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激光加热应用

Laser Heating Applications

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CHAPTER ONE

Introduction to Laser Heating Process

Contents

Advanced processing technologies are demanding focus areas of the materials and manufacturing disciplines. Lasers are considered to be advanced material processing tools filling the gap in the advanced manufacturing systems because of their precision, low cost, localized processing, and high speed of operation. In laser-machining applications, a laser beam is used as a heat source, increasing temperature rapidly to the melting and evaporation temperature of the substrate material. Since the arrangements of the optical setting for the laser beam are very precise, the localized heating can be controlled easily. With recent advancement in laser technology and computation power, laser-machining application has become almost an integral part of the aerospace, power, electronics, and sheet metal forming industries. However, in laser-machining operations, the physical processes are complicated in nature and they require a deep understanding of the process to secure improved end-product quality.

Laser machining can be categorized into two groups based on the type of processing being involved during the machining such as drilling, cutting, welding, alloying, and others. The laser processing can be pre- or post-treatment operations such as duplex treatment for coatings and scribing after coatings. In order to optimize the laser-machining process and reduce the experimental time and cost, the model studies receive considerable attention. In addition, the model studies give insight into the physical processes that take place during the heating process, being easier to accomplish as compared to experimental studies. The measurement of physical properties during laser–workpiece interaction is difficult and costly since the process is involved with high temperature, short duration, and localized heating. From the modeling point of view, laser machining can be classified into two categories: i) laser conduction limited heating, and ii) laser nonconduction limited heating. In the laser conduction limited heating situation, the substrate surface is heated up to the melting temperature of the substrate material; in this case, the substrate remains in the solid state during the process. One of the laser conduction limited applications is the laser quenching of the surfaces. In the laser nonconduction limited heating situation, the substrate surface undergoes a phase change during the processing, i.e., melting and subsequent evaporation result. The laser drilling, cutting, and welding are typical examples of laser nonconduction limited heating situation.

When a high-power laser beam is focused onto the substrate surface, the beam energy is partially absorbed by the substrate material. Depending on the focused beam diameter at the surface, laser power intensity (combining the laser output energy and pulse length), and reflectivity of the surface, the substrate material undergoes solid heating, melting, and evaporation. In the case of evaporation process, the evaporating front detaches from the liquid surface, generating a recoil pressure across the vapor–liquid interface. As the evaporation of the surface progresses, the recoil pressure increases considerably while influencing the evaporation rate. As the heating progresses further, the liquid surface recesses toward the solid bulk, forming the cavity in the substrate material. Depending on the pulse length and power intensities, the liquid ejection from the cavity occurs, which is particularly true for the long pulse lengths (∼ms pulse lengths); however, the surface ablation without liquid ejection takes place for short length pulses (∼ns pulse lengths). Moreover, the liquid ejection improves the material removal rates from the cavity. In the case of laser short-pulse processing, the recoil pressure increases substantially due to high rates of momentum exchange during the evaporation process. In this case, high pressure at the vapor–liquid interface acts as a pressure force generating surface indention and high stress levels at the liquid–solid interface. This, in turn, results in a pressure wave propagating into the substrate material. Depending on the magnitude of the pressure wave, the plastic deformation through dislocations in the surface region of the substrate material takes place. The depth of the deformed region is limited with the interaction of the loading (plastic wave) and unloading (elastic wave) waves, i.e., as the loading phase is completed (when the evaporation is completed, the recoil pressure diminishes), the unloading wave (elastic wave) from the liquid–solid interface initiates. Since the unloading wave travels faster than the loading wave, both waves meet at some depth below the surface. Since the wave motion in the substrate material is complicated, a comprehensive investigation is required for the understanding of the physical insight into the process.

Short pulse heating of metallic surfaces results in thermal separation of the electron and the lattice subsystems. Thermal communication in between both subsystems gives rise to nonequilibrium energy transport in the heated region. The collisional process taking place between excited electrons and the lattice subsystem governs the energy transfer from the electron subsystem to the lattice subsystem. This process continues until the thermal equilibrium is established between the subsystems. When the heating duration is comparable to electron relaxation time, nonequilibrium energy transfer takes place through the collisional process while dominating over the diffusional energy transfer in the solid. In this case, the Fourier heating model fails to give a physical insight into the heat transfer in the substrate material. Consequently, the electron kinetic theory approach incorporating the electron–lattice site collisions between the lattice and electron subsystems becomes essential to account for the formulation energy transport in the solids. Moreover, the closed-form solution for the governing equation of the physical problem becomes fruitful, since it provides the functional relation between the independent variables, such as time and space, and the dependent variable, such as temperature. Although the analytical approach giving the approximate solution is possible, the solution is limited in time and space scales due to the assumptions made in the analysis. Consequently, the general form of analytical solution for the nonequilibrium energy transport in the metallic substrates due to short-pulse heating becomes essential.

The word laser is an acronym for "light amplification by stimulated emission of radiation." Albert Einstein in 1917 showed that the process of stimulated emission must exist [1] but it was not until 1960 that Maiman [2] first achieved laser action at optical frequencies in ruby. The basic principles and construction of a laser are relatively straightforward, and it is somewhat surprising that the invention of the laser was so long delayed. In the time which has elapsed since Maiman [2] first demonstrated laser action in ruby in 1960, the applications of lasers have multiplied to such an extent that almost all aspects of our daily life are touched upon by lasers. They are used in many types of industrial processing, engineering, meteorology, scientific research, communications, holography, medicine, and for military purposes. It is clearly impossible to give an exhaustive survey of all of these applications.

In considering the various properties of laser light, one must always remember that not all of the different types of lasers exhibit these properties to the same degree. This may often limit the choice of laser for a given application. There are certain distinctive spatial profiles that characterize the cross sections of laser beams. The spatial patterns of lasers are termed *transverse* *modes* and are represented in the form TEM_{mn}, where m and n are small integers. The term *TEM* stands for *transverse electromagnetic*. The transverse modes arise from considerations of resonance inside the laser cavity and represent configurations of the electromagnetic field determined by the boundary conditions in the cavity.

The notation TEM_{00} can be interpreted in rectangular symmetry as meaning the number of nulls in the spatial pattern that occur in each of two orthogonal directions, transverse to the direction of beam propagation. The TEM_{00} mode has no nulls in either the horizontal or vertical direction. The TEM_{10} mode has one null in the horizontal direction and none in the vertical direction. The TEM_{11} mode has one null as one passes through the radiation pattern either horizontally or vertically. In addition, there are solutions of the boundary conditions which allow cylindrical symmetry. The mode denoted by TEM_{01} represents a superposition of two similar modes rotated by 90° (rectangle) about the axis relative to each other. In many cases, a superposition of a number of modes can be present at the same time, so that the radiation pattern can become quite complicated. It is desirable to obtain operation in the TEM_{00} mode for the machining operation. This transverse mode has been called the *Gaussian mode*. The Gaussian intensity distribution $I(x)$ as a function of the radius from the center of the beam is given by

$$I(x) = I_0 \exp\left(-\frac{x^2}{r_0^2}\right) \tag{1.1}$$

where I_0 is the intensity of the beam at the center, x is the radial distance, and r_0 is the Gaussian beam radius, i.e., the radius at which the intensity is reduced from its central value by a factor e^2. The total power is given by

$$P = \pi r_0^2 I_0 \tag{1.2}$$

The beam divergence angle θ of a Gaussian beam is

$$\theta = \frac{2}{\pi}\frac{\lambda}{r_0} \tag{1.3}$$

The spatial profile of the Gaussian TEM_{00} mode is desirable, since its symmetry and the beam divergence angle are smaller than for the higher-order transverse modes.

Spectrometric examination of temporal laser output modes reveals that the output power consists of very narrow spectral lines. The two mirrors of the laser form a *resonant cavity* and standing wave patterns are set up between the mirrors. The standing waves satisfy the condition

$$L = m\frac{\lambda}{2} \tag{1.4}$$

or

$$\nu = m\frac{c}{2L} \tag{1.5}$$

where c is the speed of light and L is the optical path length between the mirrors, in which case the wavelength λ would be the vacuum wavelength and m is an integer in Eqn (1.4). A small change in λ results in different values of m and each value of m satisfying Eqn (1.5) defines the temporal mode of the cavity.

Equation (1.5) shows that the frequency separation $\delta\nu$ between adjacent modes ($\delta m = 1$) is given by

$$\delta\nu = \frac{c}{2L} \tag{1.6}$$

As Eqn (1.6) is independent of m, the frequency separation of adjacent axial modes must be the same irrespective of their actual frequencies. Hence, the modes of oscillation of a laser cavity will consist of a very large number of frequencies, each given by Eqn (1.5) for different values of m and separated by a frequency difference given by Eqn (1.6).

The most common method for providing single-mode operation involves construction of short laser cavities, so that spacing between modes ($c/2L$, where c is the speed of light and L is the optical path length between the mirrors) becomes large and lasing action occurs in one temporal mode. It has the disadvantage that the short cavity limits the output power extracted. Further frequency stabilization is obtained by vibration isolation, temperature stabilization, and control of the mirror spacing according to the output power.

REFERENCES

[1] Einstein A. On the quantum theory of radiation. Phys Z 1917;18(6):121–8.
[2] Maiman TH. Stimulated optical radiation in ruby. Nature 1960;187(4736):493–4.

CHAPTER TWO

Conduction-Limited Laser Pulsed Laser Heating: Fourier Heating Model

Contents

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