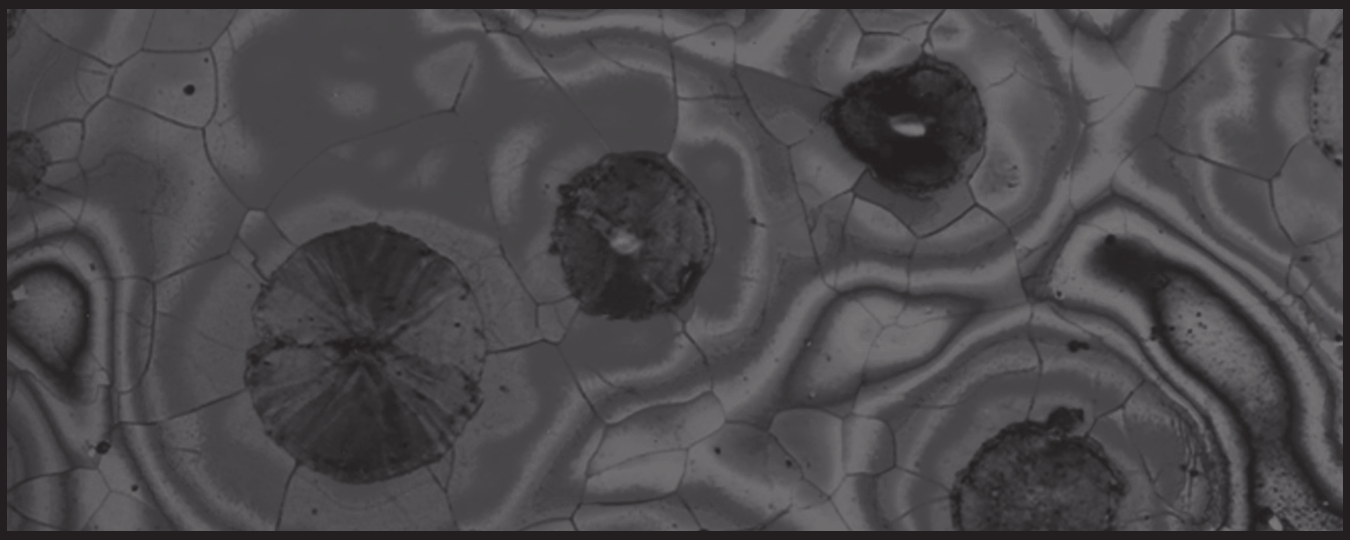
HUBERTUS COLPAERT



METALLOGRAPHY OF STEELS

Interpretation of Structure and the Effects of Processing

Updated and Translated by André Luiz V. da Costa e Silva

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ON THE COVER: Ductile cast iron, annealed. The etchant reveals silicon segregation. Silicon content decreases as the distance from the graphite nodule increases. Etched with sodium hydroxide (NaOH), picric acid, and potassium metabisulfite in 100 ml distilled water. Courtesy of J. Radzikowska, Foundry Research Institute, Krakow, Poland.

Contents

Foreword

The names of three archaeological eras are described by their dominant structural materials: the stone age, the bronze age, and the iron age. While the metals in the bronze age were obtained by smelting, early use of iron relied on finding the metallic form, mostly from meteorites. Its scarcity, together with its softness and tendency to corrode, limited its application. With time, however, extraction methods from ores and techniques such as surface hardening to improve the properties, broadened the application of iron. The first steel was made in the early iron ages but did not become a significant commodity until the middle of the nineteenth century when Henry Bessemer invented a new steelmaking process, which started the second phase of the industrial revolution. Around the same time, the introduction of microscopic investigation of materials led to a better understanding of steel properties and soon thereafter books on the metallography of steel were being published.

Metallography has a long tradition in Brazil going back to the early twentieth century. Metallography became a pillar in quality control of the construction materials used in the rapid expansion of the Brazilian railway system in the late 1920s. At this time, Hubertus Colpaert, at the Institute of Technological Research in São Paulo, began systematic work on the study of the metallographic characteristics of ferrous metals. In 1951, this work resulted in the publication of the book *Macrographic and Micrographic Metallography of Common Steel Products*. This book offered a unique combination of a metallography atlas, manual of metallographic techniques, and introduction to the fundamentals of phase transformations and thermal treatment of these alloys, and quickly became the most important Brazilian reference book for those working on processing and treatment of ferrous alloys. A second and third editions of this book was published in 1959 and 1969, respectively.

Since the publication of the third edition, advanced microscopy techniques became widely available and a significant number of new steel products have been developed. These developments are reflected in the fourth edition of the book while maintaining the spirit of the original edition, being a unique

combination of a metallography atlas, manual and textbook. For publication of the English edition, the title of the book was changed from the Portuguese original *Metallography of Common Steel Products* to *Metallography of Steels: Interpretation of Structure and the Effect of Processing*. Although this title better indicates that the book offers much more than metallography alone, it still does not fully reflect the rich content of the book.

The editor of the fourth edition, André Costa e Silva, is a professor at the Universidade Federal Fluminense in the Rio de Janeiro area, Brazil. He is an expert in the processing-properties-performance relations in steel with a focus on computational thermodynamics and its applications to steelmaking and advanced steel processing. He is also experienced in specification, inspection and failure analysis of metallic materials.

Ursula R. Kattner
National Institute of Standards and Technology
Materials Science and Engineering Division,
Thermodynamics and Kinetics Group

Preface to the Fourth Edition

During one semester in 1975, my Tuesday mornings were devoted to preparing, observing, and recording macrographs and micrographs of steels and cast irons under the guidance of Edil Patury Monteiro, with support of the book *Metalografia dos produtos siderúrgicos comuns* by Hubertus Colpaert. At the same time, I was being exposed to the theory of the kinetics of phase transformations with José Roberto Costa Guimarães. From this time on, Colpaert's book became to me—as to many Brazilian students, technicians, and engineers—a fundamental reference in academic and professional life. A very well-balanced mix of textbook and atlas of metallographic structures, for decades the book has been the companion of Brazilian metallographers, metallurgists, and steelmakers. At the end of 2006, when Paulo Mei and I concluded the second edition of *Steels and Specialty Alloys*, I was honored by the invitation from our editor, Edgard Blücher, to consider updating the text and images of the Colpaert's book. The opportunity to collaborate on incorporating technological developments to this outstanding book was an irresistible challenge.

Globally the steel industry is enjoying a time of rare expansion and vigor, with more than 1,400 Mt of steel produced each year and several years of significant increases in production. Furthermore, the production and processing of these iron-based alloys has reached an admirable degree of sophistication and control. In average quality steels, many elements are controlled to the level of parts per million in mass (1 ppm in mass is 1 g in 1 mt!) and the structure of the steels is controlled to a degree of precision never before experienced.

Metallography is one of the essential tools that made it possible to attain this degree of sophistication. It is a tool widely used in the whole field of metallurgy, in particular, for the whole spectrum of iron and steel products, from steel used in nails, springs, nuclear reactors and packaging and to cast irons used in engines, fittings, railroad parts, and so on. Metallographic techniques have evolved along with the steel industry. Besides the use of visible light, techniques that use other types of interactions with matter and in special in-

teractions between electrons and matter have become common. Techniques aimed at quantifying structural features have also greatly evolved, and the past decade has seen a dramatic advance in the techniques of three-dimensional reconstruction of material structures. If during Colpaert's time the breadth of knowledge and experience needed to write such a book were already rare—this being one reason for my respect for his work—in these days it is almost impossible for a single person to have all of the knowledge needed to bring this work up to date. Thus, the help and collaboration of many have been essential to creating an updated version with a depth and breadth comparable to the original work. Luckily the same fascination Colpaert's work exerted over me is present in a whole generation of renowned metallurgists in our country. I met enthusiastic collaboration in companies, universities, and laboratories where people volunteered to help. This has certainly been one of the most interesting technical experiences of my career. A remarkable brotherhood of people interested in steel seems to exist all over the world; indeed, the willingness of people to help me, in Brazil and abroad, was outstanding.

To all of these collaborators, who have given essential contributions to this project, I offer my thanks in the next section.

Due to the difficult decision that had to be made regarding which images of the previous editions should be replaced or removed, Editora Blucher kept all of the old images available at their website.

I hope this revised and updated edition may be as useful to today's metallurgists as the previous editions have been to me, and to a whole generation of enthusiasts of steel and cast iron development.

Acknowledgments

It is extremely difficult to decide the proper order for acknowledging all who helped me on this project. Each of the groups or individuals have in some way contributed to the success of this work. Some helped with images, some with encouragement, and others with discussions and suggestions.

In the first place, I must thank Edgard Blücher and Hubertus Colpaert's family for trusting me with this task and staying with me along the way.

The support of colleagues from the steel industry in Brazil and other countries, with images and enlightening discussions, has been essential to this project. I present them by alphabetical order of the companies (using the company names in 2008).

In Brazil: Sergio Augusto de Almeida Ferreira, ArcelorMittal Aços Longos—Juiz de Fora; Francisco Boratto, ArcelorMittal Monlevade; Jardel Prata Ferreira and João Batista Ribeiro Martins, ArcelorMittal Brasil (Tubarão); Carlos Henrique Lopes, BR Metals Fundições Ltda.; Fátima Cunha, CBV-FMC—Rio de Janeiro; Walter da Costa Reis, Antonio Augusto Martins, Nilza Cristina S.B. Zwirman and Simone Pereira Santos, CSN—Volta Redonda; Luiz Antonio Iapichini and Cícero Tavares, FIBAM Cia. Industrial Ltda.—São Bernardo do Campo; Henrique Aché Pillar, MRS Logística—Rio de Janeiro; Mauro Souza, Neumayer-Tekfor—Jundiaí; Marcelo M. Moraes, NUCLEP—Itaguaí; Gerson Ronelli, PL Fundição e Serviços Ltda.; Marcelo Martins, Sulzer-Fundinox—Jundiaí; Wilson Guesser, Tupy Fundições S.A.—Joinville; Antonio Sérgio Fonseca, Alfredo Figueiredo, Ricardo Nolasco and Osvaldo Neto, V&M Tubes do Brasil—

Belo Horizonte; Marcos Stuart, Edson Mendes Vieira, Celso Barbosa, Leonardo Sandor, Ismael Polidori, and Cristiane S. Gonçalves, Villares Metals S.A.—Sumaré.

Outside of Brazil: M. Nishimura, Daido-Steel Co., Japan; James Casey, Dofasco, Canada; Giorgio Polonioli, Metalcam, Italy (Breno); Tooru Matsumiya and Masaaki Sugiyama, Nippon Steel, Japan; Carlos Cicutti, Tenaris, CINI, Argentina.

Laboratories: Research institutes and academia in Brazil and abroad have been very generous, sharing images, clarifying points, and showing great patience with my many urgings and requests.

Following is the alphabetical order of countries.

Belgium: Frans Mampaey, Sirris.

Brazil: André Pinto, Instituto Militar de Engenharia—Rio de Janeiro; Annelise Zeemann, Tecmetal—Rio de Janeiro; Antonio Gorni; Antonio Jorge Abdala, IEAv, CTA—São José dos Campos; Antonio Ramirez, LNLS—Campinas; Carlos de Moura Neto, CTA—São José dos Campos; Carlos Sérgio da Costa Viana, Paulo Rangel Rios, Tânia Nogueira, and Carlos Xavier, EEIMVR-UFF—Volta Redonda; Fernando Rizzo, PUC-Rio; Fernando Landgraf and Hélio Goldenstein, USP—São Paulo; Luiz Henrique Dias Alves; Margareth Spangler Andrade, CETEC—Belo Horizonte; Hans-Jurgen Kestenbach, UFSCar—São Carlos; Ibrahim Cerqueira Abud, INT—Rio de Janeiro; Ronaldo Antônio Neves Barbosa and Dagoberto Santos, UFMG—Belo Horizonte.

Canada: Alec Mitchell, University of British Columbia, Vancouver.

England: Graham Thewlis, South Yorkshire; H.K.D.H. Bhadeshia and Bill Clyne, University of Cambridge.

France: Bernard Marini and Caroline Toffolon, CEA; Jacques Lacaze, CIRIMAT, NSIACET, Toulouse.

Germany: Dietmar Lober; H.W. Viehrig, FZD, Dresden; Frank Mücklich and Alexandra Velichko, Universitaet des Saarlandes, Saarbruecken.

Italy: Paolo Emilio Di Nunzio, CSM, Roma; Stefania Bruschi, Università degli Studi di Padova, Padova.

Japan: S. Mizoguchi; Toshi Emi, IRIS, Sha-Steel; Fujio Abe, National Institute for Materials Science (NIMS); Kiyohito Ishida, Tohoku University.

Netherlands: Jilt Sietsma, Technische Universiteit Delft.

New Zealand: Milo Kral, University of Canterbury, Christchurch.

Poland: Leszek Zabdyr; Janina Radzikowska, Polish Foundry Research Institute, —Krakow.

South Korea: Sunghak Lee, Pohang University.

Spain, Tomas Gómez-Acebo, San Sebastian; Jon Sertucha, AZTERLAN—Durango; Carlos García de Andrés, Carlos Garcia-Mateo, Carlos Capdevila Montes, and Francisca G. Caballero, Materialia Research Group, CENIM-CSIC—Madrid.

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buquerque; Robert DeHoff, University of Florida, Gainesville; Christoph Beckermann, University of Iowa, Iowa City; Roger K. Pabian, University of Nebraska, Lincoln.

I thank all of you for the friendship, support, encouragement, suggestions, advice, patience, and interest in sharing your remarkable knowledge about metallography and iron and steel products. This has made a tremendous difference in this new edition. To anyone I might have forgotten, my apologies and my thanks!

Whenever possible, I have tried to give the proper credit in all images and refer to the proper texts used as the basis of this publication. There will likely be mistakes, for which I apologize in advance.

Finally, I thank my family for the support, patience, and encouragement over the long nights and weekends dedicated to this project.

André Luiz V. da Costa e Silva
Rio de Janeiro, August 2008

Preface to the Second Edition

Published in mid-1951 by the *Instituto de Pesquisas Tecnológias (IPT-SP)* [Technological Research Institute of São Paulo State], Bulletin no. 40 about the metallography of common iron and steel products has helped fulfill an important demand in the mechanical and metallurgical sectors, which needed a technical book that could serve as a manual for solving problems related to the properties and applications of iron and steel products.

Notwithstanding the fact that it has been solely distributed by *IPT-SP*, the first edition went out of stock in a few years, due to its high technical and scientific quality and the excellent documentation, all in a very didactic presentation format.

Although the guidelines to be adopted for the second edition had already been defined, the sudden passing away of the author in January 1957 rendered impossible the satisfactory conclusion of the revised work.

Having had the opportunity to collaborate with Colpaert for more than 12 years, having followed the lecture notes prepared by him that led to Bulletin no. 40, and being familiar with the use of this publication as a textbook, I was honored with the task of performing the revisions needed for this second edition.

In the first edition, some of the fundamental principles were presented in a simplified manner or even omitted. During use as a textbook, it was noted that this simplification in some chapters, such as the one on micrography and heat treatment, ended up creating barriers to the best understanding. This classroom experience suggested a complete revision of these chapters, particularly the one focused on heat treatments. The simplified presentation of transformation diagrams in the austenite decomposition processes that in the first edition was made in the form of a "critical segment" was replaced with the presentation of isothermal and continuous cooling transformation diagrams. The atomic mechanisms involved in these processes were discussed in more detail so that the changes observed by the metallographic examination could be better understood.

The chapter on cast irons could not be further improved because due to the complexity of the subject, from a didactic point of view, a simplified pre-

sentation that would offer a first view acting as a basis for further studies was preferred to a detailed discussion of the graphitization processes, which could make the text almost inaccessible to those being introduced to the subject.

Alberto Albuquerque Arantes
São Paulo, November 1959

Preface to the First Edition

During the recent and solemn commemoration of the 50th anniversary of this Instituto de Pesquisas Tecnológicas [Technological Research Institute], the beginning and the further development of various technological sectors of the institute were remembered. Among these, the field of microscopic metallography has received deserved attention; having started almost at the same time as this field was developed in Europe, it is one of the oldest in the institute.

It is an important fact that in 1910, the head of the Office of Strength of Materials, Hippolyto Pujol Jr., was already teaching and applying in the country such a novel science, far in advance of our industrial development. In 1926, it was up to Ary Frederico Torres to give further drive to these studies, creating strong interest and promoting the specialization of many students from the Polytechnic School [today the Polytechnic School of the University of São Paulo]. The author of this volume was among those and in 1928 was raised to the position of head of the Metallography Section.

In the past 25 years, the application and research work performed in the Metallography Section of IPT has resulted in a very refined technique and precise documentation with more than 10,000 macrographs and micrographs.

In addition to these activities, focused on the industrial segment, the Metallography Section has paid special attention to education, either teaching the students in various courses of the Polytechnic School or opening opportunities for interns who come here in search of deeper knowledge.

Among the educational resources, one that has been extremely successful is the distribution of illustrated pamphlets condensing the subjects presented in class. The simple and accessible presentation, not only of the metallographic technique but also of the laws and basic metallurgical facts—indispensable to the understanding of metallography and useful to the steel industry—quickly garnered great interest. This intertwining of steelmaking and processing concepts with specialized metallographic concepts may seem

strange at first, but at least in our community and for the time being, this is the orientation that has proven most efficient for the desired objectives.

After various successive editions of these pamphlets, and faced with an ever-increasing demand and the growing collection of experiments, the institute has decided to publish its material in a more permanent form and in more copies, asking the author himself to collect them, after revision and considerable expansion of the illustrations, in a printed volume that came to be the present bulletin.

Maintaining the initial aim, certain theoretical concepts are presented in a simplified way while others are omitted, not because they are useless but because they can be dispensed of in view of the character and aim of this publication.

To those wishing to research the problem more deeply, the cited bibliography, however small, offers additional information. After the bibliography, the conference proceedings and the specialized journals are yet additional sources which the reader can make use of to get properly familiarized with this constantly evolving science.

The macrographs and micrographs that were reprinted in Bulletin no. 40 were selected as among the most significant cases studied in the section. For each type of occurrence, many examples were presented to illustrate the variability that certain aspects may present and to warn the less experienced metallographer about the risk of possible confusion. In the choice and presentation of this vast documentation, it was our intention to offer to those interested a real atlas of "standard aspects" that could help in interpreting cases one might face in practice. Furthermore, there was always the aim of presenting the original documents in the best way possible, without reduction and with maximum sharpness, to make it easier for the reader to properly appreciate the features in the structures.

In the course of the text, the main errors related to technique and interpretation are discussed, along with their consequences and how to avoid them.

With the goals above described, the Instituto de Pesquisas Tecnológicas hopes to have extended the usefulness of this publication to all, whether in the plant or in the laboratory, who apply metallography.

Hubertus Colpaert
São Paulo, June 1951

About the Editor

André Luiz V. da Costa e Silva graduated as a metallurgical engineer from the Military Institute of Engineering (IME), Rio de Janeiro, in 1976. He earned his M.A.Sc. from the University of British Columbia, Vancouver, in 1979 and his Ph.D. from the University of Florida, Gainesvile, in 1994. His career started as an engineer in Eletrometal Aços Finos S.A. (currently Villares Metals S.A.). He was the materials engineering manager at CBV Industria Mecanica S.A. (Currently TechnipFMC plc) and took part in pioneer projects on deepwater oilfield completion and production. He was technical director of the Brazilian Institute for Nuclear Quality, where he was certified as a Level III Inspector and a Level III Expert in the Engineering Materials area. He is currently professor at the Metallurgical Engineering School in Volta Redonda, Universidade Federal Fluminense.

His main professional interests are the processing–properties relationships in materials and the application of computational thermodynamics to the processing and development of materials in special steels and superalloys, areas in which he consults for many organizations. He has published three books on steels and has more than 205 publications. André was the chair of the Alloy Phase Diagram International Commission (APDIC) from 2008 to 2013. He was awarded the 2014 Hume Rothery Award, for distinguished achievements in relation to phase transformations by IOM^3, England, and in 2017 became the fifteenth recipient of the triennial Hubertus Colpaert Silver Medal for his contribution in metallography and physical metallurgy by ABM, Brazil. He is a member of ASM International, ABM, and TMS. André is married and has one daughter and two grandchildren.