Rapid Metal Heating

Reducing Energy Consumption and Increasing Productivity in the Thermal Processing of Metals

Technical Report

Rapid Metal Heating

Reducing Energy Consumption and Increasing Productivity in the Thermal Processing of Metals

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REPORT SUMMARY

Background

Energy intensive manufacturing operations, such as iron and steel production, forging, and heat treating, are attempting to increase productivity while decreasing energy consumption. Process heating accounts for a significant portion of total energy consumption within these industries and fossil fuel combustion is the primary energy form used. However, the industry has established very ambitious efficiency and productivity goals that are unlikely to be achieved using fossil fuel combustion technologies. This requires a search for improved forms of process heating - - or rapid metal heating technologies.

Objectives

The objective of this report is to:

- define rapid metal heating, to explain the nature of heat transfer
- identify where rapid metal heating is applicable
- differentiate the different rapid metal heating technologies
- give evidence of successful use of these processes in industrial environments

Approach

Information was gathered on energy usage and efficiency for various process heating technologies. Metrics for process performance and equipment attributes were defined and used to compare the various rapid metal heating technologies. Each technology was described and characterized according to operational parameters. Applications and safety concerns were discussed. Advantages of each technology were listed and the latest advances reviewed.

Results

The use of rapid metal heating technology may greatly assist in achieving the industry-established goals of energy reduction and improved productivity. High-energy flux densities, high heat transfer rates, and superior controllability characterize rapid heating technology, in such forms as laser, induction, direct resistance and infrared. The applications include heat treating, preheating, shrink fitting and joining.

EPRI Perspective

Process heating is an important step in the manufacturing process of many products. In metal fabrication, the electric and gas energy used for heating represents roughly 20% and 95%, respectively, of total process energy consumed. Heat treating, forging and the production of steel are energy intensive process heating activities. In the metals processing industry, the dominant metal heating method is the combustion of fossil fuel, typically natural gas. However, combustion efficiency and heat transfer rates for this method have nearly reached their limits. Dominant electric methods used for metal heating include induction heating and indirect resistance heating. Rapid and/or selective heating systems minimize or eliminate many of the inefficiencies characterized by combustion processes. Also, in most cases, rapid metal heating processes:

- are faster
- greatly reduce or eliminate environmental emissions
- provide better product quality by decreasing surface scale buildup and part distortion

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Keywords
Process heating
Heat treating
Preheating
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CONTENTS

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1 INTRODUCTION 1-1
The Challenge: Reduce Energy Consumption and Increase Productivity in the Thermal Processing of Metals 1-1
What Is Rapid Metal Heating? 1-1
Energy Usage for Process Heating 1-2
Process Heating – Important Parameters 1-5
Technology Selection for Process Heating 1-6

2 INDUCTION HEATING 2-1
Introduction to Induction Heating 2-1
    Through-thickness Heating 2-2
    Surface Hardening 2-4
Applications 2-5
Advantages 2-8
Safety 2-8
Advances 2-9
    Flux Concentrators 2-9
    Transistorized Power Supplies 2-9
    Dual Frequency Systems 2-10
EPRI References 2-10

3 DIRECT RESISTANCE 3-1
Introduction to Direct Resistance Heating 3-1
Applications 3-2
Advantages 3-4
Commercial Acceptance 3-5
Safety 3-5

Advances 3-5
EPRI Resources 3-5

***4* LASERS 4-1**
Introduction to Lasers and Laser Heating 4-1
Gas Lasers 4-4
Semiconductor Lasers 4-7
Applications 4-9
Advantages 4-10
Commercial Acceptance 4-11
Safety 4-11
Advances 4-11
  Aluminum-free Semiconductor Materials 4-11
  Multi-process Systems 4-11
EPRI References 4-12

***5* ELECTRON BEAM 5-1**
Introduction to Electron Beam Heating 5-1
Applications 5-2
Advantages 5-3
Commercial Acceptance 5-3
Safety 5-4
EPRI References 5-4

***6* ELECTROMAGNETIC RADIATION 6-1**
Introduction to Radiant Heating 6-1
Applications 6-7
Advantages 6-7
  Advantages of Radiant Heating Over Convection 6-7
  Advantages of Electric Infrared Over Gas Heating Technologies 6-7
Safety 6-8
EPRI References 6-9

***7* PLASMA 7-1**
Introduction to Plasma Heating 7-1
Applications 7-2

    Plasma Arc Melting 7-2
    Steel Mill Tundish Heating 7-2
    Controlled Plasma Glassification System 7-3
    Plasma Spray 7-4
    Plasma Cutting and Welding 7-5
  Advantages 7-5
  Commercial Acceptance 7-6
  Safety 7-6
  EPRI Resources 7-6

***A* APPENDIX A-1**
  An Alternative Process Selection Methodology A-1

LIST OF FIGURES

Figure 2-1 Principle of Induction Heating 2-1
Figure 2-2 Induction Coils 2-2
Figure 2-3 Examples of Water Quenching for Induction Heat Treating 2-4
Figure 2-4 Induction Coil Designs for Surface Hardening 2-5
Figure 2-5 Pop Up Type Unit 2-6
Figure 2-6 TFIH of Continuous Strip 2-6
Figure 2-7 Bar End Heater 2-7
Figure 2-8 Ajax 2000 kW Billet Heating 2-7
Figure 2-9 Effect of Using Flux Concentrators 2-9
Figure 2-10 Dual Frequency Heat Treating of Gear Teeth 2-10
Figure 3-1 Direct Resistance Heating Circuit 3-1
Figure 3-2 Direct Resistance Heating of Automotive Stabilizer Bars for Upsetting and Annealing 3-3
Figure 3-3 Direct Resistance Heating of 26' long x 5" Diameter Steel Bar to 1000°C in 13 Minutes 3-3
Figure 4-1 Principle Parts of a Laser 4-1
Figure 4-2 AC and DC Gas Medium Excitation 4-2
Figure 4-3 Optical Resonant Cavity 4-2
Figure 4-4 Output Profile of a Laser 4-3
Figure 4-5 Wavelength Region of Lasers 4-3
Figure 4-6 Typical CO_2 Laser Equipment 4-4
Figure 4-7 Components of an RF Excited Laser 4-6
Figure 4-8 Components of Slab RF Laser 4-6
Figure 4-9 pn-Junction Pumped Semiconductor Laser 4-8
Figure 4-10 Semiconductor Laser Bar 4-8
Figure 4-11 Industrial Diode Laser 4-9
Figure 5-1 Electron Beam Process 5-2
Figure 6-1 One Segment of the Electromagnetic Radiation Spectrum 6-2
Figure 6-2 Typical Quartz Infrared Lamp 6-2
Figure 6-3 Three Reactions to Infrared Radiation 6-4
Figure 6-4 Definition of View Factor 6-5
Figure 6-5 Parabolic Reflector 6-5

Figure 6-6 Elliptical Reflector 6-6
Figure 6-7 Multiple Reflector Arrangement 6-6
Figure 6-8 Clamshell Focused IR Lamps 6-6
Figure 7-1 Transferred Plasma Arc 7-1
Figure 7-2 Plasma Arc Melter 7-2
Figure 7-3 Plasma Torch for Tundish Heating 7-3
Figure 7-4 Two Torch Plasma Heating System 7-3
Figure 7-5 Plasma Glassification System 7-4
Figure 7-6 Plasma Spray Torch 7-4
Figure 7-7 Plasma Spray Process Schematic 7-5
Figure A-1 Selecting Process Heating Technology A-2

LIST OF TABLES

Table 1-1 Typical Energy Usage for Applications by Technology 1-4
Table 1-2 Specific Heat of Industrial Materials.. 1-5
Table 1-3 Transmitted Power Densities.. 1-6
Table 1-4 Rapid Metal Heating Technologies for Through Heating.. 1-6
Table 1-5 Rapid Metal Heating Technologies for Surface Heating.. 1-7
Table 2-1 Induction Current Penetration Depth (in.) - Carbon Steel....................................... 2-3
Table 2-2 Optimum Billet Diameter (in.) - Carbon Steel... 2-3
Table 2-3 Typical Induction Heating Parameters for Surface Hardening of Steel Shafts.......... 2-4
Table 4-1 Properties of Gas Lasers.. 4-4
Table 4-2 Case Depth as a Function of Laser Power Density... 4-5
Table 4-3 Steel Reflectivity to CO_2 Laser Light 4-7
Table 4-4 Selected Laser Surface Hardening Applications.. 4-10
Table 5-1 Electron Beam Process Parameters by Application.. 5-3
Table 6-1 Operating Properties of Various IR Lamps 6-3
Table 6-2 Infrared Absorption Values.. 6-5

1

INTRODUCTION

The Challenge: Reduce Energy Consumption and Increase Productivity in the Thermal Processing of Metals

Several energy intensive industrial groups have been challenged by the U.S. Department of Energy Office of Industrial Technology to develop a "vision" for their respective industries of how they will look in the year 2020. Some common goals exist--the desire to significantly reduce energy consumption while improving productivity by reducing cycle times. For energy intensive operations, such as iron and steel production, forging, and heat treating, productivity increases have often come at the cost of increased energy use. Running faster requires more fuel. Therefore, energy reduction goals of 20-75% seem to be at odds with productivity improvement goals of up to 50%. Major technical breakthroughs will be required for these industry groups to realize their self-determined visions.

Process heating, a vital step in the manufacture of many products, accounts for a significant portion of total energy consumption in the metal heat treating, forging and steel production industries. The primary process heating method now used by these industries is the combustion of natural gas and heat transfer by means of radiation and convection. However, combustion efficiency and heat transfer rates for this method have nearly reached their limits. It is unlikely that natural gas combustion can achieve the ambitious goals established by industry, necessitating the search for improved forms of process heating.

The use of rapid metal heating technology may greatly assist in achieving the industry-established goals. This report will focus on the requirements for rapid metal heating and how they can be achieved. Evidence of successful use of these processes in industrial environments is also provided.

What Is Rapid Metal Heating?

Rapid metal heating technology in such forms as laser, plasma, induction and electron beam can offer viable alternatives to the natural gas combustion processes. High-energy flux densities, high heat transfer rates and superior controllability characterize these technologies. The applications include heat treating, preheating, shrink fitting and joining.

Rapid metal heating is typically a function of:

- Energy (heat) transfer into the surface of the material, and
- Conduction of energy to desired depths into the part being manufactured

However, some rapid metal heating processes, such as induction and direct resistance, generate heat volumetrically and are not as dependent on heat transfer through the part surface.

The ability to rapidly heat metal parts is dependent on a number of criteria related to the part material and geometry being processed. These criteria include:

- Material type (iron, steel, aluminum, bronze, etc.)
- Homogeneity (microstructure, porosity and composite structures)
- Density
- Physical properties (thermal conductivity, specific heat, magnetic permeability, etc.)
- Part shape (round, square, sheet, wire and uniform cross-section)
- Final temperature profile
- Prior thermal history

Rapid metal heating techniques include:

- Induction
- Infrared
- Laser
- Electron Beam
- Plasma
- Direct Resistance

Energy Usage for Process Heating

Process heating is an important step in the manufacturing process of many products. In metal fabrication, the electric and gas energy used for heating represents roughly 20% and 95%, respectively, of total process energy consumed. Heat treating, forging and the production of steel are especially energy intensive process heating activities. Heat treating alone adds about $15 billion per year in metal products value by imparting specific properties that are required for the manufactured parts to function. In 1996, the heat treating industry employed about 140,000 people. About 90% worked in captive heat treating shops that are part of a larger facility, such as a steel mill or an automobile component factory. Approximately 10% worked in independent commercial heat treating companies that serve many different industries. Conversely, the majority of forging shops are independent commercial companies. In North America, about 300 plants produce custom forgings and account for over $6 billion in annual sales.

Much of the energy consumed by these industries is for heating of metals prior to further processing (shaping, size reduction and forging) or to develop mechanical properties (hardness, toughness and strength). Some metal products require through-heating - - heating the entire mass of the workpiece to a uniform temperature. For other metal products, only a thin layer of the workpiece surface needs heated (surface heating). It is more difficult to achieve energy efficiency with surface heating compared to through-heating. This is because when using heating processes with lower power densities, the workpiece surface cannot be heated fast enough to avoid unnecessary conductive heating of the entire mass of the workpiece.

In the metals processing industry, the dominant metal heating method is the combustion of fossil fuel, typically natural gas. Electric methods used for metal heating include induction heating and indirect resistance heating. As shown in Table 1-1, the heating efficiency of electric and fossil fuel methods for metal heating varies widely. Low heating efficiencies of 15% - 20% for fossil fuel are normal. The reasons for fossil fuel inefficiency stem from losses due to:

- Energy conversion (chemical to thermal)
- Flue stacks, furnace openings and tooling
- Radiation from part surfaces while heat is being conducted into the part body
- Poor oven design or decay in efficiency due to poor maintenance
- Heating more of the part than is necessary (bar end forging)

Table 1-1
Typical Energy Usage for Applications by Technology

Application/ Technology	Theoretical Energy Requirements (MMBtu/ton)	Typical Energy Use		Heating Efficiency (%)
		(MMBtu/ton)	(kWh/ton)	
Slab Reheating				
Induction	0.72	[0.93]	273	77%
Fuel Fired	0.72	3.00	[877]	24%
Large Billet Heating				
Induction	0.72	[1.19]	350	60%
Fuel Fired	0.72	3.90	[1142]	18%
Fuel Fired w/Recup.	0.72	2.06	[603]	35%
Small Billet Heating				
Induction	0.72	[1.36]	400	53%
Direct Resistance	0.72	[0.96]	280	75%
Indirect Resistance	0.72	[1.20]	352	60%
Fuel Fired	0.72	5.00	[1465]	14%
Gear Heat Treating				
Induction	0.4	[0.57]	167	70%
Fuel Fired	0.4	2.60	[762]	15%
Shaft Heat Treating				
Induction	0.52	[0.676]	198	77%
Direct Resistance	0.52	[0.620]	182	85%
Indirect Resistance	0.52	[0.809]	237	64%
Fuel Fired	0.52	2.67	[782]	20%
Steel Wire Annealing				
Induction	0.4	[0.61]	180	65%
Direct Resistance	0.4	[0.58]	170	75%
Fuel Fired	0.4	1.80	[527]	22%
Steel Pipe Normalizing				
Induction	0.5	[0.71]	209	70%
Direct Resistance	0.5	[0.59]	172	85%
Indirect Resistance	0.5	[0.83]	244	60%
Fuel Fired	0.5	2.50	[732]	20%

[ ] – denotes calculated energy equivalent

In order to reach industry established objectives, new heating systems need to be employed. Rapid and/or selective heating systems minimize or eliminate many of the inefficiencies of combustion processes. Also, in most cases, rapid metal heating processes are faster, greatly reduce or eliminate environmental emissions, and provide higher levels of product quality by decreasing surface scale buildup and part distortion.

Process Heating – Important Parameters

In process heating applications for metals, the goal is to input enough energy to raise the temperature of the metal to the required level. The specific heat of a material, (c), is the amount of heat required to raise 1 kg of material by 1°C. The heat is measured in Joules (1055 joules = 1 BTU). Table 1-2 below gives the specific heat for various materials.

Table 1-2
Specific Heat of Industrial Materials

	c (kJ/kg°C) at temperature	
Material	**Ambient (20°C)**	**Elevated**
Aluminum	0.90	1.25 (660°C)
Iron	0.44	0.74 (911°C)
Nickel	0.44	0.60 (1000°C)
Paraffin wax	2.89	N/A
Water	4.18	N/A

Specific heat is not a constant, but increases as temperature increases. As shown in Table 1-2, it takes 40%, 50% and 70% more heat, respectively, to raise the temperature of a fixed amount of aluminum, iron and nickel by 1°C at elevated temperatures compared to ambient temperature.

The power requirement for inputting the required energy over a given period of time can be calculated by multiplying the amount of material heated per hour, the rise in temperature, the specific heat (converting 3600 kilo-Joules per 1 kWh) and the heating efficiency.

$$P = \text{throughput (kg/hr.)} \times \text{temperature rise (°C)} \times \text{specific heat (kJ/kg°C)} \times \text{efficiency}$$

$$= \text{kJ/hr.} \div 3600 \text{ kJ/kWh} = \text{kW}$$

In industrial heating, productivity increases are often synonymous with increases in power density. Table 1-3 shows the transmitted power density range for the rapid metal heating process technologies of interest. Generally, heat source power densities of approximately 1000 watts /cm^2 will readily melt most metals.

Table 1-3
Transmitted Power Densities

Process	W/cm^2
Gas	1 - 10
Infrared	1 - 30
Induction	5 - 5,000
Direct Resistance	10 - 10,000
Plasma	100 - 10^5
Electron Beam	1,000 - 10^9
Laser Beam	10,000 - 10^{15}

Technology Selection for Process Heating

When selecting a process heating technology, the process performance characteristics and equipment attributes need to be considered. Also, the depth of heating desired - - through-heating or surface heating - - will dictate the most applicable technology. Tables 1-4 and 1-5 rate the technologies for the two heating applications in terms of their accomplishing the indicated standard of measure – high, medium or low.

Table 1-4
Rapid Metal Heating Technologies for Through Heating

Process	Process Performance								Equipment Attributes						
	Rapidly Achieves Uniform Trough-Thickness Heating	Tends to Achieve Lower Cycle Times	Accommodates Cross Sectional Geometry Variations	Accommodates Part Length Variations	Relatively Insensitive to Material Resistivity	Accommodates Wide Range of Lot Size	Environmental Cleanliness	Process Stability & Repeatability	Tolerance to Shop Environment	Accommodates Different Parts with Minor Equipment Changeover	Relative Capital Investment	Floor Space Requirements	Operator Skill Level Required	Relative Level of Safety	Commercial Acceptance
Induction	H	H	L	M	L	M	H	H	H	M	M	L	M	H	H
Direct Resistance	H	H	L	L	L	M	H	M	M	L	M	L	M	H	L
Infrared	L	M	H	M	H	L	H	M	L	M	L	L	M	H	M
Gas Furnace	L	L	H	M	H	H	L	H	H	H	H	H	L	L	H
H = High (favorable) M = Medium L = Low (Unfavorable)															

Referring back to Table 1-1, it is evident that induction heating uses only one-third to one-fourth as much energy as that required for combustion technologies. Direct resistance through-heating provides an additional 10-30% reduction in energy consumption compared to induction heating, but it is not an optimum technology for all applications. Infrared through-heating requires the least capital investment and works best with flat parts, although zoning and the use of focusing mirrors can broaden its applicability.

Table 1-5
Rapid Metal Heating Technologies for Surface Heating

Process	**Process Performance**						**Equipment Attributes**						
	Ability to Confine Heating to Selected Areas	Easily Produces Shallow (<0.040") Case Depths	Relatively Lower Cycle Time	Accommodates Holes, Chamfers and Other Abrupt Geometry Changes	Accommodates Part Length Variations	Process Stability & Repeatability	Tolerance to Shop Environment	Accommodates Different Parts with Minor Equipment Changeover	Relative Capital Investment	Floor Space Requirements	Operator Skill Level Required	Relative Level of Safety	Commercial Acceptance
Induction	M	M	H	M	M	H	H	M	M	M	M	H	H
CO_2 Laser	H	H	H	H	H	M	L	L	H	M	H	M	M
Diode Laser	H	H	H	H	H	M	M	L	M	L	H	M	L
EB	H	H	M	H	M	M	M	M	H	H	H	L	H
Infrared	M	L	L	L	M	M	L	L	L	L	M	H	M
Gas Flame	L	L	L	L	M	H	H	H	L	H	L	L	H
H = High (favorable) M = Medium L = Low (Unfavorable)													

In all surface heat treating of steel, the surface is hardened to its austenitizing temperature and then allowed to cool rapidly. Extremely high energy density processes, such as lasers and electron beam systems, allow the material to "self quench" - or cool - in ambient air after heating. These processes can deliver energy so rapidly that heat conduction is negligible. The total mass of material being heated at any one instant is very small. This eliminates the need for an additional gas or liquid quench and the associated equipment and material handling labor.

Another more generalized approach to process heating technology selection involves matching energy form value with the information content of a workpiece. This approach is discussed in Appendix A.

2
INDUCTION HEATING

Introduction to Induction Heating

Induction heating is a non-contact method by which electrically conducting materials (generally metals) are heated in an alternating magnetic field.

Induction heating occurs when an electrically conducting object is placed in a varying electric magnetic field and is due to the magnetic properties and resistivity of the material. The varying electric magnetic field induces a current inside the component being heated in a way similar to that of an electrical transformer. The heat is generated only in the part, not in the surrounding area except by radiation of the hot part. The location of the heating can be confined to a specified area on the metal component to achieve accurate and consistent results.

One of the simplest induction heating setups is shown schematically in Figure 2-1. The induction coil, or inductor, is a helical hollow copper conductor (or solenoid) carrying an alternating current (AC) which surrounds a cylindrical workpiece. The AC current produces an alternating magnetic field which generates lines of magnetic flux which pass through the workpiece. The induced "eddy" current path in the workpiece is parallel to but opposite of the currents in the primary induction coil.

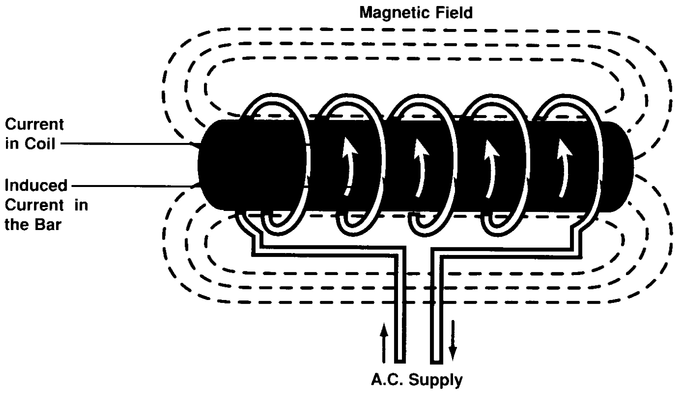


Figure 2-1
Principle of Induction Heating

The induction process generates heat via I^2R losses, the same as the elements in a resistance furnace or toaster. The difference is that the current is "induced" with magnetic flux field, rather than "applied" through physical contact. Eddy currents are more active at the object's surface, decreasing toward the center. The depth where current density drops to 37% is called the penetration depth. The penetration depth decreases with increase of frequency.

An induction heating system includes an induction power source (which provides the required power output at the required power frequency), an induction coil assembly (Figure 2-2), a method of material handling, and some method of water cooling (for the induction coil). An automated material handling system may be added, which includes a motor, gearbox and gear connector to drive wheels that are faced with a high friction material. A chain conveyor powered by the same motor may be included to carry parts to the infeed drive wheels.

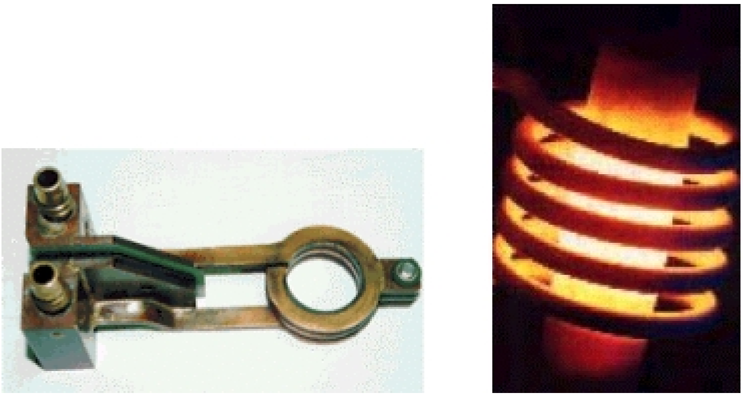


Figure 2-2
Induction Coils

Standard industrial induction equipment size varies from 2’ x 4’ x 6’ units for 10 lb. parts to 6’ x 6’ x 6’ units for handling 600 lb. parts. Smaller and larger equipment is also available. Typical equipment cost varies from $20,000 for a 5 kW benchtop unit to $250,000 for a 100 kW automated billet heating system. Coils cost several hundred dollars for a benchtop unit and $5,000 - $10,000 for a forging preheating unit. A coil for forging preheat would need to be replaced approximately every 6 months.

Through-thickness Heating

Parts should be heated as deeply as possible, but current penetration depth (D_p) should not be greater than one-third of the material thickness. The selected operational frequency must be low enough to achieve deep, even heating throughout the part, but not so low that heating efficiency drops adversely. Current penetration depth is a function of material electrical resistivity (ρ), magnetic permeability (μ) and coil current frequency (f):

$$D_p = 3160 \sqrt{\frac{\rho}{\mu f}} \text{ (English units, in.)}$$

If D_p is greater than 1/3 D, “current cancellation” occurs, heating efficiency declines and the material cannot be heated above the Curie temperature. The higher overall electrical resistivity of ferrous alloys is effectively countered by the extremely low relative magnetic permeability of non-ferrous alloys. This results in a much higher depth of penetration in nonferrous alloys for a given frequency, but only when heating ferrous metals below their Curie temperature (1470°F for steel). In steels, the magnetic permeability drops to a value of 1 (from 2,000 for mild steel) when the steel's Curie temperature is exceeded (which is equal to the permeability of nonferrous metals at all temperatures). This offers the possibility of using a two-stage heating system for maximum efficiency: a lower frequency setting for heating to just below the Curie temperature and a much higher frequency setting to heat above the Curie temperature. Table 2-1 gives the current penetration depth in carbon steel for different coil frequencies.

Table 2-1
Induction Current Penetration Depth (in.) - Carbon Steel

	60 Hz	**200 Hz**	**500 Hz**	**1000 Hz**	**3000 Hz**	**9600 Hz**
Below Curie	0.45	0.25	0.16	0.11	0.06	0.03
Above Curie	2.78	1.50	0.96	0.67	0.39	0.21

It can be noted that penetration decreases as frequency increases. Also, the current penetration depths for achieving temperatures above Curie are considerably deeper than those for below Curie. A frequency of 9600 Hz when heating above the Curie temperature is required to achieve the same depth of penetration as 200 Hz when heating below the Curie temperature. Table 2-2 gives the optimum billet diameter that can be heated with respect to operational frequency and efficiency (assuming maximum efficiency is achieved when part thickness is 4 x D_p). For instance, a frequency of 1000 Hz is the best choice for heating a 3" diameter bar to 2200°F. The frequencies required for efficient heating for forging applications fall mainly in the range from 500 Hz - 10 kHz.

Table 2-2
Optimum Billet Diameter (in.) - Carbon Steel

	60 Hz	**200 Hz**	**500 Hz**	**1000 Hz**	**3000 Hz**	**9600 Hz**
Below Curie	1.75	0.95	0.60	0.43	0.25	0.13
Above Curie	11.0	6.0	3.80	2.68	1.56	0.88

Another factor that can increase heating efficiency is the "coupling factor," defined as the ratio of the billet diameter to the coil ID (i.e. how tightly the coil fits around the billet). For instance, increasing this ratio from 0.4 to 0.7 can increase absolute efficiency more than 10%. An efficiency of about 50 - 70% is typical when heating multiple steel billets moving continuously through a helical induction coil. Bar end heaters operate at efficiencies between 35 - 45%.

Average energy requirements for induction heating applications, such as hot forging, hardening, annealing, normalizing, warm forging and stress relieving, range from 70 - 430 kWh/ton for most carbon steels, stainless steels and nonferrous metals. Hot forging and hardening of copper requires roughly 600 - 700 kWh/ton.

Through-hardening requires quenching the part immediately after heating, usually with a liquid, such as water. Quenching systems can be a separate piece of tooling usually located beneath the induction coil (Figure 2-3) or a separate tank in close proximity to the induction coil into which the part is immersed.

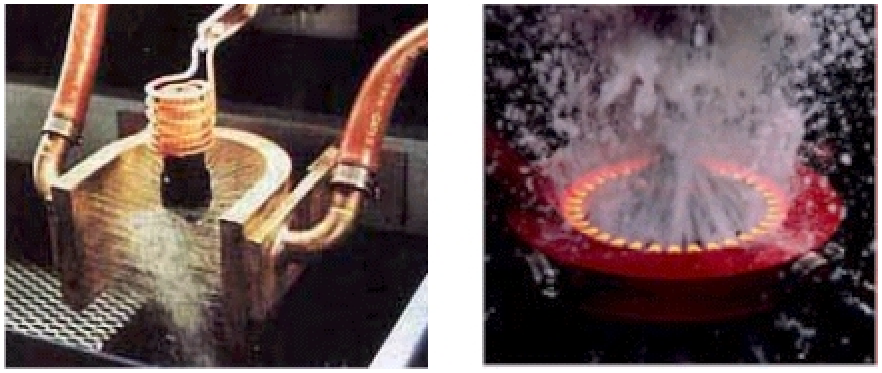


Figure 2-3
Examples of Water Quenching for Induction Heat Treating

Tempering (100 - 600°C) often follows surface hardening in order to reduce final hardness and residual stress concentrations and increase ductility, fracture toughness and yield strength. As a rule of thumb, the induction heating time for tempering is at least twice the hardening cycle time (heating plus quenching). The usual advantages of induction heating over fuel-fired convective heating are multiplied when it is possible to combine induction surface hardening and subsequent induction tempering into an integral system (using separate coils for hardening and tempering).

Surface Hardening

For surface hardening, we are interested in heating to a shallow depth very rapidly and self-quenching using the mass of the workpiece. Table 2-3 gives the power density required to achieve hardening to three different case depths in steel at two processing rates each.

Table 2-3
Typical Induction Heating Parameters for Surface Hardening of Steel Shafts

Case Depth (in.)	**Parameters**		**Processing Time/Rate**	
	Frequency (Hz.)	**Power Density (kW/in.^{2})**	**Single Shot (seconds)**	**Scanning (inches/sec)**
.150	3K	10	4.0	.25
.150	“”	20	2.0	.50
.100	10K	10	2.5	.40
.100	“”	20	1.0	1.00
.050	450K	10	2.0	.50
.050	“”	20	0.6	1.66

As induction frequency increases, doubling the power density reduces processing time up to more than threefold. The general rule of thumb is to size the power supply to produce 10-15 kW of heating per square inch of part surface area. Creative coil design can accommodate inside diameters, outside diameters, blade edges and a number of other part configurations (Figure 2-4).

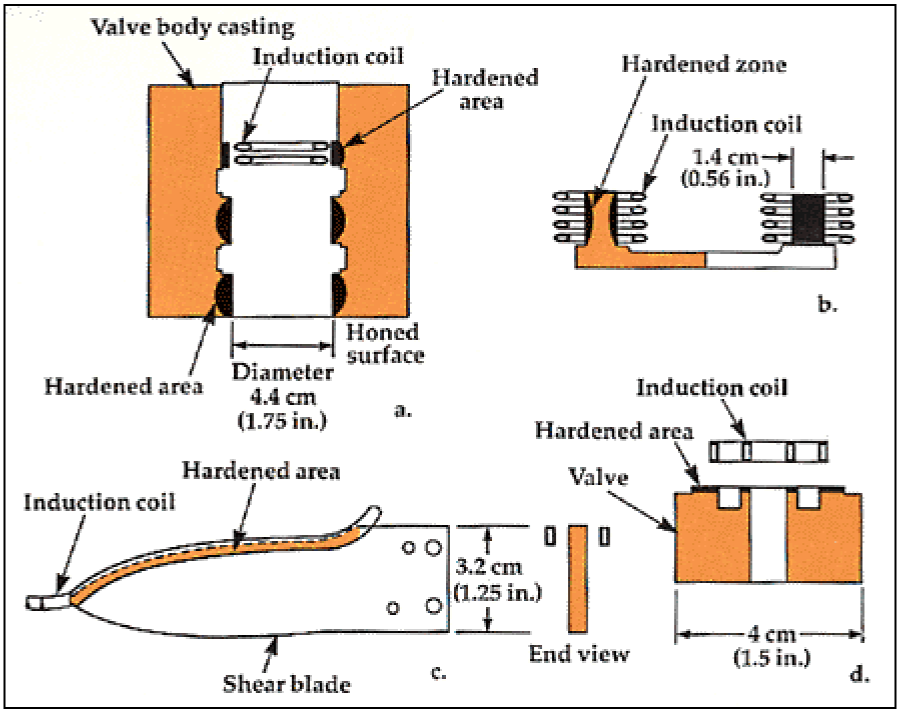

Valve body casting
Induction coil
Hardened area
Hardened area
Diameter 4.4 cm (1.75 in.)
Honed surface
a.
Hardened zone
Induction coil
1.4 cm (0.56 in.)
b.
Hardened area
Induction coil
3.2 cm (1.25 in.)
Shear blade
End view
c.
Induction coil
Hardened area
Valve
4 cm (1.5 in.)
d.

Figure 2-4
Induction Coil Designs for Surface Hardening

Applications

Heat treatment of metals - hardening, tempering, and annealing.

Using a lift/rotate submerged quench method, the pop up (Figure 2-5) design offers minimal cycle time and part handling. The integrated transistorized power supplies range from 75 kW - 225 kW @ 3, 10 or 30 kHz. With two- or three-position capability, the spindle rotation ranges from 0-200 RPM and spindle loads handle up to 150 pounds.

Transverse Flux Induction Heating (TFIH) lets the user heat a wide variety of strip widths with the same inductor and allows adjustments to the system without shutting down the line. With TFIH (Figure 2-6), the coil is in the shape of a pancake and is located on one side of the sheet or strip (as opposed to being coiled around the strip). Variable-width inductor coil design (staggered J-sections) allows easy adjustment to various strip widths.

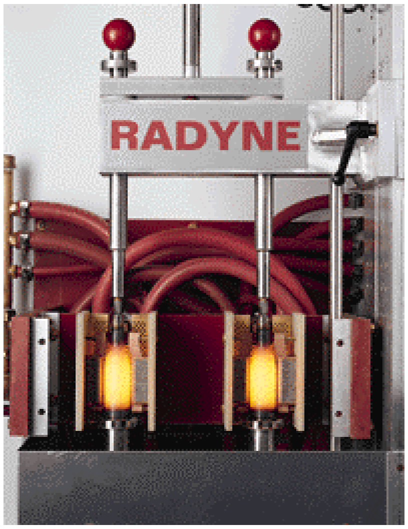


Figure 2-5
Pop Up Type Unit

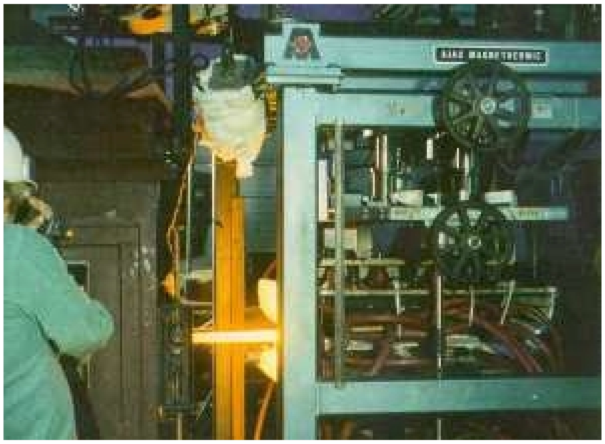


Figure 2-6
TFIH of Continuous Strip

With TFIH strip annealing, processing costs can be cut up to 22%, and scale formation reduced as much as 67% compared to fuel-fired systems. TFIH also accurately controls temperature from edge to edge using a fraction of the space of conventional heating facilities.

Preheating – preventing the undesirable extraction of heat from subsequent processing.

Induction Strip Galvannealing is easily integrated with existing coating equipment and presents many cost cutting opportunities for applications such as coating line preheating and taper heating for more uniform rolling.

Heating prior to deformation - forging, swaging, upsetting (Figure 2-7), bending and piercing.

The amount of scale formed is reduced to 0.5 per cent or less using induction heating. This can reduce material waste and increase die life up to 250%. Modular billet heating systems (Figure 2-8) can accommodate billets up to 254 mm (10 inches) in a cross section of both ferrous and non-ferrous materials.

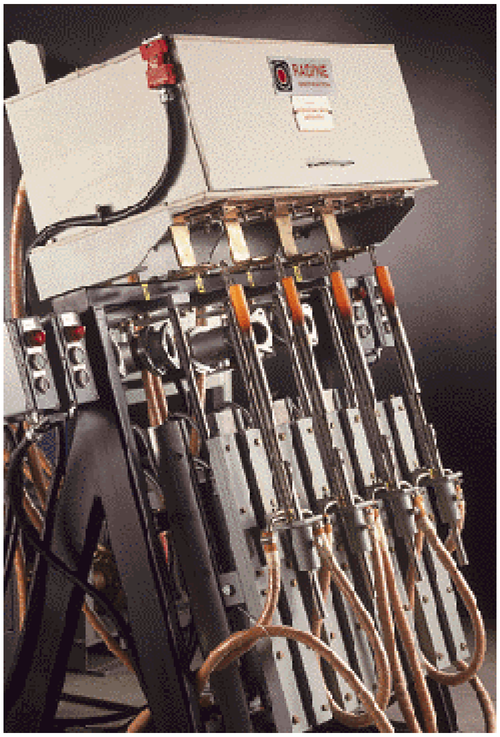


Figure 2-7
Bar End Heater

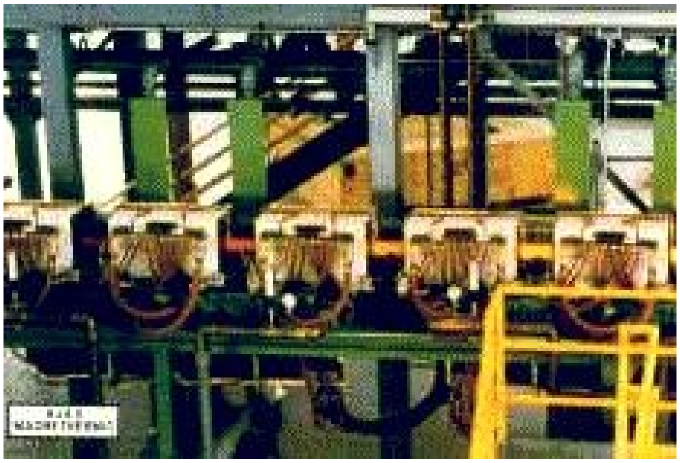


Figure 2-8
Ajax 2000 kW Billet Heating

Brazing and soldering - brazing of steel, brass and copper to each other or in combination and joining aluminum to aluminum.

In brazing, the base material is heated and the filler material melted to provide a bond between both materials. A silver alloy filler material that melts and flows at temperatures from 1150°F to 1400°F (well below the melting temperature of the base material) is commonly used for induction brazing. The filler material can be in the form of a rod, coil, powder or preform. Applications include joining dissimilar materials, such as carbide teeth to a steel tool holder, a cast iron nose to a steel base, or a tungsten carbide wear pad to a titanium compressor blade. Temperature uniformity of the base material is critical because braze filler material flows preferentially toward the hottest area. Adding of flux and controlled atmospheres keeps the parts clean and reduces the formation of oxides during heating.

Shrink fitting – Applicable to the manufacture of many products, such as, shrinkfitting of motor rotors to shafts, shrink fitting of shell casings for compressors.

Advantages

Induction heating systems provide a fast efficient method of heating materials to a precise temperature. The equipment uses clean, readily available electric power to heat either the entire surface of the workpiece or selected areas. Heat depth can be adjusted to just the surface or the entire cross section. Temperatures can be controlled to meet the requirements of the job. The most notable advantages of induction heating include:

- Precise heat location
- Rapid heating of parts
- Extended forge die life (2X)
- Superior mechanical properties
- Minimal workpiece distortion
- Fast start-up of equipment
- Lower energy costs (surface hardening)
- Ease of automation
- Easier process control and monitoring
- Decreased scale and increased scrap savings
- Compact footprint
- Minimal environmental impact

Safety

The greatest danger from the induction heating process is the high voltage (400 - 30,000 volts) in the power supply, high-frequency generators. Transistorized units tend to operate at the lower voltages (approximately 1500 volts), but that still requires caution. Injuries from high frequency voltages tend to produce severe tissue damage. Fatalities are unlikely because the current travels on the surface of the victim’s body. Care must be taken to avoid inadvertent heating of metal jewelry (such as rings) by bringing them near the induction coil during operation. People with implanted medical devices should stay 3 - 4 feet from induction power supplies and coils during operation.

Advances

Flux Concentrators

When properly located, flux concentrators increase heating in desirable zones and reduce heating in undesirable zones. Magnetic field distribution and heat patterns are controllable, efficiencies increase, cycle times decrease and energy savings result from using flux concentrators. A bare coil's magnetic field is distributed over a large area which causes undesired heating of adjacent components in close proximity to the coil. Magnetic flux concentrators (Figure 2-9) strongly reduce the back-path magnetic resistance (due to the high permeability of flux concentrators) and concentrate the induced power in the desired area of the workpiece.

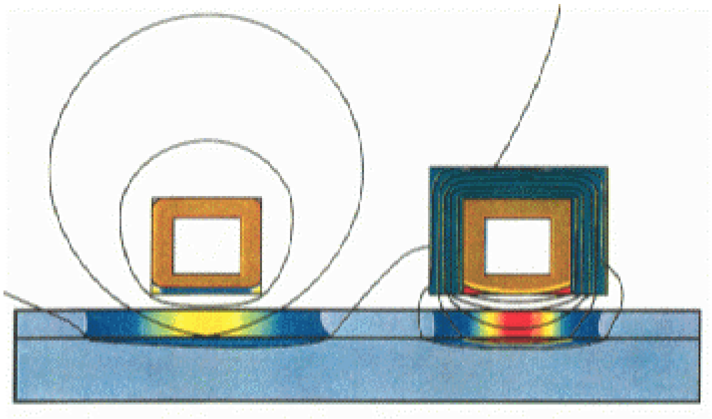


Figure 2-9
Effect of Using Flux Concentrators

Transistorized Power Supplies

Historically, induction heating power supply technologies have evolved from tubes to silicon-controlled rectifier power units. A move to transistors began in 1988 with the introduction of small, high-frequency power supplies using insulated gate bipolar transistors (IGBTs) and metal oxide semiconductor field-effect transistors (MOSFETs). The advantages of IGBT-type units include a single design that can be used over a wide range of frequencies from 1 - 50 kHz. The newest IGBT power supplies use microprocessor interfaces, diagnostic capabilities and fiber optics at higher frequencies. MOSFETs are most suitable for high-frequency power supplies greater than 50kHz. Both types increase efficiency, reduce maintenance (no tubes to replace), improve safety (lower internal voltages), improve quality (stable output), reduce cooling requirements and achieve constant power factor for varying output powers compared to traditional non-transistor power supplies. SCR power supplies are still attractive for high power applications above 1,000 kW.

Dual Frequency Systems

Dual frequency systems are used more for surface hardening parts with varying contours, such as gear teeth (Figure 2-10). The gear is induction-heated by medium frequency to the deep region for several seconds and is reheated by high frequency for a short period (taking advantage of the surface skin effect of high frequencies) followed by quenching by water spray. For instance, a conventional induction heat treatment might use a single frequency of 25kHz for 2.8 seconds. A dual frequency induction system might use 3kHz frequency for 1.8 sec in preheating and 150kHz for 0.18 sec during final heating. This new technique produces the desired thin-surface hardening with little distortion and high compressive residual stresses.

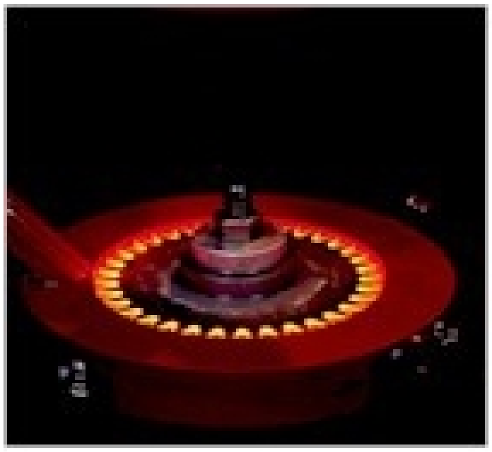


Figure 2-10
Dual Frequency Heat Treating of Gear Teeth

EPRI References

EPRI Report

- CR-107046A Induction Heating for the Steel Industry: Technology Assessment and Economic Analysis Model
- CR-107876 Technology Guidebook for Electromagnetic Induction Heat Treating Processes
- CR-108581 Continuous TFIH Annealing of Stainless Steels (92-4)
- TR-111818 Induction Heat Treating Marketing Kit

EPRI *TechApplication*

- TA-106245 Production of Galvannealed Steel by Induction Heating
- TA-104083 (V8-P2) Induction Hardening for Durable Camshafts
- TA-102594 Induction Slab Heating Works for Washington Steel
- TA-102575 (V1-P2) Post Grinding Induction Hardening
- TA-102572 (V1-P7) Induction Through-Heating for Forging

- TA-102572 (V1-P11) Induction Hardening with Flux Field Concentrator
- TA-102572 (V1-P20) Induction Heating Billets for Forging
- TA-102572 (V2-P2) Induction Susceptor Furnace

EPRI *TechCommentary*

- TC-110479 Improvements in Induction Heating Technology
- TC-104439 Transverse Flux Induction Heating
- TC-102257 (V2-P1) Induction Heating Technology
- TC-102573 (V2-P2) Induction Heat Treatment
- TC-102573 (V2-P3) Selective Induction Heat Treatment
- TC-102573 (V2-P4) Induction Tempering

EPRI FOCUS: Performance of Induction Hardened Gears NL-108244-P3,R1

EPRI Electrotechnology Update TB-110221 Induction Heating

EPRI Innovators IN-103015 Induction Heating Expertise Improves Competitiveness of Metal Extruders

3

DIRECT RESISTANCE

Introduction to Direct Resistance Heating

Heat can be produced in electrically conducive material by passing an electric current “directly” through it. Hence the origination of the term “direct resistance” heating.

The part to be heated is short-circuited across the secondary of a single-phase transformer (Figure 3-1). Thus, the secondary becomes the part itself, the contacts and the original tranforms secondary winding. Clamp or roll types of electrodes must be used to make the contact with the workpiece. These current input contacts are the most delicate part in this heating process. To assure adequate contact, the section to be heated must be carefully cut and as clean as possible (free of rust and scale). The maximum current supported by a contact point is between 4,000 A and 10,000 A. Multiple lateral contacts can replace or augment end contacts to achieve higher current densities.

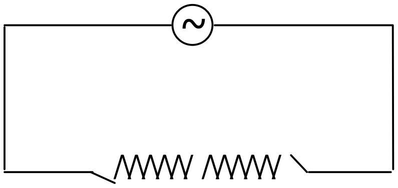


Figure 3-1
Direct Resistance Heating Circuit

Below the Curie point temperature (about 750°C for steels), AC heating produces an intense skin effect, such that the surface temperature of the product is higher than the core temperature. The temperature difference between the center of the part and the surface reaches 100 to 150°C during this phase for magnetic steels. Conversely, as soon as the Curie point is exceeded, the thermal gradient tends to reverse. With very short heating times (<20 seconds), the temperature distribution is more or less uniform throughout the cross-section. For longer heating times, the temperature in the center exceeds the surface temperature by 30 to 50°C. The higher core temperature compensates for most of the energy lost by radiation, convection and conduction during product transfer.

To ensure safety and to prevent excessive heating (which the contacts might not withstand), current flow is accomplished using low voltage, generally between 5 and 48 V. AC current at line frequency is generally acceptable for long, thick products, although use of DC current diminishes skin heating effect and eliminates the inductance load of AC current. DC current is always necessary for thin, flat products due to the skin effect when using AC current. The power factor for AC heating is about 0.3 to 0.4 on starting, increasing to 0.85-0.95 at the end of heating. For installations over several hundred kW, it is necessary to install a battery of capacitors to compensate for the power factor.

Heating time depends mainly on current density. The temperature of a square cross-section billet of 42 x 42 mm can be taken to 1,200°C in slightly less than 30 seconds with a current density of 5 A/mm^2. At a current density of 7 A/mm^2, the same billet would reach 1,200°C in half the time. In practice, normal heating times vary between about 10 seconds and 2 minutes. Allowing for downtime due to handling of the parts, the necessary power for steel is between 400 and 500 kW for a practical rate of 1 ton per hour. An installation can handle several parts at one time when mounted in parallel. Another variation is to pass individual pieces over a series of heating stations where temperature rise takes place gradually at each station. This allows parts with a smaller length-to-diameter ratio to be economically heated by proper sizing of the power transformers.

Through-heating equipment is relatively simple and consists of the power input contacts and a line frequency power supply and controls. The power contact electrodes are the critical component since they determine how much current can be passed to the workpiece, and heating rate depends on current flow. Contacts are often water-cooled to prolong their life. Material directly under the contacts does not heat nearly as much as the material between the contacts. Surface heating for hardening takes advantage of the skin effect of radio frequency (RF) current to localize the heat and decrease contact losses. A typical through-heating direct resistance system would cost $250,000 - $350,000.

For a given length of product, through-heating conduction efficiency falls nearly linearly as the product diameter increases. Conduction efficiency is about 80 - 90% for through heating products with a length-to-diameter ratio over 20. Conduction efficiency for surface heating averages around 50%.

Applications

The major metalworking applications of direct resistance heating are heating prior to forming (preheating), heat treating (annealing and hardening), and seam welding. Direct resistance heating offers manufacturers precise heat control for applications such as:

- Preheating billets for forging
- Producing unique hardening patterns on metals
- Selectively heating forging dies
- Preheating coil springs prior to bending
- Heating mining roof bolts for forging

A recent application is curing of heat set epoxies on the wrapped windings of electrical transformers.

Direct resistance heating works only for electrically conductive workpieces and is problematic for parts with non-uniform cross-sections. Generally, to obtain high production rates and adequate efficiency, the ratio of length-to-diameter must be high, equal to or greater than eight. The longer the product to be heated, the lower the line and contact losses and the higher the efficiency. Direct resistance heating systems are designed to provide efficient, automatic processing of workpieces ranging from automotive drive shafts and stabilizer bars (Figure 3-2) to steel bars up to 26 ft. long (Figure 3-3).

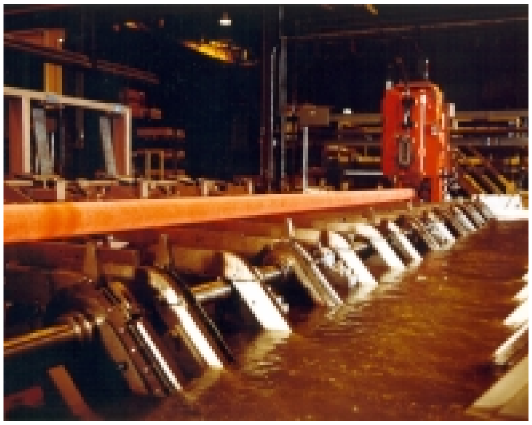


Figure 3-2
Direct Resistance Heating of Automotive Stabilizer Bars for Upsetting and Annealing

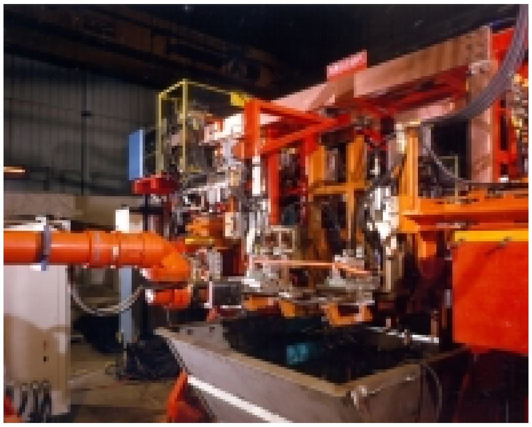


Figure 3-3
Direct Resistance Heating of 26' long x 5" Diameter Steel Bar to 1000°C in 13 Minutes

Direct resistance is used to preheat round or square metal bar stock prior to operations such as forging, stamping, extrusion, bending (for chains) and upsetting. Workpiece material and shape are both important in determining the success of direct resistance heating. Direct resistance readily heats materials with fairly high electrical resistivity, such as carbon and low-alloy steels and nickel alloys. Low electrical resistivity materials such as copper and aluminum are often not cost-effective. To ensure even heating, the cross section of the workpiece should generally be uniform. However, workpieces with variations in cross section, such as rivets, can sometimes be uniformly heated by pulsing the power during the heating cycle.

Newer electrode designs have made the condition of the workpiece ends less critical. However, they should be fairly smooth and scale-free to ensure good contact with the power electrodes and to maximize current flow. Finally, processing is most economical for loads of less than 2,000 lbs./hr. Traditionally, ferrous materials are preheated to around 2300°F before hot working. There is a trend towards "warm forging," which is done at lower temperatures of 800 - 1700°F. Direct resistance heating works equally well for both since the final workpiece temperature depends only on heating time.

In surface hardening applications, two power contacts are attached to the workpiece just beyond the ends of the area to be hardened. A water-cooled "proximity conductor" is placed close to the workpiece surface, and connected between the electrodes. When radio frequency (RF) current is passed between the power contacts, the narrow strip of workpiece surface under the proximity connector heats up. Heating depth is about 0.03 inches. The strip reaches hardening temperature (about 1600°F in steel) in about 0.5 seconds, so the surrounding workpiece material remains cool. Since the process is self-quenching, there is almost no part distortion. The resulting hardening pattern mirrors the shape of the proximity conductor. Many different, well-defined hardening patterns are possible, on either flat or tubular workpieces.

Direct resistance through-heating and surface hardening differ in their power supply requirements. A line frequency supply works for through-heating, whereas hardening usually requires a RF supply. Since RF power supplies are expensive ($100,000 to $200,000), direct resistance hardening is most economical in high volume applications.

Advantages

Direct resistance heating may well be the simplest and most economical method for through-heating or heat treating workpieces of the appropriate material and geometry.

By generating heat within the workpiece rather than in a furnace, direct resistance heating offers these benefits over fuel-fired furnaces:

- Rapid startup and heating
- Temperature distribution favorable to transformation
- Higher production rates
- Ease of automation
- Reduced metal scale (0.5% loss vs. 2% fuel-fired loss)
- Cleaner working environment
- Reduced floor space requirements (15% to 20% less)
- Low capital equipment investment
- Lower maintenance, and
- High thermal efficiency (up to 90%)

Commercial Acceptance

Direct resistance heating has not been widely accepted as an alternative to gas-fired furnace heating. There are only a few domestic suppliers of direct resistance heating equipment and the cost differences between comparable electric and gas heating applications has not been established. Therefore, the cost advantages for direct heating applications cannot be stated.

Safety

Direct resistance heating is considered a relatively safe process because there are few moving parts and the operating voltages are very low, normally less than 20 volts.

Advances

The biggest advance in direct resistance heating is the use of three power supplies: one heats the length while the other two transmit the heat through the ends under the contacts. This solves the problem of scrapping the unheated ends under the electrical contacts.

EPRI Resources

TechCommentary

- TC-102573 (V3-P8) Direct and Encased Resistance Heating

TechApplication

- TA-102572 (V1-P19) Direct Resistance Heating Blanks for Forging

EPRI Bulleting

- TB-112194 Direct Resistance Heating: A Low Cost Way to Preheat and Heat Treat Steel Bars

4
LASERS

Introduction to Lasers and Laser Heating

"Light Amplification by Stimulated Emission of Radiation" (lasers) are possible because of the way light interacts with electrons. Electrons exist at specific energy levels, or states, characteristic of that type of atom or molecule. The energy levels are like rings, or orbits, around a nucleus. Electrons in outer rings are at higher energy levels than those in inner rings. Electrons can be bumped up to higher energy levels by the injection of energy (stimulated emission or excitation), by a flash of light for example. Then, when an electron drops from an outer to an inner energy level, excess energy (photon) is given off as light. The wavelength, or color, of the emitted light is precisely related to the amount of energy released

Most lasers are constructed of three important elements, a gain or amplifying media, a pumping source and a resonant cavity (Figure 4-1). The gain media is the location of the electron energy states which participate in stimulated emission. The excitation (pumping) source provides the energy to set the energy states up so stimulated emission can occur, and the resonant cavity provides the path for the photons.

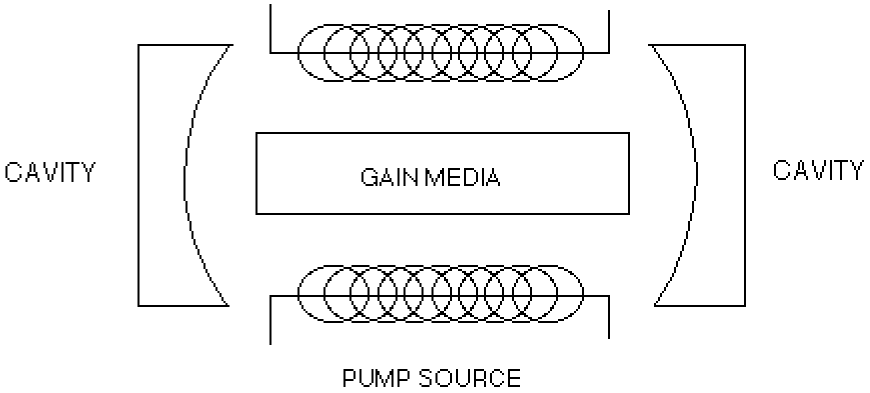


Figure 4-1
Principle Parts of a Laser

There are several ways of pumping a gain (amplifying) medium. When the amplifying medium is a solid, pumping is usually achieved by irradiating it with intense light. This light is absorbed by atoms or ions within the medium and raises them into higher energy states. When the amplifying medium is a gas, it has to be contained in some form of enclosure or tube and is often pumped by passing an electric discharge through the gas itself. For AC and DC excitation, the electrodes are located inside the tube. Figure 4-2 below illustrates pumping by passing a discharge longitudinally through the gaseous amplifying medium. However, in some cases, the discharge takes place transversely from side-to-side (radio frequency excitation) with RF electrodes located outside the tube. Many lasers that are pumped by an electric discharge can produce either a pulsed output or a continuous output depending upon whether the discharge is pulsed or continuous.

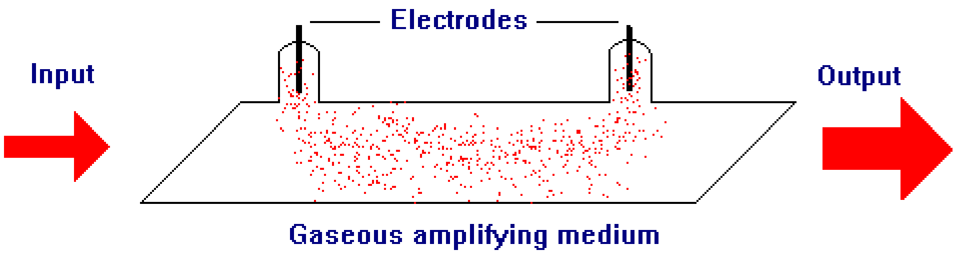

Electrodes
Input
Output
Gaseous amplifying medium

Figure 4-2
AC and DC Gas Medium Excitation

The functions of the resonant cavity are simply to 1) physically shorten the laser and 2) tailor the profile of the electromagnetic mode. In essence, the laser is simply "folded up" between the two cavity mirrors. If we do not confine this system in a special way, it would radiate spontaneously in so many different directions that we would not be able to sustain stimulated emission. This constraint can be achieved by bounding the laser medium between two mirrors to form an optical resonant cavity (Figure 4-3). One mirror is totally reflecting and the other partially reflecting to ensure that some laser light can escape and provide useful optical power.

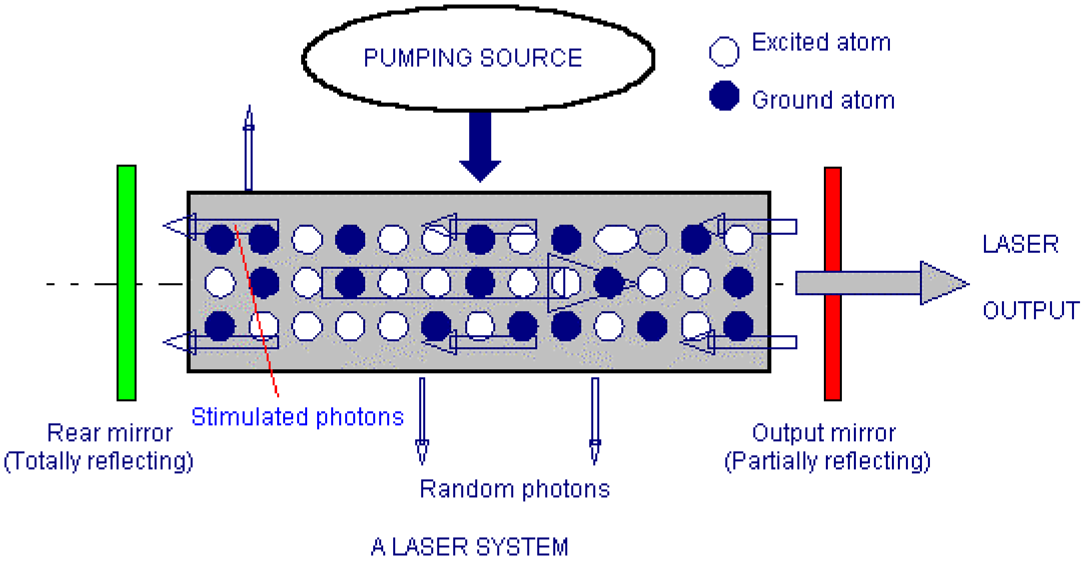

PUMPING SOURCE
○ Excited atom
● Ground atom
LASER
OUTPUT
Rear mirror
(Totally reflecting)
Stimulated photons
Random photons
Output mirror
(Partially reflecting)
A LASER SYSTEM

Figure 4-3
Optical Resonant Cavity

A laser operates only at those wavelengths for which an integral multiple of wavelengths fit into the resonant cavity. The set of possible integral multiples of the cavity length is termed the set of longitudinal modes of the cavity. There are an infinite number of integral multiples of cavity length. However, only a finite number (1-2000, depending on the laser) will fit into the gain profile of the laser gain media. Thus, the actual output profile of the laser (Figure 4-4) is the intersection of the set of possible longitudinal modes with the gain curve.

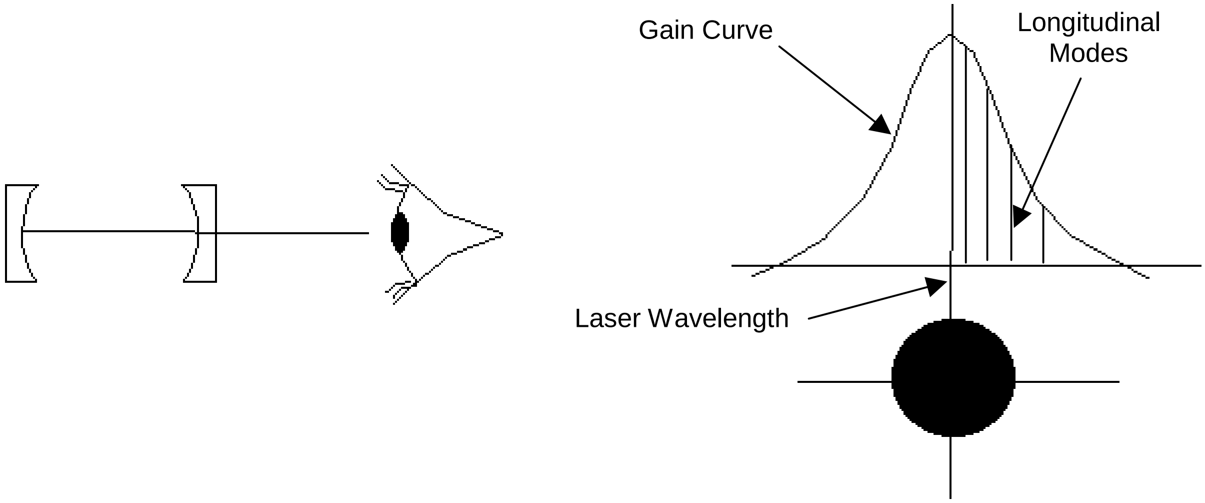

Gain Curve
Longitudinal Modes
Laser Wavelength

Figure 4-4
Output Profile of a Laser

The output "spot" of the laser beam is called the transverse electro-magnetic mode (TEM) which establishes the laser beam's radial energy distribution. The wavelength of the laser is the center of the operating wavelength. Optical radiation covers the wavelength region from approximately 0.1 - 1,000 micrometers (Figure 4-5). A micrometer or μm is one millionth of a meter (10-6 m) and is often called a "micron" for short. Wavelengths for heat treating lasers are either 10.6 microns for CO2 lasers or roughly 0.8 microns for diode lasers.

The most commercial lasers, the TEM has a Gaussian cross-section profile (Figure 4-4) that is called TEM00. This mode provides the highest quality beam attainable and can be highly focussed.

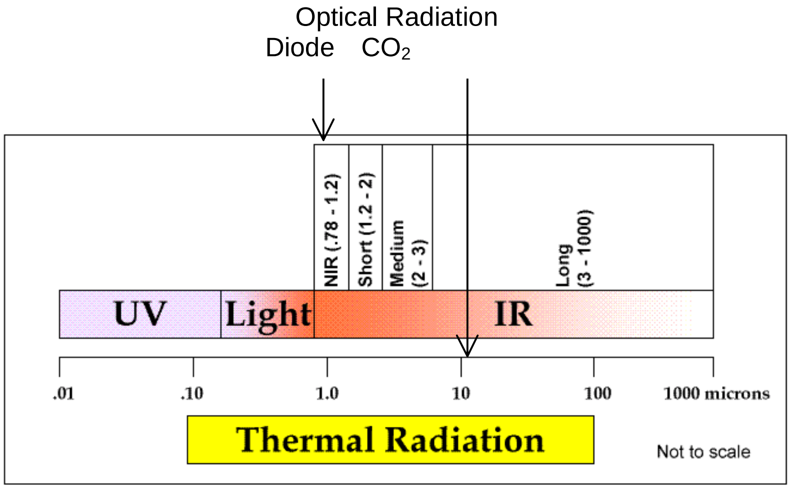

Optical Radiation
Diode
CO_2
NIR (.78 - 1.2)
Short (1.2 - 2)
Medium (2 - 3)
Long (3 - 1000)
UV
Light
IR
.01
.10
1.0
10
100
1000 microns
Thermal Radiation
Not to scale

Figure 4-5
Wavelength Region of Lasers

Beam motion plays a major role in laser processing. Light can be made to form any desired pattern using spinning, vibrating, or static mirrors. Access to inside surfaces can be accomplished using a periscope mirror arrangement, usually water-cooled because it is close to hot metal.

Gas Lasers

A Carbon dioxide (CO_2) laser system is shown in Figure 4-6. Three gases; CO_2, Nitrogen (N_2) and Helium (He); are mixed and fed into one end of a discharge tube at a pressure of a few pascals. The gas flows down the end of the tube in about one second and is pumped out the far end with a mechanical forepump (Roots blower or turbine). An electrical discharge is maintained between the metallic end flanges of the tube. The ballast resistance is required because of the negative dynamic resistance of the discharge. With a fully reflecting mirror on the left and a partially transmitting mirror on the right, the device becomes a laser which radiates in the far infrared at a wavelength of 10.6 microns.

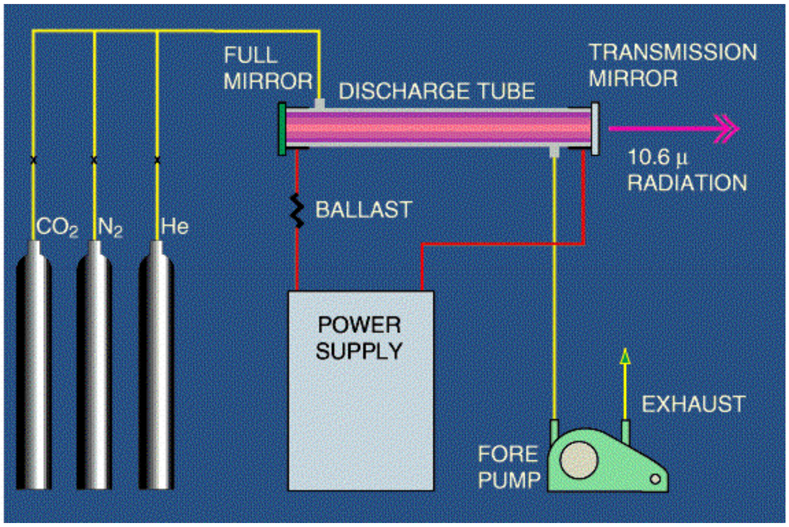


Figure 4-6
Typical CO_2 Laser Equipment

The great interest in CO_2 lasers stems from their continuous power capability, high efficiency and ease of construction. Table 4-1 illustrates their advantages over other gas lasers.

Table 4-1
Properties of Gas Lasers

Laser Type	Linear Power Density (W/m)	Maximum Power (W)	Power Efficiency
He-Ne	0.1	1	0.1%
Argon	1-10	50	0.1%
CO_2	60-80	10,000	15-20%

A 5 kW CO_2 laser beam can easily be focused to a spot 0.5 mm in diameter, producing a unit area power density of 2.5 MW/cm^2 which would easily melt most metals. For surface hardening, if that same 5 kW beam is focused into a 13 mm square, the power density drops to 3 kW/cm^2 and avoids melting. It is possible to harden steel with a 200 W laser, but most practical heat treating jobs need at least 3 kW of laser power. To obtain a 0.8 mm case depth, the processing rate (cm^2/s) can be calculated as

$$\text{Processing Rate} = \frac{P}{4{,}000}\ \text{cm}^2/\text{s where P = power in watts}$$

Processing rate is directly proportional to input power. As input power increases, heat treat time must decrease to avoid melting. Lower heat treat times at the same transformation temperature slows heat diffusion from the metal surface, resulting in more shallow case depth. Table 4-2 shows the relationship between input power density and case depth for achieving a surface temperature of 1450°C. Case depth is inversely proportional to power density.

Table 4-2
Case Depth as a Function of Laser Power Density

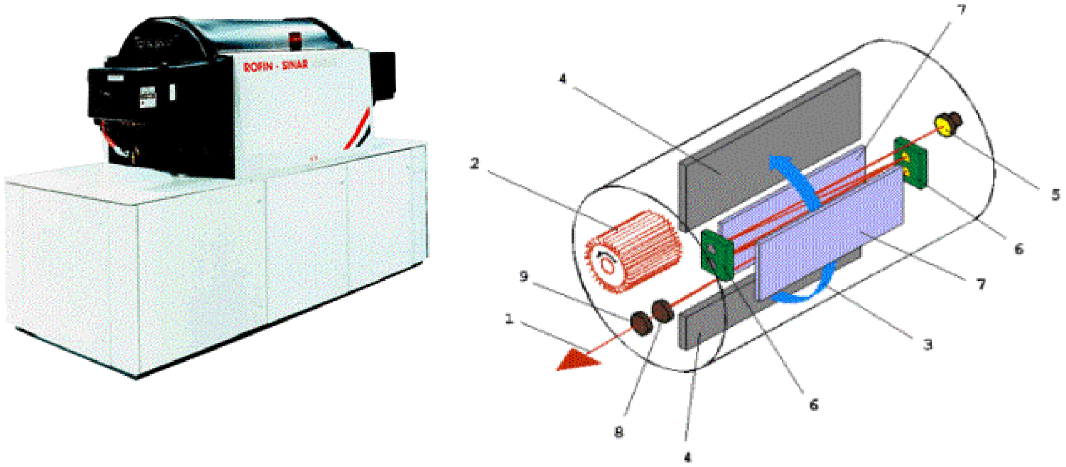
KW/cm^2	Heat time, s	Case Depth, mm	Cooling time to 300°C, s
100	0.0004	0.017	0.0021
10	0.04	0.17	0.21
1	4	1.7	21
0.1	400	17	2100

Performance of CO_2 lasers may be optimized in several ways. The parameters that affect such optimization for flowing gas systems are:

- Tube length, diameter and wall temperature
- Gas mixture, pressure, and flow speed
- Optical mode control, wavelength control, and output coupling
- Electrical discharge control and current density.

In addition, for sealed-off (non-flowing) CO_2 lasers, it appears that the gas purity and tube materials are also important.

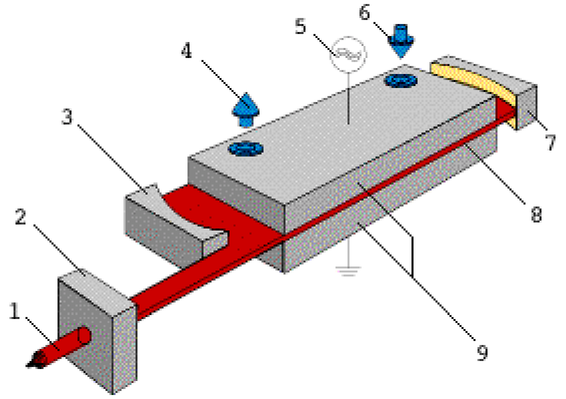
A CO_2 laser can be operated either with DC, AC, RF (radio frequency) or pulses, but the maximum average output power is achieved either with DC or low-frequency AC applied directly to the electrodes. Achievable power is less with RF, probably because it is hard to keep a long length of the discharge uniformly excited. However, the electrodes in RF-excited lasers can be mounted externally and in close proximity to the quartz glass tube that contains the CO_2 gain media (Figure 4-7). External electrodes do not deteriorate or introduce contaminants into the resonator, increasing uptime, decreasing gas consumption and eliminating power degradation over time. In addition, uniform RF excitation of the gas produces good beam quality regardless of power level. At power levels from 75% to 100%, RF excited lasers can run in a continuous wave (CW) mode as opposed to a normal pulsed mode.



1. Laserbeam
2. Tangential blower
3. Gas flow direction
4. Heat exchanger
5. Rear mirror with real time power monitor
6. Fold mirror
7. HF-electrodes
8. Output mirror
9. Output window

Figure 4-7
Components of an RF Excited Laser

The revolutionary design of the Slab RF laser (Figure 4-8) offers such decisive advantages as extremely compact design and the elimination of an external gas supply. Gas consumption is negligible, and the gas cylinder integrated into the laser head lasts for approximately 12 months of continuous use.



1. Laserbeam
2. Beam shaping unit
3. Output mirror
4. Cooling water
5. RF excitation
6. Cooling water
7. Rear mirror
8. RF excited discharge
9. Waveguiding electrodes

Figure 4-8
Components of Slab RF Laser

Front and rear mirrors and two parallel RF-electrodes form the optical resonator. Excitation of the laser gas takes place in the RF field between the water-cooled electrodes. Water-cooled electrodes (diffusion-cooled) dissipate the heat generated in the gas. Thus, the conventional gas circulation systems involving Roots blower or turbine are not required. A beam shaping module is integrated into the laser head and produces a high quality, round symmetrical beam. The resonator design produces a 45° linear polarized beam.

CO_2 lasers have traditionally been the choice for surface hardening applications because of their economical high power output. However, the reflectivity of metals presents a problem for CO_2 and other lasers operating with a wavelength in the far infrared (10.6 microns for CO_2 lasers). An energy absorbing coating such as colloidal graphite, black oxides, india ink, and zinc phosphate is required on a surface to be hardened. Table 4-3 shows the reflectivity to a CO_2 laser beam of carbon steel with various surface treatments.

Table 4-3
Steel Reflectivity to CO_2 Laser Light

Surface Condition	Reflectivity
Polished	91%
Unpolished	89%
Shot-peened	45%
Phosphate coating	22%
Graphite coating	12%

Black spray paint and colloidal graphite are frequently the most efficient and economical coatings. Nevertheless, the coating application process adds cost and requires additional process control. The level of absorption is determined by the thickness of the coating, adding another variable to the process.

The estimated cost for a 6-8 kW CO_2 laser for surface hardening is \$500,000 - \$600,000. The cost for maintenance (parts and labor) and consumables is \$10-\$12 per operating hour.

Semiconductor Lasers

Semiconductor lasers are the most basic type of laser, consisting of a small rectangular slab of semiconductor material with two cleaved facets to act as mirrors. In a laser diode, the photons must be modeled as collective entities traveling in a confined fashion down a waveguide. Semiconductor photon sources can be "pumped" by a variety of techniques. These include pumping with another optical source (photopumping), pumping with an electron beam, or pumping via a silicon doped pn-junction. However, the most common technique is via a pn-junction (Figure 4-9).

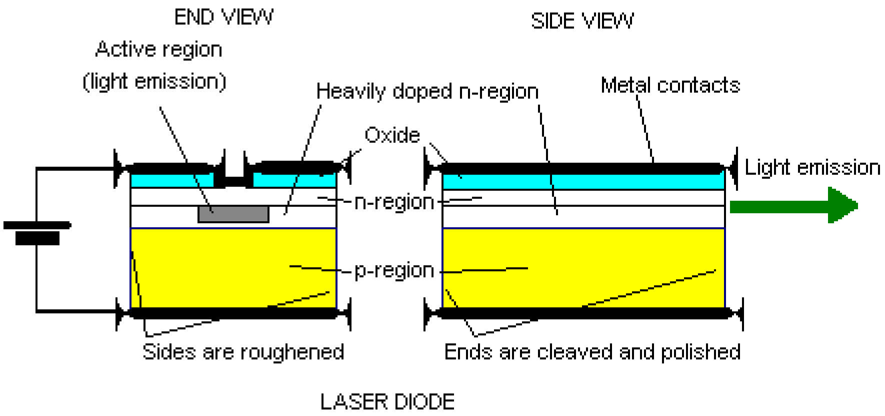

END VIEW
Active region
(light emission)
Heavily doped n-region
Oxide
SIDE VIEW
Metal contacts
Light emission
n-region
p-region
Sides are roughened
Ends are cleaved and polished
LASER DIODE

Figure 4-9
pn-Junction Pumped Semiconductor Laser

Semiconductor lasers are quite different from conventional lasers. In particular:

1. The gain of the laser material is very high.
2. The beam is not Gaussian. Its profile tends to be elliptical and the beam divergence tends to be large.
3. The gain spectrum is large (many THz or hundreds of angstroms).
4. The short cavity (several hundred microns) means that the longitudinal mode spacing is much larger than that of a conventional gas or solid state laser (on the order of GHz or angstroms).

The beam source itself is a so-called laser bar with a size of 10 mm x 0.6 mm x 0.1 mm (Figure 4-10), which is mounted on top of a cooling unit. Today's state-of-the-art output power is in the range of 30 to 50 Watts per bar. By stacking these bars, laser power of several bars can be combined by optical superposition of the single beams. Accordingly, such a configuration of loose bars is called a "stack." By further combination of two or three stacks, it is possible to reach an output power of up to 6000 Watts in the wavelength range of 800 to 980 nm (Figure 4-11).

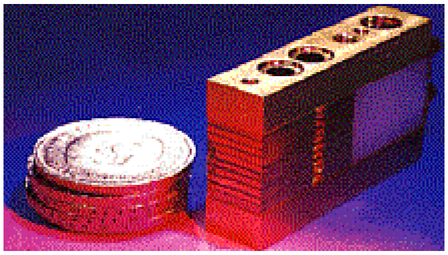


Figure 4-10
Semiconductor Laser Bar

ROFIN DL 025

Figure 4-11
Industrial Diode Laser

High-powered diode lasers run at 0.8 - 0.9 microns wavelength in the near infrared range. Metals absorb this spectrum fairly readily. An energy absorbing coating is not necessary for surface hardening applications. Diode lasers tend to be comparable or slightly less costly on a per-watt basis than CO_2 lasers and are much more energy efficient. A 1 kW CO_2 laser draws about 10 kW while a 1 kW diode laser draws only 1.5 kW of input power.

Standard diode lasers purchased off the shelf are available up to 2.5 kW. A 2kW diode laser costs roughly $160,000 and outputs a 2mm x 4mm beam size which is preferred for surface hardening. The diode stack is guaranteed for 10,000 hours (actual laser output, not idle time) and should operate for 20,000 hours before refurbishment is necessary. The cost of refurbishment is usually about 30% of the original system cost.

Applications

Any material that can be treated with conventional induction surface hardening processes can be heated with a laser. The areas in which lasers are most effective are where very high concentrations of energy are needed or where the region to be processed is small or of unusual shape. Among the materials best suited for laser surface hardening include:

- Cast iron
- Carbon steels $\geq 0.40\%$ carbon content
- Alloy steels $\geq 0.40\%$ carbon content
- Air and oil hardening types
- Superalloys (depends on carbon content)

Table 4-4 lists some laser surface hardening applications along with some details.

Table 4-4
Selected Laser Surface Hardening Applications

Part Type	Part Source	Dimensions	Steel Material	Case Depth (0.001 in.)	Hardness (Rc)
Idler Rolls	Sheet Steel Leveling Line	8” dia. X 80’ long	52100	40 - 60	64
Bearing Seats	Leveler Rolls	¾” diameter	1060	20 - 60	58-62
Guide Rails	Large Machines	½” x 1/16” x 40”, 2” x 5” x 50”	A2 and 4150	15 – 20	62
Shafts	Molding Machines	8” dia. X 10’ long	4140, 4150	40 - 60	60
Pivot Heads	Hydraulic Cylinders	6” dia. X 21” long	4145	30 – 40	58-60
Strain Rods	Presses	N/A	4140	20 – 60	N/A
Capstans	Wire Drawing	80” diameter	4150	60 – 80	62
Synchro Hub Splines	Manual Transmissions	N/A	1141	10 – 20	58-60
Rotary Cutters	Oil Drill Bits	5” diameter	4140	30 – 40	N/A
Cylinders	Diesel Engines	N/A	Cast Iron	30 – 40	N/A

Advantages

- Low distortion eliminates post machining
- Selective hardening
- Very controlled case depth
- Self-quenching
- Slightly higher hardness attainable than for induction hardening
- No scaling or decarburization
- Environmentally friendly
- Little electrical interference

Commercial Acceptance

The application of the CO_2 laser as a surface heat treating device is relatively new. Although it has found significant acceptance in the automotive, steel and heavy equipment industries, it is still not widely used. Most capability is in captive operations. Custom heat treaters offering laser services are rare. This is due, in part, to a lack of knowledge of how a laser hardens surfaces and to the reluctance of conventional heat treaters to abandon their older technologies. The more efficient, lower-cost diode lasers are expected to drive the market penetration of laser surface heat treating.

Safety

Misuse of laser equipment can result in permanent damage to the eyes and skin of operators and nearby personnel. Lasers for heat treating are categorized as Class 4 lasers by the American National Standard Institute (ANSI Z136.1) and the Center for Devices and Radiological Health (FDA Title 21, CFR-Section 1040). This applies to lasers that can produce a hazard from both direct viewing and diffuse reflections, and to lasers that can be a fire hazard. Control measures include enclosing the beam path, baffling the target area and using laser light filters in eyewear. Nonbeam-related hazards include electrical shock from high voltage power sources and harmful fumes released when laser processing certain materials. Proper nonbeam-related safety precautions are outlined in ANSI/ASC Z49.1, Safety in Welding and Cutting.

Advances

Aluminum-free Semiconductor Materials

Aluminum-free, high-power laser diode material has been a hot topic of discussion within the scientific community for several years. Comparison studies of AlGaAs and InGaAsP material show improved performance of InGaAsP in areas such as resistance to dark-line defects, sudden failures, and gradual degradation. The absence of aluminum, which typically experiences oxidation problems during wafer processing, and the availability of highly selective wet chemical etchants make the processing of InGaAsP much simpler than AlGaAs.

Multi-process Systems

Lasers can be and are being used for hardening, cladding and welding applications, but there are some limitations. Cracks can be formed when hardening, slow operating speeds are required for cladding, and lasers are not able to weld steels with more than 0.25% carbon or low-alloy steels with more than 0.20% carbon. Researchers have combined laser and induction heating processes to eliminate these limitations. This work was done in collaboration with industrial partners including a U.S. laser-manufacturer, Rofin-Sinar; and two German companies: induction heating equipment supplier EFD and Arnold Ravensburg, a special machine builder. According to Berndt Brenner, who heads the IWS Department of Material Science, the induction heating and the laser processing are arranged to work in a complementary manner.

The photon energy of the laser works primarily on the surface as the inductive energy works on the near-volume area of the materials being processed. The laser-to-induction power is on the order of 1:8 up to 1:20, depending on the application. In operation, the workpiece is first inductively heated, then the laser is brought into action. Brenner says that the result of the hardening operation on components—and applications can include camshafts, cam follower, and rocker arms—is a hard, wear-resistant surface and a crack-free, fine microstructure. Importantly, the process can be performed at a faster rate than is ordinarily attained when the two tools are used separately; as much as 10X faster. Cladding can also be performed with the laser induction process, such as applying hardfacing alloys on harden-able steels, tool steels, or alloyed cold working steels, at this 10X rate.

EPRI References

TechCommentary

- TC-102573 (V1-P4) Laser Welding
- TC-102573 (V3-P9) Laser Cutting

TechApplication

- TA-107730 Laser-Textured Rolls Brighten Outlook at CMP
- TA-102575 (V1-P6) Laser Cutting of Metal
- TA-102572 (V1-P18) Laser Hardening

5

ELECTRON BEAM

Introduction to Electron Beam Heating

The electron beam process involves the acceleration of a stream of electrons toward an object, creating heat in the object as the kinetic energy in the moving electrons is transferred to the part upon impact. Electrons are generated by heating a filament located in the electron beam gun which “boils off” electrons and forms an electron “cloud” around the filament. Because of the special design of the gun, the electron cloud is then shaped by a negatively charged bias cup (grid) to form the electron beam. These electrons are then attracted to a positively charged anode located some distance away. The beam then travels through the following:

- Anode – accelerates the electrons
- Column Valve – maintains gun region under high vacuum during chamber venting
- Magnetic Focusing Lens - establishes beam spot size
- Deflection Coil – allows complex geometric beam patterns

...and then enters the chamber work area to the part.

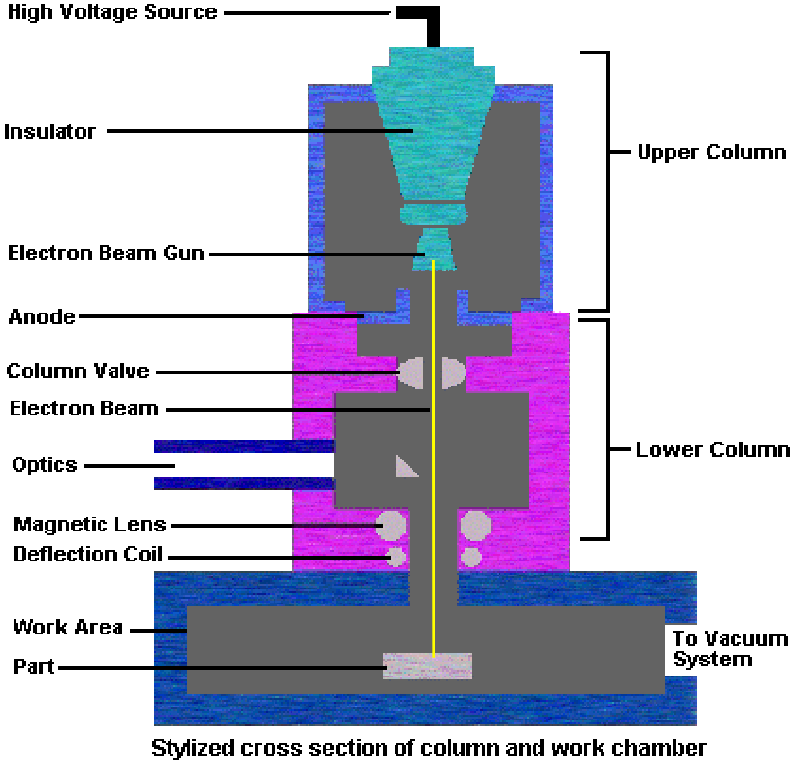

High Voltage Source
Insulator
Electron Beam Gun
Anode
Column Valve
Electron Beam
Optics
Magnetic Lens
Deflection Coil
Work Area
Part
Upper Column
Lower Column
To Vacuum System
Stylized cross section of column and work chamber

Figure 5-1
Electron Beam Process

The stream of high voltage electrons is accelerated to a velocity of approximately two thirds the speed of light, or about 117,000 miles per second, for gun operating voltages in the range of 25 kV - 200 kV. This concentrated stream of high velocity electrons impacts the metal part, creating thermal energy (heat) which results in a localized temperature rise in the part surface.

Electron beam surface hardening can be accomplished inside or outside a vacuum chamber. Vacuum levels are generally of a “medium” level between 0.001 and 25 torr (where standard atmospheric pressure is 760 torr). The major advantage of nonvacuum surface hardening is the elimination of chamber evacuation time and not limiting the size of workpieces to the size of the chamber.

There are limited applications for heat treatment by “scanning” the surface with a diffused electron beam. The surface to be heated is typically divided into a finite number of zones (up to 500), and scanning is accomplished by deflecting the electron beam in succession from one point to another. The beam dwells at each point for only 50 to 100 µs.

Applications

Electron beam technology is used for nonthermal processing (computer chip lithography, food sterilization) as well as heat treating, melting, welding and machining. Each application, of course, requires different process parameters as shown in Table 5-1 below.

Table 5-1
Electron Beam Process Parameters by Application

Application	Power Density	Beam Power	Spot Size	Beam Voltage
Lithography/doping/ curing/sterilization	$10^{-2} – 10^{2}$ W/cm^2	0.001 W – 100 W	0.1µm – 0.01 mm	20 kV-10 MV
Surface Hardening	$10^{2} – 10^{3}$ W/cm^2	100 W – 2,000 W	0.5 µ m– 30 mm	20-150 kV
Melting	$10^{3} – 10^{5}$ W/cm^2	1,000 W – 2 MW	3 - 50 mm	10-50 kV
Welding	$10^{5} – 10^{7}$ W/cm^2	100 W - 100,000 W	0.3 - 3 mm	30-300 kV
Machining	$10^{7} – 10^{9}$ W/cm^2	100 W – 10,000 W	0.03 - 1 mm	100-200 kV

Generally, the electron beam power density and beam power is lower for surface hardening than for welding, melting and machining. Not surprisingly, the spot size for surface hardening tends to be larger than for other applications since much larger surface areas need to be heated.

For surface hardening, the surface is heated to a limited and controlled depth from 10 µm to 10 mm. The depth to which the hardening occurs depends upon the dwell time of the beam and beam power as a function of time. With electron beam hardening, only the surface of the workpiece is heated due to the rapid spread of the operation. The rest of the material becomes a heat sink. This heat sink draws away the heat very quickly to allow rapid cooling through the transformation temperature. Therefore, electron beam hardening is referred to as a self-quenching process because most parts do not require a subsequent liquid or gas quench.

Advantages

The advantages of electron beam heating include:

- Minimal workpiece distortion
- Low energy use
- Ability to selectively harden portions of a surface (better process control)
- Ability to harden areas inaccessible to conventional induction techniques
- Resultant compressive stresses improve fatigue resistance
- Part-to-part repeatability, and
- High speed

Commercial Acceptance

Electron beam surface hardening is used for only very specialized applications. The purchase of new systems for surface hardening has steadily diminished over the last ten years. Improvements in laser technology, particularly diode lasers, will continue to take applications away from electron beam processing. The high cost of electron beam processing equipment is a big hurdle when compared to the decreasing cost of lasers. Also, lasers operate without the need of a vacuum chamber and do not generate hazardous x-rays. A 15-30 kW electron beam welding system can easily cost more than $1 million. For surface hardening, electron beam gun parts can be purchased that allow temporary alteration of an electron beam welding system. This adaptation of welding systems is the most likely scenario for implementing new electron beam surface hardening applications.

Safety

The four primary potential dangers associated with electron beam equipment are:

1. **Electric shock** - Electron beam hardening systems operate at very high voltage levels.

2. **X-radiation** - X-rays are produced when the electron beam impinges on the workpiece and when the beam strikes gas molecules or metal vapor. Thick steel and leaded glass usually satisfy shielding requirements for the chamber. In the case of nonvacuum systems, some type of radiation enclosure must be provided to shield the operator.

3. **Fumes and gases** - Nonvacuum and medium-vacuum systems can produce ozone and oxides of nitrogen in harmful concentrations. Proper exhausting techniques can keep fumes and gases at safe limits.

4. **Damaging visible radiation** - Direct viewing of visible radiation from heated metal surfaces can be harmful to eyesight. Proper eye protection with filters is necessary.

EPRI References

EPRI CMF *TechCommentary*

- TC-102573 (V3-P4) Electron Beam Welding and Hardening

EPRI State-of-the-Art Assessments

- EM-4526 Electron Beam Processing of Metals

6

ELECTROMAGNETIC RADIATION

Introduction to Radiant Heating

Radiation is energy emitted or transmitted in the form of waves. Although the term radiation can include acoustic and particle radiation, only electromagnetic radiation is of interest with regard to industrial process heating. Electromagnetic radiation includes an enormous spectrum of wave-like particles that include gamma rays, x-rays, ultraviolet light, visible light, infrared, microwaves, radar, and television and radio waves. Electromagnetic radiation can be viewed as waves that are made up of mutually sustaining, oscillating electric and magnetic fields. Electromagnetic waves are created whenever a charge is accelerated. Electromagnetic radiation can also be viewed as energy emitted or transmitted in the form of particles called photons that can travel through a vacuum.

Photons are tiny packets, or “quanta,” of energy that have the properties of both particles and waves. The higher the energy of a photon, the shorter the wavelength and the higher frequency of its wave properties. The lower the energy of a photon, the longer its wavelength and the lower its frequency. Traditionally, elementary texts give more emphasis to the wave properties of light, but the particle properties frequently lead to more lucid explanations of phenomena observed. Not surprisingly, photons travel at the speed of light. Photons do not need a medium to carry them, and will travel forever through space in a straight line unless they collide with a substance or are acted upon by a force field.

Infrared (IR) radiation is light. It is light we cannot see. It has less energy, shorter wavelengths and lower frequency than visible light, but is otherwise identical. The wavelengths of IR are usually measured in microns (one millionth of a meter). IR light also comes in many energy levels, but covers a very broad range, or spectrum (Figure 6-1) of thermal radiation. We arbitrarily group those wavelengths into bands that we label “near infrared wave” (NIR, the band right next to visible “red”), “short wave,” “medium wave,” and “long wave” IR. Sometimes we just divide the range into two bands called “near” (NIR) and “far” IR. Near IR has higher energy photons than far IR. Short wave IR has higher energy photons than middle wave and long wave IR. There are no other differences.

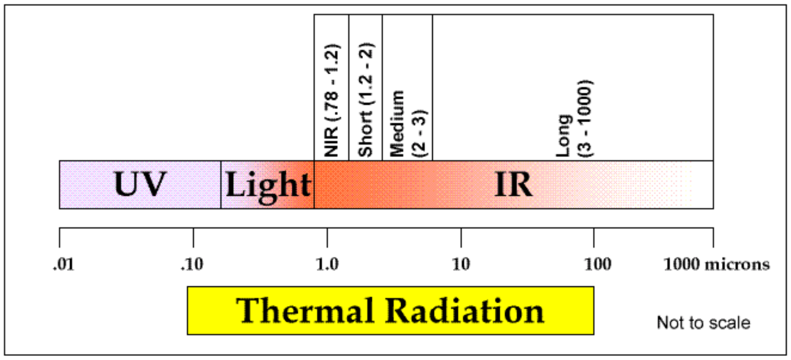

NIR (.78 - 1.2)
Short (1.2 - 2)
Medium (2 - 3)
Long (3 - 1000)
UV
Light
IR
.01
.10
1.0
10
100
1000 microns
Thermal Radiation
Not to scale

Figure 6-1
One Segment of the Electromagnetic Radiation Spectrum

IR for process heating is generated from an electrically heated metal filament or strip, usually made of tungsten or nichrome (an alloy of nickel and chromium). The metal may be in a variety of shapes, such as thin filaments, ribbons, rods, bars or screens and is often contained in a lamp. The components of an electric quartz infrared lamp is explained in Figure 6-2, and operating properties of various IR lamps are listed in Table 6-1.

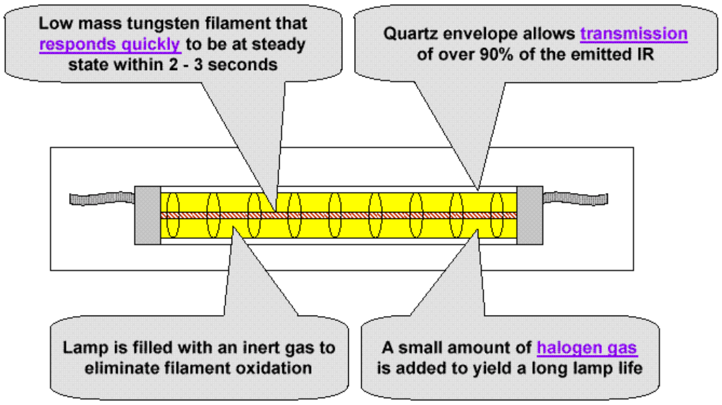

Low mass tungsten filament that responds quickly to be at steady state within 2 - 3 seconds
Quartz envelope allows transmission of over 90% of the emitted IR
Lamp is filled with an inert gas to eliminate filament oxidation
A small amount of halogen gas is added to yield a long lamp life

Figure 6-2
Typical Quartz Infrared Lamp

Table 6-1
Operating Properties of Various IR Lamps

	TUNGSTEN FILAMENT WIRE **T3 Quartz Lamp**	**NICKEL CHROME SPIRAL WINDING**		**LOW TEMP PANEL HEATER**
		Quartz Tube	**Metal Sheath Rods**	**Buried Metallic Nickel Salt Chrome**
Usual Range of Source Temperatures	3000°F to 5400°F (1649 °C to 2980°C)	1400°F to 1800°F (760°C to 982°C)	1000°F to 1400°F (538°C to 760°C)	1100°F to 400°F (593°C to 209°C)
Brightness	Bright White	Cherry Red	Dull Red	No Visible Light
Usual Size, Inches (mm)	0.375 or Dia. Tube (9.525)	0.375 or 0.625 Dia. Tube (9.525 or 15.875)	0.375 or 0.625 Dia. Tube (9.525 or 15.875)	Flat Panels - Various
Usual Range of Peak, Energy Wavelength	0.89 to 1.5 Microns	2.3 to 3.8 Microns	2.8 to 3.6 Microns	3.2 to 6.0 Microns
Usual Range of Relative Energy Distribution Radiation	72 to 86%	40 to 60%	45 to 53%	20 to 50%
Convection	28 to 14%	60 to 40%	55 to 47%	80 to 50%
Relative Response to Heat-up	Seconds	Minutes	Minutes	Scores of Minutes
Relative Response to Cool-down	Seconds	Seconds	Minutes	Scores of Minutes
Ruggedness Mechanical Shock	Good	Good	Excellent	Varies with Panel
Thermal Shock	Excellent	Excellent	Excellent	Good

All metals emit IR energy, and the hotter the metal, the more IR energy emitted. The IR emitted occurs at every temperature at every energy level in the far IR band. However, as a metal becomes hotter, it not only emits more overall IR energy, but more of the energy it emits is at the higher energy levels (higher frequencies - shorter wavelengths). The sole factor that determines the level of long, medium, or short wave IR is the temperature of the emitter.

The amount of power emitted by IR is defined by the Stefan-Boltzmann Law:

$$Q = \sigma T^4$$

Where:

Q = Total Emissive Power (watts/cm^2)
σ = Stefan-Boltzmann Constant = 5.67 E-12 (watts/ cm^2-°K^4)
T = Absolute Temperature (°K)

From the equation, it can be observed that doubling the absolute source temperature increases the heat output by sixteen times.

When IR light strikes an object, it may be reflected, transmitted, or absorbed (Figure 6-3).

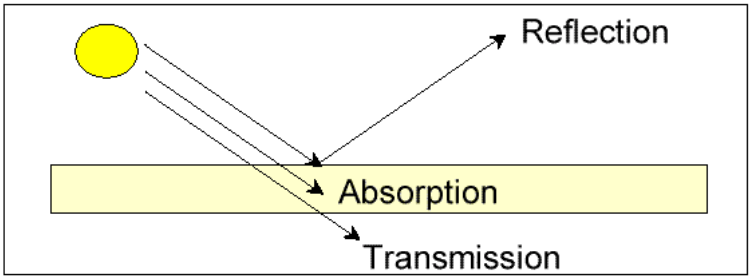


Figure 6-3
Three Reactions to Infrared Radiation

If it is absorbed, it causes atoms and molecules in the body to vibrate more vigorously. When atoms and molecules vibrate more vigorously, that's just another way of saying they become warmer. So, when an object absorbs infrared light, its temperature rises. Reflected and transmitted IR has no effect on the object's temperature.

Every substance is unique in the amount of IR energy it absorbs at each wavelength and thus has an absorption spectrum. Chemists use this fact to identify unknown substances and even refer to absorption spectra as "fingerprints." However, generalizations can be made since materials often exhibit maximum absorption at more than one wavelength, as shown in Table 6-2. These absorption peaks for industrial materials often exist in the medium infrared region.

Table 6-2
Infrared Absorption Values

Material	Absorption Peaks >80% (microns)
Water	3 & 6
Glass	8
Aluminum	3 & 8.5
Polyethylene	3.5 & 6.8

IR sources emit in all directions (Figure 6-4). The view factor term (V_f) is a fraction between 0 and 1 that defines the amount of radiant energy emitted from the source that hits the target.

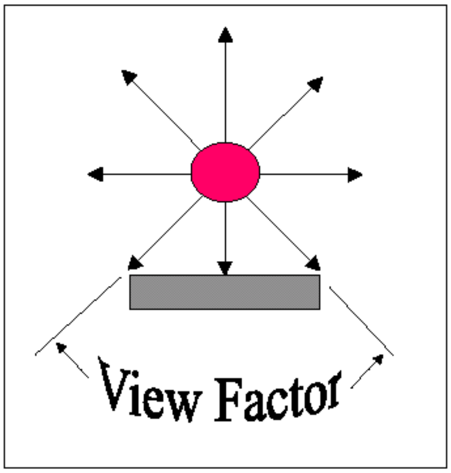


Figure 6-4
Definition of View Factor

As with visible light, IR can be reflected and focused. In IR ovens, we may use reflectors and other devices to increase V_f, the amount of light incident to the target. Parabolic reflectors (Figure 6-5) redirect the rays in a parallel fashion to effectively heat a “strip.” Elliptical reflectors (Figure 6-6) redirect the rays to converge to a line. Ellipsoidal reflectors redirect the rays to converge to a point or spot.

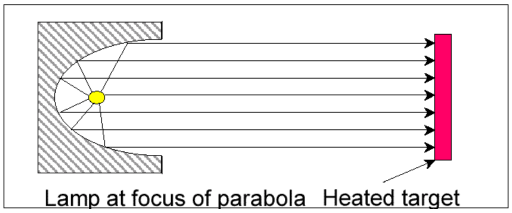


Figure 6-5
Parabolic Reflector

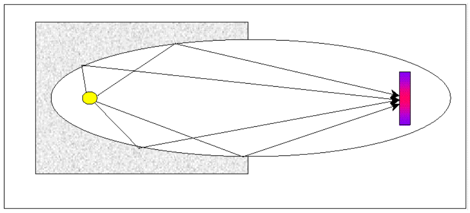


Figure 6-6
Elliptical Reflector

Multiple lamp/reflectors (Figures 6-7 & 6-8) can be arranged around the product to form a chamber. The net view factor (V_f) to the line of focus approaches a value of 1.

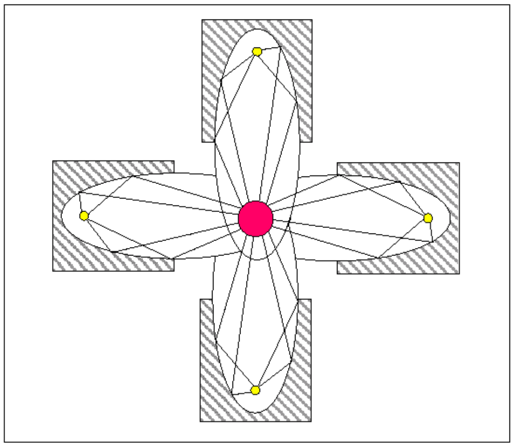


Figure 6-7
Multiple Reflector Arrangement

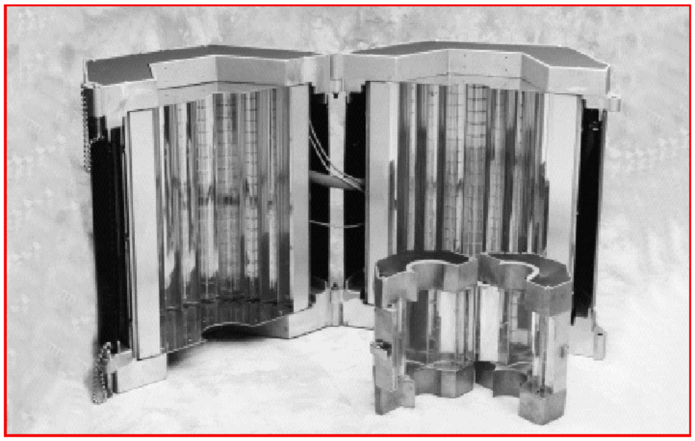


Figure 6-8
Clamshell Focused IR Lamps

Applications

- Preheating cast aluminum wheels
- Preheating steel inserts that were to be placed into molten aluminum
- Heating turbine engine vanes prior to reforming their cross-section
- Heating aluminum strip prior to bending
- Curing graphite in golf club heads
- Preheating selected areas of a magnesium turbine housing prior to weld repair
- Maintaining forging die preheat temperature

Advantages

Radiant heating includes electric infrared and gas infrared. Both have notable advantages over convection heating. In principle, convection heating includes electric convection and gas convection, but in U.S. industry convection ovens are virtually always gas.

Advantages of Radiant Heating Over Convection

- Shorter curing times
- Faster line speeds
- Smaller footprint
- Easy on/off control
- Energy efficiency

Advantages of Electric Infrared Over Gas Heating Technologies

- 2-4 times as efficient as gas convection
- Faster start-up
- Flexibility offered by modular nature
- Improved productivity
- Less product contamination
- Less noise
- Less air pollution
- Low equipment weight offers flexibility
- Lower initial costs
- More energy efficient than gas infrared

- More flexibility with reflectors
- More precise control
- More responsive to controls
- Smaller footprint
- Stand-by mode with very low, or even zero, energy consumption
- Wider range of temperatures
- Zoning much easier than with other technologies

Disadvantages of Gas Infrared Versus Electric Infrared

- Burner replacement is less frequent, but much more costly than replacing a bulb in an electric emitter
- Combustion by-products may pollute the product
- Combustion products pollute the local environment (or expensive exhaust gas treatments are required)
- Gas burners are much less controllable than electric emitters
- Initial purchase cost is higher than for electric IR
- Gas burners operate at lower temperatures than many electric IR ovens, so they produce much less radiant energy per unit of emitter surface area
- Lower temperatures lead to longer cycle times
- Reflectors cannot be used to redirect the radiant energy to hard-to-see areas of the product
- Burner operation is sensitive to physical orientation, limiting ability to adjust oven panels
- Physical size of burners makes small zones impossible

Safety

IR energy is extremely safe. IR rays are radiation, but they are not the kind of radiation that poses a significant health risk to humans. Radiation from ultraviolet rays, x-rays, and gamma rays are of more concern and have indeed been associated with health problems. There is no such health concern with IR. The only effect IR energy has on a body is to heat it.

One must be careful when working with IR, however. The tissue of the eye absorbs IR rather well and is warmed by it. Holding the eye tissue at a higher than normal temperature for prolonged periods spanning several years is thought to cause cataracts. Therefore, it is recommended that when replacing lamps or performing other maintenance on an oven in operation, the intensity of the unit should be turned down and safety glasses that filter out the IR rays should be used.

EPRI References

EPRI Report

- TR-112968 IR Market Study: Electric Infrared in Industrial Process Heating
- CR-108734 Comparison of Electric Infrared & Gas Infrared Heating Technology
- CR-108582 Infrared Heat Treating of Aluminum Wheels (92-5)
- CR-102785 Technology Guidebook for Electric Infrared Process Heating (93-2)

EPRI *TechApplication*

- TA-112686 Electric IR Booster Speeds Aluminum Aging Process

EPRI Technical Bulletin

- TB-110634 Electric Infrared Heating of Steel Plates

7
PLASMA

Introduction to Plasma Heating

Plasma energy is a naturally occurring resource. The discharged static electricity in lightning is one example. Simply stated, plasma is any ionized gas that conducts electricity.

Plasma heating technology has a proven record of success in the industry. In the 1960's plasma heaters were used by NASA to simulate space craft re-entry conditions. Today, various industrial processes are based on plasma heating technology. Plasma arc torches operate efficiently at temperatures well beyond that possible with fossil fuel burners. They can routinely create temperatures from 4,000 - 11,000 C°. This extreme heat is produced instantly, and the process is easily automated.

A direct current (DC) arc plasma is obtained by passing a pressurized gas (argon, nitrogen, helium, etc.) through a constricted orifice and into an electric arc maintained between two electrodes. In the non-transferred arc mode, the cathode and anode are both built into the torch nozzle and the ionized gas is blown across the arc and through the nozzle orifice, producing a flame effect. In the transferred arc mode (Figure 7-1), the cathode is a tungsten alloy rod in the torch and the anode is the workpiece.

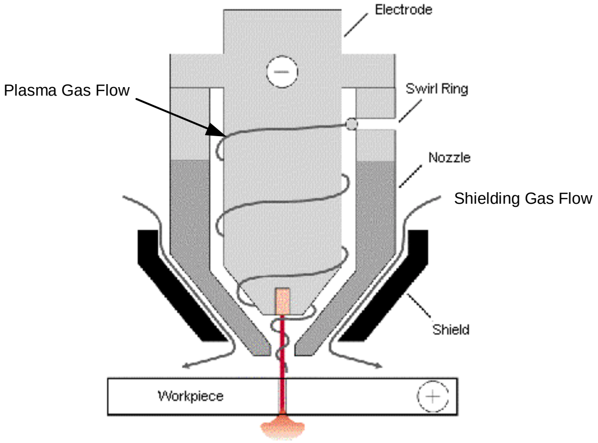


Figure 7-1
Transferred Plasma Arc

Applications

Plasma Arc Melting

Arc plasmas are used to produce special steels and refractory metals (Figure 7-2). The plasma jet first bores a well in the charge with the molten metal being used to support the arc. Heat is transferred to the rest of the charge by metal conduction and arc radiation. Unlike graphite or scrap metal electrode furnaces, current stability is constant (within 2%), and there is no short circuiting during melting. Moreover, there is no risk of the bath being contaminated by the electrode.

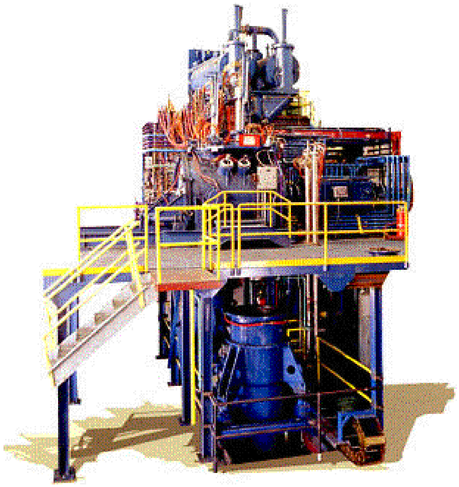


Figure 7-2
Plasma Arc Melter

Steel Mill Tundish Heating

An innovative and effective way to enhance quality and productivity is to introduce secondary heating of the steel at the final stage prior to casting (i.e. in the tundish.) In continuous casting, controlling steel temperatures, or superheat, in the tundish has been demonstrated to be one of the most effective means to increase product quality. If steel superheat can be controlled before solidification occurs, casting speed can be ideally maximized. An improved system in which two torches (Figure 7-3) of opposing polarity are used avoids modifications to the tundish to incorporate the counter electrode (Figure 7-4). Power levels range from 320 kW (1,600 amps) - 1.4 MW (7,000 amps).

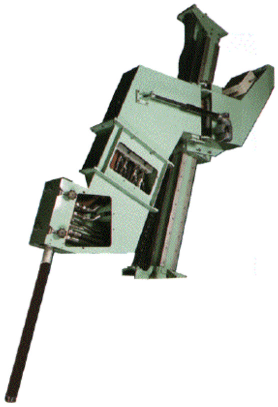


Figure 7-3
Plasma Torch for Tundish Heating

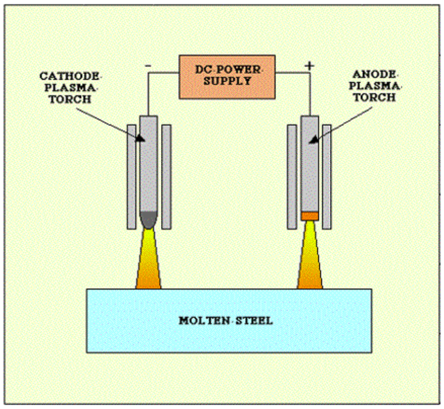

CATHODE PLASMA TORCH
-
DC POWER SUPPLY
+
ANODE PLASMA TORCH
MOLTEN STEEL

Figure 7-4
Two Torch Plasma Heating System

Controlled Plasma Glassification System

In the thermal plasma treatment of incinerator ashes (primarily municipal solid waste and sewage sludge waste) the organic species are destroyed and the inorganic fraction is fused to give a dense slag product. This product may be used as a high-grade construction material.

The overall system glassification of incinerator ashes is shown in Figure 7-5.

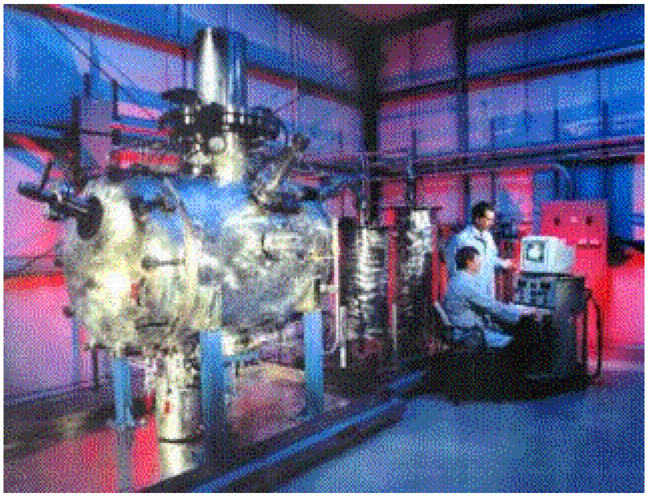


Figure 7-5
Plasma Glassification System

Plasma Spray

A high current (20-600A) arc is stabilized in the plasma torch using a constant current power supply (Figure 7-6). The arc is used to heat the plasma gas which flows through the torch. The resultant plasma shoots out of the nozzle at high velocity. The coating material, which is in the powder form, is carried from the powder feeder by a carrier gas and injected into the plasma flame (Figure 7-7). In the flame, the powder particles melt and accelerate toward the substrate. On impinging the substrate, the particles adhere and cool to form interconnected lamellar layers. Plasma spray can be used to deposit ceramic coatings, corrosion and erosion resistant coatings (ceramic and alloy coatings), wear and abrasion resistant coatings (carbide and oxide coatings) and superconducting coatings on a variety of materials.

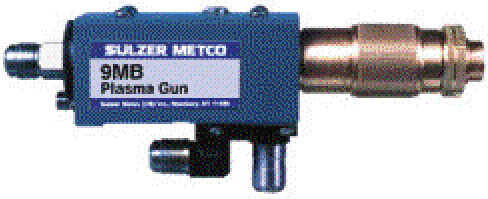


Figure 7-6
Plasma Spray Torch

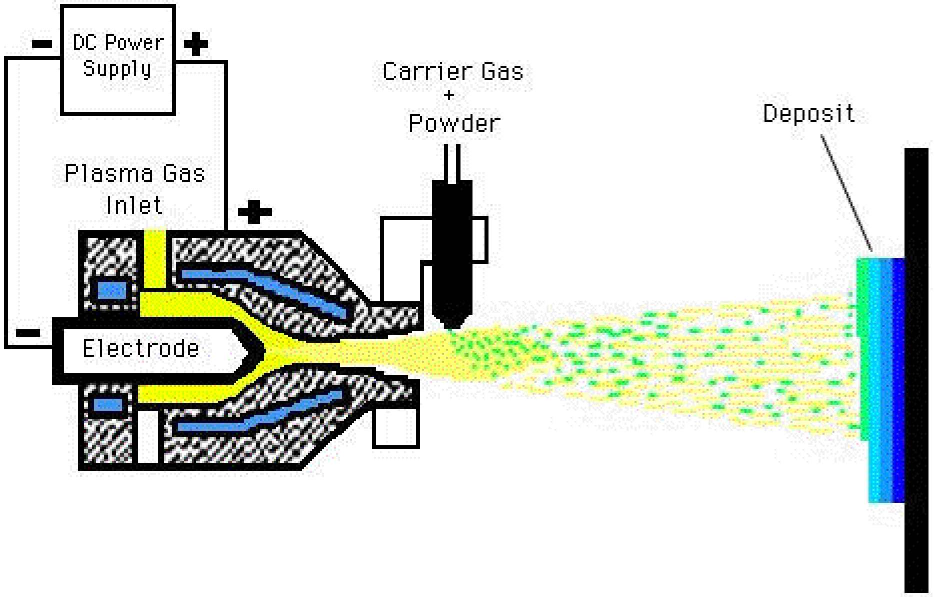


Figure 7-7
Plasma Spray Process Schematic

Plasma Cutting and Welding

Plasma is a process that uses a highly positioned nozzle orifice to constrict a very high temperature, ionized gas so that it can be used to melt and sever sections of electrically conductive metals (Figure 7-1). The plasma cutting process is very similar to the plasma welding process except for a much higher gas flow rate used to remove molten metal from the impact point. The energy density of a plasma torch is determined by the ratio of electrical current flow through the nozzle to the effective area of the nozzle orifice. This energy density can be measured as amps per square inch. Conventional nitrogen plasma cutting systems have an energy density in the range of 12,000 to 20,000 amps per square inch. Both oxygen and nitrogen plasma systems are normally used to cut materials (carbon steels, aluminum, and stainless steels) from 3/8" (9.5 mm) through 1" (25 mm) with cut edge squareness in the range of within 1 to 4 degrees of square. Generally, the thicker the material, the better the cut edge squareness. The maximum cutting thickness capability of conventional plasma systems varies depending on system manufacturer and power levels. In general terms, plasma systems are available to cut aluminum to 6" (150 mm) thick, stainless steel to 5" (125 mm) thick, and carbon steels to 1 1/4" (32 mm) thick.

Advantages

The advantages of plasma heating include:

- Accommodates highly refractory material due to very high plasma temperatures
- Highly controllable by combining the mechanical mass flow of gas with thermal effect

Commercial Acceptance

Commercial acceptance is high for plasma spraying, welding and cutting. The market penetration for plasma tundish heating and glassification systems is low but growing. There has been low acceptance of plasma arc melting (nonconsumable electrode) due to competition from vacuum arc remelting and other consumable electrode technologies.

Safety

The plasma arc process generates extreme amounts of heat and light radiation. Eye protection and suitable clothing is required to avoid against arc flash and heat burns. Adequate ventilation should be used, particularly when heating metals with copper, lead, zinc or beryllium contents. Operating voltages are relatively low, in the range of 15 - 150 volts.

EPRI Resources

EPRI *TechApplication*

- TA-105689 Plasma Tundish Heating Saves Cold Heats During Casting
- TA-105128 Plasma Cutters for Industrial Sheet Metal
- TA-104431 DC Plasma Ladle Refiner Improves Foundry’s Quality and Productivity
- TA-102601 Plasma Tundish Heating
- TA-102572 (V1-P14) Plasma Cutting

EPRI *TechCommentary*

- TC-102591 Plasma Arc Technology
- TC-102573 (V4-P5) Plasma Arc Cutting

A
APPENDIX

An Alternative Process Selection Methodology

An alternative approach to the selection of process heating technology involves matching energy value with the information content of a material/workpiece. This concept was proposed by Dr. Philip Schmidt, head of the Process Energetics Program in the Center for Energy and Environmental Resources of the University of Texas. The concept is based on the theory that one can characterize energy sources as having very random characters (inefficient thermochemical energy) or highly ordered (efficient electromagnetic energy). It is observed that the ordered nature of electromagnetic energy permits it to be focussed to a much higher degree than thermochemical energy. Also, thermochemical energy sources inherently involve a medium of transfer, i.e. the combustion products produced by chemical reaction. Electromagnetic energy does not require a medium of transfer and exhibits negligible inertia, so its intensity and direction can be changed almost instantaneously. The electromagnetic characteristics of order, spatial resolution (ability to focus), directionality, and controllability give it a higher energy form value than thermochemical energy.

Much of the added value of a product is in its information content based on the recovery of costs for research, development, engineering, labor and capital equipment. For example, common river sand (silica) as a raw material for asphalt paving needs to be dried before mixing has a low information content before and after drying. Sand for glassware needs to be cleaner and is melted and formed. It has a medium information content. Sand for integrated circuits is converted to elemental silicon, refined, remelted and grown into a single crystal. It has a very high information content.

Figure A-1 shows the relationship between the information content of a product and the energy form value required to obtain it. As information content increases, energy forms with a higher inherent ability to embody information become more valuable. Using this information-form value concept, it is apparent that choosing electromagnetic energy to dry sand for asphalt paving is as illogical as choosing coal combustion to make integrated circuit chips.

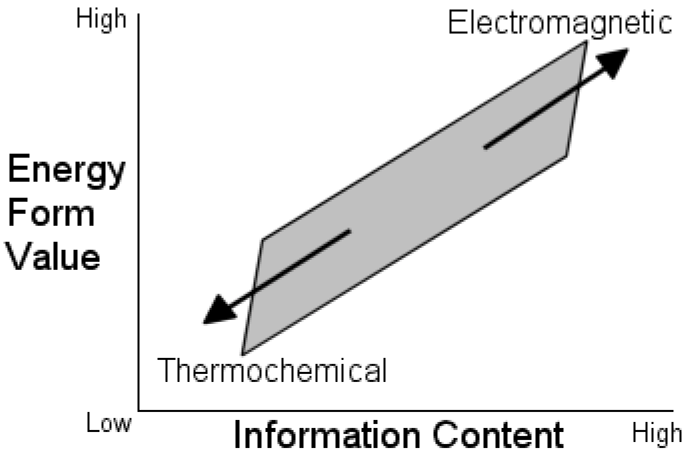

High
Electromagnetic
Energy Form Value
Thermochemical
Low
Information Content
High

Figure A-1
Selecting Process Heating Technology

Target:

Materials Fabrication

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