

**NORMAN W. LORD
ROBERT P. OUELLETTE
PAUL N. CHEREMISINOFF**

ELECTROTECHNOLOGY VOLUME 7

**ADVANCES IN
ELECTRIC HEAT TREATMENT
OF METALS**



ANN ARBOR SCIENCE



ELECTROTECHNOLOGY VOLUME 7

ADVANCES IN ELECTRIC HEAT TREATMENT OF METALS

NORMAN W. LORD

ROBERT P. OUELLETTE

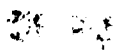
METREK Division of the MITRE Corporation
McLean, Virginia

PAUL N. CHEREMISINOFF

New Jersey Institute of Technology
Newark, New Jersey



ANN ARBOR SCIENCE
PUBLISHERS INC / THE BUTTERWORTH GROUP



Copyright © 1981 by Ann Arbor Science Publishers, Inc.
230 Collingwood, P.O. Box 1425, Ann Arbor, Michigan 48106

Library of Congress Catalog Card Number 77-85093
ISBN 0-250-40481-8

Manufactured in the United States of America
All Rights Reserved

Butterworths, Ltd., Borough Green, Sevenoaks, Kent TN15 8PH, England

TM
-65
L867

ELECTROTECHNOLOGY
VOLUME 7

ADVANCES IN
ELECTRIC HEAT TREATMENT
OF METALS

PREFACE

This book continues the series of studies initiated and sponsored by Electricité de France, surveying the status of electric technologies. The objectives have been to promote technology using electricity, and to diffuse information favorable to its development.

This volume reviews developments in electric heat treatment of metals to determine the outlook for market gain in some of the promising new technologies. The crisis in the fossil fuel supply creates higher costs for those fuels, and thus adds basic broad economic advantages to the use of electricity. As fossil fuel prices continue to rise, electric heat treatment technologies will become increasingly economical, despite their high capital costs.

Electrotechnology Vol. 2, Applications in Manufacturing (R. P. Ouellette, F. Ellerbusch and P. N. Cheremisinoff, Eds., 1978) presented the economic status and developmental state of electric technologies. Induction and other electric metal heating methods were discussed by G. Miller and M. Barbier. Several technologies, which at that time were regarded as only exotic laboratory tools, now have gained dramatically increased acceptance in commercial use, and are explored in greater detail in this volume.

The authors gratefully acknowledge Electricité de France for continuing its support in this work and sponsoring this study.

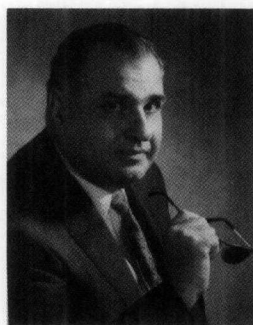
Norman W. Lord
Robert P. Ouellette
Paul N. Cheremisinoff



Norman W. Lord



Robert P. Ouellette



Paul N. Cheremisinoff

Norman W. Lord is a broad-spectrum physicist with the MITRE Corporation. Dr. Lord's research areas include the structure of solids, ocean acoustics and atmosphere-land interactions. He has consulted extensively for government and industries on a wide variety of problems in operations and estimating technological trends.

He received a BEE from Brooklyn Polytechnic Institute, and earned his MA and PhD in physics from Columbia University. Dr. Lord has been a research physicist at the Johns Hopkins University Applied Physics Laboratory, Hudson Laboratories of Columbia University and Travelers Research Center in Hartford, CT. He has written more than 40 technical papers covering these areas and his research, and is co-author of *Heat Pump Technology, Electrotechnology Vol. 4*, a 1980 Ann Arbor Science publication.

Robert P. Ouellette is Technical Director of the Environment Division of the MITRE Corporation. Dr. Ouellette has been associated with MITRE in varying capacities since 1969, and has been Associate Technical Director since 1974. Earlier, he was with TRW Systems, Hazelton Labs, Inc. and Massachusetts General Hospital. He was graduated from the University of Montreal and received his PhD from the University of Ottawa. A member of the American Statistical Association, Biometrics Society, Atomic Industrial Forum and the NSF Technical Advisory Panel on Hazardous Substances, Dr. Ouellette has published numerous technical papers and books on energy and the environment. He is a co-author of the *Electrotechnology* survey series published by Ann Arbor Science.

Paul N. Cheremisinoff is Associate Professor of Environmental Engineering at the New Jersey Institute of Technology. He is a consulting engineer and has been a consultant on environmental/energy/resources projects for the MITRE Corporation. A recognized authority on pollution control and alternative energy technologies, he is author/editor of many publications, including several Ann Arbor Science handbooks on pollution and energy, such as *Pollution Engineering Practice Handbook*, *Carbon Adsorption Handbook*, *Environmental Impact Data Book*, *Industrial and Hazardous Wastes Impoundment*, and *Environmental Assessment and Impact Statement Handbook*. He is a member of the Ann Arbor Science Publishers Editorial Advisory Board.

CONTENTS

1. Introduction	1
2. Analysis of Energy Supply System Investments	9
Costs and Production Influences.	9
Capital Investment Considerations	11
3. Induction Heating	15
Induction Heating Economics	18
Forging	24
Melting and Holding.	28
Hardening and Tempering	33
Improved Control of Induction Hardening Process.	35
Hardening Gears	37
Shafts, Clutches, Cams and Other Components	38
Steel-making Use of Induction Furnaces	39
Induction as Replacement for Arc Furnace	39
Induction as Replacement for Blast Furnace.	40
Superheating Hot Metal with Auxiliary Channel Induction Furnaces	40
Brazing, Soldering and Sintering	43
Market Outlook for Induction Heating	45
4. Lasers and Electron Beams	47
Lasers	50
Laser Machining	54
Hardening and Other Heat Treating.	56
Annealing Silicon Alloys.	60
Electron Beam Heat Treatment	62
Hardening	64
Corrosion-Resistant Coatings	66
Welding	69

5. Electric Arc and Plasma Processes	71
Jones and Laughlin Electric Steel-making.	72
A National View of Productivity	72
Steel Industry View of Productivity	73
Economic Aspects of Building and Supplying Power to New	
Electric Arc Furnaces.	75
Experiments in Arc Furnace Operation	78
Excavation of a 75-MVA High-Carbon Ferromanganese	
Electric Smelting Furnace	79
Ferrosilicon Smelting	83
Production Models for High-Carbon Ferrochromium	86
Models of Arc Furnace Operation.	91
Mathematical Models for Soderberg Electrodes	91
Submerged Arc Furnace Electric Circuit Analysis	95
Electrical Considerations in Electric Arc Furnace	
Productivity	97
Arc Furnace Operational Improvements.	100
Production of Silvery Pig Iron in Covered Submerged	
Arc Furnaces	100
Scrubbing and Water Treatment	101
Ilmenite Reduction by a Carbon Injection Technique.	103
Melting and Continuous Casting Operations at Armco	104
New Class of Packaged Vacuum Arc Melting Furnaces	106
Computer-Controlled Arc Furnace Operation	106
Operation of a Two-Furnace Ferrosilicon Plant under	
Process Computer Control.	106
Operational Results	109
Productivity of the Steelton Electric Furnace	110
New Computer-Controlled, Ultrahigh Power (UHP) Arc	
Furnace of Krupp Stahlwerke, Sudwestfalen AG,	
Siegen, Federal Republic of Germany	111
Plasma Processes.	113
Plasma Processing of Ferromanganese Slags	113
High-Rate Carburizing in Plasma Discharge.	116
Plasma Smelting of Platinum	119
6. Resistance Heating Technology	121
Electric Resistance Heating Elements	122
Heat Treatment.	124
Hot Isostatic Pressure Treatment	127
Pipe Heat-Tracing	130
Vacuum Electric Furnaces.	131
Vacuum Brazing	133

Vacuum Heat Treating	136
Electric Vacuum Furnaces for Heat Treating Steel	136
Programmed-Controlled Vacuum Furnace Annealing	138
Commercial Heat Treating Uses	138
Electronically Controlled High-Vacuum Furnaces	139
Ceramic Fiber in Vacuum Heat Treating Furnaces	139
Direct Electric Conduction in Workload.	139
Electroslag Remelting.	140
Forging	141
Internal Electrothermic Treatment of Steels and Alloys (IETT)	144
7. Market Outlook for Electric Heating Equipment	145
References	151
Index	157

LIST OF FIGURES

3-1.	Typical performance of induction furnace for melting steel	30
3-2.	<i>Lindberg/Junker automatic iron pouring system</i>	31
3-3.	Critical temperatures in plain carbon steels and constituents, which are present in iron-carbon alloys on very slow temperature changes	34
3-4.	Hardening by induction heat and quench	35
3-5.	Valve seat durability with induction hardening and unleaded fuel.	36
3-6.	Induction furnace for heating charge to BOF	41
3-7.	<i>Recommended joining procedures in using induction heating.</i> . .	44
4-1.	Heating at surface by laser beam moving in x direction	48
4-2.	Theoretical heat transfer results for 100-watt point source scanning at 0.5 cm/sec	49
4-3.	Parallel-plate laser	50
4-4.	Capital costs for CO ₂ laser equipment in 1976	53
4-5.	Laser machining	55
4-6.	Laser heat treating.	56
4-7.	Laser heat treating of diesel engine cylinder liners	58
4-8.	Comparison of laser and thermal anneal on depth diffusion of implanted impurities	61
4-9.	Electron beam system operating in a particle vacuum	63
4-10.	Electron beam energy input.	65
4-11.	Approximate melting point and boiling point range of physical vapor-deposited (PVD) materials applicable for turbine coatings	68
5-1.	Selected sampling locations for the arc furnace "dig out"	80
5-2.	Locations and approximate dimensions of distinctive arc furnace zones determined by the "dig out"	81
5-3.	Ferrosilicon arc furnace energy relationships.	85
5-4.	Ferrosilicon arc smelting interactions	87

5-5.	Electrode arc region in high-carbon ferrochromium production.	89
5-6.	Arc furnace electrical behavior.	90
5-7.	Calculated temperature and thermal stresses.	92
5-8.	Equivalent load circuit for a submerged arc furnace.	96
5-9.	Power imbalance in a submerged arc furnace.	98
5-10.	An arc circuit model	99
5-11.	Pollution control process for silvery pig iron submerged arc smelting	102
5-12.	Extended arc flash reactor.	114
5-13.	Plasma carburizing circuit	117
5-14.	Glow discharge carburizing system	118
5-15.	Hardness profiles through plasma carburized and plasma-carburized-and-diffused cases comparing tooth tip and fillet . . .	119
5-16.	Tetronic process for smelting platinum group metals from chromite-laden concentrates	120
6-1.	Heating system of Grumman autoclave after conversion to electric energy source.	125
6-2.	System for hot isostatic pressing.	128
6-3.	Instrumentation, heating and cooling of HIP furnace and load schematic	129
6-4.	Electric impedance heating	130
6-5.	Typical response for heating steel in a vacuum furnace	132
6-6.	Clad aluminum brazing sheets	133
6-7.	Comparison of carbon diffusion rates in atmosphere and vacuum furnaces	137
6-8.	Electroslag remelting	140
6-9.	Fatigue strength curves for H13 tool steel from transverse specimens of billet.	143

LIST OF TABLES

1-1.	Energy Use in GM Components of Energy Consumption in GM	4
1-2.	1977 GM Energy Consumption by Form and Process	5
1-3.	Major Process Categories at GM by Temperature	6
1-4.	High-Temperature Process Energy Consumption at GM.	7
2-1.	Dependence of Rate of Return on Ratio of Yield to Investment and Anticipated Useful System Lifetime	13
3-1.	Standardized Categories of Induction Heating Equipment	16
3-2.	Underlying Costs in Hot Forging Steel.	19
3-3.	Factors Common to Exemplary Plant Hot Forging Steel	20
3-4.	Special Function of Induction-Hot Forging Plant.	21
3-5.	Special Factors of Natural Gas Hot Forging Plant	22
3-6.	Hot Forge Operating Costs That Differ Between Induction and Natural Gas	23
3-7.	Annual Yield of Induction Heating Investment Compared to Investment.	23
3-8.	Metal-Working Thermal Parameters.	27
3-9.	Relative Cost of Alternative Sources of Energy for Melting 137.9 kg of Additional Scrap.	43
4-1.	Some Typical Lasers and Illustrative Applications in Industry . .	52
4-2.	Recent Prices for Laser Systems.	53
4-3.	Operating Parameters and Normal Tolerance for Electron Beam Treatment	67
4-4.	Preliminary Assessment of Protection of JT8D Blades from Sulfidation Corrosion.	67
5-1.	Crude Steel Production Compared to Population.	74
5-2.	Heat Balance for Ferrosilicon and Ferronickel Furnaces by the Static Model	93
5-3.	Silvery Pig Iron Arc Smelting Operation under Open and Covered Conditions	103
5-4.	Effect of Reductant in Reducing Ilmenite	104

5-5.	Large-Scale Tests	105
5-6.	Operating Results of Union Carbide Arc Furnace Computer Control	110
5-7.	Experimental Results on High-Carbon Ferromanganese with Extended Arc Flash Reactor	115
6-1.	Typical Immersion Heater Applications	123
6-2.	Alloy Systems for Vacuum Brazed Radiators	134
6-3.	Comparison of dc vs ac Supply in Electroslag Remelting	142
7-1.	Value of Shipments for Industrial Heating Equipment by All Producers	146
7-2.	Assumed Implicit Price Deflation for Heating Equipment	147
7-3.	Metal Heat Treating Industry	148
7-4.	Orders Reported by IHEA Members	150
7-5.	Profile of Industrial Heating Equipment Industry	150

CHAPTER 1

INTRODUCTION

In earlier work,* the economic status and developmental state of electric technologies as practiced in U.S. industry were surveyed. Induction and other electric metal heating methods were discussed by Miller [1] and Barbier [2]. This Volume reviews the changes in technical development and economic status of all electric metal heat treatment methods that have taken place since the earlier work was completed.

For the electric heat treatment methods discussed in 1978, advances in available commercial technology essentially have been incremental. Electric heat treatment equipment has increased its market share primarily because of government-mandated reduction in the use of oil and improved economic circumstances for the use of electricity compared to natural gas. Induction heating and vacuum resistance heating, for example, have gained because their recognized technical advantages became much more cost-competitive as natural gas prices rose. With greater routine use a wider variety of special applications were tried and proven to further expand the market.

In part spurred by the increased familiarity with electric methods of metal heat treatment, several technologies, which were regarded in 1978 as only exotic laboratory tools, now have gained dramatically increased acceptance in commercial use. These technologies are laser and electron beam methods for localized heat treatment and plasmas for melting the more refractory metals. In addition, the economic status of electric arc melting for steel and ferroalloys has become so much more favorable that conventional steel production, which relies on coal combustion, soon may be substantially displaced. Hence, these technologies have been added to the report coverage. The book therefore will cover the following major technical categories of electric metal heat treatment.

*Electrotechnology, Volume 2, Applications In Manufacturing.

2 ELECTROTECHNOLOGY—VOLUME 7

- Electromagnetic Induction
- Lasers and Electron Beams
- Arc Melting and Plasmas
- Electric Resistance Heating
 - Vacuum and controlled atmosphere furnace
 - Resistance heating elements
 - Direct conduction heating

Notably absent from these is the use of infrared process heat. Most recently reviewed by Callaghan [3], it is apparent that its use is largely limited to nonmetallic materials, which are usually processed at much lower temperatures than are used in metal heat treatment. Infrared heaters may be fired by natural gas or may use electric resistance elements. In either case there is a low effectiveness of coupling to the metallic workpiece, which is not sufficiently compensated for by greater controllability.

The acceptance of electric methods by U.S. industry may be growing but there are still many influences that are unfavorable from a strictly individual company viewpoint. In addition, the motives of private industry leading to a positive interpretation of the financial balance among all the factors involved do not match those of the U.S. Department of Energy (DOE), which attempts to influence U.S. industrial energy use from a national energy use viewpoint.

For example, any new investments in the U.S. steel industry must compete with an existing plant capacity for steel-making which is demonstrably adequate for the market. Szekely [4] has discussed this barrier facing any new steel-making technology. The average U.S. cost of steel production is about \$350/ton. Of this dollar figure, energy and raw materials comprise 45%, labor 35–45% and capital service charge 6–10%. Production of steel in the U.S. requires 36×10^9 J, 5 KWh/lb and 8.2 man-hours of labor. The book value of the plant is about \$120/ton of annual output (less than one third the operating cost), but replacement cost is estimated between \$1200 and \$1500/ton. An automated arc furnace facility may reduce the energy and materials requirements, improve the product quality, particularly in ferroalloys, and drastically diminish required man-hours per ton produced. However, the capital service charge for this new plant would be \$250–300/ton of annual output, completely overwhelming the savings in labor, increased product value and other benefits. Nevertheless, there are new plants being built because the oldest steel-making plants are much more expensive than the average, so that there is a realizable net return; also, individual company circumstances differ.

The situation in aluminum production as described by Brondyke [5] of ALCOA is somewhat different. Here, about 70% of the total energy consumed in aluminum production is used in the smelting process. It has always been feasible in aluminum production to introduce incremental energy saving improvements that have steadily reduced required energy. Brondyke cites the latest development of the ALCOA smelting process, which can produce

aluminum at an expenditure of 4.5 KWh/lb (less than steel) compared to an ALCOA average of 7.5 KWh/lb. In the steel example, higher production, better quality and lower materials loss overcome a possibly greater energy expenditure for a net saving. In the case of aluminum, the saving is direct in energy and technically feasible without the high capital requirement of whole plant replacement.

The U.S. Department of Energy takes another viewpoint, which may be illustrated by comparing the ways in which it would view these two industrial initiatives. If no other factors are involved, a net energy saving is always regarded favorably. In ALCOA's case, DOE may be inclined to help support further technical development. If, on the other hand, there is a net increase in energy usage, then the Department considers how the change bears on its concern over domestic use of oil and natural gas. As Gross [6] pointed out, the use of oil is already under a strong absolute constraint for manufacturing processes. A conversion from natural gas to an alternate fuel (such as coal) may merit a tax reduction. On the other hand, in the case of the electrification of steel production there is, at best, no conversion since the utility may already use coal to generate supplied electricity and there is, at worst, unfavored fuel conversion if the utility increases its use of oil or gas to meet the new demand.

The foundry industry has been pointed out by O. Cleveland Laird [7] of the Department of Energy as one of the best examples illustrating the balance frequently struck between increased productivity and increased energy costs. Foundries generally are owned and operated by small companies. For the last 10 years they have been shifting fuel usage from oil and gas to electricity. However, James Williams [8], of Grede Foundries in Milwaukee, said that this trend has slowed recently due to a shortage of capital. The furnaces costs have been running \$100,000-200,000/ton of melt capacity. This is a large investment for the small family-run company, which is still largely the rule in the foundry industry. At the same time, the cost rise for natural gas and propane, which had been outpacing that of electricity, has been slowed. At current price levels of 30¢/therm (100,000 Btu) for natural gas and 50¢/therm for propane, there is insufficient energy cost advantage offered by electric induction or resistance heating. The advantage would be in capability to automate the foundry operation. An example of this has been described recently by Layton [9]. Most of the product value of a foundry is represented by cost of energy used to melt and the capital cost for the furnace and pouring/molding equipment. Williams pointed out that since 1972 foundries have cut their specific energy usage 17-20%. For the small plants of less than 10 ton/hr, induction heating has emerged as a strong competitor of gas.

A very large company, facing many energy-requiring steps in its manufacturing processes, has a much more complicated decision to make, as pointed out by Gerhard Stein [10] of General Motors. This company utilizes

4 ELECTROTECHNOLOGY—VOLUME 7

a wide variety of energy-using equipment, and selection of any particular heating method must be made in the context of the company's best overall interest in its energy use profile.

For example, Table 1-1 shows the gross comparison for GM as a whole between 1972 and 1978 for electricity, gas and steam fuel. Production of vehicles at GM increased from 6.2 million in 1972 to 7.7 million in 1978. There was a reduction in energy requirements of 20% per vehicle because total energy usage was about the same— 206×10^{12} Btu vs 203×10^{12} Btu. The proportion of electric energy usage increased from 24% to 29%. However, this change reflects primarily the large reduction, per vehicle, of gas and steam fuel usage compared to a small reduction in electricity usage, rather

Table 1-1. Energy Use in GM Components of Energy Consumption in GM [10]

	1972		1978	
	TBtu	Percent of Total	TBtu	Percent of Total
Electricity	49	24	59	29
Process Gas	70	34	62	31
Steam Fuel	87	42	82	40
TOTAL	206	100	203	100

Consumption per Unit of Production (Millions Btu/Vehicle)			
	1972	1978	Percent Change
Electricity	7.9	7.6	-4
Gas	11.3	8.1	-28
Steam	14.0	10.7	-24
TOTAL	33.2	26.4	-20

Average GM Energy Cost					
	1972		1978		Percent Change in Cost
	\$/MMBtu	Ratio ^a	\$/MMBtu	Ratio	
Electricity	3.50	5.5	8.50	4.1	143
Process Gas	0.64	1.0	2.09	1.0	227
Steam Fuel	0.62	0.97	1.86	0.89	200

^aRelative to process gas.