Induction Heat Treatment of Steel

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Preface

Induction heat treatment of steel combines one of the oldest technologies, steel heat treating, with one of the most modern, induction heating. Heat treatment is the key to varying the properties of steels over a wide range, making them suitable for numerous applications. This is done by controlling the phase transformations which steels undergo in the solid state. Both time and temperature have an important influence on these transformations.

Traditionally, most heat treating operations have been carried out in fuel-fired furnaces. Such processing typically requires long heating times for completion. Through the application of induction, in which heating is accomplished by inducing electric currents within metal parts, times for many processes can be cut to minutes or even seconds. Induction heating is also attractive for applications involving surface and selective heat treating. In these cases, parts can be produced with a special blend of properties that cannot be achieved via other processing methods.

This book has been written for use by those who do not necessarily have backgrounds in metallurgy or electrical engineering. It is designed to be an introductory text or reference for undergraduate college students as well as practicing engineers. The discussion centers on the important aspects of steel heat treatment and the application of induction heating for conducting such processes. Following a brief introduction, Chapters 2, 3, and 4 deal with the fundamental principles involved in the heat treatment of steel and induction heating. In Chapters 5 and 6, the specific applications of induction heating for hardening and tempering, respectively, are described. Special considerations (e.g., post-heat-treatment properties) and uses of induction heat treatment are given in Chapters 7 and 8. The final two chapters deal with other heat treating processes for which induction may be applied and a discussion of the economics of induction heat treatment. Various appendices deal with microstructure development in steels, fundamental principles of electricity, and design of induction coils in more detail than is possible in the main body of this volume.

The impetus for writing this book came from several sources. First, and perhaps foremost, there is no other book that deals with both the metallurgical and electrical aspects of induction heat treatment. There are many books which deal with one or the other, but none which presents a balanced synthesis of the subject.

The present economic climate and the need for energy efficiency in industry have also spurred the undertaking of this project. With the volatility of both supply and price of all energy sources in recent years, the use of electricity for process heating applications in industry has seen significant increases. Electricity-based induction heating is already economically competitive with more conventional techniques and will become more so in the future. Thus, there exists a need for up-to-date information in order to apply induction heating efficiently for heat treatment.

The authors wish to express their gratitude to the organizations who made possible the writing and publication of this book. The bulk of the work was sponsored by the Electric Power Research Institute through its contract with Battelle Columbus Laboratories in establishing a Center for Metals Fabrication (CMF). The CMF conducts programs that promote the use of efficient electrotechnologies in industry. One of the major objectives of the Center is to encourage the efficient use of electricity for industrial process heating.

Thanks are also due to the publisher, the American Society for Metals. Having its roots in the area of steel heat treating, ASM has a long history of disseminating information to heat treaters. The authors appreciate the efforts taken by the ASM staff — in particular Mr. Timothy Gall — as well as by Ms. Laura Cahill, CMF Operations Coordinator, in the production of this book. The authors also are grateful to Craig Kirkpatrick and Jeffrey Lachina, Project Managers on the staff of Carnes Publication Services, Inc., for their professional skill in copy editing the manuscript.

A number of the authors' colleagues have also made substantial contributions through discussions and comments on the initial drafts of this volume. These include J. Cachat (TOCCO), T. Groeneveld (Battelle), P. Hassell (Hassell Associates), P. Miller (IPE Cheston), L. Moliterno (Ajax Magnethermic), G. Mucha (TOCCO), N. Ross (Ajax Magnethermic), R. Sommer (Ajax Magnethermic), H. Udall (Thermatool), B. Urband (Tubulars Unlimited), D. Williams (Battelle), and S. Zinn (Ferrotherm, Inc.). T. Groeneveld, P. Miller, G. Mucha, N. Ross, C. Tudbury, and S. Zinn also supplied some of the illustrations used herein. The efforts of C. Sullivan, B. Pierpoint, and R. Underwood in preparing the manuscript are also appreciated.

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Lee Semiatin
Dave Stutz
January, 1985

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Chapter 1

Introduction

"... [When the steel pieces] are very hot and almost of a white color because of the heat, in order that the heat may be quickly quenched, they are suddenly thrown into a current of water that is as cold as possible ... In this way, the steel is made so hard that it surpasses almost every other hard thing..."

V. Biringuccio, *Pirotechnia,* 1540.

Induction heat treatment of steel combines what is surely one of the oldest of all technologies, steel heat treatment, with one of the more recent, induction heating. Hardening of steel through heat treatment had its origins during the Iron Age (circa 1000 B.C.), but it was not until the latter part of the 19th century and the first part of the 20th century that this process (and the metallurgical changes that are responsible for it) came to be fully understood. Electromagnetic induction, or simply "induction," was first discovered in the experiments of Michael Faraday around 1830. Faraday noted that an electric current could be induced in an electrical conductor by suitably coupling the conductor with a coil carrying an alternating current. Such a current can give rise to heating, and thus was formed the basis for techniques such as induction melting and induction hardening. Induction melting processes were probably the first to be exploited commercially. Later, during the 1930's, induction methods for hardening razor blades and the bearing surfaces of crankshafts were introduced. Today, steel products are being induction heat treated in rapidly increasing numbers.

Steels are the most common of all engineering materials. In 1981, approximately 100 million tons of steel were made in a multitude of product forms. An understanding of why so much steel is used requires consideration of both the production characteristics and the properties of steel products. Manufacture of the various forms of steel often starts with reduction of the raw material, iron ore, to produce pig iron. Pig iron is a high-carbon iron alloy which is further refined and alloyed to make different grades of steel. The process of ore reduction is relatively easy from an energy standpoint, a circumstance which is akin to the rapidity with which many steels rust. The process of rusting, or oxidation, is merely the reverse of the chemical reaction involved in ore reduction.

The wide variety of uses for which steel is appropriate provides a second major reason for the importance of steel as an engineering material. Often we think of steel as being a "strong" material—i.e., it can support large loads in service without deforming—but if strength were the only positive attribute of these alloys they would not be used as often as they are. Unlike many materials, steel can be alloyed and processed to obtain an amazing range of properties which can be tailored to the needs of the final application (Fig. 1.1). These properties include not only strength but also toughness (the ability to resist brittle fracture) and resistance to fatigue (cyclic loading), creep (deformation at high temperatures under load), corrosion, and abrasive wear.

For a given alloy composition, the primary methods by which properties are altered or controlled may be classified under the general headings of mechanical processes and thermal processes. As the name implies, mechanical processes comprise those means involving the use of plastic (permanent) deformation and include operations such as rolling, forging, and extrusion. Besides imparting a given shape to a piece of steel, these techniques may be employed to increase strength or develop a microscopic structure ("microstructure") which gives rise to attractive properties. Thermal processes, on the other hand, involve no shaping, but rely solely on microstructural changes during heat treatment to modify properties. Sometimes, a thermal process is used in conjunction with a mechanical, or deformation, process in what is commonly known as thermomechanical treatment

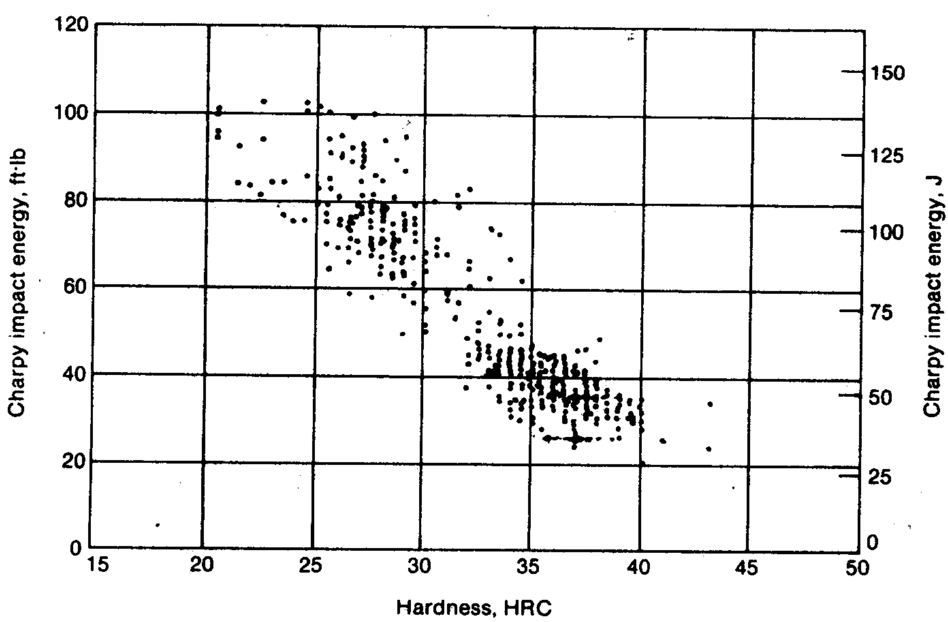

Fig. 1.1. Relationship between room-temperature brittle fracture resistance (in terms of Charpy impact energy) and hardness for a variety of quenched-and-tempered plate steels containing 0.30 to 0.40% carbon (Ref 1)

(TMT) or thermomechanical processing (TMP). In this book, only the application of heat treatment to steel will be described. As an introduction, some of the common heat treating processes used for steel will be briefly discussed. Also, the heating methods by which these operations are carried out will be summarized.

HEAT TREATING OPERATIONS FOR STEEL

Although there are many different types of heat treating operations for steel, we shall concentrate on only a rather limited number of them. Most of our attention will be focused on the treatments known as hardening and tempering. Where appropriate, other important techniques, such as recrystallization annealing and spheroidization, will be discussed.

As its name implies, hardening is used to increase the strength of steel. Usually, this involves a heat treatment in which a "hard" microstructure known as martensite is produced. How this is done will be discussed in more detail in Chapter 2. In brief, conventional hardening processes involve raising the temperature of the steel above a certain critical temperature, holding it at that temperature for a fixed amount of time, and then rapidly cooling (i.e., quenching) it to room temperature (and sometimes to even lower temperatures). In some instances, the steel is air cooled. In these cases, the operation is known as "normalizing."

In the hardened condition, the steel is strong but relatively brittle. This is because of the general nature of the quenched microstructure and of the development of internal, residual stresses set up as a result of nonuniform cooling. To overcome this situation, the heat treating operation known as "tempering" is subsequently performed. During tempering, residual stresses are relieved and the microstructure is modified so that a much tougher, albeit sometimes slightly weaker, finished product is obtained. This is done at temperatures substantially lower than those used for hardening, but the time at temperature can be much longer. Steels which undergo both of the above processes are known as "quenched-and-tempered" steels.

The other heat treatment operations mentioned above (recrystallization annealing and spheroidization) are generally used to soften the steel and thus enhance the ability of the material to be deformed during further processing. Recrystallization annealing is a high-temperature heat treatment which is employed to eliminate the effects of prior mechanical working by producing new deformation-free metal grains in the metal. The new recrystallized microstructure has generally lower resistance to deformation during working. Common applications of this heat treatment include (*a*) hot rolled or press forged steel ingots and (*b*) cold rolled steel sheet. In the former application, the recrystallization anneal serves to replace the cast ingot microstructure, which is not very workable, with a recrystallized one. Recrystallization annealing of cold rolled sheet is employed to impart the material properties required for deep drawing of the steel into such products as auto-body and appliance panels.

The other important operation used to soften steel for further working is spheroidization annealing. In this process, the steel is heated to a moderate temperature in order to change the shape of the iron carbide (cementite) particles which are produced in the steel microstructure upon cooling from higher-temperature processing. During spheroidization, the carbide particles agglomerate and become spheroidal. In this condition, the steel is as soft and ductile as it can be, making it suitable for such demanding forming operations as cold forging.

HEAT TREATING METHODS

Heat treating methods may be broadly classified as either indirect or direct. In indirect methods, heat is produced in a furnace through combustion of a fuel or by conversion of electrical energy into heat by passing a current through resistance heating elements. This energy is then transferred to the material to be heated (known as the workpiece) by radiation, convection, or conduction. In direct methods, heat is supplied directly to the workpiece without the use of a furnace. Examples of such methods include flame heating, induction heating, and direct-contact resistance heating.

For the indirect methods of heat treatment of steel, gas-fired furnaces and electric-resistance furnaces are probably the most common types of equipment. The gas-fired furnace, the workhorse of the steel heat treating industry, provides heat through combustion of natural gas. This heat is transferred to the steel in the furnace by convection (often by forced convection obtained by use of blower fans in the furnace) as well as by radiation and conduction of heat from the furnace lining of high-temperature refractory material. In the electric furnace, heat energy passes into the workpiece primarily by radiation from the electric-resistance heating elements and secondarily by conduction and convection. A third type of indirect heating equipment is the molten salt or metal bath. Typically used for small production lots, the salt or metal medium is itself heated by electric-resistance or gas-fired heaters. Once the bath is liquid, the material to be heat treated is placed in it and heated by conduction. In gas-fired and electric furnaces, the hardening and tempering operations for steel typically last between 30 minutes and several hours depending on section thickness. This time may be considerably shortened by use of salt or metal baths.

Heat treating time may be further reduced by using direct methods such as induction. With this method, electric currents are induced in the steel by surrounding it with a coil (also known as an inductor) of a configuration similar to that of the steel workpiece. An alternating current (ac) is passed through the coil. Associated with the current is a magnetic field whose magnitude varies directly with the current. This magnetic field penetrates into the workpiece and induces alternating currents (known as eddy currents) as the magnetic field changes. Because the strength of the magnetic field decreases with distance from the workpiece surface, the induced eddy currents vary in magnitude with position as well. Hence, the rate at which electrical energy is converted into heat, and thus the temperature, varies with position. This effect forms the basis for surface heat treatment of steel. Induction may also be used for through-heating and for through heat treatment. This is done by selection of equipment which provides a relatively low-frequency alternating current to the inductor. By this means, the "penetration depth" of the eddy currents is increased. In addition, the power input to the workpiece is made sufficiently low so that the heat is generated slowly at the surface of the workpiece and therefore has time to be transferred to the center, thereby decreasing the thermal gradient.

Each of the above heat treating processes has both advantages and disadvantages. For example, furnace treatments are well suited to processing of large numbers of parts (often irregular in shape) in batch-type operations. Also, because heating is done slowly, the over-all heating time can be varied within relatively wide limits without greatly affecting the properties of the final product. On the negative side, the long heating times required in furnace treatments generally give rise to large amounts of surface scaling unless the furnace atmosphere is controlled. Furthermore, furnaces — particularly those of the gas-fired type — tend to be relatively inefficient from an energy standpoint.

Induction heat treatment precludes many of the problems associated with furnace methods. Among its advantages is the rapid heating that can be achieved. For this reason, induction heat treatment is particularly well-suited to high-volume continuous heat treatment operations. With the advent of microprocessor technology, the controls necessary for such techniques have become readily available. The rate of heating is limited only by the power rating of the ac power supply and the need for through-heating rather than surface heating. Because heating times are usually short, surface problems such as scaling and decarburization and the need for protective atmospheres can often be avoided. In addition, induction tends to be energy-efficient. With proper coil design and equipment selection, more than 80% of the electrical energy can be converted into heat for treatment of the workpiece. Such efficiencies are impossible with gas-fired furnaces, in which a large proportion of the consumed energy is lost with the hot gases leaving the furnaces. Induction heating is also free of pollution, a consideration to which users of gas-fired furnaces should pay careful attention. The above attributes have resulted in the application of induction heating to a variety of heat treating processes. An estimate of the extent of its utilization is presented in Fig. 1.2.

Among the disadvantages of induction are those related to coil design and equipment selection, both of which must be tailored to the particular part to be heat treated and the temperature at which the heat treatment is to be carried out. In the automotive and oil-drilling equipment industries, production rates are high and the induction heat treating method finds wide application. In situations where only a few parts of a given design are to be made, induction heat treatment is usually not economically feasible.

SCOPE OF THE BOOK

The chapters that follow will center on the important aspects of steel heat treatment and the application of the induction heating method for this purpose. Chapters 2, 3, and 4 will deal with the fundamental principles involved in the heat treatment of steel and induction heating. In Chapters 5 and 6, the specific appli-

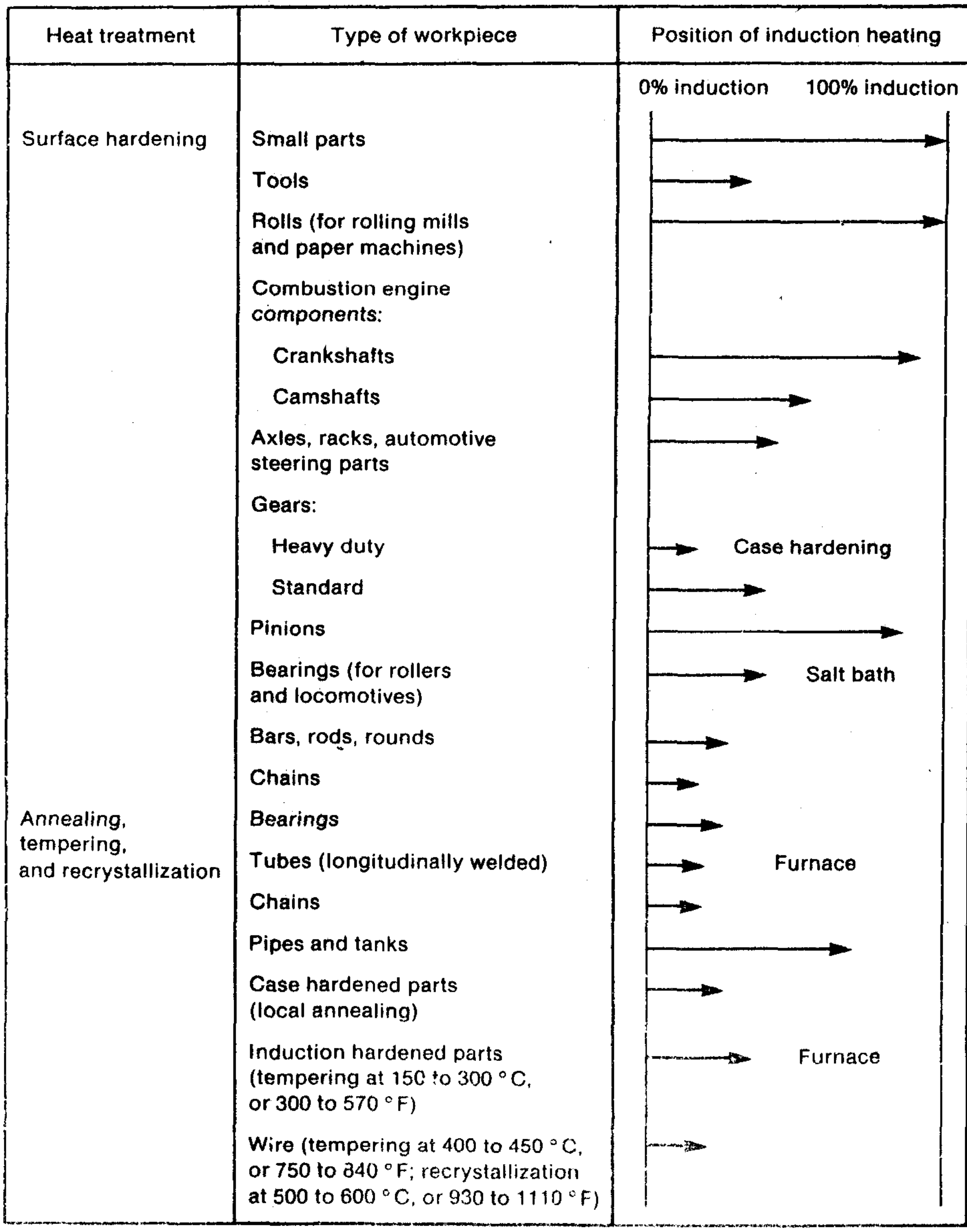

Fig. 1.2. Estimated usage of induction relative to all other heat treating processes (Ref 2)

cations of induction heating to hardening and tempering, respectively, are described. Special considerations and specific uses and case histories of induction heat treatment are given in Chapters 7 and 8. The final chapters deal with other heat treating processes to which induction may be applied (Chapter 9) and a discussion of the economics of induction heat treatment (Chapter 10).

Chapter 2

Basic Principles of Steel Heat Treatment

As was mentioned in Chapter 1, one of the main reasons why steel finds such wide application is the fact that its properties can be varied extensively by changes in chemical composition and heat treatment. Steels can be made relatively soft so that they can be shaped and subsequently hardened to various levels to provide strength for severe service applications. In this chapter, the basic principles of hardening of steel are reviewed. This discussion will be short and will describe only those aspects of practical significance which must be understood before heat treating systems based on induction can be designed. For a more complete description, the reader is referred to one of the standard books on steel heat treatment (Ref 3 to 7).

GENERAL BACKGROUND ON STEEL HEAT TREATMENT

The chemical compositions of commercial steels may include as few as two primary elements — iron and carbon — or, for steels designed for special service, as many as five or more elements. It might seem impossible to understand, let alone control, the heat treatment of such different forms of the same product, especially in light of the fact that there are thousands of different types of steel, but it must be realized that many steels can be grouped together according to the kinds of microstructures which can be developed in them through heat treatment. We have said previously that our attention will be focused on the quenched-and-tempered grades. Although different in composition, all steels under this classification respond similarly to heat treatment.

Hardening of quenched-and-tempered steels relies heavily on the fact that iron and many of its alloys undergo what is known as an allotropic transformation. This means that, depending on temperature, the metal in its solid state assumes different phases or crystal structures. For iron, the allotropic forms are two: a body-centered-cubic (bcc) structure found at low to moderately high temperatures *and* at very high temperatures; and a face-centered-cubic (fcc) structure found at