Proceedings of the
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in manufacturing

Edited by Dr. M. F. Kimmitt

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OF POOR QUALITY

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Keynote address: Why choose a laser for materials processing?

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The potential reasons for using lasers in materials processing are presented in this paper. The major materials processing lasers, Nd-YAG, Nd-Glass and carbon dioxide are reviewed and new designs discussed. The advantages and disadvantages of using lasers in such applications as joining, material removal and surface modification are discussed. Incorporation of lasers into robotics and other automated systems and recent and future developments in the areas of fiber optics and excimer lasers are described. Approximate costs and expected up-time are presented for laser systems.

INTRODUCTION

Materials processing applications for lasers are growing at a rapid rate as evidenced by worldwide sales of 103 million dollars in 1984. A 35% growth in sales is projected for 1985. Improvements in design have occurred for both YAG and carbon dioxide lasers leading to more compact lasers with higher-power output (for their size) and improved beam quality.[1]

Interest is growing in the use of lasers in welding, soldering, surface modification, marking, cutting, hole drilling and scribing. For example, in the automotive industry in the U.S., carbon dioxide lasers in the 5 to 9 kW power range have been placed in production for welding and flexible laser cutting systems are being purchased for sheet metal and softgoods cutting.

Many product and manufacturing engineers are acutely aware of the unique capabilities that lasers offer. Consequently, products and manufacturing systems are frequently designed to take advantage of those capabilities to reduce cost, increase productivity and/or quality. The days of the James Bond syndrome are pretty much a thing of the past. Engineers and managers now recognize lasers as a useful tool to add to their arsenal of sophisticated manufacturing systems.

Lasers are not used instead of conventional tools unless they offer a unique advantage. They do provide supplementary techniques to conventional and exotic techniques such as E-beam, EDM, ECM and water jet cutting. Lasers provide a broader range of design possibilities and manufacturing methods.

MATERIALS PROCESSING LASERS

The dominant lasers in materials processing are the carbon dioxide, Nd-YAG* and Nd-Glass lasers with carbon dioxide lasers accounting for the largest percentage of sales. In this section these three types of lasers and their output characteristics will be briefly described.

Nd-YAG

This laser employs neodymium (Nd) as the lasant material doped in a YAG crystal. Crystal rod sizes for the typical Nd-YAG laser range from 5-10 mm diameter to 6-15 cm in length. Excitation is by one or two krypton or xenon lamps. The wavelength is 1.06 μm, which is close enough to the visible spectrum that conventional optics can be used for lasers and windows. However, cavity mirrors must be of the dielectric enhanced reflection type to achieve sufficient reflectance.

Nd-YAG lasers can be continuously operated from a few watts to several hundred watts, but in most applications pulsed operation is preferred. For low power applications, such as marking or scribing (e.g. thick or thin film resistor trimming), Q-switching is used to achieve peak powers of kilowatts at kilohertz rates. For high power applications, such as cutting or hermetic seam welding, electronic pulsing of the lamps is utilized to produce 5 to 10 pulses per second at tens of joules of energy per pulse and pulse lengths of 0.1 to 10 mS, depending on the application. Figure 1 is a photograph of a 10W average power marking laser. The laser head is in the box on top of the cabinet, the power supply, controls and computer are in the right-hand cabinet, the garro-mirrors and marking area are in the left-hand cabinet which is partially shown.

Nd-Glass

The Nd-Glass laser utilizes neodymium as the lasant, but the host material is glass. Due to the poor thermal characteristics of glass this laser is used chiefly for spot welding and hole piercing with pulse rates of one pulse per second and 30-50 joules of energy per pulse. However, more than one laser head can be operated from the same power supply, typically two, in an alternating fashion. Glass laser rods may be circular or rectangular cylinders. Rectangular cross-section rods are frequently used for spot welding applications. Figure 2 contains a photograph of a Nd-Glass laser head.

Carbon Dioxide

Carbon dioxide lasers come in a variety of power ranges, sizes and designs. All use the molecular vibrations of carbon dioxide as the lasing mechanism. Generally, a mixture of carbon dioxide, nitrogen and helium are employed, the nitrogen is active in the excitation process and helium acts as an internal heat sink. Sometimes a small amount of oxygen is added to reduce contamination from carbon monoxide and carbon.

Carbon dioxide lasers emit radiation at 10.6 μm, which is quite far into the infra-red. This causes problems with respect to reflectance in processing metals such as copper, silver and gold, but alternatively these metals can be used as mirror materials internally or externally.

Some small sealed off carbon dioxide lasers, such as the waveguide types, use rf excitation, but most use dc electrical discharge excitation. The three major designs used in industrial processing applications are illustrated in Figure 3. These are the slow axial gas flow with axial discharge, the fast axial gas flow with axial discharge and the fast transverse gas flow with transverse discharge. The slow flow design relies on thermal conduction for cooling of the gases and consequently the cross-sectional area of the discharge region is limited; relatively narrow bore tubes must be used. Roughly 50-70 watts of power per meter of tube length can be obtained from this type of design. Beam

*Nd is the abbreviation for neodymium and YAG is the acronym for yttrium-aluminum-garnet.

quality is generally good with near Gaussian output being attainable because of the long-narrow bore tube.

The fast flow (about 60 m/s) designs use convection cooling so that much larger discharge cross sections can be achieved. Hence, the power per unit length is much higher, 600 W/m for fast axial flow and 2500 W/m for transverse fast flow. In fast transverse flow designs the beam is folded back and forth through the discharge region several times. Unstable resonator configurations are frequently employed for multikilowatt carbon dioxide lasers to eliminate transmissive optics.

The efficiency for these carbon dioxide lasers is approximately 10% (total input power divided into useful output power). This is about three times the efficiency of the other two industrial lasers described above. Figure 4 is a photograph of a 2.5 kW transverse fast flow carbon dioxide laser and laboratory workstation.

CONSIDERATIONS FOR LASER APPLICATIONS

In this section some of the advantages and disadvantages that must be weighed when considering the use of a laser in various applications will be presented.

General Considerations

The following is a list of advantages that could apply to any application:

- No tool contact
- Work in normally difficult to reach areas
- Work in a variety of atmospheres
- Minimal HAZ
- High speed
- Easily automated
- High up-time
- Minimal operator skill required

Lack of tool contact eliminates tool wear, but is also important in applications where tool force on the part is a problem. Since a laser beam propagates over long distances with little spreading, the beam can be piped around a work area using mirrors and conduit and focused inside of cylinders or other hollow parts. With Nd-YAG or Nd-Glass lasers the beam can be transmitted through transparent media such as glass or plastic before focusing on the part.

The laser beams used in materials processing are not markedly attenuated in air and virtually any gas can be used as a shield gas, examples are nitrogen, helium, argon, carbon dioxide and air.

A very high percentage of the energy absorbed by a part from a laser beam goes to perform the function intended, very little appears as waste heat. Consequently very small heat-affected zones (HAZ) are produced. This implies minimal induced chemical change and reduced damage due to thermal cracking and distortion.

In many applications the laser can perform the operation faster than conventional or other exotic techniques. Because of the lack of tool contact and ease with which a laser beam can be delivered to the workpiece, the laser is one of the most easily automated machine tools.

Industrial processing lasers, in spite of the relatively short time they have existed, are highly reliable. Up-time for carbon dioxide lasers in heat treating and welding applications of 90 to 95% are routinely reported and results for other types of lasers should be comparable. Failures are usually not directly laser related, but are the same types of problems encountered with more traditional machinery.

The skill and training required for laser operators is minimal. Lasers are really very simple to operate once a system has been properly set-up.

The following is a list of disadvantages that will apply in most cases:

- High initial cost
- Operating cost
- Routine maintenance

- Skilled maintenance people
- Safety

Lasers and the optical delivery systems that go with them are expensive. The cost (in U.S. dollars in the U.S.) for a carbon dioxide laser will run from over $150.00 per watt for a 500 watt laser to less than $100.00 per watt for multikilowatt lasers. Operating costs, including maintenance and consumables will run from $3.00 to $10.00 per hour or higher. Costs given here do not include operator wages or shield or cutting gas costs. A 20 watt Nd-YAG laser scribing system could cost $100,000.00 and cost about $2.00 per hour to operate. A 400 watt Nd-YAG welder will cost over $80,000.00, exclusive of beam delivery system, and will cost about $4.00 an hour to operate.

Lasers do require routine maintenance such as lamp replacement, cleaning of optics or the electrodes in some carbon dioxide lasers. This maintenance must be done carefully by properly trained and well supervised technicians.

There are special safety considerations associated with lasers. Aside from the serious danger of electrocution from the high voltage power supplies used in these lasers there is a severe risk of injury (particularly to the eyes) as a result of exposure to the direct, reflected or scattered radiation. Also, some high power carbon dioxide lasers produce x-rays which can be hazardous if not properly shielded. A laser safety officer should be properly trained and have authority to specify and approve safe operating procedures in all industrial installations.

Specific Considerations

There are some advantages and disadvantages which are specific to particular applications, some of those will be listed and discussed briefly here. Some advantages are:

- Weld dissimilar materials
- Weld magnetic materials
- Make deep penetration welds
- Skid welding
- Drill high aspect ratio holes
- Drill holes at large angles to the surface
- Cut complex patterns
- Narrow kerf for cut parts
- Use oxygen assist for cutting and drilling

The laser frequently does a superior job of welding dissimilar metals such as Inconel to copper or tungsten to stainless steel. Magnetic fields do not affect laser beams so demagnetization is unnecessary for magnetic materials. High aspect ratio welds can be made as a result of the phenomenon of "keyholing" when using multikilowatt power levels. The technique of "skid welding" permits filet welding of a seam between right angle pieces of metal with the underbead being produced on the seam as a result of light tracking through the seam.

High aspect ratio holes can be laser drilled or pierced (10 to 1 routinely with 20 to 1 being achieved in special cases) with precise location and repeatability. Holes can be pierced at large angles to the surface, 60^{o} is not uncommon with 15^{o} being routine in aircraft engine turbine blades. Low aspect ratio holes (large diameter) can be cut by a process called "trepanning" which simply involves bringing the beam through a focusing lens off center and rotating the lens.

In cutting applications an extremely narrow kerf can be achieved (0.1 mm or less) with extremely smooth edges free from dross and recast material. Oxygen or air can be used in gas assist cutting and drilling to increase speed and quality when working on oxidizable metals.

Some of the disadvantages specific to particular types of applications are:

- Cracking and/or embrittlement due to high carbon content during welding
- Hot and/or cold cracks in welding

- Stress cracking due to thermal shock
- Spatter on optics from welding
- Toxic vapors

The extremely rapid heating and cooling that occurs during laser processing does lead to problems on occasion. In welding this can lead to extremely brittle welds in high carbon steel which are subject to cracking and porosity. Also, steels containing low vapor point alloy materials such as lead or sulfur can result in cracking and porosity.

When cutting or drilling brittle materials such as ceramics, thermal stress cracking can be a problem. This is minimized by using rapid short pulses to reduce the heat input required for the job. This is usually accomplished by Q-switching.

Spatter damage to optics is a serious problem, particularly during welding of certain types of metal alloys such as high carbon steel or aluminum. With Nd-YAG or Glass lasers a glass shield can be placed in front of the focusing optic. With carbon dioxide lasers a strong crossflow of air may be required and use of the longest possible focal length lens or focusing mirror is recommended.

Toxic vapors may be produced, particularly during material removal operations. Since little is known about the type or toxicity of most of these vapors adequate ventilation and filtering must be provided to protect workers and others who might be exposed to these vapors.

AUTOMATION

Lasers are readily adapted to existing automated parts manipulation systems. A number of machine tool companies have incorporated lasers into existing machines designed for cutting (nibbling) and punching operations. The laser basically replaces the nibbling process because it is faster and is much less wasteful. Specially designed machines for cutting large sheet material frequently employ one axis to move the sheet and a second axis to translate the beam. The z-axis, the one that controls focal point location and nozzle position, usually floats freely on a ball bearing arrangement that rides on the sheet. When contoured parts are to be cut some sort of position sensor is used to feedback position data to the computer to numerically control the z-axis. Sensors may be capacitive, inductive, air flow or mechanical contact.

More complex automated systems may use six axes of motion or more. Frequently these systems are hybrids, utilizing part motion for some of the translational movements and beam manipulation for high speed motion and angular and/or rotational motions.

There is a tremendous interest in the marriage of lasers and robots. Again, such systems may utilize part manipulation by the robot or in more flexible systems the robot is used to manipulate the beam. Figure 5 is a schematic of a robot system for a carbon dioxide laser which uses an articulated mirror system to direct the beam to a focusing assembly at the end of the robot's wrist. The beam is directed down a conduit which has two or three knuckles to give it flexibility. Figure 6 is a schematic of a beam-guide. Each knuckle contains three mirrors which maintain the direction of the beam along the axis of the conduit regardless of their orientation. Such robot systems may have six or seven degrees of freedom and show great promise for laser welding and cutting of complex shapes. Examples are automotive welding and trimming of stamped metal parts.

The use of fiber optics to deliver Nd-YAG or Nd-Glass laser beams to the workpiece for welding, drilling or cutting shows great promise. A system is already available for soldering which delivers the beam in this manner. Powers of several hundred watts have been transmitted through 1 mm diameter quartz fibers over distances in excess of 25 m and prototype laser robot systems have been built and tested.[2] This approach provides a high degree of flexibility since the laser can be quite remote from the robot and work area and losses are extremely low for the length of optical fiber required. You simply have to design a system so that the fiber will not be twisted or too severely bent and an optical system for launching the laser beam into the fiber and properly focusing it after it exits. The robot manipulates the focusing package which is placed at the end of its wrist.

Unique safety considerations are required in the installation of robotic laser beam manipulation systems because of the potential for uncontrollable movements of the robot while the laser is on, particularly if the focusing element is broken allowing the raw, undiverged beam, to become exposed.

FUTURE DEVELOPMENTS

Possible future developments are too numerous to describe in detail. Only a few of those which at present appear to have a likelihood of making a significant impact in the near future will be briefly mentioned.

Substantial improvements in existing laser types such as the carbon dioxide, Nd-YAG and Nd-Glass will be made. The next generation of carbon dioxide lasers will extend the power range to the 20-30 kW range for routine industrial applications. These lasers will be of the transverse flow types. Continued beam quality improvements will be made for lower power carbon dioxide lasers. The development of coated potassium chloride optics (KCl) may result in stable resonator designs up to 20 kW or higher with good beam quality. Very compact carbon dioxide lasers capable of 1000 W power output may become available for mounting directly on to robots. Zinc selinide (ZnSe) or other types of optical waveguides may become available for carbon dioxide laser radiation for remote location of the laser and robot manipulation.

Nd-YAG and Nd-Glass lasers using slabs instead of rods and employing total internal reflection will extend the power range and improve beam quality for the lasers making them more attractive for flexible manufacturing systems.

Excimer laser power levels and reliability will improve to the point that they become practical for many materials processing applications. An excimer laser utilizes a compound of an inert gas in an excited state, and a halogen as the lasant, e.g. the xenon chloride (XeCl) laser. When the inert gas atom returns to the good state, the excimer "molecule" dissociates and the energy is given off as a photon which leads to laser action under the proper conditions. Such lasers have extremely high gain and operate in the ultraviolet (uv) part of the spectrum. The absorbtion of metals in the uv is nearly 100%, which suggests many interesting materials processing possibilities. Additional safety problems are posed because of the use of toxic gasses such as chlorine and flourine and the potential for x-ray generation in the workpiece.

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2. Marshall, G. J. and G. Georgalas, "Flexible Beam Delivery for Material Processing Laser Power Through a Fiber Optic Cable". Laser News, Vol.6, No.4, pp.11-12 (July 1984).

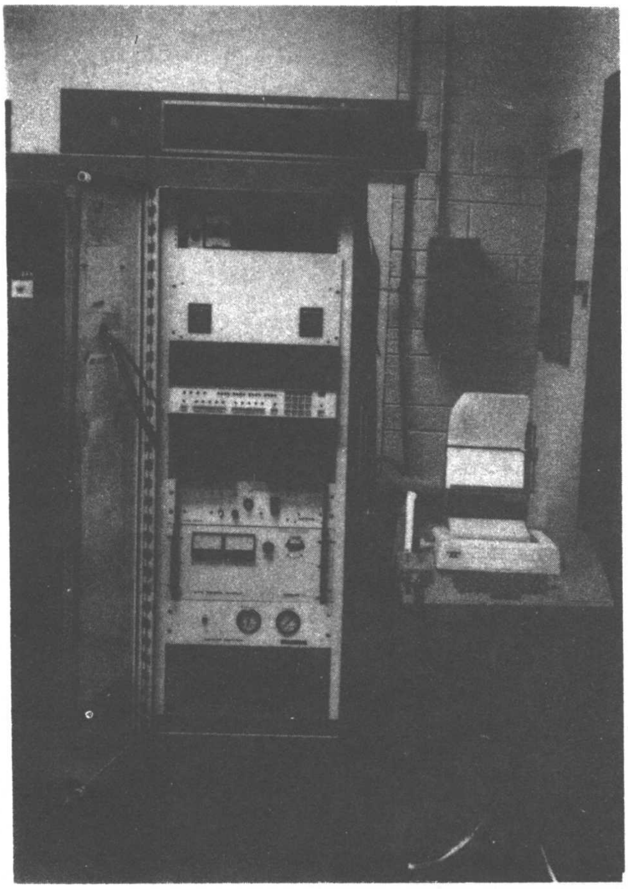

Fig.1. Nd-YAG marking system.

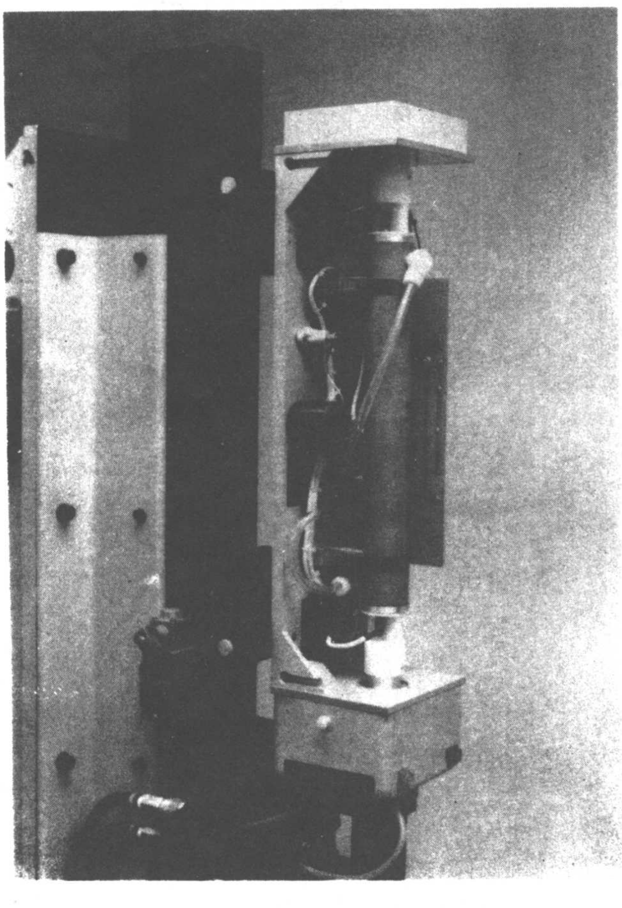

Fig.2. Nd-Glass laser head.

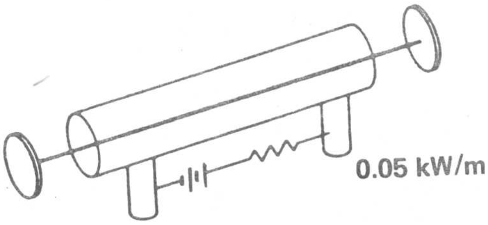

Fig.3a. Slow axial flow.

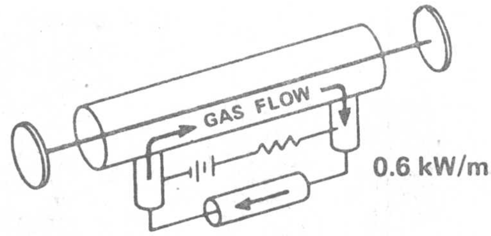

Fig.3b. Fast axial flow.

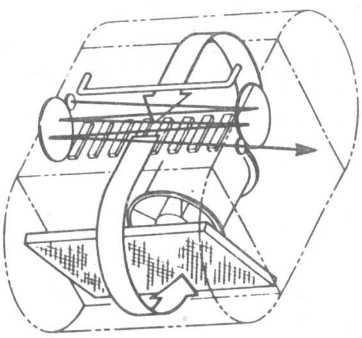

Fig.3c. Transverse electrical discharge with fast transverse gas flow.

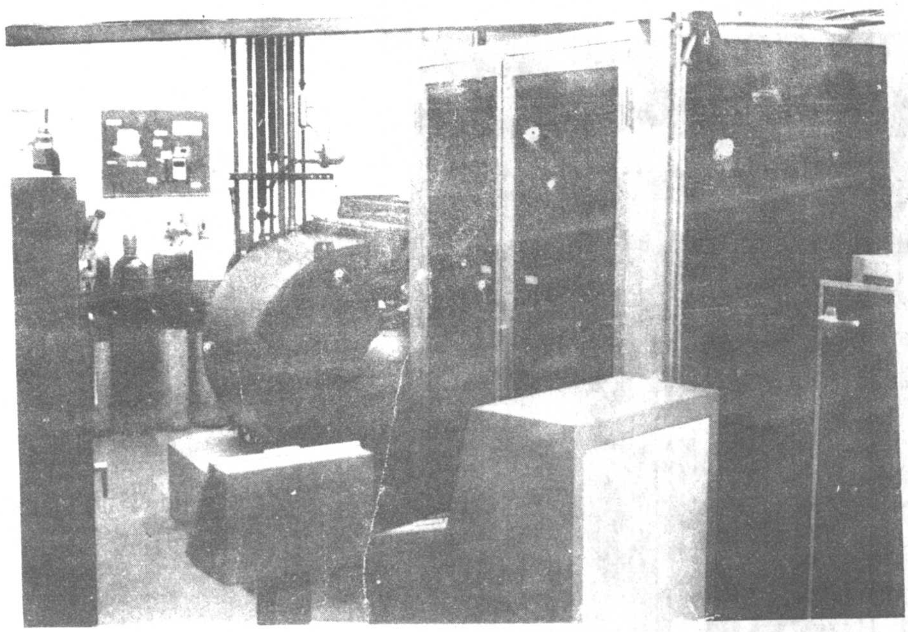

Fig.4. 2.5kW fast transverse flow CO_2 laser and work station.

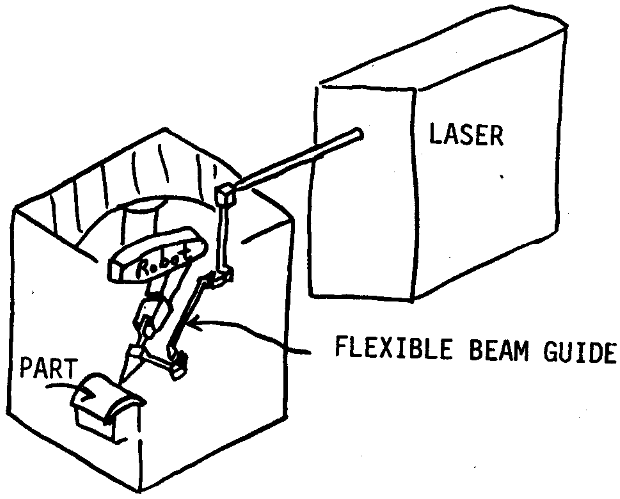

Fig.5. Schematic of robot-laser system.

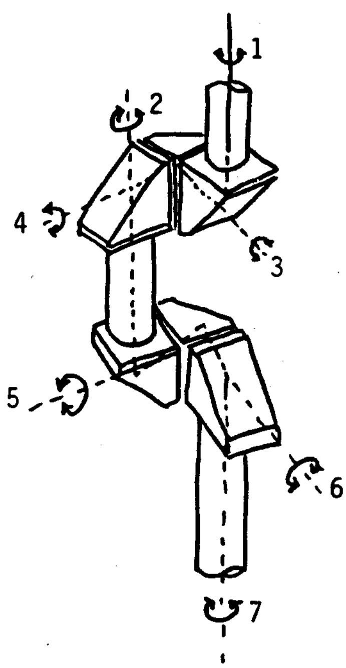

Fig.6. Schematic of mirror beam-guide system for a CO_2 laser.

What choice for high integrity joints: electron beam or laser beam welding?

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Through few industrial application examples, specific characteristics and advantages of high energy density beams (EB and LB) will be illustrated ; thus justifying the use of the processes in production. Technical performance comparison of the two processes and economical considerations will permit to define three types of applications : thin gauge material for which LB is more appropriate ; thick gauge material for which EB is more appropriate ; and medium gauge material for which effective and strong competition exist between LB and EB.

INTRODUCTION

Electron Beams (EB) and Laser Beams (LB) can be concentrated to produce very high energy density heat sources. When used in welding they can achieve high integrity joints with specific characteristics.

High energy density beams are regularly employed in metal working production and specially in welding. Several thousands of welding systems are used in industrial production in the various fields: aeronautics, nuclear, automobile, electrical appliances etc.

EBW was introduced in industry about 25 years ago thanks to its many advantages, among which was the fact that it produced welds impossible to achieve with other welding processes.

Multikilowatt LBW was used about 6 years ago in production. It can produce welds very similar to EBW and do have some additional advantages in some specific conditions. One can note today a strong competition between the two processes to resolve the same type of problems with the same high performances..

In the first part of the paper we shall present the general characteristics of high energy density beam welds. The present technical situation of the process will be analysed through a number of existing industrial applications.

By comparing the technical performances and the economical positions of the two processes, the paper will define the domaines and the type of application where each process is most suitable. Three types of applications will be recognized : those most suitable for LBW, those most suitable for EBW and those where a strong competition exists between the two processes.

1 - SPECIFIC FEATURES OF EB AND LB WELDING -

I.1. High power density.

Power density obtained by EB and LB is about 1000 to 10000 times that of conventional welding heat sources. This high power density level engenders beam/material interaction that differs significantly from conventional processes. During welding, the metal under the beam spot sublimates, creating a capillary which is instantaneously filled up with plasma type metallic vapors. Heat transfer from the beam into the joint occurs along the entire thickness of the joint instead of being diffused by conduction from the surface as in the case of conventional processes. This produces joints having the following characteristics :

. high depth to width ratio (10 to 50)
  commercially available beam powers exceed 100kW for EB and 10kW for LB. The majority of applications concern thicknesses less than 30mm for EBW achieved by about 20kW and less than 4 to 5mm for LBW achieved by about 3kW (figure 1 gives some macrographies of welds),

. minimal heat input and heat affected zone (HAZ). Owing to the nature of heat transfer between the beam and the joint, the total heat input in EB/LB is much lower than in conventional processes (a factor of 10 and more for heavy sections),

. minimal distorsion and residual stress. EB/LB welded assemblies are usable as welded without intermediate heat treating (if metallurgy permits) or machining operations. This production advantage, fully exploited by the automotive industry for the assembly of gears and other mechanical components, is a consequence of the low heat input. Over 60% of EB/LB industrial installations produce components for the motor industry.

1.2. Flexibility and automation in production.

. Use as a flexible tool.

The electrons transported in the beam have almost insignificant masses ($m_e = 9.1 \times 10^{-31}$ kg, therefore practically inertialess) and travel at a velocity between one-half and two-thirds that of light when accelerated by a voltage on the order of 60 to 150kV. They can be focussed or deflected in various patterns by the application of electromagnetic fields. The action is instantaneous and similar to what is obtained on a television screen. It is thus possible to rapidly displace the beam according to pre-defined heat distributions for better control the thermo-mechanical phenomena. Additionally, the characteristics inherent to electrons allows their use for auxiliary operations, such as automatic seam tracking.

The laser beam is composed of photons that travel at the speed of light ; it can be focussed and transmitted by ordinary optical lenses and mirrors. This permits manipulation and transmission from one point to another, and confers high mobility and flexibility to the process. Their flexibility is probably the most fascinating feature of lasers in welding and metal working. Flexible manufacturing centers utilizing a central laser beam supplying several work stations are being implemented in the US and Japan.

. Automation and productivity of the processes.

Because of the flexibility of the processes and their automation which could be CNC control ; high productivity could be achieved with EB/LB techniques. It is mainly because of the high productivity that industrial use of such processes can be justified economically even though the initial investment is much larger than conventional processes.

1.3. Pressure environment in EB/LG.

Electron beam technology requires a high vacuum level (10^{-4} to 10^{-5} mbar) surrounding the cathodic emitting surface and the high voltage electrodes.

Laser beam technology requires an accurate control of the pressure (30 to 70mbars) in the lasing cavity and constant characteristics of gaz (mixture, temperature, flow, speed, etc.).

To prevent beam dispersion caused by the electrons colliding with gaz molecules, the pressure in the zone through which the beam travels should be less than 10^{-2} mbar. This means that the workpiece should be entirely put in a vacuum chambre, or eventually only the seam area should be brought to the low vacuum (local vacuum systems). The vacuum in EB can bring an advantage by protecting the molten zone against oxidation and hydrogen susceptibility. High quality welds can be made in reactive materials such as Zircalloy, Ti and refractory metal .

Laser beam can travel at atmospheric pressure without significant dispersion, thus it does not need a vacuum chambre. Nevertheless a protective gaz is needed around the molten metal to avoid its oxidation. On the other hand laser beam welding in vacuum (some torrs) produce deeper welds in heavy sections ($>$ 6mm) than in atmosphere (2 to 3 times more) by reducing the dispersion of laser beam by the plasma created at the point of impact.

2 - RECENT DEVELOPMENT AND INDUSTRIAL EXAMPLES OF EB/LB WELDING -

Our analysis will concern welding applications which employ multikilowatt power beam. Consequently, we shall not consider cutting or micro welding applications which employ laser sources not exceeding few hundred of watts.

The majority of the applications will be drawn from the motor industry where the following advantages of EB/LB welding can be seen :

. complex geometries are reduced to simple to manufacture components which are then joined,

. each component in an assembly can be made from the best suited material,

. EB/LB welding processes lend themselves to automation and high productivity,

Here are some examples which can be achieved indifferently by EB or LB welding.

Pignon gears shown on figure 2 are welded on a diameter of 60mm, with a beam power of 2kW and a welding speed of 2.2m/mn.