SOFT MAGNETISM
Fundamentals for Powder Metallurgy and Metal Injection Molding

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In remembrance of
The One
who taught me all
I ever really needed to know.
Chaman Lall is Vice-President and Technical Director at Midwest Sintered Products Corporation, a powder metal parts producer in the Riverdale suburb of Chicago, Illinois, U.S.A. His technical interests include process and materials research on high-performance soft magnetic materials, stainless steels, and structural steels.

Chaman joined this facility in 1989, after nearly a decade of successful research and management activities with E.I. du Pont de Nemours and Company, and the P/M group within its Remington Arms Company. These activities included the development of high performance alloys and production processes for metal and ceramic injection molding. He also performed fundamental research and development at the University of Pennsylvania (1976-1977) and Drexel University (1978-1979). Chaman studied "Physical Metallurgy and the Science of Materials" at the University of Birmingham (England, UK), and received his B.Sc. degree in this subject in 1972 and a Ph.D. degree in 1976.
The Iron Pillar\(^{(1)}\) in Delhi, India, is often mentioned as one of the finest early examples of an article made by the process we call powder metallurgy (P/M). This particular example illustrates two aspects of powder metallurgy that prevail even today. The first is the degree of excellence to which a powder metal product can serve in a particular application, and the second is the "black art" of processing that allows one to make such an outstanding product.

Articles made by powder metallurgy are often perceived to have very poor corrosion resistance. Yet this Iron Pillar is over 1,500 years old and has held up very well against the elements for all these centuries. What is also remarkable is that the capability to handle such a large iron article (24 feet tall and weighing more than 6 tons) would not be possible in Europe until the 19th century. It is now believed that the silicon in the iron ore found in local quarries and used to make the pillar resulted in a dual benefit. First, the high silicon content enabled the early practitioners to bond the lumps or granules at low sintering temperatures. Second, the silicon in the form of a complex oxide coating turned out to be an excellent barrier to corrosion. It is unlikely that the "powder metallurgists" of that era fully understood the science of their process.

A similar sense of awe and confusion appears to surround the parts produced by powder metallurgy for sophisticated magnetic applications. Magnetism is regarded as a mystical phenomenon because of our inability to touch and feel it. Much in the same manner as gravity, one can only observe the effects of magnetism. Magnetism is purported\(^{(2)}\) to be the force behind exotic devices that can improve the taste of wine, soften water, make hair silkier, improve automobile gas mileage, and reduce exhaust emissions!

The fact is that both magnetism and powder metallurgy are understood to the extent that each can be practiced as a science. It is the purpose of this monograph to bring these two subjects together in a sufficiently coherent manner so that both producers and users of powder metal components can discuss and develop magnetic applications in a systematic manner.

Powder metallurgy has developed into a scientifically understood fabrication technology within the last half of the twentieth century. Much of the focus has been on developing products for structural applications, so that the majority of components in use today utilize the mechanical attributes of the P/M offering.

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A potentially strong growth market for P/M is one where the magnetic properties of a component are functionally important. The products for this general market can be divided into two categories; soft and hard magnetic devices. These quite distinctly separate groups, while falling in the general field of magnetism, have totally different objectives during the manufacture of the product. Soft magnetic components are produced with the goal of obtaining a defect-free microstructure, with as large a grain size as possible. In contrast, hard or permanent magnetic components should have as many precipitates, inclusions, etc., as possible.

The fundamentals of the powder metallurgy process are described, with a view to relating how the process variables influence the soft magnetic performance of the product. A logical extension of the powder metal process is the newer technology referred to as metal injection molding (MIM). Conventional P/M is limited to producing shapes that can be formed by the vertical motion of tooling members, inside a die that creates the peripheral features of the part. The MIM technology enables features to be formed by the motion of tooling members normal to the vertical direction. In this way, the MIM forming method complements the conventional P/M process in that another dimension can be freely designed by the user. A truly three-dimensional shape forming technology is in the offering. Furthermore, the MIM process has the potential to process a wider range of alloys and produce a more uniform product, than P/M.

The primary emphasis in this text is to promote an understanding of the magnetism phenomenon and describe the important parameters that define the magnetic characteristics of a given material. Some selected test methods for the evaluation of magnetic properties are briefly described. Furthermore, the relationship of the measured parameters to the performance of soft magnetic devices is discussed.

The properties of materials manufactured by powder metallurgy and metal injection molding are presented and, in addition, compared to their wrought counterparts. Some example devices are described to illustrate the kinds of applications that require soft magnetic properties. This book is complemented with several appendices that provide guidance on terminology and standards that are in current use.

No attempt has been made to derive well-known formulae that may be found in standard text books on physics. The primary focus is on providing a qualitative and practical understanding of the phenomena under discussion. Wherever possible, the International System of Units (SI) has been used. However, the c.g.s. system of units is fairly widely-accepted and preferred for magnetism in the U.S.A. and many other parts of the world. For this reason, values using the c.g.s. or other “customary” units have been included in parentheses.

This book is primarily intended for those individuals responsible for the optimization of the manufacturing process as well as those engineers
designing and specifying soft magnetic components. The pursuit of education of the engineering and marketing communities has been the driving force behind this book.

I would like to express my appreciation to many of my friends and colleagues for their support. In particular, I wish to thank Mr. H. C. (Hal) Munson and Mr. Louis W. Baum, of Remington Arms Company, and Professor C. D. (Chad) Graham, of the University of Pennsylvania, for introducing me to this subject and for the motivation to pursue this intriguing and fascinating field. I also wish to thank all of my associates who supplied data or examples for this monograph; each is recognized at the appropriate point in the text. An endeavor such as this would have been practically impossible without the support and encouragement from my wife Samitra, to whom I am very grateful. Finally, my thanks to all the unsung heroes at MPIF headquarters for their assistance in completing this monograph.

Chaman Lall
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Chapter 1
FUNDAMENTALS OF MAGNETISM

The fundamental basis of magnetism is developed with regard to the effect of a moving charged particle and the influence of material structure. The majority of this initial chapter is devoted to describing soft magnetism and the associated phenomena. Short sections on permanent magnetism and some selected measurement techniques serve to complete this introduction to basic magnetism.

1.1 Introduction

The fascinating aspect of magnetism is its ability to generate forces between objects that are not in physical contact with each other. This invisible force is responsible for our inability to push together two powerful magnets that are oriented so as to repel each other. The same force enables a permanent magnet to pick up a pile of paper clips or nails that were previously unattracted to each other.

Magnetic forces are just one example of several forces that can cause interactions between matter that is not in physical contact. The concept of forces and force fields is developed first, in order to provide a framework to describe magnetic interactions. Initial discussions focus on gravitational, electrostatic and magnetic fields, since an understanding of these subjects serves to demonstrate the similarities (and differences) between them. This is followed by a discussion of how a magnetic field created by the flow of electric current interacts with magnetic materials. Some terminology and the parameters used to characterize magnetic properties are introduced at this point.

1.2 Force Fields

While the exact mechanisms that enable forces to interact across empty