climate simulations, among others.

Nevertheless, although knowledge of friction materials structure and properties has increased, surprisingly the design of formulas and processes is still a basic "trial and error" development in many companies. Sometimes it is supported by experimental design techniques coupled with an approximated knowledge of raw materials. This situation is often due to the basic facilities and limited resources of the small and medium size companies, while the larger ones often dedicate their resources to increase their friction testing facilities (such as the number of dynamometric benches) in order to increase their probability of success through the growth of the total number of tested formulas. My scientific works, my background, and the many collaborations around the world (especially in Mexico) that have enriched me led me to a wide knowledge of the raw materials and compounds involved in the development of friction materials. These are a constellation of polymers, inorganic fillers, ceramic compounds all held together by a binder, usually phenol formaldehyde resin.

In spite of many books focused on testing and standards related to the automotive industry and brake performances, very little information has been dedicated to the raw materials. Moreover, what information exists commonly confuses the means with the objectives, since many technicians feel more comfortable focusing their attention on what they can control easily, such as test procedures, rather than taking the risk of getting into the difficult world of raw materials.

However, finding the proper tests and measurement tools to select the most adequate material to suit real needs is another topic that an expert in the field should deal with in another book. In fact, it is noteworthy to remember that materials and products are developed for actual end-users and not to fit test machines. For these reasons, the goal of this book was to fill only one of these voids, specifically related to raw materials, and offer the first extensive and succinct outlook on the several raw materials used in formulations of friction materials as well as their main friction effects and material structure. This volume allows the younger (less experienced) material engineer as well as the elder (more experienced) practitioner to find the way to move through this wide world. I am aware that this book is not all-encompassing, but the objective was to include the most common raw materials and provide some elements for selecting new ones, being aware of their cross-interactions due to tribochemical reactions.

I am very grateful for the several conversations about carbon materials, mainly graphite and coke, that I have had with Albert Tamashausky of Asbury Carbons (USA), R&D chief, who, additionally, contributed with several scanning electron microscopy images to this piece of work and oriented me towards an understanding of the key factors of this class of raw materials, all based on his long experience in characterizing and classifying these technologically worthy materials. Doubtless, this work was also benefited by my old friendship with Carlo Navire, owner and chief engineer of Isibond (an Italian friction company), with whom I had the honor to work and discuss friction subjects, among others, for many years. My colleague and friend Bruno Tron, a pioneer in bench testing, also influenced me with his clear views and explanations on noise phenomena of friction materials. Dr. Gaetano Fasano, a process engineer and buider of machines, also influenced me with his clear ideas about processes and methods. Many other people have also influenced me in my scientific work and approach towards friction materials. For instance, my experimental approach towards chemical phenomena by means of spectroscopic methods was forged during my thesis work with Prof. Adriano Zecchina, one of the most prominent physical-chemists in the world, when I was a graduate student. My Ph.D. mentor, Prof. Enrique Geffroy, routed me in the detailed analysis of rheological phenomena. More recently, cooperation with Prof. Jesús Martín Gil, a very enthusiastic chemist with eclectic interests, increased my interests and dedication to methods of solid state synthesis of nanomaterials, while Prof. Czeslaw Kajdas was my mentor for tribochemistry of engineering materials.

Contents

Friction materials: Friction for brakes

1

Friction is one of the most common phenomena in nature; it is everywhere in our daily lives without our even noticing it, since it is intimately part of almost everything we do that involves movement or change. It is so common that many times we are not aware that, without it, many aspects of our life would be very difficult, if not impossible. The purpose of this short chapter is not to introduce the reader to the principles of friction, but only to provide a different insight into friction, in order to look at friction, friction materials, and brakes as part of a larger context. A frictionless world would be that ideally depicted in the physics created by Galileo and Newton, characterized by a movement without energy losses. However, the simple acts of holding a water glass with our fingers or walking would be impossible without a friction force that balances and opposes the force of gravity or the reaction force, respectively. Friction makes many things both difficult and possible at the same time: for example, car movement, which consumes energy to feed engines to overcome the friction of wheels against the ground, but also needs the wheels' friction against the ground to make movement possible.

Another important aspect to be mentioned is that friction is characterized by systems composed of many fundamental particles (atoms, molecules, crystals, etc.), such as surfaces in sliding contact, gases, and liquids. Systems composed of many particles imply interactions among them, and therefore imply irreversible processes—that is, a net entropy increment in our world. These interactions can be attractive or repulsive, mechanical, and ultimately they generate forces. This kinetic energy dissipation causes heat and produces wear, as well as many other forms of energy. The science that studies friction between surfaces is called *tribology* and was founded as a new discipline in the 1960s. The major concern at that time was to decrease the coefficient of friction between sliding surfaces and consequently reduce wear in machines, especially those dedicated to manufacturing, so that energy consumption and parts replacement could be improved. Another important topic is *tribochemistry*, which is a new scientific branch dealing with chemical reactions activated by the work of friction. Triboreactions exhibit rates much higher than those of thermally activated chemical reactions.

There is only one technical device in which a high coefficient of friction is desired: the brake. Since machine motion exists, the manner to decrease velocity and stop the motion is a fundamental issue. The need for powerful brakes began when vehicle speeds increased and became necessary to control them. Brakes fulfill this role by transforming kinetic energy into other forms of energy, with heat being the most relevant. This, then, also implies the task of dissipating that heat.

The basic concept of any brake is to dissipate kinetic energy, whether in a horse-drawn carriage, a car, a train or an aircraft; this energy is dissipated through friction

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due to viscosity, such as in magnetorheological brakes, or friction between sliding surfaces. The following equation of power dissipation can be considered the basic equation for each type of brake, because it introduces the concept that an external force is necessary and that is the origin of the force opposing motion:

$$\frac{\delta W_{\mathrm{d}}}{\mathrm{d}t} = w\left(\vec{X}\right) F_{\mathrm{N}} v \tag{1.1}$$

where W_{d} is work dissipated, t is time, $w\left(\vec{X}\right)$ is a coefficient of proportionality and $\vec{X}$ the set of variables that affect $w\left(\vec{X}\right)$, v is the speed, F_{N} is the force component normal to and between the interacting surfaces, which can be either electric, or magnetic, incident pressure, or a combination of several forces. F_{N} can be formally considered to be an attractive force between the two opposing surfaces. Controlling F_{N} means to control the power dissipation and therefore the vehicle and machine speed. This equation highlights the importance of instant dissipation since this determines many surface effects, which depend upon the energy shots rather than on the total amount of energy dissipated.

A more general equation than Equation (1.1) is the following, which relates the friction force to the dissipated power:

$$\frac{\delta W_{\mathrm{d}}}{\mathrm{d}t} = F_{\mathrm{T}} v \tag{1.2}$$

In the case of dry friction $w\left(\vec{X}\right)$ is the coefficient of friction μ, which is affected by temperature, speed, and other variables (for an outlook on the friction law, see the book *Tribology* by I.M. Hutchings [1]), so that μ can be expressed in the following way:

$$\mu\left(\vec{X}\right) = \left(\frac{\delta W_{\mathrm{d}}}{\mathrm{d}t}\right) / F_{\mathrm{N}} v \tag{1.3}$$

This equation expresses the dependence of the coefficient of friction on some of the main variables that may affect it in vehicle brakes.

For example, consider an 80 kW car moving at maximum power to be stopped within 10 m and 10 s, and if we assume that the two front brakes are dissipating 100% of the kinetic energy, and that each brake pad has an apparent area of 200 cm^2, and a normal force of 10 bars applied to the friction material, we obtain that the coefficient of friction must be at least 0.4, which is considered a "magic number" in car brakes.

The power dissipated per unit area is another important aspect that we usually do not think about, but the aforementioned pads dissipate 0.1 $kW\,cm^{-2}$ at the maximum power of operation. This is a significant power for a small area; a heavy truck brake pad can dissipate 0.2–1.0 $kW\,cm^{-2}$. These facts explain the reason for such a great variety of brake sizes, types and brake lining areas, depending upon the particular application, power, speeds, the vehicle momentum of inertia, and other variables.

For example, aircrafts need to dissipate a great quantity of energy in a small space, so that the dissipated power in Equation (1.3) is very large and consequently so is the amount of heat produced that must be disposed of.