Tribology in Metalworking

Friction, Lubrication and Wear

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Preface

Some thirteen years ago, Professor S. Kalpakjian and Drs. J.A. Newnham and C.H. Riesz cooperated with me in producing a reference book on "Metal Deformation Processes: Friction and Lubrication," published by Marcel Dekker, Inc., New York (1970). The intervening years have seen a veritable explosion of information in the field that meanwhile has come to be described as "tribology," a term encompassing the science and technology of friction, lubrication, and wear. Knowledge pertaining to metalworking tribology has also increased greatly. Contacts with colleagues in industry and research have impressed upon me the need for a book that would serve better as a self-learning text. Therefore, when the American Society for Metals expressed interest in an updated version, I decided to write an essentially new research monograph, which, hopefully, will be found more useful as an introduction to the subject while serving also as a reference source. In view of its importance, the tribology of machining processes is now also included.

I could have chosen to limit the scope of this volume strictly to metalworking, and to direct the reader to the vast literature from which the necessary background could be acquired. Such an approach would have been patently unfair to the majority of readers, who may be specialists in one field but not in others, or who may be newcomers to the entire subject. Tribology itself is a truly interdisciplinary discipline, drawing on various aspects of physics, chemistry, mechanical engineering, and materials science. Metalworking tribology is yet further broadened by the inclusion of the mechanics and metallurgy of metalworking processes. Therefore, I have endeavored to give a brief but comprehensive account of the essential background material, so that the volume can stand on its own, and so that the reader need delve into the literature only if interested in following up specific aspects.

The material relevant to metalworking tribology would easily fill several monographs of this size. Complete coverage thus not only was an unrealistic goal but also would have made the volume virtually indigestible, with a quite unreasonable number of references. Therefore, some selection had to be exercised, and this necessarily involved personal judgments of what is most important and what can be readily followed up on elsewhere. In making such judgments, I have endeavored to keep in mind the varied background of the readership: what is trivial to a chemist may be new to a mechanical engineer, and *vice versa*. The emphasis here is on physical observations and their interpretation; details of analysis, for the interested reader, can be found in the references given. I hope that this volume, as a result of the selections made, will provide adequate information for the novice without boring the expert.

In writing the text I had to venture into areas beyond my immediate expertise. To ensure accuracy of treatment, I imposed on friends for advice. I am greatly indebted to

Donald H. Buckley, Bernard J. Hamrock, John Hickman, J. Brian Peace, Clyde A. Sluhan, Joseph L. Tevaarwerk, Joseph Wright, and several graduate students for their valuable remarks on Chapters 2 to 5; to Ranga Komanduri, Milton C. Shaw, and Paul K. Wright for their suggestions regarding Chapter 11; and to George E. Dieter for the enormous task of reviewing all but Chapter 11. For any remaining errors, I alone am responsible.

An operating grant from the Natural Sciences and Engineering Research Council of Canada allowed me to explore topics that were in need of clarification, and I made extensive use of the library facilities and services of the University of Waterloo.

There are many friends and colleagues without whose help this undertaking would have been impossible. Kurt Lange provided me with the opportunity to search the German literature in his Institut für Umformtechnik, and his co-worker Th. Gräbener made available his collection of references. Bruce Uttley and Marjorie Kohli of the University of Waterloo found solutions to the many problems of transferring the text from word processor to phototypesetter; Beryl Hultin, together with others, helped in correcting the text on the word processor. I enjoyed working with Timothy L. Gall of ASM and with William J. Carnes in the preparation of this volume. The brunt of the task was carried by my wife, Gitta, who for three years spent endless hours working on references, typing drafts, and typing the text for the OCR transfer; to her I dedicate this volume.

It is neither likely nor necessary that anyone should read this volume from cover to cover as a continuum. Cross references are included to facilitate reading on individual topics and processes. I should be most grateful to have readers' reactions and suggestions regarding the treatment and any errors that may be found.

John A. Schey

Waterloo, Ontario
February, 1983

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Background and Method of Treatment

The history of tribology, set against the broader background of industrial and social development, is the subject of a recent and thoroughly enjoyable book by Dowson [1]. Regrettably, it contains but few references to metalworking; therefore, a brief account based on the earlier review of Schey [2] is given here, followed by some remarks on the method of treatment adopted in the present book.

1.1 Historical Background

Metalworking is probably the earliest technological occupation known to mankind; native metals were forged and shaped more than 7000 years ago. Considering the importance of lubricants in deformation processes, it is rather amazing that no account of their use can be found until relatively recent times.

There are, perhaps, three main reasons for this anomaly. First, the composition, manufacture, and use of lubricants were—and to some extent, still are—the most closely guarded secrets of the whole operation. Second, nature very kindly provided some of the best lubricants known today, so that the artisan engaged in metalworking did not have to rely on the skills and knowledge of other crafts, arts, or sciences; he was not compelled to reveal his practices, and the nonexpert observers reporting on metalworking processes failed to grasp the significance of the little they may have been allowed to see. Third, lubricants assumed a vital role only at a relatively late stage of development.

1.1.1 Forging

There is little doubt that forging was the first, and for a long time the only, bulk deformation technique. Native gold, silver, and copper were hammered into thin sheets and then shaped into jewelry and household utensils as early as 5000 B.C. [3]. These metals, and, later, copper reduced from ores, were readily cold worked without a lubricant. Some unintentional lubrication may have occurred, for instance, when sheet was driven into asphalt for shaping, or was placed between animal skins for thinning down to metal (gold) leaf. Copper was annealed well before 4000 B.C., and hot forging must have soon followed. Copper oxide is a good parting agent, as is the oxide of iron, a metal which was worked with great skill under the Hittites in the 13th century B.C.

Iron became the dominant material for weapons, tools, and agricultural implements from 800 B.C. on, replacing the cast and also wrought bronze that dominated earlier centuries [4]. This marks the ascendancy of the blacksmith, with his Greek god Hephaistos [5]. The cold forming of metals, nevertheless, continued uninterrupted. Cast bronze forms were used for hammering decorative parts from sheet, and the first known coin was driven into a die with several punch strokes in the 7th century B.C. Again, no reference to lubricants is known and it is probable that natural contaminants, even if only from greasy fingers, provided all that was needed.

One must not forget, though, that seed oils, animal oils, tallow, and waxes were available in early antiquity [6]. In the 5th century B.C. Herodotus wrote about the extraction of bitumen and light oil from petroleum, and in about 60 A.D. Pliny the elder described the manufacture of soap [7]. Thus, at whatever point of development the first lubricant may have been used, a variety of eminently suitable substances certainly must have been available.

Forging continued to be the dominant metalworking process for many centuries. Coin pressing achieved high standards under the Romans, who drove the blank with a hand punch of suitable profile into a counterforming die [4]. The first forgings made in closed dies were produced in the northern Germanic areas, where local iron ores yielded higher-carbon iron and, therefore, better weapons. Chain mail was probably first made there and, while the starting material would ideally have been drawn wire, it is now generally conceded that this wire was actually forged in swaging dies. Cast bronze anvils survive from the Bronze Age with indentations that probably served for the forging of needles, and the goldsmiths and silversmiths had no problem in shaping their precious metals into decorative wire.

Forging is, nevertheless, the only hot working process that can claim a long history of lubrication. Steel rifle parts were forged in die impressions for interchangeability as early as the 18th century [4]; lubrication practices were probably not too different from those found some fifty years ago, with sawdust, a thin smear of a heavy oil, or oil mixed with graphite serving as a lubricant.

1.1.2 Wiredrawing

The argument on the earliest date of wiredrawing is still not settled. Theophilus, the German monk writing in the early 12th century, treats wiredrawing as an established art [8]. He refers to steel dies used for drawing a tin-lead alloy, and to oak dies for smoothing hammered gold and silver wire. Iron and steel plates bearing a number of holes, connected with a surface channel, have been identified by many researchers as drawing dies, on the assumption that the surface channel served for retaining the lubricant [9]. The earliest such finds date back to the first century A.D. and, if the interpretation of the channels is correct, these would provide circumstantial evidence of the use of metalworking lubricants for two millenia.

Guilds of wiredrawers were registered and regulated as early as the 13th century [10], and water power was introduced in the 14th [11]. Yet, the first written reference to wiredrawing lubrication is of much later date. Biringuccio [12], writing of the drawing of gold and silver wire, admonishes to "remember that while you are working it you must always keep it greased with new wax, for besides easing its passage through the holes, this also keeps its color yellow and beautiful." Rather casual references to oil-soaked rags, applied to the iron wire before it entered the drawing die, were made by early 18th century observers [8]. It is likely that the lubricant was a locally available product—probably lard oil in the north, and vegetable oils in the south, of Europe [6]. Records show that olive oil was imported into Altena, the center of the German steel wiredrawing industry, far in excess of any conceivable household needs, and it is reasonable to assume that this was used for drawing the highest grades of iron and, later, steel wires [10].

It was in Altena that the first surface treatment was discovered. For many centuries the wire had been prepared for drawing by hand scouring it with bricks or sand,

and it was only in the 17th century that bundles were mechanically threshed with a waterwheel, with frequent dashes of water and sand [10]. With the usual grease or oil lubrication, it was possible to draw the clean rod, but only if made of the softest, best quality Osmund iron. Steel, while known to be superior for many applications, including needles, fish hooks, and the like, could not be drawn, presumably because high friction caused the wire to break. It remained for one Johann Gerdes to discover the value of a surface treatment around 1650, the story being recorded by a wandering minstrel only a few years later. As related by Lewis [10], after an unsuccessful effort, Gerdes threw the steel rods out of the window, into the area where "men came to cast their water." After a while, he retrieved the rods and—without bothering to remove the soft, brown film that had formed on them—found that they now drew with great ease. This original sull-coating technique was used for almost 150 years. Then dilute sour beer was found just as effective, and in another 50 years it was recognized that plain water would serve equally well, although the original technique has survived in some places until this century.

Prior to the introduction of sulfuric and hydrochloric acids, light scale was removed or softened on the wire surface by lengthy immersion in weak solutions of tartaric acid, brewers' yeast, or similar organic liquids. Acid cleaning was first used for iron sheet in the early 19th century. Pickling, lime coating, and baking were developed for steel wire in the middle of the 19th century when large quantities of signal wire were demanded by the expanding railroad networks.

Wet drawing practices employing oils, emulsions, or greases as lubricants remained dominant in Europe until recent years, and were often aided by the deposition of a thin copper or copper-tin coat on the steel wire by drawing from baths containing copper sulfate. Like so many innovations, this too was a result of accident; the coating was observed to develop when hot brass ingots were used for warming up an acid pickling bath [13]. While thin steel wire was drawn wet with a copper-tin coat, dry drawing with a soap was the main production technique for heavier gages in the U.S. [8] but found general acceptance in Europe only in the last few decades. The latest change affecting lubrication in wiredrawing came with the introduction of the sintered tungsten carbide die in 1923 [11] and phosphate coating of steel in 1934 [14].

1.1.3 Rolling

Rolling lubricants, which now occupy such an important position, have a much shorter history. Rolling itself was first applied to metals in the cold working of lead and gold in the 15th century [5], and for narrow strips of coinage alloys in the 16th century [15]. The first sketch of a mill is due to Leonardo da Vinci. The 17th century saw the appearance of slitting mills in which forged flats were split with collared rolls, then rounded by forging, and finally drawn into wire. Grooved rolls were used in 1728 in France by M. Fleuer some 60 years before they were patented by Henry Cort in England. To quote Lewis [16], "these early ironmasters never scrupled to make use of a process many years before it had been invented." Nevertheless, it was another hundred years before wire rod was regularly rolled, and Bedson's continuous mill appeared in Manchester in 1862 [17]. Rounds and sections, however, were and still are often rolled without any lubricant, and we must look to the rolling of sheet to trace the development of lubricants.

Sheet was traditionally hammered from a cast ingot, with up to 50 layers forged in a pack for tinplate [5]; rolling had to wait until rolls could be turned accurately. Wide lead sheet was rolled in the 18th century, and nonferrous metal sheets were soon cold rolled in gradually increasing widths. However, lubrication requirements of copper and