

# STEELS

Processing, Structure, and Performance

Second Edition

George Krauss



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# Preface to the Second Edition of *Steels: Processing, Structure, and Performance*

In this twenty-first century, steel, in its many chemistries and forms and as a major material for load-carrying applications, is under intense pressure from many directions: to reduce energy and find just the right time and temperature in processing to achieve the best combination of structure and properties, to optimize alloying, to improve properties for vehicle weight reduction and safety, and to increase life in demanding applications. The last ten years have seen dynamic responses to these challenges, and production, research, development, technical conferences, and publication have not stopped. Hence, a second edition of *Steels: Processing, Structure, and Performance*. Every chapter in the first edition has been examined, and not only has recent information been added, but also important references to past discoveries and insights, not included in the first edition and in danger of being forgotten, have been added and discussed.

Structure is the unifying key to understanding steels, and the need to characterize the many elements of structure continues to expand. Where earlier, microstructure as resolved by light microscopy was emphasized, now macrostructure, crystal structure, substructure, and nanostructure and their length scales are integrated with microstructure as a function of chemistry, processing, and performance. This integration is being accelerated by analysis techniques such as electron backscatter diffraction (EBSD) and atom probe tomography (APT), only widely used since the first edition of *Steels*, as well as improvements in established light and electron microscope techniques and specimen preparation.

This second edition of *Steels* is actually the fourth volume on steels I have authored. The first volume, entitled *Principles of Heat Treatment of Steel*, American Society of Metals, 1980, was a rewritten version of *Principles of Heat Treatment* by M.A. Grossmann and E.C. Bain. As I noted in the preface of the 1980 volume, “*Principles of Heat Treatment* covered developments between 1935 and 1964, and Grossmann, Bain, and their contemporaries did their work so well that the heat treatment and metallurgy of carbon steel was almost taken for granted.” Certainly, tremendous advances in understanding steels have occurred, but the statement regarding the expertise of Grossmann and Bain still rings true with respect to hardenability, a field in which austenitic grain size is no longer considered a major factor as outlined by Grossmann and Bain. Reasons for this shift are discussed in this second edition of *Steels*.

Color has been added to the second edition of *Steels*, in part to highlight microstructural features but also because new characterization techniques, such as EBSD and APT, provide so much data that color is necessary to differentiate various parameters. Almost all chapters have been updated with figures and/or discussion to illustrate structures and phenomena as well as to present new information. In addition to hardenability, the peritectic reaction and other steelmaking aspects, some new sheet steel developments, microalloying, boron effects, spherical carbide dispersions, new views of tempering, the strengthening components of tempered martensitic steels, pearlitic wire and rail steels, cracking during primary steel processing, reheat cracking in welds, hydrogen embrittlement, residual-stress development and oxidation in carburizing, and effects of rolling-contact stresses on high-carbon steel microstructures are among the topics that have been added or have received substantial modification. I hope these additions to the tutorial baseline of structures and steel products in the first edition of *Steels* will be of value to experienced ferrous metallurgists as well as new generations of individuals from many backgrounds in the materials and manufacturing communities that must produce, use, and study steel.

I sincerely thank all of my many colleagues at the Colorado School of Mines who have helped with discussions, recommendations of references, and/or by contributing figures: Scott Cowley, Corrine Packard, Brian Gorman, Gary Zito, John Chandler, Lee Rothleutner, Dean Pierce, Steven Thompson, Kip Findley, John Speer, and David Matlock. John Verhoeven, Iowa State University, and Bob Hackenberg, Los Alamos National Laboratory, helped with history; Bob Glodowski, Evraz Sratcor, Inc., with microalloying; Amy Clarke, Los Alamos National Laboratory, with APT figures; Nobuhiro Tsuji, Kyoto University, with EBSD of lath martensite; and Harry Bhadeshia, University of Cambridge, with references on rolling-contact fatigue. Karen Marken, Madrid Tramble, Kate Fornadel, and Scott Henry, ASM International, provided welcome encouragement and

professional expertise for copyediting and production of this second edition of *Steels*. My wife Ruth deserves my deep thanks for her unwavering support during this period of authorship.

George Krauss  
Evergreen, Colorado  
October 21, 2014

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# Preface to *Steels*: *Processing, Structure, and Performance* (2005)

This edition of *Steels* is dedicated to the men and women who make, use, study, and design with steel. It is an entry into the broad, dynamic physical metallurgy of steels, with an attempt to summarize the state-of-the-art just past the turn into the twenty-first century. Eleven new chapters expand the coverage in previous editions, and other chapters have been reorganized and brought up to date. The interrelationships between chemistry, processing, structure, and performance, i.e., the elements of physical metallurgy, are integrated for all the types of steel discussed, but as before, descriptions of the evolution, characterization, and performance of steel microstructures, with increased emphasis on deformation and fracture, are major objectives of this text. Heat treatment remains a vital aspect of the manufacture of steel products, and the coverage of thermal processing and its effect on steels is expanded in this edition. However, heat treatment has been dropped from the title of this edition to reflect a broader view of steels. Also, the chapter on cast irons, included in the 1990 edition, has been dropped in view of the sharper focus on steels.

There have been dramatic changes in steel manufacture in the 15 years since the publication of the 1990 edition. Low-carbon sheet steels have experienced the most dynamic changes: thermal processing of sheet steels on a massive continuous scale has produced new grades with only subtle changes in chemistry. Low-carbon sheet steels, together with strengthening mechanisms, developments in microalloyed forging steels, steels with bainitic and a variety of ferritic microstructures, quench and tempered steel performance, high-carbon steels for rail and ultra-high strength wire, and the causes of low toughness and embrittlement are all discussed in new chapters. I have made some brief comments on the history of steel and

noted the time frame for some important developments. A link to steel-making and solidification is made in the chapter on the effects of primary processing on steel microstructure.

The text is meant to be informative, readable, up-to-date, and self-contained. Principles, concepts, and understanding of microstructural evolution and performance, within the framework of processing and properties, are illustrated, by plots of data, micrographs, and schematic diagrams. Some scientific and technological background is assumed, and if interested in more information or background, the reader is directed to listed references. Only a small number of references out of the massive literature on ferrous metallurgy have been selected, and a special effort has been made to include references to the most pertinent books, reviews, and technical papers on a given subject. Reference titles that often serve as mini-abstracts of paper content have been included. Each listed reference opens up further reference lists on a given topic.

The activities of the Advanced Steel Processing and Products Research Center, an industry/university cooperative research center at the Colorado School of Mines, have continued to be a vital source of research on steel, and I am grateful for the combined efforts of the industrial sponsors, students, and staff of the Center for their contributions. I thank Professors Steven Liu and John Speer, Colorado School of Mines, for their contribution of figures for this edition; Dr. Young-Kook Lee, Yonsei University, for unpublished work on high-temperature tempering; Dr. Bruce Kiefer, Morgan Construction Company, for his references on Stelmor processing; and Professor Brian Thomas, University of Illinois at Urbana-Champaign, for his references on continuous casting and inclusion-related phenomena. I value very much and am grateful for the continued insights and inspiration provided by my colleague Professor David Matlock at the Colorado School of Mines over the years. The support of my wife, Ruth, and my sons Matthew, Jonathan, Benjamin, and Thomas, with their growing families and expanding lives, is also very gratefully acknowledged.

George Krauss  
Evergreen, Colorado  
December, 2004

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# Preface to *Steels: Heat Treatment and Processing Principles* (1990)

The 1980s have been a dynamic period for manufacturing, and it is appropriate that *Principles* be expanded to describe a broader selection of ferrous alloys used in manufacturing. Not only is deeper understanding of the performance of conventionally treated steels now available, but new alloys and new processes also have been developed. For example, new alloys under active development or brought to market in the '80s include duplex stainless steels, microalloyed bar and forging steels, ultrahigh-nitrogen stainless steels, low-cobalt maraging steels, steels with low manganese and silicon that are resistant to temper embrittlement, and austempered ductile cast irons. The success of these new alloys, as well as that of improved conventional steels, is often directly coupled to advances in melting, and the 1980s have seen the widespread adoption of ladle metallurgy and other special steelmaking techniques.

The most dramatic changes in processing have come in the area of surface modification, ranging from improvements in induction heating and gas carburizing to the development of plasma, physical vapor deposition, and laser heating processes. Thermochemical modifications, coatings, solid-state transformation hardening, and rapidly solidified, thin-surface layers are all possible with the new techniques. Thus exciting possibilities exist for manufacturing surfaces with special properties and engineered materials systems incorporating ferrous alloys.

For the revised edition of *Principles of Heat Treatment of Steel* I have added chapters on new surface modification techniques, stainless steels,



tool steels, and cast irons, and have expanded four of the original chapters. Thus the revised text covers many aspects of alloying, processing, and microstructure evolution beyond those involved in conventional heat treatment of carbon steels. Also, the new surface modification techniques are often directed to producing engineered composite systems quite different from traditionally processed steels. In order to reflect the broader scope of the present edition, the title *Steels: Heat Treatment and Processing Principles* was selected. This new title moves steels to a prominent position, and recognizes the importance of processing other than heat treatment.

The principles of microstructure development, and the effects of microstructure on properties and performance, within the context of alloying, phase equilibria, and processing, remain the dominant theme of this book. About 110 new figures have been added, many of them selected to illustrate characteristic and special microstructural features of ferrous alloys. While heat treatment and thermal processing are still of prime importance, solidification, thermomechanical, mechanical, and surface deposition processing are also recognized as major factors which establish structure property relationships in a broad spectrum of ferrous alloys.

Selected literature is cited throughout the text in order to lead readers to in-depth sources of information regarding topics of special interest. Unfortunately, the references cannot recognize all who have contributed to the vast field of processing, heat treatment, and performance of steels. Handbook and manufacturing literature must be referred to for processing details and property tabulations which cannot be included here.

The Army Research Office and National Science Foundation have continued to support steel research at the Colorado School of Mines into the 1980s, and I am grateful for continuing support of the AMAX Foundation for my professorship. In 1984, the Advanced Steel Processing and Products Research Center (ASPPRC), a cooperative industry-university research center, was established at the Colorado School of Mines with a seed grant from the National Science Foundation. This Center has made possible a renewed effort to deepen understanding of steel as a vital manufacturing material. I acknowledge with gratitude the support and interest of the following organizations who were sponsors of ASPPRC at the time of the writing of this second edition: Army Materials Technology Laboratory, Bethlehem Steel Corporation, Carpenter Technology Corporation, Caterpillar Incorporated, Chaparral Steel Company, Chrysler Corporation, Do-fasco, Eaton Corporation, Ford Motor Company, Inland Steel Company, Lake Ontario Steel Corporation, National Institute for Standards and Technology, LTV Steel Company, Lukens Steel Company, North Star Steel Company, Rouge Steel Company, Stelco Incorporated, The Timken Company, and United States Steel Division, USX.

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I thank Scott Diets for his help with the figures, and I am especially grateful for the collaboration and support of my colleague, David K. Matlock. We have shared and accomplished much together in the 1980s. My wife Ruth supported this effort in many ways, including the word processing of many revisions of the final manuscript, and I thank her deeply for her help.

George Krauss  
Evergreen, Colorado  
July 30, 1989

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# Preface to *Principles of Heat Treatment of Steel* (1980)

This book is a completely rewritten version of *Principles of Heat Treatment* by M. A. Grossmann and E. C. Bain. It is a pleasure to acknowledge the contributions of these authors. Much of their work, especially that concerning the development of hardenability concepts, is incorporated here. *Principles of Heat Treatment* covered developments between 1935 and 1964, and Grossmann, Bain, and their contemporaries did their work so well that the heat treatment and metallurgy of carbon steels was almost taken for granted. Steels, however, are wonderfully complex, and continued effort in the last twenty years has brought deeper understanding of their response to thermal and mechanical treatments. New theoretical approaches to 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 foundations of steel heat treatment developed by earlier workers. My approach has been to develop the structure-property-processing relationships that underlie the many heat treatments applied to steels. The origin and characterization of microstructures are emphasized because they are so often forgotten as the source of the handbook graphs and tables of processing parameters and properties.

The give-and-take of many conferences and the contributions of many investigators to the literature have been the basis for our growing understanding of steels and their behavior. I have drawn widely from published

sources and through the cited references hope to recognize at least some university and industrial scientists and their contributions. The reference lists are by no means complete, but every paper opens up an area by listing tens or even hundreds of additional references.

Especially rewarding has been my association with other investigators. Morris Cohen initiated my interest in steel, and the enthusiasm of my colleagues and students has sustained that interest. I have learned from every thesis investigation, and examples of the work of my students are shown throughout this book.

In recent years I have benefited much from association with the treatment activities of the American Society for Metals, first through membership on the Heat Treatment Technical Division Council, and more recently as editor of the *Journal of Heat Treating*. These associations have made me aware of the scope and sophistication of new approaches to the heat treatment of steels, and I am especially grateful to Norman Kates, Dale Breen, Jon Dossett, and Joe Riopelle for their introduction to the demanding, practical world of heat treatment.

A university research effort is very much dependent on outside support. I gratefully acknowledge the Army Research Office, the National Science Foundation, the Bethlehem Steel Corporation, the AMAX Foundation, and the American Iron and Steel Institute for the support that has enabled me and my students to remain actively involved in research on the behavior of steels. I acknowledge also fruitful discussions with Professors Glenn Edwards, Tom Bell, and Norman Breyer concerning parts of the text and am grateful for micrographs supplied by Professors R.W.K. Honeycombe, Robert Hehemann, and Marvin Wayman. Mark Geib deserves special mention for his help with some of the figures. Finally, I am deeply grateful to my wife, Ruth, for her competent assistance, her unwavering support, and the typing of the manuscript—all given between a busy schedule of rehearsals and performances of the Central City Opera and the Evergreen Chorale.

George Krauss  
Evergreen, Colorado  
September 25, 1979

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# About the Author

Dr. George Krauss is currently University Emeritus Professor at the Colorado School of Mines and a metallurgical consultant specializing in steel microstructural systems. He received the B.S. in metallurgical engineering from Lehigh University in 1955 and the M.S. and Sc.D. degrees in metallurgy from the Massachusetts Institute of Technology in 1958 and 1961, respectively, after working at the Superior Tube Company as a development engineer in 1956. In 1962–63, he was an NSF Postdoctoral Fellow at the Max Planck Institut für Eisenforschung in Düsseldorf, Germany. He served at Lehigh University as assistant professor, associate professor, and professor of metallurgy and materials science from 1963 to 1975, and in 1975, joined the faculty of the Colorado School of Mines as the AMAX foundation professor in physical metallurgy. He was the John Henry Moore Professor of Metallurgical and Materials Engineering at the time of his retirement from the Colorado School of Mines in 1997.



**GEORGE KRAUSS, FASM**  
ASM President (1996–97)

In 1984, Dr. Krauss was a principal in the establishment of the Advanced Steel Processing and Products Research Center, a National Science Foundation Industry-University cooperative research center at the Colorado School of Mines, and served as its first director until 1993. In addition to the three editions of the present volume, he coauthored the book *Tool Steels, Fifth Edition*, ASM International, 1998, and edited or coedited conference volumes on tempering of steel, carburizing, zinc-based coatings on steel, and microalloyed forging steels. He has published over 300 papers and lectured widely in technical conferences, universities, corporations, and ASM International chapters, including a number of keynote, invited and honorary lectures. He presented the Edward DeMille

Campbell Memorial Lecture of ASM International in 2000 and the Howe Memorial Lecture of ISS in 2003.

Dr. Krauss has served as the president of the International Federation of Heat Treatment and Surface Engineering (IFHTSE), 1989–91, and as president of ASM International, 1996–97. He is Fellow of ASM International, TMS, and IFHTSE. He has been awarded the Adolf Martens Medal of the German Society for Heat Treatment and Materials, the Charles S. Barrett Silver Medal of the Rocky Mountain Chapter of ASM, the George Brown Gold Medal of the Colorado School of Mines, and several other professional and teaching awards, including the ASM Albert Easton White Distinguished Teacher Award in 1999. He is an Honorary Member of the Iron and Steel Institute of Japan, a Distinguished Member of AIST, an Honorary Member of ASM International, and an Honorary Member of the Japan Institute of Metals.