AWS C7.2M:2010
An American National Standard

Recommended Practices for Laser Beam Welding, Cutting, and Allied Processes

American Welding Society



AWS C7.2M:2010
An American National Standard

Approved by the
American National Standards Institute
June 24, 2010

Recommended Practices for Laser Beam Welding, Cutting, and Allied Processes

2nd Edition

Supersedes ANSI/AWS C7.2:1998

Prepared by the
American Welding Society (AWS) C7 Committee on High-Energy Beam Welding and Cutting

Under the Direction of the
AWS Technical Activities Committee

Approved by the
AWS Board of Directors

Abstract

This document presents recommended practices for laser beam welding, cutting, drilling, and transformation hardening. It is intended to cover common applications of the process. Processes definitions, safe practices, general process requirements and inspection criteria are provided.

American Welding Society
550 N.W. LeJeune Road, Miami, FL 33126

International Standard Book Number: 978-0-87171-777-1
American Welding Society
550 N.W. LeJeune Road, Miami, FL 33126
© 2010 by American Welding Society
All rights reserved
Printed in the United States of America

Photocopy Rights. No portion of this standard may be reproduced, stored in a retrieval system, or transmitted in any form, including mechanical, photocopying, recording, or otherwise, without the prior written permission of the copyright owner.

Authorization to photocopy items for internal, personal, or educational classroom use only or the internal, personal, or educational classroom use only of specific clients is granted by the American Welding Society provided that the appropriate fee is paid to the Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923, tel: (978) 750-8400; Internet: <www.copyright.com>.

Statement on the Use of American Welding Society Standards

All standards (codes, specifications, recommended practices, methods, classifications, and guides) of the American Welding Society (AWS) are voluntary consensus standards that have been developed in accordance with the rules of the American National Standards Institute (ANSI). When AWS American National Standards are either incorporated in, or made part of, documents that are included in federal or state laws and regulations, or the regulations of other governmental bodies, their provisions carry the full legal authority of the statute. In such cases, any changes in those AWS standards must be approved by the governmental body having statutory jurisdiction before they can become a part of those laws and regulations. In all cases, these standards carry the full legal authority of the contract or other document that invokes the AWS standards. Where this contractual relationship exists, changes in or deviations from requirements of an AWS standard must be by agreement between the contracting parties.

AWS American National Standards are developed through a consensus standards development process that brings together volunteers representing varied viewpoints and interests to achieve consensus. While the AWS administers the process and establishes rules to promote fairness in the development of consensus, it does not independently test, evaluate, or verify the accuracy of any information or the soundness of any judgments contained in its standards.

AWS disclaims liability for any injury to persons or to property, or other damages of any nature whatsoever, whether special, indirect, consequential, or compensatory, directly or indirectly resulting from the publication, use of, or reliance on this standard. AWS also makes no guarantee or warranty as to the accuracy or completeness of any information published herein.

In issuing and making this standard available, AWS is neither undertaking to render professional or other services for or on behalf of any person or entity, nor is AWS undertaking to perform any duty owed by any person or entity to someone else. Anyone using these documents should rely on his or her own independent judgment or, as appropriate, seek the advice of a competent professional in determining the exercise of reasonable care in any given circumstances. It is assumed that the use of this standard and its provisions are entrusted to appropriately qualified and competent personnel.

This standard may be superseded by the issuance of new editions. Users should ensure that they have the latest edition.

Publication of this standard does not authorize infringement of any patent or trade name. Users of this standard accept any and all liabilities for infringement of any patent or trade name items. AWS disclaims liability for the infringement of any patent or product trade name resulting from the use of this standard.

Finally, the AWS does not monitor, police, or enforce compliance with this standard, nor does it have the power to do so.

On occasion, text, tables, or figures are printed incorrectly, constituting errata. Such errata, when discovered, are posted on the AWS web page (www.aws.org).

Official interpretations of any of the technical requirements of this standard may only be obtained by sending a request, in writing, to the appropriate technical committee. Such requests should be addressed to the American Welding Society, Attention: Managing Director, Technical Services Division, 550 N.W. LeJeune Road, Miami, FL 33126 (see Annex B). With regard to technical inquiries made concerning AWS standards, oral opinions on AWS standards may be rendered. These opinions are offered solely as a convenience to users of this standard, and they do not constitute professional advice. Such opinions represent only the personal opinions of the particular individuals giving them. These individuals do not speak on behalf of AWS, nor do these oral opinions constitute official or unofficial opinions or interpretations of AWS. In addition, oral opinions are informal and should not be used as a substitute for an official interpretation.

This standard is subject to revision at any time by the AWS C7 Committee on High-Energy Beam Welding and Cutting. It must be reviewed every five years, and if not revised, it must be either reaffirmed or withdrawn. Comments (recommendations, additions, or deletions) and any pertinent data that may be of use in improving this standard are required and should be addressed to AWS Headquarters. Such comments will receive careful consideration by the AWS C7 Committee on High-Energy Beam Welding and Cutting and the author of the comments will be informed of the Committee's response to the comments. Guests are invited to attend all meetings of the AWS C7 Committee on High-Energy Beam Welding and Cutting to express their comments verbally. Procedures for appeal of an adverse decision concerning all such comments are provided in the Rules of Operation of the Technical Activities Committee. A copy of these Rules can be obtained from the American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126.

This page is intentionally blank.

Personnel

AWS C7 Committee on High-Energy Beam Welding and Cutting

P. W. Hochanadel, Chair	*Los Alamos National Laboratory*
T. A. Palmer, 1st Vice-Chair	*Lawrence Livermore National Laboratory*
K. W. Lachenberg, 2nd Vice-Chair	*Sciaky, Incorporated*
M. Rubin, Secretary	*American Welding Society*
P. Blomquist	*Applied Thermal Sciences, Incorporated*
D. D. Kautz	*Los Alamos National Laboratory*
G. R. LaFlamme	*PTR Precision Technologies Inc.*
E. D. Levert	*Lockheed Martin Missiles and Fire Control*

Advisors to the AWS C7 Committee on High-Energy Beam Welding and Cutting

P. E. Denney	*Connecticut Center for Advanced Technology*
R. D. Dixon	*Retired*
P. W. Fuerschbach	*Sandia National Laboratory*
R. W. Messler Jr.	*Rensselaer Polytechnic Institute*
J. O. Milewski	*Los Alamos National Laboratory*
T. M. Mustaleski	*BWXT Y-12 LLC*
D. E. Powers	*PTR – Precision Technologies, Incorporated*
R. C. Salo	*Sciaky, Incorporated*

AWS C7C Subcommittee on Laser Beam Welding and Cutting

P. Blomquist, Chair	*Applied Thermal Sciences, Incorporated*
P. E. Denney, Vice-Chair	*Connecticut Center for Advanced Technology*
M. Rubin, Secretary	*American Welding Society*
R. D. Bucurel	*WEC Welding & Machining*
S. L. Engel	*HDE Technologies, Incorporated*
D. F. Farson	*The Ohio State University*
A. P. Hoult	*IPG Photonics*
J. P. Hurley	*Cosma Power Laser*
D. D. Kautz	*Los Alamos Natcional Laboratory*
R. P. Martukanitz	*Applied Research Laboratory, Pennsylvania State University*
V. Merchant	*Electrical and Optical Solutions*
L. R. Migliore	*Coherent, Incorporated.*
T.Palmer	*Applied Research Laboratory, Pennsylvania State University*
G. C. Schmid	*Bechtel Bettis, Incorporated*

Advisors to the AWS C7C Subcommittee on Laser Beam Welding and Cutting

R. D. Dixon	*Retired*
P. Hochanadel, Ex-Officio	*Los Alamos National Laboratory*
S. Jensen	*Visotek, Incorporated*
T. A. Jones	*Ford Motor Company*
J. O. Milewski	*Los Alamos National Laboratory*
D. E. Powers	*PTR – Precision Technologies, Incorporated*

This page is intentionally blank.

Foreword

This foreword is not part of AWS C7.2M:2010, *Recommended Practices for Laser Beam Welding, Cutting, and* Allied Processes, but is included for informational purposes only.

The first practical demonstration of a laser occurred in 1960. As laser output power increased through maturing technology, the use of lasers for material processing became widespread by the early 1970s. Currently, lasers are an accepted industrial tool for traditional and nontraditional materials processing operations that benefit from the laser's unique characteristics. While the materials processing applications of lasers in industry are diverse, this document focuses on welding, cutting, drilling, and transformation hardening.

The data contained in this *Recommended Practices* has been compiled and reviewed by the C7C Laser Beam Welding and Cutting Subcommittee of the American Welding Society, which included representatives from manufacturers and users of laser beam welding, cutting, and drilling equipment.

As industrial lasers gain wider acceptance, there is a greater need for skilled process engineers and technicians. The American Welding Society is contributing in this regard, by offering these *Recommended Practices for Laser Beam Welding, Cutting, and Allied Processes*. The intended users of these *recommended practices* are engineers and technicians involved, or planning to become involved, in laser materials processing.

It should be noted that the operating and processing parameters given in this Standard may not be the only parameter combinations that can be employed for successfully processing the materials and thicknesses shown. Changes in material chemistry, dimensional tolerances, laser beam characteristics, machine calibration, and other factors can produce different results. Therefore, the procedures presented here are simply meant to provide a set-up and design guide to help users to organize and learn the process of developing and refining a particular application.

Comments and suggestions for the improvement of this standard are welcome. They should be sent to the Secretary, AWS C7 Committee on High-Energy Beam Welding and Cutting, American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126.

This page is intentionally blank.

Table of Contents

Page No.

Personnel v
Foreword vii
List of Tables xiii
List of Figures xiii

1. Scope 1

2. Normative References 1

3. Terms and Definitions 1

4. Safety Considerations 10
4.1 Introduction 10
4.2 General Safety 10
4.3 Laser Safety 10
4.4 Electrical Hazards 11
4.5 Laser Radiation Hazards 11
4.6 Visible Radiation Hazards 12
4.7 Hazards from Fumes and Gases 12

5. Equipment Description 12
5.1 Description of Process 12
5.2 CO_2 Lasers 12
5.3 Nd: YAG Lasers 17
5.4 Output Characteristics of Nd: YAG Lasers 18
5.5 Other Types of Material Processing Lasers 19
5.6 Laser Systems 20
5.7 Fixturing 26

6. Process Control and Monitoring 28
6.1 Introduction 28
6.2 Laser Beam Quality 28
6.3 Power Density Control 29
6.4 Laser Power Measurement 34
6.5 Laser Beam Characterization 36

7. Laser Beam Welding (LBW) 37
7.1 Process Description 37
7.2 Advantages and Limitations 37
7.3 Types of Welding Lasers 38
7.4 LBW Process Parameters 38
7.5 Laser–Material Interaction 40
7.6 Designing for Laser Welding 47
7.7 CNC for Laser Welding 50
7.8 Thick-Section LBW with High-Power CO_2 Lasers 52
7.9 Thin-Section LBW 58

8. Laser Welding Metallurgy . . . 64
8.1 Introduction . . . 64
8.2 Heat-Affected Zone (HAZ) Effects . . . 65
8.3 Fusion Zone Effects . . . 68
8.4 Metallurgical Considerations for Welding Various Materials . . . 68
8.5 Dissimilar Metal Joining . . . 71

9. Laser Beam Cutting (LBC) and Laser Beam Drilling (LBD) . . . 72
9.1 Process Descriptions . . . 72
9.2 Advantages and Limitations of LBC and LBD . . . 73
9.3 Types of Cutting and Drilling Lasers . . . 74
9.4 Laser Beam Cutting Parameters . . . 76
9.5 Materials . . . 83
9.6 Characteristics of Cuts . . . 85
9.7 CNC for Laser Cutting . . . 86
9.8 Parameter Selection for LBC . . . 87
9.9 Parameter Selection for LBD . . . 91

10. Laser Transformation Hardening (LTH) . . . 100
10.1 Introduction . . . 100
10.2 The Laser Transformation Hardening Process . . . 102
10.3 Equipment and Processing Considerations . . . 104
10.4 Materials Consideration . . . 107
10.5 Process Control . . . 107
10.6 LTH Applications . . . 108

11. Record Keeping . . . 108
11.1 Introduction . . . 108
11.2 Laser Parameter Description . . . 111

12. Inspection and Testing . . . 112
12.1 Introduction . . . 112
12.2 Weld Inspection . . . 113
12.3 Inspection Techniques . . . 113
12.4 Inspecting Laser-Cut Parts . . . 115
12.5 Acceptability Limits . . . 115

13. Specifications for Laser Beam Welding . . . 115
13.1 Purpose . . . 115
13.2 Alternatives to Use of Published Specifications . . . 116

14. Equipment Maintenance . . . 116
14.1 Maintenance Schedule and Records . . . 116
14.2 Troubleshooting . . . 117
14.3 Specific Components . . . 117
14.4 Alignment . . . 120

15. Personnel Training . . . 122
15.1 Safety . . . 122
15.2 Laser System Operation . . . 122
15.3 Laser System Maintenance . . . 122
15.4 Other Training . . . 123
15.5 Sources of Training . . . 123

Annex A (Informative)—Informative References . . . 125

Annex B (Informative)—Guidelines for the Preparation of Technical Inquires . . . 127

List of Tables

Table		Page No.
5.1	Operation Comparison of CO_2 and Nd:YAG Material Processing Laser	13
5.2	Spatter Masking Materials for Laser Processing	28
9.1	Assist Gas Selection	90
9.2	Typical Gas Pressure for CO_2 Laser Beam Cutting	91
9.3	Typical Power Densities for Drilling	95
9.4	Typical Pulsed Laser Drilling Parameters	95
9.5	Hole Diameters for Specific Drilling Methods	97
11.1	Laser Equipment Set-up Factors	109

List of Figures

Figure		Page No.
4.1	Sample Precautionary Sign for a Class 4 Laser System	11
5.1	Four Major Components of a Laser	13
5.2	Stable Laser Resonator	14
5.3	Confocal Unstable Laser Resonator	14
5.4	Examples of laser Temporal Pulse Shapes	15
5.5	Spatial Intensity Distribution for a Near Gaussian Mode Laser	16
5.6	Schematic Diagram of a Slow Axial Flow Laser	16
5.7	Schematic Diagram of a Transverse Flow Laser	17
5.8	Schematic Diagram of a Fast Axial Flow Laser	18
5.9	Schematic Diagram of a Solid-State Nd:YAG Rod Laser	18
5.10	Schematic Diagram of a Total Internal Reflection-Face Pumped(TIR-FP) Slab Laser	19
5.11	Schematic of the Basic Components of a Fiber Laser	20
5.12	Principle of Thin-Disk Laser Cavity	21
5.13	Laser Beam Welding Equipment	23
5.14	Focusing Head	24
5.15	Transmission of Laser Beam Through a Fiber Optic	25
5.16	Schematic of Fiber-Optic Focusing System	26
6.1	The Equations for Propagation of Multimode Laser Beam Through a Focusing Lens	29
6.2	Schematic Showing Focusing of a Beam in the Far Field of a Laser	30
6.3	An Example of the Effect of Average Power of a Pulsed Nd:YAG Focused Spot Diameter	31
6.4	Comparison of Predicted and Measured Spot Size for a CO_2 Laser at 300 W	31
6.5	Proper Lens Type Orientation	32
6.6	Principle for Establishing Focus Position Using an Acrylic Wedge Block	33
6.7	Example of Technique for Finding Focal Plane Region	33
6.8	Calorimeter Type Power Meter	34
7.1	Photomicrograph of Conduction Mode Weld	41
7.2	Schematic View of Keyhole (Deep Penetration)Welding	41
7.3	Room Temperature Reflectivity as a Function of Wavelength for Several Metals	42
7.4	Absorption at 250°C as a Function of Roughness R_Z (Mean Value of Maximum Height) between Peaks and Valleys	43
7.5	Transition in Laser Welding Energy Transfer at the Grit Blasted Region on Aluminum for Aluminum for the Pulsed Nd:YAG Laser Beam Welding Process	43

Figure **Page No.**

7.6 Ray diagrams Showing the Refection of Light from the Workpiece for Different Lens Positions 44
7.7 Microprobe Profile Across 5456 Aluminum CW Nd:YAG Laser Weld 45
7.8 Microhardness Traverse of 5456 Aluminum CW Nd:YAG Laser Weld 45
7.9 Laser Welds in Butt Joint 48
7.10 Laser Welds in Corner Joints 49
7.11 Laser Welds in T-Joints. 50
7.12 Laser Welds in Lap Joints 51
7.13 Laser Welds in Edge Joints 52
7.14 Self-Aligning Joints. 53
7.15 Schematic Plasma Control Concepts. 54
7.16 Schematic Relationship between Power (*P*), Travel Speed (*S*), and Depth of Penetration 55
7.17 Welding Parameter to Fabricate through Thickness Weldments in ASTM A36 Plate of Different Thicknesses 55
7.18 Heat Input for Incipient Complete Joint Penetration vs. Laser Power for 304 Stainless Steel. 56
7.19 Comparison of (a) Autogenous Laser Weld and (b) Narrow-Gap Laser Weld. 57
7.20 Schematic Representation of Interaction Region between the Gas Management System, Wire Delivery System, and Laser Beam Delivery System 58
7.21 Metallographic Determination of Optimum Lens Position Relative to Workpiece for Pulsed Nd: YAG Laser Beam Weld 59
7.22 Effect of CO_2 Laser Power on Melting Efficiency 60
7.23 Comparison of Laser Beam Welding Melting Efficiency with Conventional Arc Welding Processes . . . 61
7.24 Bead-on-Plate Welding Speeds for High-Power CW Nd:YAG Laser Beam Welding of Mild Steel. 62
7.25 Welding Speeds for 1.7 kW and 2.5 kW CW CO_2 Laser Beam Welding of Carbon and Stainless Steel . . . 62
7.26 Dependence of Penetration in Three Metals on the Operating Conditions for Pulsed Lasers of Three Power Ratings 64
8.1 Conduction Mode Pulsed Nd:YAG Spot Weld in Type 304L Stainless Steel 66
8.2 Continuous Wave CO_2 Welding Edge Joint in 17-4 PH Stainless Steel. 66
8.3 Subsolidus HAZ Cracks in Nitronic 60 Pulsed CO_2 Weld 67
9.1 Mechanism of Laser Cutting 72
9.2 Geometry of an Electromagnetic Wave 77
9.3 Geometry of Reflection 78
9.4 P-Polarized Light. 78
9.5 S-Polarized Light. 79
9.6 Reflectivity of a Dielectric Surface for P-and S-Polarization 79
9.7 Reflectivity of a Metal for P-and S-Polarization. 80
9.8 The Effect of Polarization on Laser Cutting 81
9.9 Programming Sharp Corners. 87
9.10 Typical Cutting Rates for CW CO_2 Laser Beam Cutting of Steel 88
9.11 Typical Cutting Rates for CW CO_2 Laser Beam Cutting of Stainless Steel. 88
9.12 Typical Cutting Rates for CW CO_2 Laser Beam Cutting of Aluminum Alloys 89
9.13 Cutting Rates for High-Power CW Nd:YAG Laser Beam Cutting of 1010 Steel 89
9.14 Cutting Rates for Low-Power Pulsed Nd:YAG Laser Beam Cutting of Stainless Steel 90
9.15 Examples of Taper Effect from Relationship of Short Lens Focal Length to Material Thickness in Percussion Drilling. 92
9.16 Examples of Taper Effect from Relationship of Long Lens Focal Length to Thin and Thicker Materials in Percussion Drilling 93
9.17 Focusing Technique for Material Processing with an Excimer Laser. 94
9.18 Temporal Pulse Shaping for Drilling 96
10.1 Isothermal Transformation Diagram. 103
10.2 Laser Hardened Groove in AISI 4140 Steel, for Ball Bearings 103
10.3 Tempering of Steel Due to Reheating by Side-by-Side Passes. 104
10.4 Beam Integrator. 106
10.5 Beam Scanner 106

Figure **Page No.**

10.6 Kaleidoscope . . . 107
11.1 Laser Cutting and Drilling Process Parameter Schedule . . . 110
11.2 Laser Welding Process Parameter Schedule . . . 111
12.1 Radiographic Windows . . . 114
14.1 Typical Maintenance Schedule (Daily) . . . 116
14.2 Typical Maintenance Schedule (Weekly/Monthly) . . . 118
14.3 Typical Maintenance Schedule (Six Month/Yearly) . . . 119
14.4 Typical Maintenance Schedule (Periodic) . . . 120

This page is intentionally blank.

Recommended Practices for Laser Beam Welding, Cutting, and Allied Processes

1. Scope

These recommended practices present a description of laser beam equipment and procedures that can be used for welding, cutting, drilling, and transformation hardening of various materials. These recommended practices stress the process basics, parameters, and applications. Practical information has been included in the form of figures, tables, and graphs which should prove useful in determining capabilities and limitations in the processing of various materials. Readers who desire additional information about lasers and laser materials processing should consult the Reference Documents shown in Annex A, as well as the various references given throughout this document.

Any specific manufacturer product depicted in any sketch, figure, table, or product description in the document, shall not be construed as an endorsement of that particular manufacturer or product by AWS.

This standard makes sole use of the International System of Units (SI).

Safety and health issues may not be fully addressed by this standard. Users of this standard should consult ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes*, applicable federal, state, and local regulations, and other relevant documents concerning safety and health issues not addressed herein. ANSI Z136.1, *Safe Use of Lasers*, is another important source for safe operation of laser equipment. Please consult Clause 4 for more information.

2. Normative References

The following standard contains provisions which, through reference in this text, constitute provisions of this AWS standard. For undated references, the latest edition of the referenced standard shall apply. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply.

AWS Documents:[1]

AWS A3.0, *Standard Welding Terms and Definitions*

3. Terms and Definitions

The following terms and definitions are specific to laser beam material processing. Terms that are not part of common welding vocabulary are defined and the definitions of some standard welding terms are changed slightly to more accurately describe those terms as they apply to the laser beam process. Common terms pertaining to all welding processes that are not listed in this compilation shall be found in AWS A3.0, *Standard Welding Terms and Definitions*. Some of the Terms and Definitions have been extracted from *The Photonic Dictionary*.

For the purposes of this document, the following definitions apply:

absorption. The transfer of electromagnetic energy to an atom or a group of atoms that may be in a gas, gaseous plasma, liquid, or solid form. This energy may be released as heat (dissipative absorption) or re-emitted as electromagnetic energy. Most laser material processing involves the transfer of energy by dissipative absorption.

[1] AWS Documents are published by the American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126.

absorption coefficient. In the passage of a beam through an absorptive material, the loss of intensity of the beam per unit length of the material, usually expressed in cm-1.

absorptivity. A dimensionless measure of absorption which has a value of 1 for a perfect absorber. For an opaque material, absorptivity has a value of 1 – (reflectance). For a transparent material, absorptivity has a value of 1 – (reflectance) – (transmittance).

active medium. A substance in a laser generator in which stimulated emission of radiation, rather than absorption or spontaneous emission, will take place after pumping from an energy source has produced a population inversion.

aerodynamic window. A device used to transmit the beam from inside of the resonator to the beam delivery optics in some high-power gas lasers (>10 kW). It uses a rapid flow of gas, usually air, to create a pressure gradient between laser cavity pressure and atmospheric pressure. This pressure gradient isolates the gases inside the laser cavity from the atmosphere, and prevents contamination of the laser gas.

amplitude. The magnitude of the electric field in a radiation field. The intensity of the radiation in W/cm^2, is proportional to the square of the amplitude.

amplification. The growth of the radiation field in the laser resonator cavity. As the light wave bounces back and forth between the cavity mirrors, it is amplified by stimulated emission on each pass through the active medium.

angle of incidence. In laser materials processing, the angle between the optical axis of the incident laser beam and the normal or perpendicular to the workpiece or an optical component. A perpendicular angle is most often used.

aperture. The diameter of an opening through which light or laser radiation passes. Also, a device containing a hole through which some percentage of laser radiation passes to alter or measure beam characteristics.

aspheric lens. A lens element in which at least one face is shaped to a nonspherical surface of revolution about the lens axis.

assist gas. A gas used to blow molten metal away to form the kerf in laser beam inert gas cutting, or to blow vaporized metal away from the beam path in laser beam evaporative cutting. In some cases, the assist gas may chemically react with the laser-heated workpiece, producing additional heat which aids the laser-cutting process.

attenuate. To reduce the intensity of the laser beam. This can be accomplished by passing the beam through a partially transmitting medium or through an optical element.

autofocus. A method or device to automatically set the focusing head so that the focusing optic is maintained at a constant distance above the workpiece.

average power. The pulsed laser beam power that is the summation of all the laser pulses averaged over time. Average power (in watts or kilowatts) can be determined by multiplying pulse energy (in joules or kilojoules) times pulse frequency (in hertz).

beam alignment. Adjustment of the optical elements so that the axis of the laser beam coincides with the optical axis of the lenses, mirrors, beam tubes, etc.

beam delivery system. The use of optics, such as mirrors, lenses, tubes, and fibers arranged in such a way that a laser beam can be precisely directed to a specific location in a safe manner.

beam diameter. The diameter of a circular aperture which, if placed in the beam path, would transmit 86.5% (1e2 value) of the total power in the beam.

beam expander. An optical system used to increase the diameter of an optical beam. In a laser, this device also serves to collimate the beam.

beam quality. The focusability of a laser beam, commonly specified by the product of the radius of the resonator beam waist and the far field divergence angle. See M^2.

beam splitter. An optical device used to split an optical beam into two or more optical beams at predetermined power levels.

beam waist. The narrowed region of a laser beam as produced by an optical resonator or at the focal plane of a focusing optic.

brightness. A term often used to describe laser sources, typically by describing the power delivered into the beam focus area expressed in watts per square centimeter. The term can have several meanings, however.

CAD. An acronym for computer-aided design describing a drawing created using computer drafting software, often used with drafting software linked to computer-aided engineering (CAE) software for calculating stress or thermal distributions of objects under load.

CAD/CAM. An acronym for the process of computer-aided design and computer-aided manufacturing, where computers are used both in the design and manufacture of a part.

calorimeter. A thermally sensitive device used to measure the amount of laser output power or pulsed energy.

carbon dioxide laser (CO_2). A gas laser which uses carbon dioxide as the lasing medium and which radiates at a wavelength of 10.6 micrometers (μm). Nitrogen and helium are also used within the laser medium for better excitation and efficiency.

cavity. See **resonator**.

circularly polarized light. A light beam in which the electrical vector is rotating around the axis of propagation at the frequency of the beam. A circularly polarized beam is often used to optimize performance in contour cutting.

classification of lasers. The American National Standards Institute (ANSI) has introduced a classification scheme for lasers or laser systems, based on the laser's potential to inflict injury to personnel. The system is based upon the intensity of emitted radiation from the laser or laser systems. The higher the classification number, from one to four, the greater the potential hazard.

CNC. An abbreviation for computer numerical control, a device that controls a machine tool by reading numerical data and transforming it into movement of machine axes.

coherence. A property of radiation in which the phase between any two points in the radiation field has a constant difference, or is exactly the same throughout the duration and extent of the radiation. Laser light is coherent radiation.

collimated beam. Radiation in which a ray in a given point in the cross-section of a beam is nearly parallel to every other ray, with the degree of parallelism limited by the laws of diffraction.

collimator. An optical system which creates a collimated beam.

conduction mode welding. A melting and fusing operation in which the incident beam energy is transferred to the root of the weld solely by conductive and convective heat flow in the molten metal. See **keyhole mode welding**.

continuous power. See **continuous wave**.

continuous wave (CW). A laser beam which is produced continuously rather than as a series of pulses.

contour cutting. Laser cutting involving motion of the beam relative to the workpiece either by moving the beam or by the workpiece in two or more axes.

cosmetic pass. A partial penetration weld pass made primarily to enhance surface quality and appearance.

damage threshold. The power density at which optical components such as windows, mirrors, and rods are damaged by laser radiation.

depth of focus. The distance along the direction of propagation of a beam for which the power density is greater than 90% of its peak value in the focal plane.

diffraction. The tendency of light to spread out as it passes through space due to wave nature of light. As laser light passes by an opaque edge or through an aperture, secondary weaker wavefronts are generated, apparently originating at that edge. These secondary wave fronts will interfere with the primary wave front as well as with each other to form various diffraction patterns.

diffraction limited. The property of a high quality laser beam, whereby only the effects of diffraction determine the spot size produced by an optical system.

diode laser. A type of laser in which the active medium is a semiconductor with polished end facets forming mirror surfaces. Also called semiconductor laser. Diode lasers used for alignment emit in the visible; other diode lasers emitting in the infrared are used for material processing.

disk laser. Characterized by a heat sink and laser output that are realized on opposite sides of a thin layer of active gain medium. Despite their name, disk lasers do not have to be circular; other shapes have also been tried. Disk lasers should not be confused with Laserdiscs, which are a disk-shaped optical storage medium.

divergence. The expansion angle (measured in milliradians) of an optical beam in the far field. In specifying the beam divergence, one should note whether it is the full-angle or half-angle divergence.

divergence, full-angle. The expansion angle of an optical beam measure on both sides of the optic axis.

divergence, half-angle. The expansion angle of an optical beam measured from the optic axis to the extremities of the beam (as specified by the beam diameter).

doping. The process of adding a small concentration of a lasing ion or atom to a host material. The host material supports the dopants, influences the emission of energy from the dopants, and conducts away excess heat.

dross. The melted and resolidified metal or metal oxide produced during cutting or drilling that adheres to the top or bottom edge of a cut or drilled surface.

duty cycle. The fraction of time that a repetitively pulsed laser is producing pulsed output.

effective spot diameter. See **melted spot diameter**.

energy density. Laser output energy per unit area, expressed, for example, as J/cm^2.

energy transfer efficiency. The ratio of the heat absorbed by the workpiece to the incident laser beam energy.

enhanced pulse. A laser pulse output containing an initial short-duration burst of power when the discharge is first energized, which subsequently decays to a lower level of output. See **leading edge spike**.

excimer laser. A laser that emits ultraviolet energy from molecules called *excimers* that are created in pulsed electrical discharges and exist only for a very short period of time, on the order of nanoseconds. Excimer lasers use combinations of a gas such as argon, xenon, or krypton with halogens such as fluorine. Wavelengths from 0.193 to 0.348 μm have been generated.

excitation. Process of transferring energy from the energy source to the active medium.

far field. Far from the laser source; a term used in describing how a laser beam propagates. Mathematically, far field occurs at a distance D such that

$$D > \frac{\pi w_o^2}{\lambda} \qquad \text{(Equation 1)}$$

where,

λ = laser wavelength

w_o = minimum radius of the output laser beam

fast axial flow (FAF). A laser design in which the active medium (gas) is transported at a high speed along the optical axis of the laser resonator so that it can be cooled by external heat exchangers. In industrial CO_2 lasers, where this design is common, either a Roots pump or a centrifugal compressor is used to move the laser gas through the discharge region and heat exchangers.

fiber laser. A solid-state laser design in which the active medium is a doped optical fiber. Ytterbium is the most common active element doped into the fiber.

fiber optic. A small diameter solid fiber made of a transparent material such as fused quartz (or fused silica) and coated to achieve total internal reflection of a laser beam along its path. A fiber optic beam delivery system transmits the output power of the laser to the workpiece and can be bent at a shallow radius, eliminating the use of mirrors.

flashlamp. A device that converts electrical energy into light by means of a sudden electrical discharge. Flashlamps are a source of excitation in a pulsed solid-state laser.

fluence. See **energy density**.

fluence threshold. The energy density level (measured in joules/cm^2) at the surface of a material, at which there is sufficient energy to cause molecular bonds to break or some interaction to take place.

F-number. The ratio of the focal length of a lens or focusing mirror to the diameter of the beam incident on the lens or mirror. Note the definition is somewhat different than that for photographic systems.

focal length. In a lens or lens system, the distance from the principal plane, the surface at which the projections of an entering and exiting ray intersect, to the focal point. In a thick lens or system of lenses, the principal plane is often inside the lens itself; for setup purposes, operators often use the back focal length, which is the distance from the front surface of a focusing lens or mirror system to the focal point.

focal plane. A plane through the focal point at right angles to the direction of propagation of the beam where the minimum spot size occurs.

focal point. A nonstandard term for focal spot.

focal spot. A location at which the beam has the most concentrated energy and the smallest cross-sectional area.

focusing head. An assembly located near the end of the beam path that is used to converge an unfocused laser beam for processing materials. The assembly consists of one or more focusing lenses or mirrors, and may include assist- and purge-gas delivery system, a focal point adjustment mechanism, and optic protection devices.

following error. In CNC equipment, the deviation of the actual path traced by the focused beam or by a machine tool from the programmed motion. This error is most important when making abrupt turns at high speed and can be reduced by slowing the speed.

fused quartz. A glass formed by heating crystalline quartz to white heat, then cooling. It has a lower index of refraction than crystal quartz.

fused silica. Glass consisting of almost pure silicon dioxide. It is purer than fused quartz.

gallium arsenide (GaAs). A synthetically grown crystal used, among other things, in laser optics like lenses and mirrors.

gas laser. A laser in which the lasing medium is a gas. This type of laser is subdivided by medium into atomic (such as helium–neon laser), molecular (such as carbon dioxide laser), and ionic (such as argon, krypton, xenon, or helium–cadmium laser, for example). Excimer lasers are also gas lasers.

gas recirculation. A system to circulate the laser gas through the active laser region and the heat exchangers in a closed loop. The gases are cooled and re-excited continually. Commonly used in high-power lasers, a means to circulate the laser gas through the active laser region and heat exchangers in a closed loop.

Gaussian distribution. A symmetric two-dimensional equation which approximately describes the spatial power distribution of many laser beams. The equation of the Gaussian distribution is:

$$P(r) = P_o e^{\frac{-2r^1}{w^2}} \qquad \text{(Equation 2)}$$

where,

$P(r)$ = power density
P_o = maximum power density
r = radial distance out from the center of distribution
W = radius at which power density is 0.135 times maximum

(see **beam diameter**)

Gaussian mode. The fundamental transverse mode of a stable laser resonator (called TEM_{00} *mode*). A laser operating in this mode produces a beam having a Gaussian distribution.

glass laser. A laser in which the active medium is an optical glass doped with a small concentration of a lasing material, typically neodymium. Glass is easier to produce than YAG, especially in large sizes, but its thermal properties are not as good as the YAG crystal. See **YAG**.

helium-neon laser. A laser in which the active medium is a mixture of helium and neon, and which commonly has wavelengths in the visible range (400 to 700 μm). They are used widely with materials processing lasers for alignment.

hermetic. The rating of a seal that prevents the exchange of fluids (gases or liquids) between a contained volume and an exterior environment.

irradiance. See **power density**.

infrared (IR). Electromagnetic radiation possessing wavelengths between those of visible light and microwaves, i.e., approximately 0.8 μm to 1 mm.

joule. An SI unit of energy equivalent to 1 W of power lasting 1 second. Used as a unit of measure of the output of pulsed lasers.

kaleidoscope. Optical device used to integrate the transverse mode of the laser beam to be evenly distributed across the beam. Both transmission and reflective types are available.

kerf. The width of a cut produced during a cutting process.

keyhole mode welding. A technique that employs a concentrated heat source with sufficient intensity to vaporize some workpiece material. This results in the formation of a vapor hole ("keyhole"), surrounded by molten material that penetrates deeply into or through the work piece. As the concentrated heat source is advanced, molten metal flows around the walls of this vapor hole, fills in the trailing edge, and solidifies to produce a continuous weld.

kissing weld. A weld on a corner, T-, or lap joint in which the laser beam is incident at a small angle with respect to one of the surfaces being joined, and with respect to the joint to be welded.

laser. A device that produces a concentrated coherent light beam by stimulated electronic or molecular transitions to lower energy levels. Laser is an acronym for "Light Amplification by Stimulated Emission of Radiation."

laser beam. The output radiation of a laser that can be steered and focused by mirrors, lenses, or both, to do useful work.

laser system. A machine or fabrication tool consisting of a laser, a workpiece holder, and a means of delivering the beam to the workpiece and deflecting it over the workpiece in a controlled manner. The most common type of controller is a computer numerical controller, or CNC.

leading edge spike. The initial phase of a pulse from some pulsed lasers, in which the instantaneous peak power is considerably greater than the average power during the pulse. The leading edge spike is useful in rapidly heating a workpiece to temperatures at which the absorption is greater than that at room temperature. The trailing edge of the laser pulse is used to maintain the high temperature and process the material.

lens. A transparent optical element with curved surfaces, used to converge or diverge light rays via refraction.

M. The magnification ratio of an unstable resonator (i.e., the ratio of the outer diameter to the inner diameter in an annular-shaped beam).

M^2. A measure of beam quality that compares a laser beam with a theoretically ideal beam that is limited solely by diffraction (i.e., when $M^2 = 1$).

melted spot diameter. The diameter of a melted spot on the workpiece (also known as *effective spot diameter*).

meniscus lens. A lens having one surface convex and the other concave.

micrometer (micron). A distance of one millionth (10^{-6}) of a meter. This term is commonly used in specifying the wavelength of light and is abbreviated as μm.

mirror. An optical element which reflects nearly 100% of the laser beam.

mode. A stable condition of oscillation in a laser. There are transverse modes and longitudinal modes. Longitudinal modes occur at slightly different frequencies; most lasers operate on a large number of longitudinal modes simultaneously. Transverse modes describe the distribution of energy in a plane perpendicular to the direction of propagation. A laser can operate in one transverse mode (single mode) or in many modes simultaneously (called *multimode* or *mixed mode operation*).

monochromatic. Light which consists of single wavelength. Most lasers emit their light in a very narrow band of wavelengths around a central wavelength.

multimode. See **mode**.

near field. A term used to describe the propagation of a laser beam, referring to the beam characteristics at positions close to the laser.

Nd:glass. Neodymium-doped glass which is utilized as the lasing material in some solid-state lasers. The neodymium atoms are the active medium.

Nd:YAG. Neodymium-doped yttrium aluminum garnet (YAG) crystal which is utilized as the lasing material in a common type of solid-state laser. The neodymium atoms form the active medium. See **YAG**.

nozzle. A device projecting from the focusing head with an outlet to direct gas into the laser beam processing area.

optical axis. An imaginary line through an optical system along which the center of a laser beam is expected to follow; the line usually passes through the center point of all optical elements such as lenses, mirrors, apertures, and gain media.

optical coating. Dielectric or metallic coating on an optic with one or more thin surface layers to control surface reflection or transmission as a function of wavelength.

output coupler. A partially transmitting mirror at one end of the laser resonator which allows the extraction of laser energy from the laser.

peak power. The peak power is often approximated by dividing the energy of the pulse, or the energy contained in a leading edge spike, in joules, by the pulse duration in seconds.

percussion drilling. A process by which repeated pulses remove material and increase the depth of a hole until the workpiece is perforated. Subsequent pulses enlarge the hole and remove recast material.

photodiode. A semiconductor device in which light is directly converted to a flow of electricity which can be displayed in a time resolved fashion, for example with an oscilloscope.

photon. The quantum, or small discrete amount, of electromagnetic energy that moves at the speed of light.

plane polarized light. Light in which the oscillation of the electric field is only in a single plane (also called *linearly polarized light*). There are two possible plane polarizations, each one perpendicular (orthogonal) to the other.

plano convex. An optical element with a flat (planar) face on one side and a rounded outward (convex) face on the opposite side, which converges the light incident on the convex side.

plasma plume. See **plume**.

plume. The vapor cloud that forms above the laser material interaction zone. It can consist of excited and partially ionized assist gases and atoms of the material vaporized by the intense laser beam and can have a temperature equivalent to tens of thousands of degrees. Under certain conditions, the plume can absorb or scatter the incoming laser beam, reducing transmission of the beam, the energy absorbed by the workpiece, and weld penetration.

polarization. Limitation of the vibration direction of the propagated electromagnetic field (laser beam) to a single plane. Various forms of polarization can be found; these include random, linear, elliptical, and circular.

polarizer. An optic which transmits light of only a single polarization, or otherwise alters the polarization of radiation.

population inversion. A state in which more atoms or molecules of a lasing medium are at a higher energy level than at some lower energy level. This is necessary to promote the release of photons so that the lasing process can occur.

power. With respect to lasers, power is the rate of energy flow from the radiation source. Power is usually measured in watts (W), an energy flow of a joule per second, or kilowatts (kW).

power density. Intensity, or the power per unit area, of the output of a laser; expressed as, for example, W/cm^2.

power meter. A device used to measure laser beam power. See also **calorimeter**.

power ramping. A controlled change in the power level of a laser beam. Power ramping is useful for smooth completion of circular welds and for preventing depressions or fractures at the end of the weld.

pulsed laser. A laser which emits light as a pulse or a series of pulses rather than continuously.

pulse duration. The duration measured between the half-peak-power points at the front and trailing edges of a pulse.

pulse energy. The total energy contained in a laser pulse, or a series of laser pulses from a repetitively pulsed laser, usually measured in joules. It is calculated by dividing the measured average power by the pulse repetition rate.

pulse enhancement. See **enhanced pulse**.

pulse frequency. The output pulse repetition rate, in pulses per second (Hz), for a pulsed laser.

pulse length. See **pulse duration**.

pulse overlap. In spot welding with a repetitively pulsed laser, the amount (usually expressed as a percentage of the diameter of the melted zone) by which the diameter of the melted area created by one pulse overlaps that created by the preceding pulse.

pulse shape. The variation in time of the amplitude of a single laser pulse during the pulse duration.

pulse width. See **pulse duration**.

pump. An energy source used to excite the active medium and create a population inversion.

pumping. See **excitation**.

pyroelectric. A crystal which is a source of electrical current when radiation is incident on it; the current is proportional to the time rate of change of the crystal's temperature. The term also refers to laser detectors containing these crystals, which may be used to measure either the laser energy or laser power depending on crystal properties and associated circuitry.

Q-switch. A device used to produce very short duration and intense pulses from ruby or pulsed YAG lasers. A large amount of energy is stored during the off time and a burst of energy is released during the on time.

quarter-wave plate. A polarization retarder which causes light of one linear polarization to be retarded by a quarter wavelength (90 degrees) relative to the other polarization. The quarter wave plate is utilized to convert linear polarization to circular polarization, primarily for cutting applications.

recast. A layer of metal which melts and then solidifies along the walls of a hole or cut edge of a laser processed metal.

reflectance. The ratio of reflected power to incident power.

repetition rate. See **pulse frequency**.

resonator, optical. An optical system formed by two or more mirrors that reflect most light emitted by the medium back into the medium allowing light amplification to take place.

resonator, stable. A resonator in which the radiation reflected between the cavity mirrors converges on the longitudinal axis. A stable resonator can produce a beam with a Gaussian mode.

resonator, unstable. A laser resonator in which a light ray reflected between the cavity mirrors will move away from the cavity axis. The resonator is "unstable" for light propagation rather than mechanically unstable. Usually, laser energy is extracted by a mirror at a 45 degree angle to the optical axis which contains a hole which is aligned with optical axis.

RF excitation. A method of laser excitation using radio frequency waves. This allows excitation though the glass or quartz envelope of the tube, so that the electrodes are isolated from the lasing gas.

rod, laser. A cylinder of transparent lasing material with polished end faces used as the active medium in a laser.

ruby laser. A laser in which the lasing material is a single crystal of aluminum oxide doped with chromium ions. The cylindrical ruby rod is pumped by a pulsed xenon flash lamp, producing a laser output in the red region of the spectrum, at a wavelength of 0.694 μm. Ruby is the material in which laser operation was first demonstrated in 1960.

shutter. A mechanical or optical device used to block or control the transmission of laser beams.

slab laser. A solid-state laser in which the host medium is a rectangular or trapezoidal block of material, usually YAG. Formation of the light beam occurs more uniformly in the material than in a rod laser reducing the thermal gradients in the material.

slow flow. A gas laser in which the flow of gas is along the axis of the laser beam, but is relatively slow so that the extraction of waste heat from the gas is done primarily by thermal conduction through the walls of a tube to a cooling medium.

spherical aberration. The failure of a spherical surface of a lens or mirror to form a perfect image; light rays incident on the surface at different radii come to focus at a different distance from the surface along the optical axis.

spot size. The diameter of a focused laser beam. See **beam diameter**.

stability. The ability of a laser system to maintain a beam with constant output characteristics, such as power level or mode.

standoff. The distance between the focus head's beam exit aperture and the work surface. The standoff distance influences the dynamics of the assist gas interaction with the material being processed.

stimulated emission. The emission of a photon from an atom or a molecule in an excited state in response to the presence of another photon of approximately the same wavelength. The resulting photon will have the same wavelength, polarization, phase, and spatial coherence as the original one.

TEA laser. An acronym for "transversely excited, atmospheric pressure laser." The TEA laser is a gas laser for which excitation of the active medium is provided by an electric discharge transverse to the optical axis of the medium at pressures of one atmosphere or greater. This type of laser is used primarily for marking applications.

TEM_{00}. Laser radiation of the fundamental transverse electric mode. The spatial intensity has a Gaussian distribution. See **transverse mode**.

thermal diffusivity. The controlling transport property for the transient diffusion of heat into the base metal during laser materials processing.

$$\alpha = \frac{\kappa}{\rho C_p} \qquad \text{(Equation 3)}$$

where,

κ = thermal conductivity
ρ = density
C_p = specific heat

thermocouple. A type of sensor consisting of two electrically conducting circuit elements of different thermoelectric characteristics joined at a junction.

thermopile. An arrangement of thermocouples in series so that the voltages from individual thermocouples add. In a thermopile, the series of thermocouples are arranged such that the alternate junctions of the thermocouple are at the measuring temperature and the reference temperature.

Transverse Electromagnetic Mode (TEM). See **transverse mode**.

transverse flow. Refers to the direction of the gas lasing medium in a gas laser. Transverse flow lasers have the gases flowing at right angles to the direction of laser beam propagation.

transverse mode. The distribution of energy in a plane perpendicular to the direction of propagation. See **mode**.

transmittance. The ratio of transmitted power to incident power.

trepan. A type of drilling where a circular hole is made either by rotating the laser optics within the focusing head, or by programming a circular motion of the focusing head.

up-collimator. See **beam expander**.

wavelength (λ). The distance between two points in a periodic wave which have the same phase.

YAG (Yttrium Aluminum Garnet). A synthetic crystal used as a laser rod host material in Nd:YAG laser.