When it comes to metal rolling, understanding and controlling frictional phenomena are essential to improving product and developing a more effective approach to friction reduction. Providing a historical perspective that goes as far back as the days of Leonardo da Vinci and continues until the present day, *Friction and the Hot Rolling of Steel* chronicles the fundamental causes of friction. This book includes well-documented, on-site observations in various commercial plants, presents and examines practical problems, and provides a critical analysis of literary data related to the subject.

It explains the base mechanisms of friction, and offers insight and instruction on improving the control and understanding of friction in hot strip mills and other industrial plants. The text presents mathematical models of friction in control and general engineering in a way that enables engineers to test and refine them in their plants. Engineers have the ability to use them to control friction and minimise its negative effects, particularly as it relates to energy waste and product defects.

Organized into four sections, this book outlines the evolutional concepts of friction, and covers the general phenomena relevant to the rolling of metals. This includes the impact of roughness and velocity, basics of liquid and solid lubrication, mathematical modelling, and the properties of materials that affect friction in steel rolling, such as metals, oxides, and carbides. It connects the theoretical concepts, laboratory-scale observations, and phenomena in other areas of science and engineering to the large-scale industrial process of hot rolling. It also addresses roll properties, oxidation, wear and chemical composition of rolls and their impact on friction, the evolution of friction over schedules and roll campaigns, and mathematical modelling of friction in hot rolling.

*Friction and the Hot Rolling of Steel* contains a large body of technical information that includes various chemical and physical properties of relevant materials, mathematical models, and plant and laboratory observations. It also provides an extensive reference list of sources that address specific problems and interests in more detail.
Friction and the Hot Rolling of Steel

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Preface

One of the greatest obstructions to the mechanical powers of engines proceeds from the friction, or resistance of the parts rubbing on each other; which in general, is greater, or less, as the rubbing parts bear the greater, or less pressure; and yet this obstruction is but little attended to. The theorist makes no allowance on account of friction; and the practical mechanician, who feels the effects, yet, as if unavoidable, seldom takes the trouble of searching for a remedy.

Fitzgerald, 1763

But, however important a part of mechanics this subject may constitute, and however, from its obvious uses, it might have been expected to have claimed a very considerable attention both from the mechanic and philosopher, yet it has, of all the other parts of this branch of natural philosophy, been the most neglected. The law by which the motions of bodies are retarded by friction has never, that I know of, been truly established.

Vince and Shepherd, 1785

From the attention that has hitherto been paid to this important branch of mechanical science, and from the many elaborate dissertations and experiments that have appeared at different periods, it would naturally be concluded, that the subject had been so fully elucidated, as to admit of little if any further investigation: but the diversity of opinions still prevalent among philosophers, and the difficulty of reducing to a satisfactory state the doctrines already advanced, incline me to the opinion that the subject is as yet but imperfectly understood.

Rennie, 1829

... a complete description of its fundamental causes and a single quantitative model—which is generally applicable to any frictional situation—remains elusive.

Blau, 2009

Friction is everywhere, and it affects our lives in both good and bad ways; a car expends 20% of fuel to overcome friction in the engine and drive train, but cannot move on a slippery surface (Burke, 2003). Without friction, we would be slipping and falling instead of walking, and steel strips would never enter the gap between rolls in a steel mill.

The bad aspects of friction seem to be more noticeable. In 1904, Davis described it as a ‘… highway robber of mechanical energy … levying tribute
on all matter in motion, exerting a retarding influence and requiring power to overcome it.’ Friction is associated with wear, and various estimates in the United States, Great Britain and Germany suggest that friction and wear cost many billions of dollars annually (Rabinowicz, 1995; Ludema, 1996; Stachowiak and Batchelor, 2005).

Friction in the hot rolling of steel is particularly important. These days, more than a billion tonnes of steel are produced annually, and most of that steel is hot rolled. Many practical problems of hot rolling are linked to friction: chatter, skidding, excessive rolling force, very high friction of some rolls and the like. These problems prompted the author to study a vast body of literature, only to find out that

1. There are no satisfactory mathematical models of friction in either hot rolling or general engineering.
2. Even the qualitative understanding of it leaves much to be desired.
3. Many laboratory experiments were reported, but the findings and interpretations often contradict each other.

However, the available information can improve the control and understanding of friction in hot strip mills and other industrial plants. First, many problems can be understood if one is aware, at least qualitatively, of the base mechanisms of friction. Second, critical analysis of the literature data, combined with the observations in commercial plants, may explain some contradictions.

The main aim of this book is to present this body of knowledge systematically, and make it available to the wide engineering audience. It is organised in four sections:

Section I (Chapters 1–4), which outlines the history of our understanding of the fundamental causes of friction, from Leonardo da Vinci to the twenty-first century. Understanding of these causes will make the analysis of frictional phenomena in engineering much easier.

Section II (Chapters 5–11) covers the general phenomena relevant to the rolling of metals. These include the impact of roughness and velocity, basics of liquid and solid lubrication, mathematical modelling and the properties of materials that affect friction in steel rolling, such as metals, oxides and carbides.

Section III (Chapters 12–17) connects the theoretical concepts, laboratory-scale observations and phenomena in other areas of science and engineering to the large-scale industrial process of hot rolling. It addresses roll properties, oxidation, wear and chemical composition of rolls and their impact on friction, as well as the evolution of friction over schedules and roll campaigns, and mathematical
modelling of friction in hot rolling, with examples from a five-stand, million-tonnes-per-year commercial mill.

Section IV gives technical details, that is, the properties of important species, and interesting diversions, which are presented in appendices.

Finally, some details should be mentioned:

- Wear and lubrication are only considered to the extent relevant to friction in steel rolling.
- The term ‘tribology’ is often used in this document. Basically, it is the science of friction, wear and lubrication, or as Persson (1999) put it more rigourously, the ‘science and technology of interacting surfaces in relative motion’.

References

This is my first book, and I would like to thank Jonathan Plant and Amber Donley of CRC Press for the assistance given during its preparation, for their courtesy, and for taking stress out of this rather strenuous exercise. The kind permission by the following institutions to reproduce copyrighted images and tables is gratefully acknowledged: The Association for Iron and Steel Technology, EDP Sciences, Elsevier, Fédération Française de l’Acier, Iron and Steel Institute of Japan, Lafayette Photography (Cambridge), The Minerals, Metals and Materials Society, Oxford University Press, Royal Society Publishing, Springer, Taylor & Francis, and Wiley–VCH.

My interest in friction was sparked by enthusiastic discussions with the expert roll technologist, John Steward, followed by involvement in his carefully organised plant trials of novel roll designs and operational conditions. The author was also lucky to have excellent colleagues to exchange ideas with, in particular Gregory Fraser, Ron Gloss, Arthur Liolios, Boris Srkulj, Robert Steward and Peter Wray. I would also like to acknowledge the supply of high-quality photos and very constructive remarks by Dr Mario Boccalini Jr, of the Institute de Pesquisas Tecnologicas, São Paulo, and Prof Amilton Sinatora of the University of São Paulo.

My wife Milica and daughter Tamara showed enormous patience and provided a loving environment during the long hours I spent on my iMac preparing the manuscript, for which I am very grateful. Finally, I would like to thank my parents Olga and Ljubomir for all their support in my quest for knowledge.
Vladimir Panjkovic, PhD, grew up in the picturesque historic town Srbobran, in the Serbian province of Vojvodina. He graduated with a degree in electrical engineering from the University of Novi Sad, majoring in control and computer engineering, and earned his PhD in materials science and engineering from the University of New South Wales, for mathematical modeling of novel ironmaking processes. After a brief stint as a research assistant at the University of Novi Sad, he has worked for a quarter century as a research and process engineer in the Australian steel and manufacturing industry. His fields of work include the applications of artificial intelligence to process control, development and deployment of mathematical models of ironmaking processes and steel rolling, analysis of tribological problems in hot strip rolling, and the design and commissioning of thermal equipment. For his work Dr Panjkovic has been awarded the BlueScope Steel Research Excellence Award, the National Project Excellence Award in Automation, Control and Instrumentation, and the John A. Brodie medal in chemical engineering, the latter two by the Institute of Engineers Australia. He has published 7 journal papers, more than 20 conference papers, approximately 40 technical reports, and is commissioned to prepare the chapter on vibrations in steel rolling for the forthcoming Encyclopaedia of Iron, Steel and Alloys, to be published by Taylor & Francis in late 2015.
Section I

History of Friction: From da Vinci to Now
1

Early Studies of Friction

That there is a Loss of Force in the working of Engines on account of the Rubbing or Friction of their Parts, has been observ’d by most Writers of Mechanics; but that Friction has not been enough consider’d by them … Projectors contrive new Machines (new to them, tho’ perhaps describ’d in old Books, formerly practiced and then disus’d and forgot) which they suppose will perform much more than they have seen done with the same Power; because they allow too little for Friction. Full of this they go to the Charge of 70 or 80 l. for a Patent for their new Invention; then divide it into Shares, and draw in Persons more ignorant than themselves to contribute towards this (suppos’d advantageous) Undertaking; till after a great deal of Time and Money wasted, they find their own Engine worse than others which they hoped by many degrees to excel. This has been very much the Practice for these last twenty Years: For tho some Projectors have been altogether Knaves, yet the greatest part have first deceiv’d themselves; and those who are really deceiv’d, by their eagerness and earnestness most easily deceive and draw in others. For this reason, I thought it would be of Use to the Publick, to give as full an Account of friction, as I possibly could gather from the Experiments made by others (especially the Members of the Royal Academy at Paris) and my own Experiments and Observations.

Desaguliers, 1745

Those who cannot remember the past are condemned to repeat it.

Santayana, 1905

Solomon saith, There is no new thing upon the earth. So that as Plato had an imagination, That all knowledge was but remembrance; so Solomon giveth his sentence, That all novelty is but oblivion.

Bacon, 1787

When studying a subject, it is prudent to study its history first, even briefly, to avoid the reinvention of wheel. The history of tribology contains many examples of sound ideas that were forgotten or ignored, and rediscovered much later:
1. Leonardo da Vinci proposed the two basic laws of friction in the beginning of the sixteenth century, but they were rediscovered by Amontons almost two centuries later.

2. Robert Hooke proposed in 1685 that deformation and adhesion are the primary causes of friction, which is consistent with modern views. The adhesion was refuted by Leslie in 1804, and revived more than a century later.

3. Guillaume Amontons in 1699 represented the elastic contacts between surfaces with springs or bristles. This concept is now widely used in the friction models devised by control engineers.

This history starts with addressing da Vinci, the first known person to study friction scientifically, and the works of Hooke and Amontons in the seventeenth century. The next section is dedicated to developments in the eighteenth century, followed by the section on the revolution in liquid lubrication and the research of dry friction in the nineteenth century. The fourth section is about the progress of tribology in the twentieth century and beyond. It includes the Stribeck curve, the assertion of Bowden and Tabor that adhesion and ploughing are the key causes of friction, studies at the atomic scale, and the application of thermodynamics to the calculation of the coefficient of friction (COF, \( \mu \)) in hot rolling.

### 1.1 Leonardo da Vinci

Leonardo da Vinci (1452–1519, Figure 1.1) was the first known person to conduct systematic experiments with friction and summarise observations as laws. These laws were quoted by Dowson (1998) as follows (the literal translation from Italian is in italics):

1. The force of friction is directly proportional to load (*friction produces double the amount of effort if the weight be doubled*).

2. The friction is independent of the apparent contact area (*friction made by the same weight will be of equal resistance at the beginning of its movement although the contact may be of different breadths and lengths*).

He noted that for smooth surfaces ‘every frictional body has a resistance of friction equal to one-quarter of its weight’; that is, \( \mu \) is 0.25, which is well within the range encountered in practice.

Amontons conducted the next systematic studies almost two centuries later, and literally rediscovered his laws. Although the contributions of da Vinci and Amontons to tribology are well known, they are rarely
appreciated, with the notable exception of Dowson, that, before Amontons, Hooke reported profound ideas about the nature and control of friction. The works of these two pioneers are described in more detail below.

1.2 Robert Hooke

For reasons widely debated, Hooke (1635–1703) was much maligned by his contemporaries and posterity, although the greatest gossiper of that day, Aubrey, recorded that ‘... he is of prodigious inventive head; so he is a person of great vertue and goodness ... certainly the greatest mechanick this day in the world’ (Anon., 1813). This polymath contributed to many areas of science, and at the age of 30 published the first scientific bestseller, *Micrographia*. In 1685, deeply impressed by Stevin’s sailing chariot, a sailing boat on wheels devised for Prince Maurice of Orange, he proposed the following notions (Hooke, 1685):

1. The rolling friction is influenced by deformation and adhesion, which is a modern view (see Section 4.4): ‘Next, we are to consider, what Impediment to its Motion, a Wheel, thus roll’d upon a Floor,
receives from that Floor. ... The first and chiefest, is the yielding, or opening of that Floor, by the Weight of the Wheel ...; and the second, is the sticking and adhering of the Parts of it to the Wheel'.

2. Adhesion is analysed in detail: ‘The Second Impediment it receives from a Floor, or Way, is the sticking and adhering of the Parts of the Way to it ... there is a new Force requisite to pull it off, or raise the hinder Part of the Wheel from the Floor, or Way, to which it sticks. ... The force of adhesion depends on surface properties: ... the harder the Ways are, the less Impediment they give to the Motion of Carriages. …’

3. The term ‘friction’ was used for the first time in its modern mechanical meaning, as a phenomenon hindering motion (see Appendix A): ‘... because the gudgeons, halving the weight, may be made very much smaller, and so will not cause a tenth part of the friction which is necessary in the other way’.

4. Amontons proposed 14 years later that the friction is caused by the asperities of one surface climbing up over those on the opposing surface (Amontons, 1699). Hooke had discounted this well before the better known refutation by Leslie (1804; see also Section 3.1):

   ... for, if the Floor be perfectly hard (as also the Parts of the Wheel) tho’ it be very unequal, yet is there little or no Loss, or considerable Impediment to be accounted for; for whatever Force is lost, in raising or making a Wheel pass over a Rub, is gain’d again by the Wheel’s descending from that Rub, in the same Nature as a Ship on the Sea is promoted by the descending down of a Wave, as much as impeded by its ascending, or a Pendulum is promoted by its Descent, as much as impeded by its Ascent.

5. Practical advice is given to reduce friction:

   The less rubbing there be of the axle, the better it is for this effect; upon which account, steel axes, and bell-metal sockets, are much better than wood, clamped, or shod with iron; and gudgeons of hardened steel, running in bell-metal sockets, yet much better, if there be provision made to keep out dust and dirt, and consistently to supply and feed them with oil, to keep them from eating one another. ...

As Dowson observed, Hooke recommended the use of soft metal bearings to reduce friction. He anticipated the ideas proposed by Bowden and Tabor (Section 4.4) in the mid-twentieth century, without knowing the concept of shear strength.
Larsen-Basse (1992) proposed that regarding the causes of friction, there were two early schools. The French school was promoted by Amontons, and later Coulomb, and emphasised the mechanical (elastic) interaction of surface roughness and asperities. On the other hand, the English school, represented primarily by French-born Desaguliers, advocated ‘cohesion’, or adhesion between the materials. Even before the French school was established, Hooke refuted it, and preceded the English school by about a half century.

1.3 Guillaume Amontons

Da Vinci’s laws were unnoticed or forgotten, to be rediscovered via the systematic experiments by Amontons (1663–1705), who summarised the findings as follows (1699):

1. The resistance caused by friction increases or diminishes in proportion to pressure, the magnitude of which is larger or smaller depending on whether the area of rubbing surfaces is bigger or smaller.

2. The resistance caused by rubbing is similar for iron, copper, lead and wood combined in any manner, if the surfaces are coated with old pork fat.

3. The resistance is about one-third of the load, suggesting $\mu \sim 0.33$.

4. The resistance between the rubbing bodies depends in a complex way on normal pressure, time and sliding speed.

Amontons’ laws are derived from the first statement, and it can be seen that they are practically identical to da Vinci’s rules:

1. The force of friction is directly proportional to the applied load.

2. The force of friction is independent of the apparent area of contact.

Amontons contended that friction on hard surfaces is associated with the force required to lift asperities of one surface over those of another, in a movement along an inclined plane. On softer surfaces, there could be an elastic component of friction, and it was represented with elastic springs as shown in Figure 1.2. This representation has been widely used in the friction models developed by control engineers (Canudas-de-Wit et al., 1995).

According to Kragelsky and Shchedrov (1956), these findings were received with some scepticism by the French Academy. Philippe de la Hire (1640–1718) was commissioned to verify them, and they were confirmed by his experiments. De la Hire developed his theory:
1. Friction is caused by the interlocking of asperities, which are either elastic or hard.

2. The elastic ones are bent like springs, and the more bent they are, the larger the friction. At given pressure, the bending is inversely proportional to the number of springs, and that’s why friction does not depend on surface area.

3. If asperities are hard, force is required to lift the asperities of one surface over those on the opposite surface (Figure 1.3). The friction is then proportional to pressure.

De la Hire also envisaged a case when the friction depends on the contact surface area. That occurs when the asperities are broken, that is, snipped during motion. The resistance to motion is then proportional to the number of broken asperities, that is, to the surface area.

Generally, Amontons’ laws hold in many practical cases. However, Ringlein and Robbins (2004) quoted the example of sticky tape, which exhibits friction without load. Also, with sticky and compliant objects, friction increases with the contact area.
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Anon. 1813. *Letters written by eminent persons in the seventeenth and eighteenth centuries: to which are added, Hearne’s journeys to Reading, and to Whaddon Hall, the seat of Browne Willis, Esq. and Lives of eminent men, by John Aubrey, Esq*. London: Longman, Hurst, Rees, Orme, and Brown, and Oxford: Munday and Slatter.


Eighteenth Century

This century saw a surge in the studies of friction. Many notable scientists in Western Europe (France, Great Britain, Holland and German-speaking lands) conducted experiments and/or proposed the causes of friction. The development of science started in earnest in Russia, and friction attracted significant attention.

2.1 France: Parent, Camus, Bélidor

Between Amontons and Coulomb, there were three French tribologists of some note:

1. In 1700, Antoine Parent (1666–1716) reported observations that, with light lubrication, the COF is ~0.33 for iron, lead, copper and wood. He confirmed Amontons’ results, but considered that speed does not affect friction. However, he proposed that the COF may differ slightly between various materials (Kragelsky and Shchedrov, 1956).

2. François Joseph des Camus (1672–1732) published in 1724 the results of his extensive experiments, and pointed out that the COF depends on the physical properties of surfaces, that is, whether they are dry, wet, or lubricated. The observed range (0.15–0.45) was much wider than reported by anyone earlier. He also argued that the COF decreases with increasing normal load, and, surprisingly, that lubrication increases friction. Nevertheless, he recommended lubrication, to reduce wear and make sliding smoother (Kragelsky and Shchedrov, 1956).

3. Bernard Forest de Bélidor (1698–1761) is credited to be the first to apply calculus to engineering problems (Day and McNeil, 1996). He published a seminal book on hydraulics, noted both for the depth of knowledge, and for the beautiful illustrations (Figure 2.1). In the book, he represented the surface roughness by the arrays of spheres, and calculated the force required to pull one layer of spheres over another (Bélidor, 1737). The estimated COF was ~0.35.
FIGURE 2.1
The top plate shows the COF derivation, and the bottom plate the admirable aesthetics of Bélidor’s illustrations. (Reprinted from B.F. de. Bélidor, Architecture hydraulique, premiere partie, Paris: C.-A. Jombert, 1737. With permission.)
2.2 German-Speaking Lands: Leibniz, Leupold, Euler

Given their penchant for smart machinery, it is not surprising that Germans became involved in the early studies of friction, as shown by Kragelsky and Shchedrov (1956):

1. Gottfried Wilhelm von Leibniz (1646–1716) briefly delved into friction. He argued that the COF is not constant, but depends on the physical properties of surfaces in contact, and pointed out that the friction of rolling is smaller than the friction of sliding.

2. Jacob Leupold (1674–1727) was involved in the design of machines. He confirmed the findings of Amontons and obtained a COF of 1/3 for dry wood. Compared to the dry case, the COF roughly doubled with kerosene as a lubricant, and was somewhat smaller for a soaped surface. He also questioned the constancy of $\mu = 1/3$, arguing that it depends on roughness, the properties of rubbing surfaces, and the shape of asperities.

3. Leonhard Euler (1707–1783) introduced the symbol $\mu$ for COF in 1748 (Euler, 1750a,b). Also, he concluded by theoretical reasoning that kinetic friction is smaller than static friction. As did French scientists, Euler explained friction via the climbing of asperities of one body over the asperities on the opposing surface.

2.3 Russia

The treatment of friction in Russia illustrates the importance of its studies in the eighteenth century. A few scientists mentioned here were involved, directly or indirectly.

1. Peter the Great established the Russian Academy of Sciences in 1724 as the Saint Petersburg Academy of Sciences. Leibniz was the key advisor in this undertaking.

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† Seireg (1998) claims that Themistius in the fourth century BC had observed that friction is much smaller in rolling than in sliding. However, Themistius lived in the fourth century AD. See also the next footnote.

‡ Cotterell and Kamminga (1992) argued that Themistius had said that kinetic friction is smaller than static friction. This is supported by Hecht (2003), who attributed to Themistius the saying: ‘Generally, it is easier to further the motion of a moving body than to move a body at rest’.

‡ Peter the Great was technically minded and a science enthusiast. As a young potentate he visited Greenwich and Oxford, studied the city building in Manchester, and inspected shipbuilding in England and the Netherlands. Allegedly, he worked as a carpenter in the largest shipyard of the day, that of the Dutch East India Company, to gain hands-on experience.