Heat Treatment of Gears

A Practical Guide for Engineers

A.K. Rakhit

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ASM International®
Materials Park, OH 44073-0002
www.asminternational.org

First printing, December 2000

Comments, criticisms, and suggestions are invited, and should be forwarded to ASM International.

ASM International staff who worked on this project included Veronica Flint, Manager, Book Acquisitions; Bonnie Sanders, Manager, Production; Carol Terman, Copy Editor; Kathy Dragolich, Production Supervisor; and Scott Henry, Assistant Director, Reference Publications.

Library of Congress Cataloging-in-Publication Data

Rakhit, A.K.
Heat treatment of gears / A.K. Rakhit.
p. cm.
Includes bibliographical references and index.
1. Gearing—Heat Treatment. I. ASM International. II. Title.
TJ184.R35 2000 621.8'33—dc21 00-059341

ISBN: 0-87170-694-6
SAN: 204-7586

ASM International®
Materials Park, OH 44073-0002
www.asminternational.org

Printed in the United States of America

This book is dedicated to my parents, Mr. and Mrs. Upendra C. Rakhit; my wife, Ratna, for her understanding and inspiration; and my son, Amit, and daughter, Roma, for their love and support.

ASM International Technical Books Committee (1999–2000)

Preview for: *Heat Treatment of Gears: A Practical Guide for Engineers*, by A.K. Rakhit, ASM International, 2000
Full digital book available at https://doi.org/10.31399/asm.tb.htgpge.9781627083478

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Preface

At the beginning of my career in gear design and manufacturing, I experienced a great deal of difficulty learning the art of gear heat treatment. I struggled a lot, attended a number of seminars on the subject, and spent a great deal of time experimenting with gear heat treatment. Over the last 50 years, a great deal of research has been carried out and published in the disciplines. Unfortunately, very little has been published on heat treatment of gears that is both easy to understand and useful to the gear engineer. This book has been specially written for the benefit of gear engineers engaged in design and manufacturing because I thought it would be beneficial to share my experience with the gear engineers of the future. I believe the information presented in this book will give them a good start in their careers.

Gears have been in existence for a long time. Before the invention of steel, gears were made of materials that were readily available and easily machinable, such as wood. Obviously, these gears did not last long and required frequent replacement. Cost was not as important as it is now.

Today there is continual demand for gear designs that transmit more power through smaller, lighter, quieter, and more reliable packages that must operate over a wide range of service conditions, with an increased emphasis on cost containment. The average life requirement for a gear in industrial service is now measured in millions of cycles. These requirements have accelerated the development and use of high-strength materials. Gears made of certain steels are found to meet these demands and to become especially effective when they are heat treated and finish machined for high geometric accuracy. This makes gear design and manufacturing more complex. In order to perform these tasks efficiently, a gear engineer needs to excel in various other disciplines besides design, such as manufacturing, lubrication, life and failure analysis, and machine dynamics.

Designing gears is a process of synthesis where gear size and geometry, materials, machining processes, and heat treatment are selected to meet the expected level of quality in the finished gears. These considerations are critical if the gears are to perform satisfactorily under anticipated service conditions. This led to the development of various design guidelines for an optimum gear set. However, in my opinion, the quality of gear heat treatment and its effect on gear performance and related cost are still not addressed.

In this book, I discuss gear heat treat distortion for the major heat processes in detail because my experience is that distortion of gears after heat treatment always presents difficulty in minimizing manufacturing cost. Hence, distortion control offers a challenging opportunity to a gear engineer not only in ensuring a high-quality product but also in controlling cost. A case history of each successful gear heat treat process is included. These case histories will provide important information on the quality of gear that can be expected with proper control of material and processes. This information will be beneficial not only in understanding distortion, but also in the selection of the proper gear material and appropriate heat treat process for a wide range of applications.

Writing a book takes a great deal of support and cooperation from many people. I wish to acknowledge all those who helped me with this project, with special thanks to Solar Turbines, Inc; to Mr. Bruce Kravitz of Kravitz Communications for proofreading and making many valuable editorial suggestions; and to Mrs. Sharon Jackson of Solar Turbines Inc., for typing the manuscript. I am also very grateful to Mr. Darle W. Dudley of Dudley Technical Group, Inc. for his guidance and encouragement with this project.

Finally, I would like to thank my many colleagues at the various gear manufacturing organizations with which I am associated for their help and inspiration.

A.K. Rakhit
June 2000

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Full digital book available at https://doi.org/10.31399/asm.tb.htgpge.9781627083478

CHAPTER 1

Introduction to Gear Heat Treatment

MODERN GEARS are made from a wide variety of materials. Of all these, steel has the outstanding characteristics of high strength per unit volume and low cost per pound. These are the primary reasons that steel gears are used predominantly in industry today. Furthermore, the vast majority of gears made from either plain carbon or alloy steels is heat treated to increase strength and life. Although both plain carbon and alloy steels with equal hardness exhibit equal tensile strengths, alloy steels are preferred because of higher hardenability and the desired microstructures of the hardened case and core needed for high fatigue strength of gears. Over 90% of the gears used in industrial applications today are made from alloy steels. Hence, the scope of this guide is limited to the heat treatment of alloy steel gears.

Heat treatment of alloy steel gears is a complex process, and its scope lies from surface hardening to core treatment with proper control of both case and core microstructures. A well-controlled heat treatment produces the desirable surface and core properties for resistance to various failure modes. These failure modes include bending and contact (pitting) fatigues, and failures due to simple surface wear of gear teeth. The type of heat treatment used significantly affects metallurgical properties of the gears and the subsequent failure modes of the gears.

In addition to hardness and acceptable case/core microstructures, a gear design engineer expects gears to maintain pre-heat-treat tooth geometry after heat treatment, if possible. This allows gears to be finished with such minor operations as honing or lapping at acceptable quality and cost. But, unfortunately, the quality of gear geometry after heat treatment, carburizing in particular, deteriorates due to distortion to the extent that grinding of gear teeth becomes essential; the degree of distortion depends on the material, heat treat process, and equipment used. Although grinding can improve the geometry of gear teeth even with high distortion, this increases manufacturing cost significantly. Furthermore, ground gears with high distortion may not perform satisfactorily due to the fact that grinding may remove the required case and lower the surface hardness of teeth. Thus, for optimal gear performance and reasonable manufacturing cost, it is essential that gear designers and manufacturing engineers have a good understanding of the various heat treatment processes that are used primarily for industrial and aerospace gears.

Of the various heat treating processes currently available, five are frequently used to heat treat alloy steel gears. These processes are through hardening, case carburizing and hardening, nitriding, carbonitriding, and induction hardening. Analyses of these processes show case carburizing and hardening offers the highest torque-carrying capacity of gears. In fact, the torque capacity of a carburized and hardened gear set can be three to four times higher than that of a similar through-hardened gear set. It is also significantly higher than a nitrided or an induction-hardened set. For this reason, case carburized and hardened gears are extensively used in industrial, automotive, and aerospace applications. Nitriding process is used primarily because of low distortion and in applications where gears are not heavily stressed and do not require high case depths, for which nitriding is not cost effective. High case depths often produce unacceptable microstructures of the nitrided case detrimental to gear life.

Until recently, carburized and ground gears were not considered economical because of high finishing cost. This concept was based on some inefficient carburizing equipment and processes. With the recent development of improved heat treat equipment and some high-quality carburizing grade steels, it is now possible to control and predict heat treat distortion during carburizing and quenching to the extent that grinding time is significantly reduced. In some cases, minor modifications of pre-heat treat gear-cutting tools (hobs, shaper cutters) help to compensate heat treat distortion that reduce grind time even further. Also, carburized and hardened gear sizes are smaller compared with those heat treated by other processes for the same horsepower (hp) because of higher allowable stresses in design. This results in smaller gear units with lower cost/hp and shorter center distances between the gears. Hence, the use of carburized gears is increasing continually.

In spite of the fact that more gears are being carburized than in the past, the process is not yet fully understood from a distortion point of view. A large number of heat treating organizations still regard the process as a black art. These manufacturers forget that case carburizing, like any other manufacturing process, is very much a scientific process. The problems associated with this process are easily identifiable with proper explanation. This book has been specially prepared for this purpose. It is expected to provide a better understanding of the carburizing process to gear engineers. In this regard, problems associated with commonly used gear materials such as American Iron and Steel Institute (AISI) 8620 and AISI 9310 are discussed. Also discussed are problems with high-alloy steels such as AISI 4330 and HP 9-4-30 that are used extensively in the aerospace industry. In many of these applications, even with high material cost per pound, an optimal design is achieved with gears made from these steels. This is due largely to controllable heat treat distortion of these materials that helps to reduce gear finishing cost.

To appreciate the advantages of the carburizing process, other heat processes such as through hardening, nitriding, carbonitriding, and induction hardening also are discussed, especially the limitations of these processes to optimal gear design. The distortion in the nitriding process, sometimes considered an alternative to carburizing, is comparatively less but cannot be ignored, particularly when conventional gas nitriding is used. For example, the quality of gas-nitrided gears may drop from American Gear Manufacturers Association (AGMA) class 10 to class 9 after nitriding, whereas the quality of similar carburized gears may go down to AGMA class 8. From the last decade to date, the use of through-hardened gears has been reduced significantly. On the other hand, induction hardening, particularly the dual frequency method, sometimes provides an alternative to carburizing and nitriding for large-sized gears.

As already mentioned, minor modification of pre-heat treat cutting tools designed to accommodate the expected distortion minimizes finishing operation and thus, gear cost. But this is possible only with known and consistent distortion of gears. Unfortunately, distortion characteristics of gears for various heat treat processes and materials are not easily available. For an optimal design, therefore, it is imperative that both design and manufacturing engineers become familiar with the various gear heat treat processes and understand the mechanism of heat treat distortion, for which some knowledge of the properties of iron (the basic ingredient of steel), iron-carbon phase diagram, and the properties of some common alloying elements is considered helpful.

Chapter 11: Selected References

Technical Papers

- J.O. Almen, Peened Surfaces Improve Endurance of Machine Parts, *Met. Prog.*, Feb 1943, p 9–15

- R.A. DePaul, High Cycle and Impact Fatigue Behavior of Some Carburized Gear Steels, *Met. Eng. Q.*, Nov 1970 doi: 10.4271/710277

- R. Drago, "An Improvement in the Conventional Analysis of Gear Tooth Bending Fatigue Strength," *Fall Technical Meeting*, American Gear Manufacturers Association, 1982

- D.W. Dudley, "How Increased Hardness Reduces the Size of Gear Sets," *Prod. Eng.*, Nov 1964

- D.W. Dudley, "Load Rating Practices of Carburized and Nitrided Gears," *presented at the 10th Round Table Conference on Marine Gearing*, Brunnen, Switzerland, 25– 26 Sept 1975

- J.R. Eagan and C.H. Shelton, "Recent Test Data on Selection of Alloy Steels for Gears and Bearings," *Society of Automotive Engineers (SAE) Report 720301*, 1972 doi: 10.4271/720301

- H. Fugio and T. Aida, "Study on Gear Distortion Caused by Hardening," *ASME Paper 80-C2/DET-51*, American Society of Mechanical Engineers, 1980

- K. Fujita and A. Yoshida, Surface Durability of Steel Rollers, (Case-Hardened and Nitrided), *Bull. JSME*, Vol 21 (No. 154), April 1978 doi: 10.1299/jsme1958.21.761

- R.C. Graham, A. Oliver, and P.B. Macpherson, "An Investigation into the Mechanisms of Pitting in High-Hardness Carburized Steels," *ASME Paper 80-C2/DET-118*, American Society of Mechanical Engineers, 1980

- F.E. Harris, Case Depth—An Attempt at a Practical Definition, *Met. Prog.*, Vol 44 (No. 2), p 265–272, 1943

- W.J. Harris, The Influence of Shot Peening on the Fatigue Properties of Steel, *Metallurgia*, Vol 45 (No. 272), June 1952

- J.M. Heberling, "Engineering Report on Hardenability of Gear Steels," Allied Signal Aerospace Company, Torrance, CA, 1989

- H.M. Hiersig, "Capacity Limits of the Largest Pairs of Carburized Gears to be Produced with Available Equipment," *ASME Paper 84-DET-84*, American Society of Mechanical Engineers, 1984

• B. Hildenwall and T. Ericsson, *Hardenability Concepts with Application to Steel*, The Metallurgical Society AIME, New York, 1978, p 579

• M. Hirt and H. Weiss, "Increase of Load Capacity by Use of Large Case-Hardened Gears," *Fall Technical Meeting*, American Gear Manufacturers Association, 1981

• M.A.H. Howes and J.P. Sheehan, "The Effect of Composition and Microstructure on the Pitting Fatigue of Carburized Steel Cases," *Paper 740222*, Society of Automotive Engineers, 1974 doi: 10.4271/740222

• A. Ishibashi and S. Tanaka, "Appreciable Increase in Pitting Limit of a Through-Hardened Steel," *ASME Paper 80-2/DET-28*, American Society of Mechanical Engineers, 1980

• R.F. Kern, Selecting Steels for Carburized Gears, *Met. Prog.*, July 1972, p 53–64

• H.O. Kron, "Gear Tooth Sub-Surface Stress Analysis," *Congres Mondial des Engrenages, Paper A10*, 1977

• F.T. Krotine, M.F. McGuire, and A.R. Troiano, The Influence of Case Properties and Retained Austenite on the Behavior of Carburized Components, *Trans. ASM*, Vol 62 (No. 4), 1969, p 829–839

• W.L. McIntire, R.C. Malott, and T.A. Lyon, "Bending Strength of Spur and Helical Gear Teeth," *Fall Technical Meeting*, American Gear Manufacturers Association, 1967

• M.A. Miner, Cumulative Damage in Fatigue, *J. Appl. Mech.*, Vol 12, 1945 doi: 10.1115/1.4009458

• S. Oda, Y. Shimatomi, and K. Nobuyuki, "Study on Bending Fatigue Strength of Helical Gears," *Bull. JSME*, Vol 23 (No. 177), Paper 117-17, 1980 doi: 10.1299/jsme1958.23.461

• R. Pederson and R.L. Rice, Case Crushing of Carburized and Hardened Gears, *Trans. SAE*, 1964, p 250

• G.W. Powell, M.B. Benet, and C.F. Floe, Carbonitriding of Plain Carbon and Boron Steels, *Trans. ASM*, Vol 46, 1954, p 1359–1371

• A.K. Rakhit, "Distortion Control of Carburized and Hardened Gears," *ASME Paper 84-DET-224*, American Society of Mechanical Engineers, 1984

• A.K. Rakhit, "Optimization of Case Depth and Core Hardness for Carburized and Hardened High Alloy Steel Gears," *Engineering Report ME89-145 AKR*, Allied Signal Aerospace, Torrance, CA, 1989

• A.K. Rakhit, "Effect of Uncontrolled Heat Treat Distortion on the Pitting Life of Ground, Carburized and Hardened Gears," *Paper 98FTM4, presented at the AGMA Fall Technical*

Meeting (Cincinnati, OH), American Gear Manufacturers Association, 1998 doi: 10.1115/DETC98/PTG-5787

• C. Razim, Influence of Residual Austenite on the Strength of Case-Hardened Specimens under Conditions of Fluctuating Stress, *Hart.-Tech. Mitt.*, Vol 23, 1968, p 1–8

• V.S. Sagaradze, Effect of Heat Treatment on the Properties of High Carbon Alloyed Steels, *Met. Sci. Heat Treat.*, No. 12, 1964, p 720 doi: 10.1007/BF00660227

• V.K. Sharma, G.H. Walter, and D.H. Breen, "An Analytical Approach for Establishing Case Depth Requirements in Carburized Gears," *ASME Paper 77-DET-152*, American Society of Mechanical Engineers, 1977

• J.P. Sheehan and M.A.H. Howes, "The Role of Surface Finish in Pitting Fatigue of Carburized Steels," *Paper 73058*, Society of Automotive Engineers, 1973 doi: 10.4271/730580

• D.P. Townsend and E.V. Zaretsky, "Effect of Shot Peening on Surface Fatigue Life of Carburized and Hardened AISI 9310 Spur Gears," *NASA Report TP-2047*, NASA Lewis Research Center, Cleveland, OH, 1982

• D.P. Townsend, "Improvement in Surface Fatigue Life of Hardened Gears by High-Intensity Shot Peening," *NASA AVSCOM Technical Report 91-C-042*, NASA Lewis Research Center, Cleveland, OH, 1992 doi: 10.1115/DETC1992-0082

• T. Ueno, Y. Ariura, and T. Nakanishi, "Surface Durability of Case Carburized Gears: On a Phenomenon of 'Gray-Staining' of Tooth Surface," *ASME Paper 80-C2/DET-27*, American Society of Mechanical Engineers, 1980

• F. Vodopivee and L. Kosee, The Fatigue Strength and Influence of Non-Metallic Inclusions on the Fatigue Fracture of Case Hardening Steels, *Hart.-Tech. Mitt.*, Vol 22, 1967, p 166

Books

• *Carburizing and Carbonitriding*, American Society for Metals, 1977

• "Design Engineering Specification for Gears," *ES 9-45*, Solar Turbines, Inc., San Diego, CA

• T.G. Diggs, S.J. Rosenberg, and G.W. Geil, *Heat Treatment and Properties of Iron and Steel*, National Bureau of Standards Monograph 88, 1966 doi: 10.6028/NBS.MONO.88

• D.W. Dudley, *Gear Handbook*, McGraw-Hill Book Company, Inc., 1962

• D.W. Dudley, *Handbook of Practical Gear Design*, Technomic Publishing Co., Inc., 1994

• D.W. Dudley and H. Winter, *Gears*, Springer-Verlag, Berlin, 1961, in German

• "Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth," *ANSI/AGMA 2001-C95*, American Gear Manufacturers Association, 1995

• "Gear Materials and Heat Treatment Manual," 2004-B89, American Gear Manufacturers Association, 1989

• "Ion Nitriding," *AMS 2759/8*, Society of Automotive Engineeers (SAE) Aerospace Material Specification, 1992

• *Manual of Shot Peening Technology*, Wheelabrator Frye, Inc., Mishawaka, IN, 1977

• *Nitralloy and the Nitriding Process*, The Nitralloy Corporation, New York, 1954

• *Nitreg Nitriding Technology*, Nitrex Metal, Inc., Canada, 1991

• *Plasma-Triding*, Metal Plasma Technology, Valencia, CA

• "Recommended Practice for Carburized Aerospace Gearing," 926-C99, American Gear Manufacturers Association, 1999

• *Republic Alloy Steels*, Republic Steel Corporation, Cleveland, OH, 1961

• *Shot Peening Applications*, 6th ed., Metal Improvement Company, Paramus, NJ, 1980

• C.A. Siebert, D.V. Doane, and D.H. Breen, *The Hardenability of Steels: Concepts, Metallurgical Influences, and Industrial Applications*, American Society for Metals, 1977

• "Surface Temper Inspection Process," 230.01, American Gear Manufacturers Association, 1968

• D.P. Townsend, Ed., *Dudley's Gear Handbook: The Design, Manufacture and Application of Gears*, 2nd ed., McGraw-Hill Inc., New York, 1991