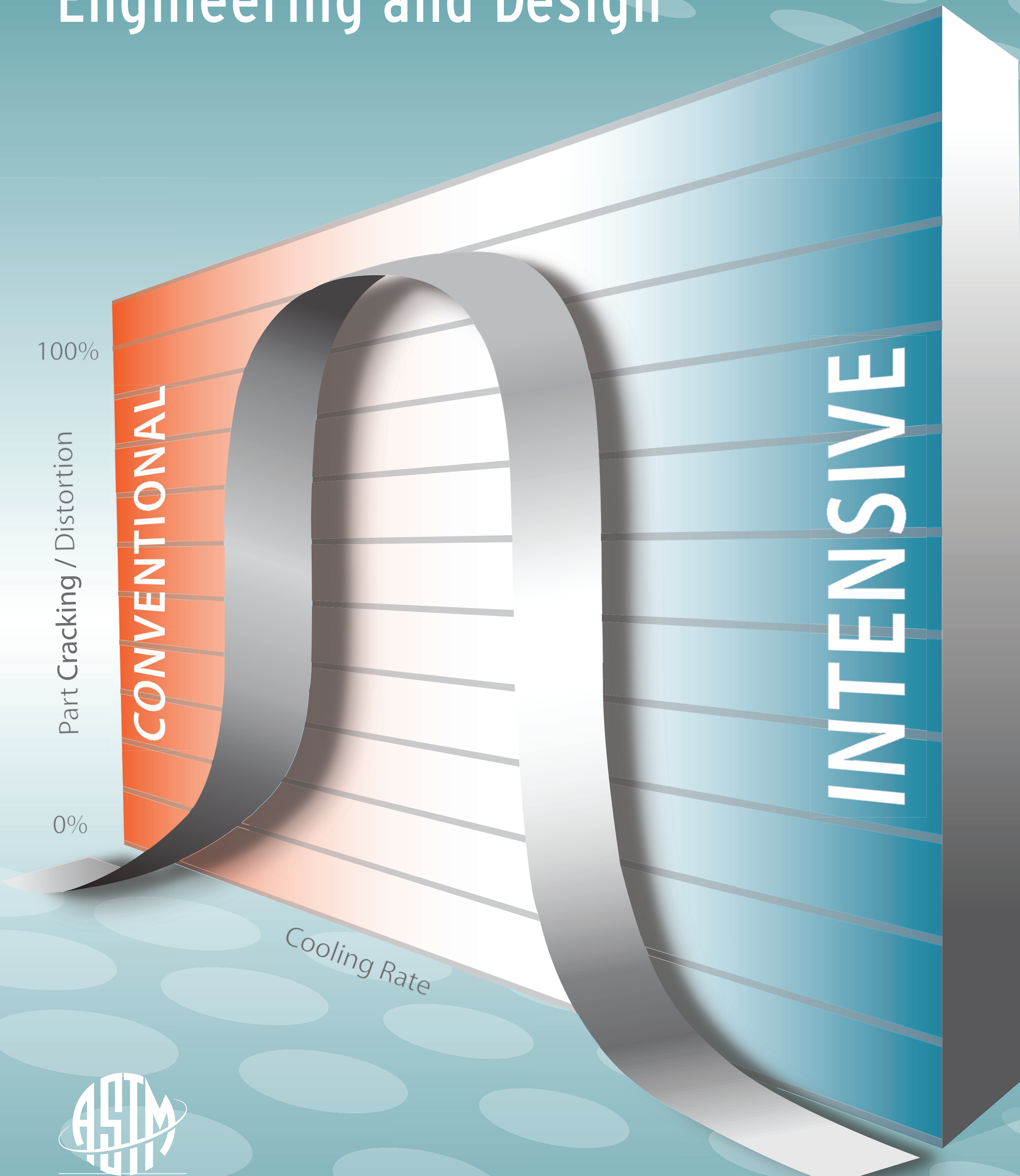
Intensive Quenching Systems:
Engineering and Design



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Foreword

THIS PUBLICATION, *Intensive Quenching Systems: Engineering and Design,* was sponsored by Committee D02 on Petroleum Products and Lubricants. This is Manual 64 in ASTM International's manual series.

Contents

Preface

From 1964 to 1999, one of the authors of this volume, Dr. Nikolai Kobasko, worked at the Thermal Science and Engineering Institute of the National Academy of Sciences of Ukraine in Kyiv. At the institute, there were approximately 1,200 scientists and engineers working in all areas of thermal science: heat conduction, radiation, thermal dynamics, and fluid dynamics. In addition to the thermal sciences, Dr. Kobasko placed a heavy emphasis on metallurgical science and physics, as demonstrated in his book *Steel Quenching in Liquid Media Under Pressure*, published in 1980.

The present book, *Intensive Quenching Systems: Engineering and Design*, is an attempt to knit together three disciplines: thermal sciences, metallurgy, and physics. The cross-pollination of these disciplines shows the fundamental correlations that exist between metallurgical processes and the underlying thermal science. These correlations form the foundation for more recent computer modeling of the complex physical interactions that happen in the heat-treating process.

Why is it important to read our book?

Knowing the fundamentals of the quenching processes, the reader will be able to solve the following problems:

1. Calculating the cooling time (for dwell time in the intensive quench for speed of conveyors, etc.) that will provide an optimal quenched layer after intensive quenching of steel parts
2. Creating beneficial high compressive residual stresses at the surface of steel parts, even when they are through-hardened
3. Using the benefits of the “steel superstrengthening” phenomenon to make higher-power-density parts
4. Developing synergies between the benefits from high compressive residual stresses and the superstrengthening phenomenon to increase the fatigue life and service life of steel parts significantly
5. Improving the environmental conditions in a factory by switching from oil and polymer quenching to clean, fast intensive quenching in plain water–thereby allowing the incorporation of the heat-treating processes into the part manufacturing cell
6. Optimizing distortion control in the quenching of steel parts

In essence, this book is intended for use by both metallurgists and mechanical engineers to assist them in their work designing and implementing quenching systems. A critical component of any quench system is the quenchant. This book is an effort to break down the quenching process into many smaller, manageable increments and to examine the dynamics present at surface of the part, as well as how each phase of the quench and each phase in the material will affect the end result.

This book will also be useful for undergraduate and postgraduate students who are interested in learning more about generalized equations for calculating the cooling time of any configuration of steel parts and the duration of the transient nucleate boiling process. Both generalized equations create a basis for quench system engineering design.

We will show that it is much easier to evaluate the generalized Biot number (value of Bi_V) than to determine the Grossmann factor H (see Chapters 6 and 13). The use of the generalized Biot number will allow the designer to get the quenching process quickly into the proper “neighborhood,” from where more sophisticated finite element and computation fluid dynamics (CFD) modeling (or actual part trials) can fine-tune the process to its proper “home.”

The book examines the use of intensive water quenching, IQ processes, to achieve the desired mechanical properties in steel parts made with steel alloys of lower hardenability (and presumably less expensive). Higher cooling rates and the higher hardenability of the intensive quench process also means that the carburization processing time can be reduced (or eliminated). Since less carbon content is needed in the carbon gradient, intensive quenching in water can achieve the same hardness profile as oil-quenching a part that has been carburized to a deeper total case.

In particular, this book discusses the development of high compressive stresses on the part’s surface, both during quench cooling (“current” compressive stress) and as residual compressive stress, through the establishment of a very high (“intensive”) cooling rate, applied uniformly through the martensite transformation range, and the control of distortion. The beneficial effects of these compressive stresses on a part’s properties are also discussed. In addition, the authors examine the relationship between hardness (and the corresponding tensile strength, yield strength, and ductility) and the management of residual stress profiles in the hardened layer of the part to increase the fatigue life of the hardened part.

Introduction

This ASTM manual, *Intensive Quenching Systems: Engineering and Design*, contains 13 chapters. The primary focus of this book is on highly forced heat transfer—that is, intensive quenching (IQ) processes. Particular attention is paid to the replacement of relatively expensive alloyed steels with less expensive carbon steels for machine parts subjected to normal operating conditions. The use of carbon steels with increased strength properties instead of alloyed steels will provide opportunities for cost savings related to the reduction of alloying elements such as tungsten, nickel, molybdenum, chromium, and others. In addition, IQ processes, which are based on water and aqueous solutions, provide an excellent and environmentally friendly alternative to petroleum quenching compositions. These various advantages are accomplished through the use of the newly developed IQ processes described herein.

Chapter 1 describes contemporary approaches of obtaining high-strength materials. High-temperature and low-temperature thermomechanical treatments are discussed, and alternative methods of creating high-strength materials by intensive quenching are considered. The primary focus of this chapter and of the manual as a whole is to describe the attainment of high-strength materials by intensive quenching within the martensite range. It is emphasized that the combination of high-temperature and low-temperature thermomechanical treatments with accelerated cooling within the martensite range significantly increases a part's mechanical and plastic material properties. It is shown that in some cases even intensive quenching of low-carbon alloy steels by itself may increase yield strength by 15 % and impact strength by 250 %. Intensive quenching results in additional material strengthening and creation of high surface compressive residual stresses—both of which increase the service life of steel parts. IQ process technology is inexpensive and beneficial.

Chapter 2 is a study of transient nucleate boiling during quenching of steel, which includes the self-regulated thermal process. The main purpose of this chapter is to describe the utilization of the duration of transient nucleate boiling as a basis for designing quenching processes. The generalized equation for the calculation of the duration of transient nucleate boiling relative to the creation of IQ methods is discussed. Calculation and experimental results correlate well. These processes are explained and illustrated by many practical examples used in the heat-treating industry.

Chapter 3 shows that the cooling capacity of quenchants can best be characterized by the critical heat flux densities and heat transfer coefficients during the three phases of cooling:

1. film boiling process
2. nucleate boiling process
3. single-phase convection

A new and preferred technique for determining the critical heat flux densities is described.

Chapter 4 presents the criteria (dimensionless dependencies) for the calculation of convective heat transfer coefficients with respect to steel quenching in directed water streams and intensive jets. The primary focus is on intensive quenching of steel parts in water flow, and calculation examples are provided. It is shown that very intensive quenching of splined cylindrical specimens in pressurized water jets prevents crack formation and increases surface hardness. The results can be used for process and equipment design and can be combined with other information provided throughout this text to optimize quenching of steel parts.

Chapter 5 describes the generalized equation for calculation of the cooling time for bodies of arbitrary shape, based on regular thermal condition theory. The generalized equation can be used for designing manufacturing processes and calculation of conveyor speeds for quenching systems. This information is obtained from simplified and rapid calculations and is required during the initial stages of design of heat-treating and quenching systems for steel parts. The equation makes it possible to calculate the ideal critical size of steel parts of low-hardenability steels to provide an optimal quenched layer and residual stress distribution. The equation may also be used for the design of two-step interrupted intensive quenching and two-step quenching processes combined with cryogenic treatment. Comparison of the generalized equation with various analytical solutions and calculation accuracy is discussed.

Chapter 6 describes Kondratjev form factors (K), which are used in the generalized equations described throughout this book. Also discussed are three methods for their determination: analytical, numerical, and experimental, which have been developed for practical use. The results provided here can be used for creating databases of Kondratjev form factors suitable for use with different part geometries. Throughout this discussion, there are literature references to the development and use of Kondratjev numbers. Finally, the determination of average heat transfer coefficients using standardized probes is discussed.

Chapter 7 describes the distribution of transient and residual stresses during steel quenching. It has been established that high compressive stresses are formed at the surface of parts quenched under conditions of intensive cooling. It has also been shown that there exists an optimal depth of the hardened layer where compressive stresses reach their maximum value. The results introduced in this chapter were used for the creation of three intensive quenching methods designated IQ-1, IQ-2, and IQ-3. Due to high residual compressive stresses at the surface, the service life of steel parts has been significantly increased.

Chapter 8 describes the characteristics of steel quenching under pressure. It has been shown that for conditions where the Biot number Bi approaches infinity, it is possible to control the surface temperature during nucleate boiling. This expands the potential for low-temperature thermomechanical treatment (LTMT) and steel quenching in water under pressure. Illustrations of the implementation of such processes are provided. High-temperature thermomechanical treatment (HTMT) is widely used for the mass production of rebars. Information provided in this chapter suggests the possibility of combining HTMT with LTMT and intensive quenching to reduce production costs and increase service life. In addition, these new technologies are environmentally friendly.

In Chapter 9, it is shown that intensive cooling within the martensite range results in additional strengthening ("superstrengthening") of a material, with simultaneous improvement of its plastic properties. This phenomenon is observed when the cooling rate within the martensite range is higher than a critical value. There is also a different point of view, according to which very fast cooling above the martensite start temperature results in additional strengthening of metals due to "freezing of vacancies" formed during heating. Both hypotheses are presented in this chapter. The mechanism of additional improvement of the material's mechanical properties is explained, as well.

Five intensive steel quenching methods, designated IQ-1 through IQ-5, are discussed in Chapter 10, and illustrations of their application are provided. IQ processes result in the creation of high compressive residual stresses at the surface of steel parts and small tensile residual stresses at the core. Such an optimal residual stress distribution created by intensive cooling within the martensite range significantly increases the mechanical properties of a material and improves its plastic properties. Examples of the use of simplified calculations are provided to aid in the design and application of intensive quenching processes.

Chapter 11 describes the calculation of conveyor speed for various kinds of conveyors and devices. These results are particularly of interest for designers dealing with industrial line construction.

Chapter 12 presents the rich experience of the use of IQ methods in the United States and other countries. It has been shown that, compared to traditional oil quenching, the service life of steel parts after intensive quenching increases by 1.5 to 2 times, or even more in some cases.

The final chapter analyzes heat flux densities and heat transfer coefficients obtained by solving heat conduction inverse problems. Current methods of solving inverse heat conduction problems are described. These methods are needed to study the initial period of the quenching process and to determine the cooling characteristics of different types of quenchants. The need for many industries to develop standardized probes and methods for the quenchant cooling capacity evaluation on the basis of solving inverse heat conduction problems is discussed.

This manual contains results published previously in the monograph "Steel Quenching in Liquid Media Under Pressure" and results that were achieved by IQ Technologies, Inc. (see Chapter 12), a company established in 1999 by Joseph A. Powell (president), Dr. Michael A. Aronov (CEO), and Dr. Nikolai I. Kobasko (COO), Fellow of ASM International (FASM). Later, John Vanas (president of the Euclide Heat Treating Company) built a furnace for batch intensive quenching and became the vice president of IQ Technologies. Due to their enthusiastic and creative work, IQ processes have become familiar to a wide audience in the United States.

We would like to acknowledge the continued and vital financial support of the Edison Materials Technology Center (EMTEC) in Dayton, Ohio, for the development of IQ technology. Our thanks go to Dr. George E. Totten, FASM, for the idea to write this book, his support, and his editing. We also acknowledge prior fruitful cooperation with Prof. Hans M. Tensi, FASM, and Prof. Bozidar Liščič, FASM, for their contributions to the IQ processes, especially measurements of their intensity. And finally, we would like to express special appreciation to Deformation Control Technology, Inc., for its very fruitful cooperation, to many other U.S. companies with whom IQ Technologies has worked, and to Ukrainian colleagues from the Thermal Science Institute of the National Academy of Sciences of Ukraine and Intensive Technologies, Ltd., Kyiv, Ukraine.

Nikolai I. Kobasko, PhD, FASM

Dr. Kobasko received his Ph.D. from the National Academy of Sciences of Ukraine. He is a leading expert on quenching and heat transfer during the hardening of steels. He was the Head of the laboratory of the Thermal Science Institute of the National Academy of Sciences of Ukraine. He is Director of Technology and Research and Development for IQ Technologies, Inc., Akron, Ohio and President of Intensive Technologies, Ltd, Kyiv, Ukraine. The aim of both companies is material savings, ecological problem-solving, and increasing service life of steel parts. He is an ASM International Fellow (FASM).

Dr. Kobasko is the author and co-author of more than 250 scientific and technical papers, several books and more than 30 patents and certificates. He received the Da Vinci Diamond Award and Certificate in recognition of an outstanding contribution to thermal science. Dr. Nikolai Kobasko was Editor-in-Chief and Co-Editor of the WSEAS Transactions on Heat and Mass Transfer; and is currently a member of the Editorial Board for the International Journal of Mechanics (NAUN) and the Journal of ASTM International (JAI).

Dr. Michael A. Aronov

Dr. Aronov received his B. S. and Masters degrees in Thermal Science and Fluid Dynamics from the St. Petersburg Polytechnic Institute in Russia. Dr. Aronov received his Ph.D. degree in Thermal Science and Engineering from the Institute of Metallurgical Thermal Engineering also in Russia. He is the Chief Executive Officer of IQ Technologies, Inc. of Akron, Ohio.

Dr. Aronov has 37 years of experience in the field of heat and mass transfer, combustion, and thermodynamics in industrial, commercial, and residential heat transfer systems. He has extensive experience in experimental research, mathematical modeling of heat and mass transfer in combustion forging, and heat treating furnaces and quenching machinery. Dr. Aronov also has extensive experience in the design and development of heating and cooling systems for forging and heat-treating applications. Dr. Aronov has published more than 70 technical papers and has ten patents, four of which are related to different types of quenching equipment and technology.

Joseph A. Powell

Joseph A. Powell received his B.S. in Industrial Management from the University of Akron, and was granted a Juris Doctorate from the University of Akron School of Law. Mr. Powell is President, and a principal of IQ Technologies Inc, and of Akron Steel Treating Company (AST), a family business, in Akron, Ohio.

Mr. Powell is a founding member of the Heat Treating Network part of the Metal Treating Institute, a member of the Akron Chapter of ASM, the ASM/Heat Treating Society, and the ASM Quenching and Cooling Committee. He is also a member of the Metal Treating Institute (MTI), an associate member of the National Tooling & Machining Association (NTMA), and the Summit County Machine Shop Group.

Mr. Powell has a patent for "Variable Cooling Rate Quench Media, Cooling Rate Monitoring System and Real Time Computerized Control System for the Quenching of Metals during Heat Treatment or other Controlled Cooling or Solidification Operations."

George E. Totten, Ph.D., FASM

George E. Totten received his B.S. and Masters degrees from Fairleigh Dickinson University in New Jersey and his Ph.D. from New York University. Dr. Totten is past president of the International Federation for Heat Treating and Surface Engineering (IFHTSE) and a fellow of ASM International, SAE International, IFHTSE, and ASTM International. Dr. Totten is a Visiting Research Professor at Portland State University, Portland, Oregon, and he is also president of G.E. Totten and Associates LLC, a research and consulting firm specializing in thermal processing and industrial lubrication problems.

Dr. Totten is the author, coauthor, or editor of over 500 publications, including patents, technical papers, book chapters, and books and sits on several journal editorial boards, including the Journal of ASTM International.

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