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Foreword

With the continuous improvement in, the output power, beam quality, and energy efficiency, high power lasers as light and heat sources of high-energy density beams have been widely applied to material processing, forming a significant part of special or non-traditional material processing technologies. The laser materials processing technology has various advantages, including non-contact, precise energy control, wide material suitability, greater flexibility, high quality, and environmental friendliness. For this reason, this technology can be used not only for efficient automatic mass production, but also for a large variety of small batch processing, and further, for customized production. Thus, laser processing has become an essential technology for the manufacturing industry to transform and upgrade. After years of R&D, laser processing technology has become one of the most important technical means of high-energy beam processing in five major manufacturing fields: welding, cutting/drilling/marking, surface engineering, micro/nano fabrication and additive manufacturing (3D printing).

Laser welding is a process to join similar and dissimilar materials by fusion. It has many advantages over traditional arc welding, including higher speed, higher energy density and depth-to-width ratio of weld joints, smaller heat-affected zones and deformation, better quality and performance of the joints, more efficient production, and more flexible control and operation, which shows enormous potential as an advanced welding technology. Nevertheless, given the high energy density of laser beam, the dynamic state of melt pool at very high welding speeds is more complex. Welding defects elimination, welding process stability and deformation control have become key technological challenges that need to be understood. To establish a fundamental theory of laser welding, particularly the keyhole welding, understanding of laser weld pool dynamics is essential.

Professor Shuili Gong and his research team have long been engaging in laser welding basics and engineering application research. They have systematically carried out in-depth research on interaction mechanisms between lasers and materials, weld pool behavior and its influence on welding processes, having established a series of theories to aid the development of laser welding technologies and applications. This book is an extract and summary of achievements made by the author's team through many years of research, and is a collection of theoretical findings on the topic of laser keyhole weld pool behavior. Professor Gong's research team has proposed and established various theories on the dynamic behavior of laser welding pool, which provide a theoretical basis for revealing welding defect mechanisms, welding process stability mechanism and its equilibrium conditions, guiding the practical engineering applications. At the same time, the theories also underpin the research and application of other laser process technologies.

This book is a monograph on the basic study of laser welding, particularly on laser keyhole welding, laser welding with wire filler, laser welding of thick section materials and laser vacuum welding. It would be a valuable reference for researchers and engineers. I am very happy to recommend this book to the readers.

July 2020

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Preface

In 1917, Albert Einstein, put forward the concept of stimulated emission and discovered the photoelectric effect, laying theoretical foundation for the invention of laser. In May 1960, Dr. Maiman, an American physicist, created the world's first ruby laser based on the development of quantum electronics, marking the beginning of research on laser and its application. In the early 1960s, reports began to appear about the technical applications related to laser drilling and welding. With continuous improvement on laser technology and laser beam quality and increasing output power, lasers are quickly applied to material processing as the light and heat sources of high-energy density beams, forming a special material processing technology cluster of great significance—laser processing technology. This technology has a wide range of advantages such as non-contact, precise energy control, suitability to a variety of materials, strong flexibility, high quality, resource saving, and environmental friendliness. It can be used not only for efficient and automatic mass production, but also for small-scale processing of multiple varieties of materials, and even for product customization. This makes the laser processing technology essential for transformation and upgrading of the traditional manufacturing industry. After years of development, the laser processing technology has developed into a high-energy beam processing technology, becoming one of the three important technical means in three major manufacturing technologies—welding and removal, surface engineering and additive manufacturing (3D printing). The laser processing technology can be divided into many categories, such as welding, cutting, drilling, rapid prototyping, etching, micro-nano processing, surface modification, spraying and vapor deposition, and play an important role in many fields of national economy and defense development.

Compared with traditional arc welding technology, the laser welding technology, typical of the laser processing technology, has an array of advantages such as high-energy density (up to 10^{15} W/cm^2), high depth-to-width ratio of weld joints, small heat-affected zone, small deformation, high quality and performance of the joints, high production efficiency, and flexible control and operation. The laser welding technology has enormous potential for welding.

The laser welding technology develops along with the advancement of laser technology. The laser welding method moves from heat conduction welding towards deep penetration welding as the laser output power increases, beam quality improves, and theoretical research and technology continues. The welding technology constantly develops. Laser butt welding, laser superposition welding, hybrid laser-arc welding, laser welding with filler wires, dual-beam laser welding, multi-beam laser welding, dual-beam laser welding with filler wires, ultra-narrow gap laser welding, all-position laser welding, long-focal-length dynamic laser welding, and other technologies emerge and develop one after another. Accordingly, welding equipment, welding systems, and process detection and control technologies are improved, laying a solid foundation for the application of laser welding technology in the national economy and defense development.

Since the laser technology has been applied to welding, the theoretical research of laser welding moves along. Systematic research has been carried out from different modes of the interaction mechanism of lasers and materials, the weld pool behavior and its influence on the welding process, which provides solid theoretical support for the development and application of the laser welding technology. The scientific and technical workers have studied the interaction mechanism of lasers and materials and the physical state change process of materials, obtaining two typical welding modes of laser heat conduction welding and deep penetration welding. They realized that the laser energy density is the key parameter of the mutual transformation of the two welding modes and found that the weld pool generated in deep penetration laser welding is characterized by the dynamic keyhole behavior, and the thermodynamic equilibrium in weld pool keyholes of deep penetration welding is a necessary condition for the stable formation of keyholes. Through application research and engineering practice of laser welding, welding scientific workers discovered that the weld pool behavior in deep penetration laser welding plays an important role in the stability of laser welding. Studying and mastering the dynamic behavior of weld pools in laser welding becomes the key foundation for the optimization of technical parameters and stability control in welding.

Over the years, with the support of government agencies and organizations, Beijing Aviation Manufacturing and Engineering Institute, Huazhong University of Science and Technology, Xi'an Jiaotong University, Harbin Institute of Technology, Dalian University of Technology, etc., have conducted in-depth research on the technology basis of laser welding, and have carried out continuous study on the weld pool behavior in laser welding, systematically revealing the weld pool behavior in laser welding and its influence, providing theoretical support for the practical application and promotion of the laser welding technology, and laying a solid foundation for drafting this book.

This book systematically describes the main research achievements on the weld pool behavior of domestic laser welding in recent years. It refines and summarizes the relevant research work from the institutions such as National Defense Science and Technology Key Laboratory of High Energy Beam Processing Technology in Beijing Aviation Manufacturing and Engineering Institute, Huazhong University of Science and Technology, Xi'an Jiaotong University and Taiyuan University of Science and Technology. The research work of the authors' research team especially provides great support to this book.

This book consists of 9 chapters, which systematically describe the weld pool behavior during laser welding and its influencing factors, including the experimental research, theoretical calculation and process simulation technology, physical state transformation behavior of weld pools, and the impact of technical conditions on the weld pool behavior. The research achievements of this field in China are intensively reflected in the research results, some of which present the latest frontier research work of the authors' research team, such as the weld pool behavior of dual-beam laser welding, the weld pool behavior of laser welding with filler wires, and the weld pool behavior of heavy-thickness full-penetration laser welding and laser welding in vacuum and low vacuum conditions, etc. Those who participated in compilation of this book are Shuili Gong, Shengyong Pang, Hong Wang, and Linjie Zhang, among which Shuili Gong is responsible for the content of preface and Chapter 1, Shengyong Pang for the content of Chaps. 3–5 and Chaps. 7–9, Hong Wang for the content of Chap. 2, and Linjie Zhang for the content of Chap. 6. The whole book was reviewed and finalized by Shuili Gong. This book not only can be used for reference for engineering technicians, scientific researchers in the field of laser material processing, scientific researchers majored in material science, and teachers and students in colleges and universities, but also have high reference value for research and development personnel in the field of laser equipment, optical scientific researchers, scientific and technical personnel in the related fields of laser application physics, and teachers and students in colleges and universities.

During the compilation of this book, we received great support and help from our research team. We would like to thank National Defense Science and Technology Key Laboratory of High Energy Beam Processing Technology in Beijing Aviation Manufacturing and Engineering Institute, Huazhong University of Science and Technology, Xi'an Jiaotong University and Taiyuan University of Science and Technology, and especially thank Professor Jianxun Zhang of Xi'an Jiaotong University for his guidance for this book, Professor Jianzhong Xiao and Professor Jianxin Zhou of Huazhong University of Science and Technology for their strong support for this book, and our colleagues' support and help. We would like to thank the authors listed in the bibliography of this book for their works and papers which have contributed greatly to the compilation of this book.

We'd like to comfort Professor Lunji Hu and Professor Liliang Chen of Huazhong University of Science and Technology with this book. Without their support and guidance over the years, the authors may not have completed this book.

Due to the authors' limited knowledge, it is inevitable that there are inadequacies and shortcomings in the book. You are welcome to criticize and correct us.

Beijing, China
July 2017

Shuili Gong

Introduction

This book systematically describes the weld pool behavior in laser welding and its influencing factors from the perspectives of testing technology, theoretical calculation and process simulation technology, physical state transformation behavior of weld pools, and the impact of technical conditions on the weld pool behavior. The book covers extensive research achievements made by China in this field, some of which represent the latest cutting-edging research conducted by the authors' research team. These latest research efforts mainly relate to the weld pool behavior of dual-beam laser welding, laser welding with filler wires, full-penetration laser welding of very-thick parts, and laser welding in vacuum and low vacuum conditions.

This book can be used by teachers and students in universities and colleges and engineering technicians for reference.

Contents

Chapter 1
Laser Welding Basics

Abstract This chapter introduces the basics of laser welding process. The principles of laser material interactions, the characteristics and theories of laser welding, and the research outlines of weld pool dynamics of laser welding process are presented.

1.1 Interaction of Lasers and Materials

The interaction process between laser and material is complicated, involving multiple disciplines such as laser physics, heat transfer, plasma physics, non-linear optics, thermodynamics, gas dynamics, fluid mechanics, mechanics of materials, and solid-state physics. Laser welding, which is one of the major applications of the laser processing technology, also utilizes the physical phenomenon generated by the interaction between laser and material, and these physical phenomena may come down to the thermal and mechanical effect of the material being processed. The main research content and direction include the reflection, absorption, and energy conversion of the laser by the material, and the heating, melting, thermocompression shock wave, vapor ejection, plasma expansion, and shock wave of the material by the laser. Nevertheless, during the laser welding research, the focus is on the absorption of the laser by the welded material and the thermophysical and mechanical effects of the material itself (such as heating, melting, vaporization, and plasma effect). The main physical phenomena are shown in Fig. 1.1.

1.1.1 Laser Absorption by Materials and Material Heating

The regular motion of damped oscillation of the charged particles in the atom is described by the classical mechanics; that is to say, the charged particles are regarded as the oscillators following the classical mechanics. The oscillators vibrate as bound close to a certain equilibrium position by the elastic restoring force directly proportional to the displacement. In case of deviating from the balanced position, the oscillators will be acted by a restoring force. In terms of metal, oscillators in the metallic

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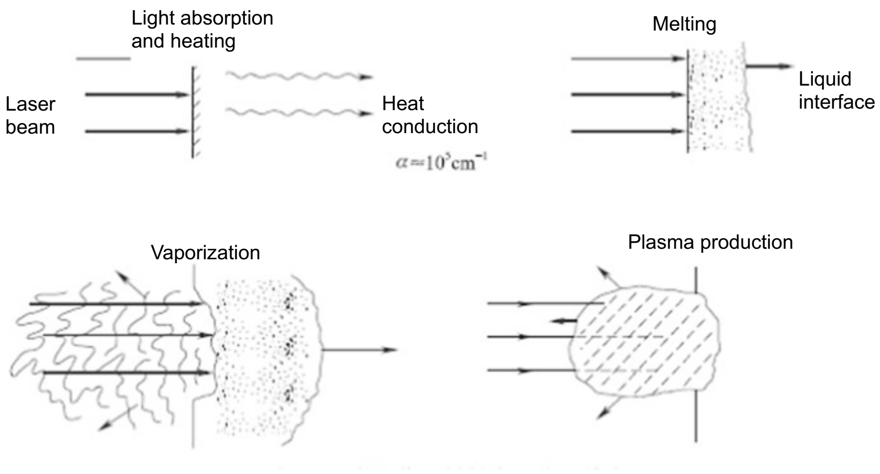

Fig. 1.1 Physical effect on the material surface under the laser action

material are mainly free electrons. Absorption in the metal is mainly completed by the vibration of free electrons which can move freely under the electric field action without the effect of the restoring force. The natural vibration frequency of the oscillators is $\omega_0 = 0$, and the relationship between refractive index n, extinction coefficient κ, and damping factor γ, plasma frequency ω_p is as follows:

$$n = \left\{ \frac{\sqrt{\left(1 - \frac{\omega_p^2}{\omega^2+\gamma^2}\right)^2 + +\left(\frac{\omega_p^2 \gamma}{\omega^3+\gamma^2\omega}\right)^2} + \left(1 - \frac{\omega_p^2}{\omega^2+\gamma^2}\right)}{2} \right\}^{1/2} \tag{1.1}$$

$$\kappa = \left\{ \frac{\sqrt{\left(1 - \frac{\omega_p^2}{\omega^2+\gamma^2}\right)^2 + +\left(\frac{\omega_p^2 \gamma}{\omega^3+\gamma^2\omega}\right)^2} - \left(1 - \frac{\omega_p^2}{\omega^2+\gamma^2}\right)}{2} \right\}^{1/2} \tag{1.2}$$

where

$$\omega_p = \sqrt{\frac{Ne^2}{m\varepsilon_0}} \gamma = \frac{e^2 \omega_0^2}{6\pi \varepsilon_0 c^3 m}$$

The plasma frequency ω_p is the strength parameter, which determines the relative strength of the oscillators; the damping factor γ is the parameter of the band width. As we can see from Eqs. (1.1) and (1.2), when the laser frequency is far less than the plasma frequency, n and k increase rapidly, most of laser is reflected, and very little is absorbed; when the laser frequency is close to the plasma frequency, n shows the local minimum value, and k value monotonically decreases. Therefore, the laser can be absorbed well when the laser frequency is near the plasma frequency; when the laser frequency continues to go up and far more than the plasma frequency, n is quickly approaching 1, and k quickly becomes 0, in which case, the metal is transparent. The plasma frequency of the metallic material is between ultraviolet and near-infrared band, so the laser from near-infrared, visible, to ultraviolet band is relatively favorable to metal processing; the far-infrared laser is almost reflected by the metal. For the infrared light with low photon energy, the light frequency electromagnetic wave only works on the free electrons in the metal, while for the visible light or UV-light with high photon energy, the optical frequency electromagnetic wave can also work on the bound electrons in the metal as the inherent frequency of bound electrons in the metal is within the visible or UV-light frequency band. Under the action of the bound electrons, the reflecting capacity of the metal reduces, the transmitting capacity increases, and the laser absorption capacity increases, indicating certain non-metal optical property.

Due to interaction between the laser and the electrons, ions, lattice vibration, impurities, and defects in the material, the laser can be absorbed by the material. Therefore, the optical properties of the material are closely correlated to laser absorption.

Transmission of the laser action in the material can be described by Maxwell's equations. When electric field intensity of the laser in the material is substituted into the Maxwell's equations, the relation between the complex refractive index $\hat{n}(\hat{n} = n - ik)$ and the material's physical constant, which can reflect the electromagnetic wave propagation features, can be obtained.

$$n^2 = \frac{\mu}{2}\left[\sqrt{\varepsilon^2 + \left(\frac{4\pi\sigma}{\omega}\right)^2} + \varepsilon\right] \tag{1.3}$$

$$\kappa^2 = \frac{\mu}{2}\left[\sqrt{\varepsilon^2 + \left(\frac{4\pi\sigma}{\omega}\right)^2} - \varepsilon\right] \tag{1.4}$$

where: ω—Frequency;

ε—Dielectric constant;

μ—Magnetic conductivity;

σ—Electrical conductivity;

n—Refractive index;

κ—Extinction coefficient, which reflects the attenuation characteristic of the electromagnetic wave amplitude.

Equations (1.3) and (1.4) show that the refractive index and extinction coefficient of the material are closely correlated to the permeability, dielectric constant, electrical conductivity, and laser frequency.

For the isotropous homogeneous substances, according to Lambert–Beer-Bouguer law, the laser intensity I decreases exponentially with the transmission distance z

in the material, $I_z = I_0 exp\ (-\alpha_0 z)$, where α_0 is the absorption coefficient. The relationship between the absorption coefficient and the laser frequency and extinction coefficient is as follows:

$$\alpha_0 = \frac{2\omega\kappa}{c} = \frac{4\pi\kappa}{n\lambda} \tag{1.5}$$

where, c—Laser speed in the vacuum;

λ—Laser wavelength in the vacuum;

$1/\alpha_0$—Light absorption length, defined to be the light beam propagation distance when the light beam intensity reduces to 1/e (37%) of the original due to the photon energy being absorbed.

The feature of the absorption coefficient related to the laser wavelength is called the selective absorption, while the absorption where the absorption coefficient does not change with the laser wavelength is called the general absorption. Normally, the absorption coefficient has nothing to do with the laser intensity.

Absorption of the laser in the material depends on the permeability, dielectric constant, electrical conductivity, and laser frequency. During laser processing, once the laser frequency is determined, the absorption coefficient is only correlated to the extinction coefficient. Therefore, analysis of the absorption of the laser in the material can be converted to analysis of the extinction coefficient and physical characteristics of material. The higher the dielectric constant of the material is, the lower the electrical conductivity will be, the higher the refractive index will be, and the less the extinction coefficient will be, so the less the absorption coefficient will be; the higher the material permeability is, the higher the electrical conductivity will be, and the lower the dielectric constant will be, so the higher the absorption coefficient of material will be. In addition, laser absorption is also correlated to the microstructure and surface status of the material.

1.1.2 Laser Heat Source Model and Laser Heating Effect

When the substance absorbs the laser, excess energy appears first in some mass points (kinetic energy of free electron, excitation energy of bound electron, or excess phonon), other than the heat. These orderly original excited energies can be converted into the heat energy through two steps: Step I is the stochastic motion of the excited particles in both space and time. This process is completed during particle collision time (momentum relaxation time), which is a very short moment; Step II is the uniform distribution of the energy between each mass points. This process contains a mass of collision and intermediate state, especially non-metallic materials. Finally, a certain form of energy distribution will take shape in the material. In conclusion, the heating process of the material under the laser action is extremely short.

To study the thermal action due to interaction between laser and material, it's generally assumed that a heat source with its laser energy distribution the same as the absorbed laser energy distribution applies to the material surface, and under this precondition, the temperature field model is built to analyze the heating and cooling process during the laser processing. The heat transfer phase from the surface material into the matrix mainly follows the Fourier law of heat conduction. The heat source model of the laser varies with different materials. For metallic material, the laser absorption length is very limited. Laser absorption occurs within 1–5 μm of the material surface. The heat source model can be expressed as follows:

$$Q_{V(x,y,z,t)} = AI_0(x, y, t)\delta(z) \tag{1.6}$$

where: A—Absorptivity of the laser by the material;

I_0 (x, y, t)—Distribution of the laser intensity on the material surface;

δ (z)—Dirac function.

The laser intensity I_0 (x, y, and t) is usually represented as the production of spatial distribution I_0 (x, y) and dimensionless time waveform B (t). Typical wave forms B (t) include step wave, rectangular wave, triangular wave, trapezoidal wave, and Gaussian waveform, etc.

During the laser heating process, the thermal physical parameters of material (absorption coefficient, specific heat, thermal diffusivity, and thermal conductivity coefficient) vary with the temperature, however, for most of materials, the change of heat physical parameters is relatively little as the temperature changes, nearly equal to a constant, or the temperature in the process may be regarded as average value. In the following discussion, it's assumed that the thermal physical parameters of material are independent of the temperature.

When the laser beam of Gaussian distribution stands still relative to the material surface, the maximum value distribution of the temperature field on the semi-infinite material surface is as follows:

$$\Delta T = \frac{AP}{k\pi^{3/2}r}\arctan\sqrt{\frac{4\alpha\tau}{r^2}} \tag{1.7}$$

where: A—Laser absorptivity;

P—Laser power;

r—Equivalent radius of the laser beam;

k—Heat conductivity coefficient of material;

α—Thermal diffusion coefficient of material.

Heating of the material by the laser is correlated to various factors, such as laser power density, equivalent radius of the laser beam, and material heating time by the laser. The equivalent radius is generally defined as the distance from the center of the laser beam to the position when the light intensity drops to 1/e of the central light strength. For the Gaussian beam, the equivalent radius is $\omega/\sqrt{2}$ (ω is the spot size of the Gaussian beam). If the time characteristic constant $\tau_0 = r^2/4\alpha$ is introduced, Eq. (1.7) can be rewritten as:

$$\Delta T = \frac{AP}{k\pi^{3/2}r} \arctan\sqrt{\frac{\tau}{\tau_0}} \tag{1.8}$$

If the laser-material action time τ is far less than the time characteristic constant τ_0; that is to say, the laser irradiation time is very short, then

$$\arctan\sqrt{\frac{\tau}{\tau_0}} \approx \sqrt{\frac{\tau}{\tau_0}}$$

Equation (1.8) can be simplified to be:

$$\Delta T = \frac{AP}{k\pi^{3/2}r} \sqrt{\frac{\tau}{\tau_0}} \tag{1.9}$$

If the laser-material action time τ is far more than the time characteristic constant τ_0, the laser irradiation time is relatively long and the temperature field approaches steady state, thus,

$$\arctan\sqrt{\frac{\tau}{\tau_0}} \approx \frac{\pi}{2}$$

Equation (1.8) can be simplified to be:

$$\Delta T = \frac{AP}{2k\pi^{1/2}r} \tag{1.10}$$

If the laser-material action time τ is close to the time characteristic constant τ_0 (generally $0.1\ \tau_0 \le \tau \le 3\tau_0$), then

$$\arctan\sqrt{\frac{\tau}{\tau_0}} \approx \frac{\tau}{4}\left(\frac{\tau}{\tau_0}\right)^{3/8}$$

Equation (1.8) can be simplified to be:

$$\Delta T = \frac{AP}{4k\pi^{1/2}r}\left(\frac{\tau}{\tau_0}\right)^{3/8} \tag{1.11}$$

Heating of the material by the laser is mainly applied in the laser heat treatment technique. Usually, under the heat treatment condition, the laser beam applies to the material surface in the form of scanning, and the laser beam in this case is regarded as the moving heat source. The temperature field generating the moving heat source is the quasi-steady state, equivalent to the static temperature field dragging in the material at the laser scanning speed v, in which case, it's necessary to define an equivalent laser action time $\tau^* = Cr/v$. To approximately describe the temperature change of the moving laser surface using the static laser surface temperature, the constant C can be properly adjusted, usually equal to 1.25.

When the laser equivalent action time $\tau^* = 1.25r/v$ is substituted to Eq. (1.7), the maximum temperature at the center of the light spot can be obtained.

$$\Delta T = \frac{AP}{k\pi^{3/2}r}\arctan\sqrt{\frac{5\alpha}{vr}} \tag{1.12}$$

The characteristic velocity $v_0 = 5\alpha/r$ is introduced. Generally, in the actual lasering heat treatment, the laser scanning speed is near v_0, in which case, Eq. (1.12) can be rewritten as:

$$\Delta T = \frac{AP}{k\pi^{3/2}r}\arctan\sqrt{\frac{v_0}{v}} \tag{1.13}$$

As it can be seen from Eq. (1.13), the material surface temperature is directly proportional to the square root of the heating time. For the laser heating pulse at the given energy, when the power density increases, the pulse duration (i.e., heating time) will definitely be shortened and the temperature on the material surface will raise; that is to say, the laser pulse with high peak power and short duration can heat the material surface more effectively.

1.1.3 Material Melting Under Laser Action

Physical issues more closely related to the laser processing is melting and vaporization of the material caused by the laser. When the temperature of the material surface heated by the laser is up to the melting temperature and vaporization temperature, Eq. (1.7) is no longer true. The material has to absorb latent heat during melting and vaporization. After melting and vaporization, the heat conductivity of the material changes greatly and the heat conduction gets very complex.

When the laser with a certain strength beats down on the material surface, and the material surface temperature is up to the melting point T_m, the isothermal level (prior to the melting wave $T = T_m$) will transfer into the material at certain speed, with the propagation velocity depending on the laser power density and thermodynamic parameters of the material in both solid and liquid phases. The melting without vaporization is usually defined to be shallow melting. In case of shallow melting, the light spot is larger than the weld pool in diameter, and the effect of transverse thermal diffusion can be ignored. Maximum depth at the shallow melting zone can be represented as:

$$Z\frac{1.2k}{AP}_v\left(\frac{T_v}{T_m} - 1\right)_{m,\max} \tag{1.14}$$

where T_m—Melting temperature of the material;

T_v—Vaporization temperature of the material.

In terms of the material characteristics, the larger the ratio of the thermal conductivity coefficient k of the material to T_v/T_m is, the greater the melting depth $Z_{\max}$ will be. For the laser characteristics, to improve the melting depth, the relatively low laser power density shall be adopted because it can take relatively long time to heat the material surface to T_v. Therefore, at the given laser pulse, the laser power density shall be adjusted so that the material surface can just reach the vaporization temperature at the end of laser pulse, in order to obtain the maximum melting depth. Under normal circumstances, the maximum depth of the pure melting of the material under laser irradiation is about several microns to several hundred microns.

What the shallow melting corresponds to is deep melting which is defined to be situation where the melting depth is no less than the radius of the light spot. For deep melting, only equilibrium vaporization occurs at the gas–liquid phase surface, the vapor is transparent to the laser. The threshold value of the laser power density causing deep melting of the material under continuous Gaussian beam irradiation is about:

$$I_{md} = 2kT_m/(\sqrt{\pi}\alpha A) \tag{1.15}$$

During deep melting, the diameter of the weld pool is larger than that of the light spot. A stable vaporization wellblock with the diameter less than that of the light spot appears in the center of the weld pool. The vapor in the wellblock has low density, basically transparent to the laser, so that the laser can directly enter and irradiate on the gas–liquid interface at the bottom of the wellblock, and then be absorbed. The absorbed laser energy is used for heat dissipation of the side wall and vaporization at the bottom. Assumed that the radius of both laser spot and vaporization wellblock is R_s, the depth of the deep melting can be expressed as:

$$Z_v = \frac{R_s^2 A I_0}{k_q T_v}\left[1 - \exp\left(-\frac{k_q T_v}{R_s^2 L_v \rho_q} t\right)\right] \tag{1.16}$$

In the deep melting, the length-diameter ratio of the vaporization wellblock Z_v/R_s cannot be too large (generally $0.5 \leq Z_v/R_s \leq 40$), or unstable movement may occur to vapor and solution.

If the laser intensity is relatively high, vaporization at the gas–liquid interface in the wellblock will exacerbate, and the vapor pressure will rise. The vapor pressure and vapor reaction can overcome the tension on the solution surface and the solution static pressure, resulting in appearance of keyholes and transfer of liquid mass. The keyhole is like black body, which is in favor of absorption of the beam energy, indicating the “wall focusing effect". Since the laser beam after focusing is not parallel beam, it will make certain angle of incidence with the keyhole wall. After radiating on the keyhole wall, the laser beam reaches the bottom of the keyhole after multiple reflection, and finally be completely absorbed.

The high-pressure steam in the keyhole pushes the melt to splash out along the edge of the weld pool or the wall of the vapor well, causing liquid mass transfer. Liquid mass transfer of this kind will greatly improve the efficiency of some laser processing, such as laser drilling or laser cutting. The squeezing effect of material vapor is an important cause of liquid mass transfer. Assuming that the vapor is produced from equilibrium vaporization at the gas–liquid section, ignoring the momentum and energy of the vapor, and only taking into consideration the vapor pressure P_{v}, when the vapor pushes the nonviscous incompressible solution layer of a certain thickness, the work of the vapor will be completely converted into the kinetic energy of the solution, and the mass of the liquid material transferred from a unit area of laser beam spot within a unit time at the ambient pressure of P_0 is the liquid mass transfer rate $\dot{m}_q$ of liquid mass, which is

$$\dot{m}_q = \left[\frac{2\lambda_q}{R_s}\ln\left(\frac{T_v}{T_m}\right)\right]^{1/2} \rho_q^{3/4}[2(P_v - P_0)]^{1/4} \tag{1.17}$$

1.1.4 Evaporation of Materials Under Laser Action

It can be seen from the melting of material under laser action, the melting process is usually accompanied by evaporation of the material. The evaporation mechanism is closely related to laser power density.

The time from the start of laser irradiation to the material surface reaching the evaporating temperature T_{v} is called the evaporation starting time t_{v}, which can be estimated as

$$t_v = \frac{\pi}{4\alpha}\left(\frac{kT_v}{AI_0}\right)^2 \tag{1.18}$$

For the metal with a low evaporating temperature, when AI_0 *is* 10^4~10^6 W/cm^2, t_v is about a few milliseconds to microseconds; for the metal with a high evaporating temperature, when AI_0 is 10^5~10^7 W/cm^2, t_{v} is about a few milliseconds to several hundred nanoseconds; If t_{v} is much less than the width of the laser pulse, the evaporation of the material surface is considered to start immediately once the laser irradiates.

When the laser power density is not very high, the evaporation of material is not drastic, the saturated vapor pressure is balanced with the ambient pressure, and the velocity distribution of the vapor particle is isotropic, in the Maxwell Distribution of translational equilibrium. Myriad laser equilibrium evaporation models have been established by scholars across the world. At present, the theoretical model of laser evaporation has only qualitative significance, and the quantitative understanding mainly relies on experiments. In all evaporation pressure formulas obtained with laser equilibrium evaporation models, the vapor pressure is considered to be proportional to the laser power density.

When the laser power density is high, the material evaporation rate increases, and the vapor pressure increases. When it is significantly higher than the ambient pressure, the number of particles in the vapor that return to the solution decreases, and the velocity distribution will deviate from the balanced Maxwell Distribution. The vapor particles leaving the liquid surface must pass a distance and collide with each other to reestablish a translational equilibrium. The thin layer above the liquid surface where the vapor is in the transition from a non-equilibrium state to an equilibrium state is called the Knudsen layer. In the extreme of strong evaporation, the vapor on the outer surface of the Knudsen layer flows at the sound velocity, and the vapor flowing outward is noticeably colder and thinner than the saturated vapor on the surface of the solution.

Under continuous laser irradiation, the velocity of evaporation front (namely the receding velocity) rises rapidly from zero to an approximately constant value, and the evaporation enters a steady state. The establishment time t_{sv} of a steady state is related to the steady receding velocity U_{v}. Usually t_{sv} is dozens of times greater than t_{v}. For example, when AI_0 is 10^7 W/cm^2, the receding speed of aluminum is about 2.34 m/s, and the corresponding velocity $t_{\mathrm{sv}} \approx 15$ µs, while t_{v} is less than 0.3 µs.

Due to the action of the vapor pressure, t_{v} in Eq. (1.18) should be greater than the normal evaporating temperature under standard atmospheric pressure. When the laser power density is between 10^6 and 10^7 W/cm^2, the temperature of the evaporation front of the metal is slightly greater than the normal evaporating temperature. When the laser power density is between 10^6 and 10^{10} W/cm^2, the temperature of the former evaporation front is several times to dozens of times that of the latter. Since T_{v} increases with the laser power density, it leads to the receding velocity U_{v} in the range above 10^8 W/cm^2 decreasing with the increase of the laser power density, and the decrease is more obvious in the range above 10^0 W/cm^2.

The gaseous mass transfer rate $\dot{m}_v$ depends on the receding velocity, $\dot{m}_v = \rho U_v$, and the total gaseous transfer mass is $\rho \int_{t_v}^{t} U_v dt$. When the laser power density is low, the heat lost by thermal diffusion has an obvious influence on U_{v}, and the rate of gaseous mass transfer is also low. The calculated values of the receding velocity and gaseous mass transfer rate are usually noticeably different from the experimental results, which is caused by two reasons. For one thing, it is because the reflectivity, absorptivity and thermal physical characteristics are all related to temperature and the actual laser waveform is highly irregular. For the other, it is because that mass transfer is actually a comprehensive result of various mechanisms, in which the main part of the transferred mass is composed of the splashed droplets by vapor pressure.

1.1.5 Laser-Induced Plasma and Its Effects

When laser acts on the surface of the material, vapor is induced. The vapor continues to absorb laser energy, causing an increase in the temperature and eventually forming a high-temperature and high-density plasma. A plasma is a mass composed of large quantities of charged particles (electrons and ions), atoms and molecules, which as a whole is electrically neutral. There are three main mechanisms of plasma generation by high power density laser: photoionization, thermal electric ionization and collision ionization. Photoionization refers to the phenomenon that when electrons in atoms are irradiated by laser and absorb sufficient photon energy, ionization occurs due to the photoelectric effect or the multi-photon effect. Photoionization is mainly applicable to the generation process of initial charge carriers in a relatively cold medium, while the laser plasma is in a completely ionized state, and therefore photoionization is not the main mechanism for its formation. Thermal electric ionization refers to that when the temperature of the vapor under laser action is high enough, the atoms with high thermal velocities at the high temperature collide with each other, making their electrons excited, and the energy of some of the electrons exceeds the ionization potential, which leads to the ionization of atoms. Collision ionization refers to that charged particles in vapor accelerate under the action of electric field and collide with neutral atoms, resulting in energy exchange, which enables the electrons in the atom to acquire sufficient energy to ionize.

The ionization degree of vapor in the thermodynamic equilibrium state is completely determined by the density and temperature of vapor. In a partially ionized gas, the energy of the incident laser is absorbed by the thermally excited atoms through the binding-free mechanism and by the particles through the inverse bremsstrahlung. Vapor absorbs laser energy and heats up, leading to further increase in the ionization degree and absorption coefficient. This kind of positive feedback contributes to the formation of plasma in the vapor.

The plasma absorbs the energy of the laser beam propagating in it through various mechanisms, which increases its temperature and ionization degree. Inverse bremsstrahlung absorption is the main mechanism of plasma absorbing laser energy. Inverse bremsstrahlung absorption refers to that the electrons in a laser electric field are excited to oscillate at high frequency, and collide with particles with a certain probability to transfer energy to heavier particles (ions and atoms), thus heating up the plasma.

The vapor of a metallic material is a monatomic gas, which has a very high evaporating temperature T_{v} but a very low ionization potential, so the evaporating rate of the material is not high. When the vapor pressure is only slightly higher than the ambient pressure, there are also a large number of free electrons in the weakly ionized vapor, which can lead to effective inverse bremsstrahlung absorption of laser. In other words, free electrons in an ion Coulomb field absorb laser energy, and accelerate or change the direction of motion, thus transferring the laser energy to ions and heating up the vapor.

When the light intensity is high and the energy absorption rate of the vapor exceeds its various losses, the vapor ionizes and the number of free electrons increases exponentially with time, making the vapor completely ionized and opaque to the laser. As the size of the plasma increases by absorbing energy, the power density of the laser reaching the surface of the material decreases, and therefore the evaporation effect weakens, resulting in a drop in the density and temperature of the plasma, as well as in its absorptivity; conversely, as the absorptivity weakens, the laser power density reaching the surface of the material increases, and therefore the evaporation effect is enhanced, resulting in an increase in the density and temperature of the plasma, as well as in its absorptivity.

The absorption of the laser by the plasma prevents the laser from reaching the surface of the material, cutting off the energy coupling between the laser and the material. This effect is called plasma shielding. The ratio of energy absorbed by plasma to the energy of the incident laser is called plasma shielding coefficient. The plasma shielding coefficient is related to the laser wavelength. The plasma shielding effect of a long wavelength laser is stronger than that of a short wavelength laser, and appears earlier. In laser welding technology, the absorption and scattering of plasma affect the transmission efficiency of laser and reduce the laser energy reaching the work piece. Meanwhile, the negative lens effect (refraction) of plasma expands the area of action of laser energy on the work piece, thus reducing welding quality.

1.2 Principles and Characteristics of Laser Welding

Laser welding is a special fusion welding method in which a focused laser beam with high energy density (10^6–10^{12} W/cm^2) is used as a heat source to heat and melt the work piece. It is a fusion welding based on the above-mentioned photothermal effect of the interaction between the laser and the material. Its premise is that the laser is absorbed by the material and converted into the thermal energy required for welding. In general, the physical phenomena resulting from laser action on the material surface vary, including the increase of surface temperature, melting, evaporation, formation of keyhole, and generation of laser induced plasma (see Fig. 1.2).

These physical phenomena determine the thermal action mechanism of the welding process, which leads to two laser welding modes: heat conduction welding and deep penetration welding. The transition of the two modes depends primarily

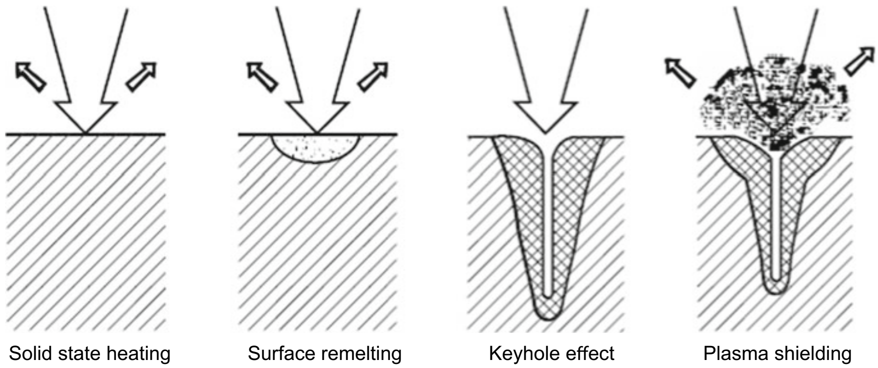

Fig. 1.2 Physical processes of laser of different intensities acting on metal surface

on the power density of the laser spot acting on the material. For some particular materials, there is a specific threshold of power density. When the power density of the laser acting on the material is lower than this threshold value, the laser energy is absorbed by the surface of the material and transferred to the interior of the material quickly, forming a heat conduction weld with a relatively large width and depth. However, when the power density of the laser acting on the material is higher than this threshold value, the laser energy makes the material surface heat up, melt and evaporate rapidly before the work piece surface can transfer the heat into the material, and with the continuous input of laser energy, a keyhole in the direction of penetrating the thickness is formed. The keyhole, surrounded by a weld pool of liquid metal, is filled with high-temperature metal vapor and plasma. The expansion force of the high-temperature metal vapor and plasma acts together with the gravity and surface tension of the liquid metal around the keyhole to maintain a stable existence of the keyhole (see Fig. 1.3).

The keyhole moves along the welding direction, and the weld pool behind it quickly cools and solidifies, forming a deep penetration weld with a large width and depth, as shown in Fig. 1.4. Therefore, the laser welding mode is closely related to the laser power density and welding heat input which determine the thermal mechanism.

Laser welding is an extremely complex physical and chemical process, containing phenomena such as rapid heating, melting, evaporation, ionization, rapid cooling and non-equilibrium solidification of the material, and involving the formation and of different states of matter, such as solid, liquid, gaseous and plasma forms and the complex interaction between them. The welding area is in a dynamic supernormal thermophysical state, in which the behavior of heat and mass transfer and the process of non-equilibrium solidification and structure evolution are more complicated than that of conventional heat source welding. The dynamic behavior of these complex phenomena has an important influence on the welding quality and the mechanical properties of the joint. Furthermore, the key components to be welded often have complex three-dimensional shapes, and dynamic working conditions, such as

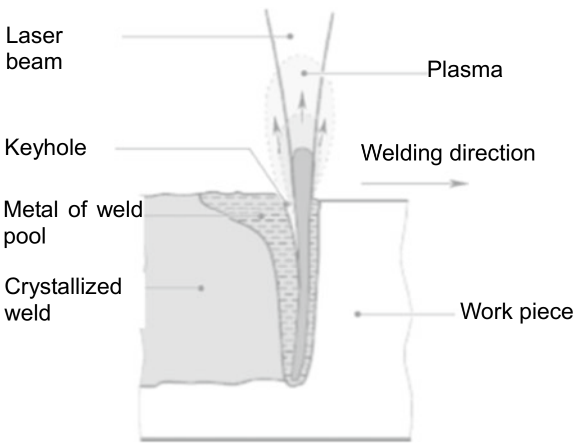

Fig. 1.3 Diagram of keyhole formation in laser welding

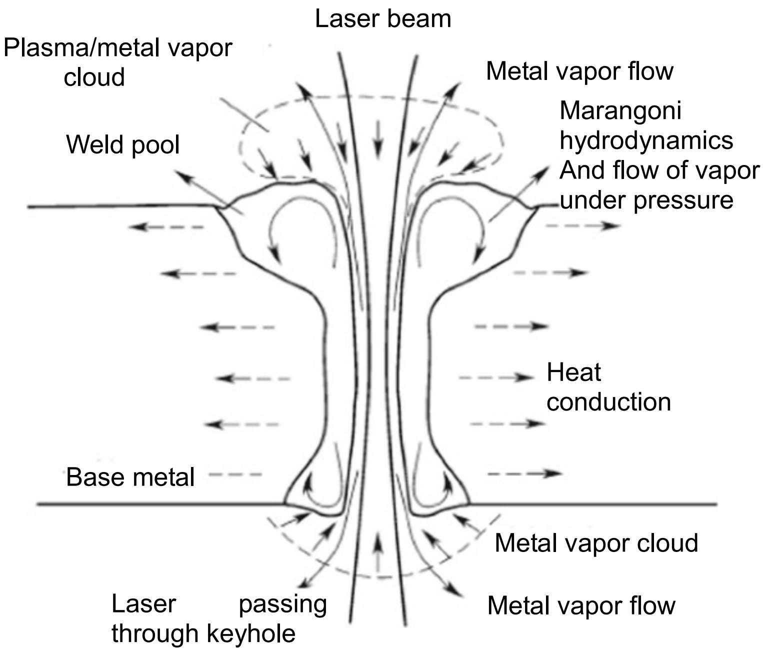

Fig. 1.4 Diagram of laser penetration welding principle

weld layout and slight thermal deformation caused by welding process, inevitably affect the stability of welding process. Therefore, various complicated theoretical and technical problems are exposed in the welding process. The first one is the poor welding process stability and repeatability, such as frequent interruptions in the welding process, which make it impossible to maintain a stable welding in the whole process. The second one is that the generation mechanism of welding defects is unclear, and the control technology is not well developed, which lead to negligible advancement of laser welding. In addition, the performance of laser welding joint is uneven with poor consistency, which makes the welded structure fail to meet the demand for functions. These problems seriously affect the application and promotion of laser welding technology.

1.3 Research on Weld Pool Behavior in Laser Welding

Compared with the conventional arc welding method, the deep penetration laser welding, which is based on the theoretical basis of keyhole effect, has attracted wide attention for its high energy density, low heat input, high depth-to-width ratio of weld, small heat affected zone (HAZ), small deformation, high welding quality, high production efficiency, flexible control, etc.