The Physical Metallurgy of Steel and the 2015 Publication of *STEELS: Processing, Structure, and Performance* Second Edition

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Introduction

Steel is a remarkable material, highly versatile, manufactured and used in vast tonnages throughout the world in many grades and forms for demanding applications. It is, however, a complicated material in view of its processing and chemistry which may include ten or more chemical elements in addition to iron as the base. *STEELS: Processing, Structure, and Performance,* Second Edition (ASM, 2015)**,** addresses the dynamically changing state-of-the-art of the physical metallurgy of steel. The text is designed to be of importance to many different groups of readers as described in the following sections.

The Physical Metallurgy of Steel

Physical metallurgy has effectively three components: processing, structure, and properties or performance, hence the title of *STEELS*, Second Edition. Processing involves defined manufacturing steps by which a steel part is made, such as steelmaking, hot rolling or forging, or final heat treatment. Alloying, mechanical deformation, and heating and cooling in the various steps establish the internal structure of a steel which in turn determines its properties and performance. Performance may be as designed or may in fact be below expected because of some embrittling failure mechanism operating within the structure of the steel.

A major purpose of *STEELS* is to describe the microstructures of steels, how they are created by the processing steps, and how they determine performance. Steels in the solid state are composed of crystals of iron and other elements. The crystal arrangements that make up microstructures are produced by solid state phase transformations, effects of time and temperature during heating and cooling, and mechanical deformation. All of the many elements added during or surviving steelmaking must be incorporated somewhere into the crystal structure of steel. The location of the various elements on an atomic scale has required the development of instrumentation with high resolution, a process that continues to this day.

Another continuing aspect of the processing-structure-performance paradigm is the characterization and understanding of the nano or atomic scale substructure that is a component of steel microstructures. Examples are very fine precipitates and dislocation densities that determine strength, plasticity, and fracture of steels. Again, the characterization of substructure has required the development of instruments of higher resolution than the light microscopes first used to characterize the microstructure of steel.

A Half-Century of Progress in the Manufacture and Performance of Steels

STEELS, Second Edition is in fact the fourth version of the book I published in 1980 to extend the information in the classic text by Marcus Grossmann's and Edgar Bain's *Principles of Heat Treatment***,** 1964**.** By the 1950s, steel phase transformations and microstructure on a scale resolvable in the light microscope were well established as described by Grossmann and Bain, but dramatic changes in the production and characterization of steel were underway. Basic oxygen furnace (BOF) and electric arc furnace (EAF) steelmaking and continuous casting were replacing Bessemer and Open Hearth furnace steel making and ingot casting, and transmission electron microscopy was developed and characterized structure on a finer scale than possible in the light microscope.

The Preface to my 1980 book, *Principles of Heat Treatment of Steel*, sets the stage for changes incorporated into the Grossmann/Bain edition: "New theoretical approaches to the diffusion-controlled and martensitic transformations, the characterization of fine structure by transmission electron microscopy, fractography with the scanning electron microscope, new electron beam microanalysis techniques, fracture toughness testing, continued examination of hardenability, and the relationship of microstructure and fine structure to strength, toughness, and ductility are all areas, highly developed only in the last twenty years, that I have attempted to build onto the solid foundation of steel heat treatment developed by earlier workers."

From that starting point, each version of *STEELS* has added more insights into the effects of alloying and processing on the microstructure, substructure and performance of steels, and I now realize that the Second Edition, in addition to technical and scientific information, provides a rough history of the revolutionary changes that have developed in the physical metallurgy of steel during the last half century. Established features, as documented by the technical literature, have been retained and enhanced through the various versions, and new descriptions have been added as they have been discovered.

I have tried to indicate time periods for important developments in the text of *STEELS*, as for example continuous annealing of sheet steels, thin slab continuous casting, and microalloying of forging steels. In many other cases additions to the knowledge base of steel structure are supported by references, and the

references not only recognize the many contributing individuals, but also the dates at which the contributions have been made. To mention just a few, I have been privileged to know and learn from Hub Aaronson (bainite and ferrite), Bill Leslie (his book "*The Physical Metallurgy of Steels*"), Mike Korchynsky (microalloying), Gareth Thomas (electron microscopy and steel), Keith Brimacombe (solidification and cracking), and (Fereshteh Ebrahimi (tempering and fracture), excellent ferrous metallurgists active in this half century, now passed on, but remembered by references to their work.

Steel Solidification—The Anchor of Physical Metallurgy of Steel

In the 1950s, physical metallurgy was largely devoted to solid steel microstructure and properties and steelmaking and solidification were considered independently as extractive metallurgy, emphasizing slag/metal thermodynamics and liquid steel reactions. As a graduate student, at MIT in the late 1950s, I was required to take qualifying examinations in both physical metallurgy and extractive metallurgy, and in preparation for the latter took excellent courses from Professors John Chipman and John Elliott.

Although still a quite independent specialty, steelmaking and solidification have also moved to the characterization of the structure of as-cast steel, made possible in large part by the development of scanning electron microscopy and associated energy dispersive spectroscopy which make possible the characterization of inclusion chemistry and morphology. Attention has also been paid to interdendritic segregation that occurs during the solidification of liquid steel. Thus, for the physical metallurgist consideration of the microstructural features introduced by steelmaking must be integrated into the physical metallurgy and performance of finished steel parts.

In view of this consideration, the Second Edition of *STEELS* has introduced sections related to primary processing and the effects of inclusions and interdendritic segregation on steel performance and fracture. There are sections on primary processing, cracking during primary processing, and hot shortness associated with copper. This attention to steelmaking effects hopefully will be useful for readers in steel companies as well as those readers in companies that form and heat treat finished parts of steel from the sections produced by the steel companies.

Additions to the Second Edition of *STEELS: Processing, Structure, and Performance*

As noted above, the revision to *STEELS*, Second Edition started with an already substantial base of steel physical metallurgy. To this base was added new information based on investigations between 2005 and 2015, but also added were more complete descriptions of phenomena based on valuable older references that run the risk of being forgotten as vast amounts of new information are generated. Each chapter was examined and almost all were modified in some way. The challenge was to incorporate the new information in a readable fashion with that already published. *STEELS*, Second Edition is not meant to reproduce the vast amount of information found for example in ASM Handbooks, but is designed to help readers understand the background for that information. Following are some of the changes made in the Second Edition.

Brief descriptions and references to established and new analytic techniques used to characterize structure start the Second Edition, necessary now because readers new to steel need to understand how some of the structural information is generated. More attention is paid to the peritectic reaction in iron-carbon systems because of increased attention in the steel making community to cracking that develops during solidification of low-carbon steels. Extensive discussion of nonlamellar ferrite/cementite formation instead of lamellar pearlite has been added to the chapter on pearlite. Characterization of the block morphology of lath martensite from Electron Backscatter Diffraction (EBSD) has been added to the chapter on martensite. Sections on steels with fully martensitic microstructure, high manganese Twinning-Induced Plasticity (TWIP) steels, and quenched and partitioned steels have been added to the low-carbon sheet steel chapter.

Dispersions of spherical carbides, not only produced during spheroidizing heat treatment but also during austenitizing and tempering are discussed in more detail and with added references. The importance of nitrogen to microalloyed forging steels and the effect of finish temperature and various amounts of ferrite and pearlite are emphasized. Fracture mechanisms of pearlitic steels patented and drawn to wire and pearlitic rail steels are discussed more extensively. The hardenability discussion is modified to minimize austenitic grain size as a major variable and to point out that undissolved carbides retained during austenitizing may strongly affect hardenability. Boron and phosphorus effects on hardenability are introduced into the Second Edition.

The application of atom probe tomography to identify nanoscale chemistry changes of cementite particles during tempering is introduced, and the very fine residual martensite crystal size in high-temperature-tempered martensite is noted and discussed as a major strengthening mechanism. A consideration of all of the components of tempered martensitic microstructures and their effects on strengthening and fracture is presented. The

discussion of cracking during primary processing is enlarged, a section on stress relief cracking, and increased attention to hydrogen embrittlement, are additions to the chapter on Low Toughness and Embrittlement Phenomena in the Second Edition of *STEELS*. The discussion of carburizing has been revised with the additions of sections on surface oxidation, residual stress and microstructure, and contact fatigue in addition to microstructure effects on bending fatigue.

Summary and Dedication to the Readers of *STEELS: Processing, Structure, and Performance,* Second Edition

The Second Edition of *Steels: Processing, Structure, and Performance*, as well as the First Edition, is warmly dedicated to the men and women that make, use, study, and design with steels. Many potential readers in these groups come from outside of the materials community, from other engineering, manufacturing, and technical fields. Many have taken courses or acquired books for the non-metallurgist; therefore, they are prepared for a more extensive treatment of steels. *STEELS* is written to be tutorial and review basic information as well as to go into more depth for the professional benefit of newcomers in the industries involved in steel manufacture.

The importance of steelmaking has already been noted in the above paragraphs, and steelmakers in all phases of the primary processing of steel should benefit from *STEELS*, Second Edition. More and more, steel company personnel are also required to assist client companies without expertise or staff experienced in steel manufacture; therefore, the up-to-date extensive coverage of steel physical metallurgy in *STEELS* should be of help to those steel company employees and their clients.

There is a vast pool of individuals already involved and experienced in all practical aspects of steel manufacture. Heat treatment, a major subject in *STEELS*, Second Edition, is a critical aspect responsible for the performance of finished steel parts. Also, emphasis on microstructure in *STEELS* should help metallographers and their colleagues relate microstructure to processing and performance of their steel products. By providing state-of-the-art information, *STEELS*, Second Edition may provide valuable new information that busy individuals may not have had the time to acquire. For the experienced individuals interested in a particular topic, attached references are provided for more detailed information if desired.

A critical aspect of the use of steels is the analysis of failures that may occur during manufacture or application. *STEELS*, Second Edition emphasizes fracture and the embrittlement mechanisms that are often the cause of performance lower than expected. Not only are the modes of fracture but also the underlying alloying, microstructural, and processing causes of fracture described in *STEELS* for each of the major types of steels. In view of this emphasis, failure analysts and forensic professionals should benefit greatly from the Second Edition.

STEELS, Second Edition is dedicated to the students of steels. As experienced steel professionals retire, a new work force must take their place. Certainly, students with degrees in materials science will qualify for those replacements, but because of the need to cover all materials, university focus on steels is decreasing. Therefore, the in-depth coverage of the fundamentals of *STEELS*, Second Edition should be an important supplement to the education of university graduates.

Finally we are all students, no matter what our age and experience, and we can continue to learn throughout life. The changes and additions to the four versions of my books on steels over the last half century attest to that learning in my life as an author.