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Role of Lasers in Modern Materials Processing

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Abstract

Lasers, in general, and the carbon dioxide laser, in particular, have provided an extraordinary impetus to the materials community. The ability to apply a high power density heat source with precise spatial and temporal resolution has extended the boundaries of conventional materials processing to include the effects of rapid, non-equilibrium processes, extended solubilities, and rapid solidification. This paper will review significant changes that have occurred in the materials community as a result of laser processing and cautiously, yet optimistically, comment on further innovations.

KEYWORDS: (Lasers) (Welding) (Cutting) (Drilling) (Cladding) (Transformation) (Hardening)

Introduction

The laser was first demonstrated by Maiman (1) in 1960. Since that time many different investigators have shown that a wide variety of materials were capable of producing a laser beam. These laser beam cover a spectrum of wavelengths and powers. The "efficiency" of the interaction of this laser beam with a material is a function of, among other things, the wavelength of the laser, its power, and the material to which the laser beam is impinged. It is not the purpose of this paper to describe this interaction, but to assess those cases in which the interaction has been demonstrated as either an economically feasible method of production or as a feasible process based on laboratory test but not yet widely accepted as a manufacturing process. In order to provide a coherent paper, the paper will first discuss lasers, then provide an overview of selected laser/material interactions of interest to the materials community, and finally discuss each of these interactions in view of the future of laser processing.

Lasers

A laser is a device that produces an intense, concentrated, and highly parallel beam of light. Every laser must consist of three fundamental, distinct parts: (1) a laser material or medium, (2) a method of excitation, and (3) a resonant cavity.

The most efficient laser currently available for materials processing applications is the CO2 laser, which can be utilized in both high power continuous wave and pulsed operating mode. Carbon dioxide lasers use an electric discharge as the source for exciting the lasing medium, which is the CO2 gas molecule. The gas mixture for the laser is usually a combination of helium, nitrogen, and carbon dioxide. Carbon dioxide lasers are classified according to their gas flow system.

The simplest CO2 laser has an axial flow system; the gas flow is in the same direction as the laser beam and the electric field. The axial flow of gas is maintained through the tube to replenish molecules depleted by the effects of the multikilovolt discharge of electricity used for excitation. A mirror is located at each end of the discharge tube to complete the resonant cavity. Typically, one mirror is totally reflective and the other is partially transmissive and partially reflective. An axial-flow laser is capable of generating a laser beam with a continuous power rating in excess of 50 W for every meter of resonator length.

The transverse excited atmospheric CO2 laser is capable of producing pulsed output laser beams of very high peak power. The gaseous lasing medium is maintained at atmospheric pressure and is excited by an electric discharge from electrodes placed longitudinally along the optical resonator. Because of the proximity of the electrodes, a relatively low potential is required to maintain high field strength. Very short discharge times facilitate a uniform electrical discharge. Transverse excited atmospheric lasers can generate 10 MW or more of power in a single pulse less than 1 μs long. These lasers usually operate at the rate of a few pulses per second.

The gas transport laser operates by continually circulating the gas across the resonator cavity by means of a high speed blower, while maintaining an electric field perpendicular to both the gas flow and the laser beam. Because the volume of the resonator is large relative to its length, large mirrors can be placed at each end to reflect the beam through the discharge region several times before it escapes through the output coupler. The ability to achieve a relatively long effective optical path in a short actual distance allows the gas transport laser to be a compact structure that generates high output power. Continuous wave lasers capable of output powers between 1 and 25 kW are available.

Laser/Material Interactions

A schematical illustration of some of the various laser/material interactions that occur when lasers of various powers interact with metals for different times is shown in Fig. 1.

At very high power densities and very short interaction times the phenomena of shock hardening (2) occurs. In these experiments the laser beam is impinged on either a glass or quartz plate, which, in turn, transmits a shock wave to its water backing. The water conducts the shock wave into the material. The result of this shock wave on the material is to increase its dislocation content and modify its residual stress distribution.

At slightly lower power densities and interaction times, the surface of a metal can be significantly modified by rapid solidification (3), melting, and alloying. The surface of the metal is melted by the laser beam and solidification occurs before equilibrium is attained. The results are that non-equilibrium structures are obtained and structures and alloys that are unattainable by conventional processing are readily available. The creation of new alloys is left to the cleverness and desires of the experimentalist.

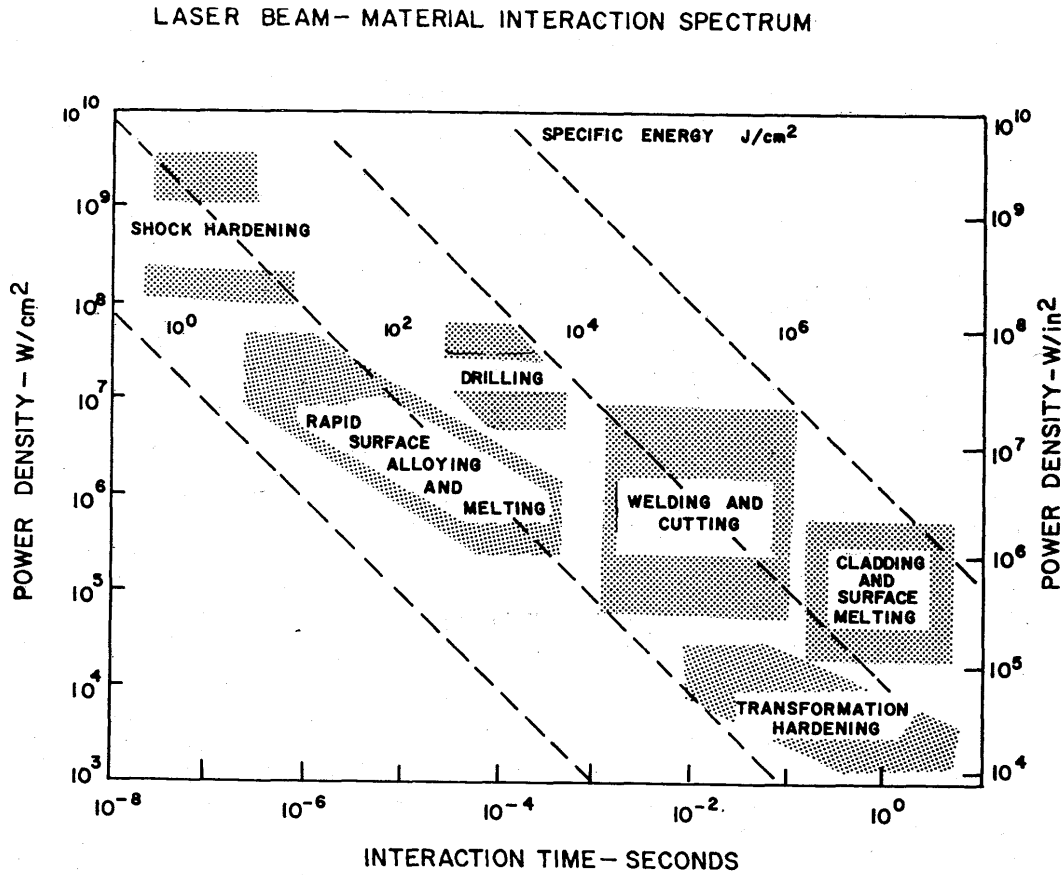

Figure 1. Laser beam-material interaction spectrum.

At higher powers and slower interaction times laser drilling (4) occurs. A highly concentrated, focused beam of laser energy is directed onto the surface of the material. The laser beam interacts with the material in such a way as to expel the molten drops from the hole. By repeated applications of laser power a hole can be drilled through the thickness of the material. By controlling the power and interaction time the diameter of the hole and its taper can be readily controlled.

Welding and cutting occupy the same envelope in Fig. 1 and although they are similar, marked differences in the processes are prevalent. Each process will be discussed separately.

More carbon dioxide lasers are sold for laser beam cutting (5) than for any other laser/material processing application. In laser beam cutting the focused laser beam is directed at the workpiece and a stream of either inert or reactive gas is also directed to the same area. If the reaction of the gas and the metal is exothermic, the gas is utilized as the cutting tool and the laser more or less simply ignites the gas. If the gas is inert, the laser beam drills a hole through the thickness of the plate and the inert gas provides a means of protecting the hot metal from the atmosphere, while at the same time, expelling the liquid metal from the hole. Laser beam cutting is readily adapted to computer numerical control, resulting in an efficient, versatile machine tool.

Laser beam welding (6) is similar to laser beam cutting in that the laser beam drills a cavity into the workpiece. This cavity is surrounded by a liquid pool which, by moving either the workpiece or the laser beam, can be moved along the line to be joined to create a weldment. The interaction of the laser beam and the workpiece creates a plasma. Part of this plasma (7) is required for the welding process, but the other part can very effectively reduce the depth of welding. Many techniques have evolved over the years to decouple the laser beam from the extraneous plasma and thus increase welding depth and/or welding speed. The extremely high power density, the low heat input, and the rapid solidification that are characteristic of laser beam welding have been shown to have many beneficial effects when compared with other welding processes.

Cladding and surface melting (8) are related processes; the difference being the introduction or lack of a different material into the molten pool. Surface melting occurs as a result of the laser beam traversing the material when the laser power and interaction time are insufficient to drill into the material but sufficient to melt the surface of the material. Cladding is similar to surface melting except that a different material, usually a wear resistant or oxidation resistant alloy, is added to the molten pool. A true metallurgical bond is formed at the interface of the two materials, and the amount of dilution of the added material by the base material can be minimized.

The final envelope on the power density-interaction time plot is labeled transformation hardening (9). Transformation hardening occurs in steels when the laser beam heats the alloy sufficiently to change the microstructure of the region to austenite. This region cools to form martensite, using the conductivity of the material to rapidly change its temperature. This self-quenching process results in high hardness values in this region, little distortion of the entire material, and an efficient and productive method of hardening parts.

All of these areas of power density-interaction time envelopes have received a great deal of laboratory testing, experimentation, and modeling. Most of these areas are viable, economic production methods. Each of these sections, with the exception of shock hardening, will be discussed in more detail; with more of an emphasis on the physical processes involved and present applications in order to set the stage for comments and insights into future applications.

Rapid Surface Alloying and Melting

Of all of the power density-interaction time envelopes, this particular area has been exploited least, but perhaps has the highest potential for future application. The concept of this section is simple, yet the implications are staggering. The laser beam is transversed across the surface of the material in such a way as to create a very small, shallow molten pool. This molten pool resolidifies at extremely fast cooling rates, and the heat is conducted away by a self quenching process. The interaction time is sufficiently small to limit thermal effects to a shallow surface. Rapid surface melting thus occurs in a time in which an almost negligible amount of thermal energy can be conducted into the base plate, producing extremely sharp temperature gradients between the solid and the liquid. Since there is always intimate solid/liquid contact, very rapid quenching of the melt to the cold, solid substrate material results from these high thermal gradients. As a result of this rapid chilling, a variety of interesting metallurgical structures is produced. For simple alloys the result of this rapid solidification is a very fine grain size surface. For more complex alloys, for example those alloys that are known to solidify with an amorphous structure at fast cooling rates, the structure of the surface melted region can be amorphous. By the addition of different elements to the molten pool, an entirely new series of alloys that are metastable can be created. The addition of a powder to the melting process has permitted the extension of the process in order to have structural control of thicker sections in a variety of shapes and sizes, yet, at the same time, retaining a controlled gradient of microstructures. Thus, this process is readily amenable to the development of a product in which the properties and environment of the product's use dictate its microstructures.

The very obvious applications that immediately come to one's mind are: 1) a very hard, wear resistant surface layer on top of a strong, tough, ductile base; 2) a corrosion resistant surface; 3) a surface with superior oxidation resistant properties; 4) a material with a property gradation adapted for the particular application.

The knowledge, art and skill of the designer and materials engineer must be combined to satisfy the creation of these new, metastable, unconventional alloys. The fundamental concepts of ferrous metallurgy must be challenged, and better explanations of the role of alloying elements on the structure-property relationships than are presently in vogue must be forthcoming. The structures that these new materials will possess are unconventional, non-equilibrium phases, and the properties that are being sought are for high performance, critical applications. The opportunity exists not only to modify the concepts of ferrous metallurgy but also to challenge the limits of non-ferrous metallurgy, and it is here that perhaps an even greater opportunity exists. Nickel based alloys, titanium and aluminum alloys can all be improved by laser beam processing in this envelope. The degree of improvement and the implications of the results are left only to the cleverness, desire, and imagination of the materials research engineer.

Drilling

Laser drilling has long been recognized and utilized as a viable production process. The coolant holes in most high performance turbine engines have been machined by a laser drilling process. Originally ruby lasers were used extensively, however, in recent years the Nd-YAG and Nd glass lasers have been used more frequently.

Laser drilling in the laser power density-interaction time envelope is the result of the laser beam melting, vaporizing the material and ejecting the solid particles. This ejection is usually the result of the thermal stresses when they are higher than the cleavage strength of the material. The formation and ejection of disintegration products are usually observed at the very beginning of the laser pulse. With increasing diameter and depth of the hole an increasing part of the disintegration products consist of the molten material which is melted on the walls and the bottom of the hole and expelled by vapor pressure. By the end of the pulse the ejection of the disintegration products decreases owing to the reduction of the laser power density. With decreasing power density the disintegration products consist mostly of the molten material, and when the power density is even lower only the surface of the material is melted. The metal disintegration products are ejected outside as a jet perpendicular to the irradiated surface.

A part of the incident laser energy is absorbed and dissipated by the disintegration products. The major contribution to radiation absorption is made by the vapor of the material, which is a low temperature, weakly ionized plasma whose transmittance depends on its concentration and temperature. The main radiation absorption processes in the gas are absorption by atoms and absorption by electrons; the condensate particles in the vapor also absorb and dissipate laser energy.

For given focusing conditions the ultimate parameters of the laser drilled hole are determined by the energy and duration of the laser pulse. The depth and diameter of the laser drilled hole are determined by the product of the laser power and the laser pulse, i.e., by the total energy of the laser pulse. The size and shape of the laser drilled hole are considerably affected by the conditions of focusing of the laser beam, i.e., by the focal distance of the focusing system and by the position of the focal plane of the system with respect to the surface of the workpiece.

The techniques used for improving the accuracy and reproducibility of laser beam drilling fall into two areas. The first area involves the laser operation directly, e.g., the selection of the drilling conditions providing for minimized heat transfer to the walls of the hole, the regulation of the shape and structure of the pulse, the selection of an appropriate laser drilling procedure, etc. The second area includes various calibration procedures, chemical etching, blowing out of the holes with air or inert gases, etc.

Considerable strides have been made in laser beam drilling, unfortunately much of this effort is proprietary to the individual companies and is not available to the public. However, parametric studies of the process will certainly lead to holes with less taper and smoother internal sides, deeper holes in materials with extremely good high temperature properties, and a better understanding of the mechanisms of laser beam hole drilling.

Laser Cutting

The general characteristics of the laser beam cutting process are sufficiently attractive and unique to explain the great breadth of applications which have been or are being developed. They also suggest that many new cutting applications will develop in the near future far beyond those currently adopted. Some of the characteristics of laser beam cutting are: a very narrow kerf; a very narrow heat-affected zone; very smooth, square edges; no mechanical stress on the edges other than that from the heat-affected zone; no heavy restraining forces on the workpiece; a wide variety of materials can be cut from soft to hard; no contact with the work piece and no tool wear; blind cuts can be made and started from anywhere in any direction; fast cutting speeds that are easily automated.

Laser beam cutting can be done in a variety of ways: vaporization; melting and blowing; burning in reactive gas; thermal stress cracking or controlled fracturing; scribing. Laser beam cutting by vaporization occurs when the laser beam heats the substrate to above its boiling point and material leaves as vapor and ejected material. Melting and cutting is a laser beam cutting process in which the laser beam melts the substrate and a jet of inert gas blows the molten material out of the cut region. In burning with a reactive gas, the laser beam heats the material to the kindling temperature, which then burns in a reactive gas jet. Thermal stress cracking, or controlled fracturing, occurs when a thermal field in a brittle material is set up by the laser beam. Scribing is used to cut a material when a blind cut is used as a stress raiser allowing mechanical snapping along the scribed lines.

An understanding of the physical mechanisms involved in laser beam cutting leads to the conclusion that several areas for potential development should be developed. Among these areas are: the need to increase the total energy input by a) using higher power lasers to cut, b) utilizing additional energy sources, c) improving the coupling of the laser and the workpiece; the need to increase the power density by decreasing the spot size, especially in multimode lasers; the need to increase the ease of removal of molten products by a) increasing drag, and b) increasing fluidity.

A great deal of research and development in laser beam cutting has been directed towards improvements in nozzle design and gas flow effects. These efforts can be subdivided into the effect of nozzle diameter, the effect of nozzle gas pressure, the effect of nozzle/plate distance, and the effect of gas type.

The one area that has recently come into the forefront is the use of the laser to cut the material and then, without any additional effort on the cut edge, to laser beam weld this piece to another. As this technique is developed for critical applications, both laser beam cutting and welding will receive a large impetus.

Laser Beam Welding

Laser beam welding is a high energy density, low heat input process that can be utilized to join a wide variety of metals and alloys. The significant advantages of laser beam welding are: fast travel speed; simple geometry of the weld joint; lack of a need for preheat, postheat or interpass temperature; usually lack of a need for filler metal; low distortion and consequently very little postweld straightening; very good mechanical properties, including fracture toughness; and the need to automate the process.

In the interaction between the laser beam and the surface of the piece to be welded, part of the laser beam energy is absorbed and part of it is reflected. If the energy density is sufficient, melting occurs. In the case of high power laser beams, deep penetration welding with a high depth-to-width ratio occurs as a result of keyholing in which the laser beam drills a thin "cylindrical" volume through the thickness of the material. A column of vapor, which is surrounded by a liquid pool, is produced in this volume. As the column is moved along between the plates to be joined, the material on the advancing side of the vapor column is melted throughout its depth. The molten metal flows around the vapor column and solidifies along the rear. The vapor column is stabilized by a balance between the energy density of the laser beam and the welding speed. Thus it is important that the energy density of the laser beam and the welding speed be chosen so as to complement each other. An energy density that is too high will result in an unstable molten pool which can drop through, whereas an energy density that is too low will not permit vaporization and the formation of a keyhole. A welding speed that is too fast will result in incomplete fusion, whereas a welding speed that is too slow will result in a very wide fusion zone and possibly undercut and/or drop through.

When the high power laser beam interacts with the workpiece, vaporization occurs and a plasma is formed. This plasma, consisting of vaporized metal ions and electrons, is opaque to the laser beam, moves over the surface, and effectively decouples the laser beam from the workpiece. In order to weld with a laser beam it is necessary to minimize the absorption of the laser beam by the plasma. This is usually accomplished by directing a high velocity jet of inert gas into the area of the interaction and displacing the plasma continuously from the top of the workpiece.

Laser beam welding results in a high depth-to-width ratio (typically greater than 4) and a fast solidification rate. Very little direct experimental data is available on the solidification and cooling rates of the welds, but knowledge of the solidification mode and the fact that the heat affected zone is narrow leads to the conclusion that the solidification and cooling rate is very fast.

The mechanical properties of autogenous laser beam weldments are for most alloys equal to that of the base plate. In steels this is particularly true. Fracture toughness of steels has been related to the cleanliness of the alloy and its carbon content. The strengthening mechanism of the base plate --i.e., whether the strength of the alloy is a result of a tempered martensite in a quench and temper steel or the result of a precipitation hardening mechanism,-- dictates to some extent the properties of the fusion zone, and especially its fracture toughness as measured by a Charpy V-Notch or dynamic tear specimen. The addition of a clean alloy to the fusion zone has indicated that solidification cracking can be controlled in "dirty" steels and that the low temperature fracture toughness of several alloys can be improved.

The data on laser beam welding of nonferrous alloys is much more scarce than that of ferrous alloys. Titanium and its alloys have been shown to weld very nicely and to have good mechanical properties. Aluminum and its alloys are very difficult to weld with a high power laser beam. The stability of the keyhole is a major factor in the laser beam welding of aluminum alloys. Some recent work has indicated that copper alloys can be welded with a high power laser beam.

Cladding and Surface Melting

Laser beam cladding and surface melting are grouped together in the laser power density-interaction time assessment because the laser/material interaction is essentially the same. In both cases the laser beam energy is utilized to melt the workpiece in a very controlled manner. The difference between the processes is that in cladding a different metal or alloy is added to the melt pool and a surfacing material is fabricated. Since considerably more effort has been placed in understanding laser beam cladding, and the potential applications are significantly greater than laser beam melting, this section will be limited to cladding.

Laser beam cladding is essentially the fusing of an alloy to the surface of a substrate with a minimum of dilution from the substrate. Large areas can be clad by an overlapping process. The laser is utilized as the heat source required to create a molten pool. The process can be performed by either preplacing a powder on the substrate or blowing the powder into the molten pool. Other means of adding the cladding material are in wire form, sheet form, plasma spray coating, or electroplate coating.

In preplaced powder cladding, the laser melts the powder bed. Since the powder bed has a low thermal conductivity, the pool is almost thermally insulated until it reaches the substrate surface. At that moment it freezes back, forming only a solid/liquid bond which is relatively weak compared to a full fusion bond. Continued heating will remelt the resolidified material and then cause a fusion bond to form. This process is very akin to laser beam welding, and for simple geometries and multipass cladding is very convenient and extremely simple. Preplaced chips are another form of this technique and one that is used in a production application. Usually in this type of application either a defocused laser beam or a beam that has been integrated by a mirror is used. This is a convenient method of cladding a significant track (up to 19 mm wide) in a single pass. Obviously the width of the track that can be clad is a function of the available laser power.

In blown powder cladding the powder is blown by an inert gas into the laser generated melt pool. The leading edge of the melt pool will incorporate the substrate. Particles arriving in this area will be solid. If the leading edge is also solid, then the particle will not adhere and cladding will not occur. If, however, the leading edge is molten, then the particles will adhere and will melt almost instantly under the power of the laser beam, thus forming a fusion bond. The level of dilution is controlled by the powder feed rate determining the size of the substrate's molten leading edge. Uniform clad layers are formed by overlapping single tracks. The process critically depends upon a uniform powder feed rate.

In the past, laser beam cladding has been restricted to the use of powders or chips that were available because of either their wear or corrosion resistance properties. Recent work, using custom engineered powders, indicates that laser beam cladding can result in a product which has properties that are only restricted by the imagination, knowledge, and adeptness of the processing engineer.

Transformation Hardening

Laser beam heat treating is the last of the power density- interaction time envelopes to be discussed, but it was one of the first successful applications of production laser beam processing in the United States. Laser beam heat treatment is primarily used on steels and cast irons with sufficient carbon content to allow hardening. The metal surface is first prepared with an absorbent coating. After the coating is applied, the laser beam is directed at the surface. As the beam moves over an area of the metal surface, the coating absorbs the energy of the laser beam, usually burning off much of the coating while transferring its thermal energy to the substrate. In the substrate the temperature starts to rise and heat is conducted into the metal part. Temperatures must rise to values that exceed the critical transformation temperature of the substrate but are less than the melting temperature. After the beam passes over the area, cooling occurs by a self quenching process. The time above the critical transformation temperature can be critical in that the carbon atoms must have sufficient time to diffuse.

The three important variables in laser beam heat treatment are; 1) the coating, 2) the heating of the metal, and 3) the cooling of the metal. In some cases, a post heat treatment process can be required, but this is dependent on whether or not all of the coating must be removed or whether or nor a final machining operation is required for the part. The coating that is used is determined by its ability to absorb laser beam energy and transfer this energy to the substrate, as well as its ease of application. Among the coatings utilized are (in order of efficiency): phosphates (zinc, iron, lead, or manganese); iron oxide; high temperature paint; graphite (spray); and molybdenum disulfide. The process of metal heating is a balance between the absorbed laser energy and the thermal energy conduction into neighboring regions. As soon as the laser beam moves to another area of the metal surface, cooling occurs by thermal heat conduction into the surrounding metallic region. Mathematical models of heat flow have been developed to characterize the thermal profile in laser beam heat treatment.

Laser beam heat treatment has long been established as a production technique, and will continue to be utilized as one in existing and future applications as long as the economics of the process are favorable.

Conclusion

This paper has attempted to review those areas of the laser beam-material interaction spectrum which will result in viable, economic processes being developed in the near future. This assessment is limited in that some other laser beam-material interactions have been neglected because of the lack of near term production applications in these areas.

One of the resources that the author has utilized for the last several years is a compilation of some of the publications by Professor Arata (10). This book has proven to be invaluable as a reference and also as an indication of the extremely high caliber of research that has been completed at the Welding Research Institute.

References

1) T. H. Maiman: Stimulated Optical Radiation in Ruby Lasers, Nature, Vol.187 (1960), p.493.

2) A. H. Clauer and B. P. Fairand: Interaction of Laser-induced Stress Waves with Metals, in Applications of Lasers in Materials Processing, E. A. Metzbower, Ed. ASM International, Metals Park, Ohio, 1979, p.291.

3) E. M. Breinan and B. H. Kear, Rapid Solidification Laser Processing at High Power Density, in Laser Materials Processing, M. Bass, Ed.,North-Holland Publishing Co., Amsterdam, 1983, p.235.

4) N. Rykalin, A. Uglov, and A. Kokora, Laser Maching and Welding, MIR Publishers, Moscow, 1978.

5) W. M. Steen and J. N. Kamalu, Laser Cutting, in Laser Materials Processing, M. Bass, Ed., North-Holland Publishing Co., Amsterdam, 1983, p.15.

6) J.Mazumder, Laser Welding, in Laser Materials Processing, M. Bass, Ed., North-Holland Publishing Co., Amsterdam, 1983, p.113.

7) Y. Arata, N. Abe, and T. Oda, Beam Hole Behavior during Laser Beam Welding, Proceedings ICALEO '83, Vol.38, E. A. Metzbower, Ed., LIA, Toledo, Ohio, 1983, p.59.

8) W. M. Steen, Laser Surface Cladding, in Laser Surface Treatment of Metals, C. W. Drapper and P.Mazzoldi, Ed., Martinus Nijhoff Publishers, Dordrecht, 1986, p.369.

9) V. G. Gregson, Laser Heat Treatment, in Laser Materials Processing, M. Bass, Ed., North-Holland Publishing Co., Amsterdam, 1983, p.201.

10) Y. Arata, Plasma, Electron and Laser Beam Technology Development and Use in Materials Processing, ASM International, Metal Park, Ohio, 1986.