

Lasers in the factory

Nd: YAG and CO₂ lasers are growing in popularity for cutting, drilling, welding, scribing, and heat-treating a host of metals and nonmetals

The laser has moved rapidly out of the laboratory, where it is still a research item, onto the factory floor as a production tool. Capable of delivering enormous thermal energy with pinpoint precision at very high speeds, the industrial laser can be found performing a host of material-treatment applications, including surface hardening, cutting, drilling, engraving, welding, material removal and scribing. And the types of materials undergoing laser processing are growing. The list now includes a variety of metals, plastics, rubber, wood, paper, cloth, ceramics, semiconductor materials, and crystals such as diamonds.

Industrial applications of the laser for material processing are a relatively recent development. The reasons for the laser's industrial popularity include:

- Higher and more predictable reliabilities, leading to less downtime.
- More industrially compatible laser system designs to withstand the punishment of the factory environment and to accept material and production-line variables.
- Computer control, leading to higher processing throughputs and greater versatility.

There are pros and cons to use of the industrial laser for material processing. Some advantages, such as operation at a distance, make for unique applications. With lasers, it is possible to process material in air, special gases or, if necessary, in a vacuum. Welding or drilling can be done at otherwise inaccessible sites—a spot inside a pipe or around a corner, say—through the use of optical mirrors that bend the laser's beam.

Although the industrial laser sometimes competes with established processing techniques, such as gas jets, electric discharges, plasma arcs, and electron beams, more often it complements them. And for many applications, it is clearly not the answer. Figure 1 outlines the major steps in evaluating whether processing by laser is practical.

A major advantage of the industrial laser is that it can add value to a material while processing it. A good example is in metal-hardening and welding applications, where reduced "metal fatigue," better hermetic seals, and longer life result.

Mostly two types of lasers

Table 1 lists about one dozen of the most popular lasers, only two of which are used for nearly all materials-processing applications: the Nd:YAG (neodymium: yttrium-aluminum garnet) and the CO₂ (carbon-dioxide) laser. Both account for nearly 90 percent of all industrial laser material-processing uses. Figure 2 illustrates the schematic diagrams for both Nd:YAG and CO₂ lasers.

The Nd:YAG laser, which operates at a wavelength of 1.06 μm , is used principally for precision machining of

thin metals and for scribing silicon semiconductor wafers and trimming resistor networks. The CO₂ laser, with a longer wavelength of 10.6 μm , is of higher output power and is used on heavier metals. Both lasers are also used to process many other materials.

The Nd:YAG laser ranges in continuous output power from a few tenths of a watt to about 1000 W. It can also be operated in a pulsed mode, where output power up to 10 kW is possible for short periods. The CO₂ laser, on the other hand, is operated mostly in the continuous mode, with output power of 10 to 20 000 W (up to 10 MW of peak power with a TEA, or transversely excited atmospheric, CO₂ laser operating in a pulsed mode). Thus some overlap exists for CO₂ and Nd:YAG laser applications in the 0.1-to-1-kW output range, particularly for welding and cladding metals.

Because a laser's output beam represents an intense source of energy that spans a wide range of the electromagnetic spectrum (from ultraviolet through the infrared, depending on the type of laser), several factors determine how this beam interacts with the material it irradiates and what the resulting power density (the amount of power applied to a given material unit surface area) will be. These factors include how the laser beam is focused onto the material (through the use of optics), the type of material being processed, the distance from which the laser beam is projected onto the material's surface, the laser-beam mode and output power level, and the length of time the beam is focused on the material. All can be varied to produce in the material the following:

- Submelting—for phase changes, annealing or hardening.
- Melting—for welding, cladding or alloying.
- Vaporizing—for cutting, drilling, material removal, etching, scribing, trimming, etc.

These laser variables are easily controlled by computer, enhancing the laser's versatility as a processing tool. Required power density varies as a function of the laser-beam interaction time for materials processing at different energy levels (Fig. 3). Figure 4 shows how various metals and nonmetals react to CO₂ laser-beam processing. Figure 5 shows how the cutting speed of CO₂ laser is influenced by material thickness.

Metal treatment is the largest application

Metals absorb less laser-beam energy, and are generally more reflective of a laser beam than nonmetals. For some applications, like heat treating, better energy absorption is achieved by chemically treating the surfaces of metals prior to laser processing. And the energy from the 1.06 μm -wavelength Nd:YAG laser is more readily absorbed by metals than that of the 10.6 μm -wavelength CO₂ laser. However, the CO₂'s higher output power tends to compensate for this drawback.

Roger Allan Associate Editor

Laser treatment of metals is by far the largest segment of industrial-laser applications. Two of the more popular metal-treatment applications are welding and surface hardening, with steel and cast iron the most common metal treated. Other metals include aluminum, magnesium, titanium, and many other metallic alloys.

At the General Motors Saginaw Steering Gear Div. in Saginaw, Mich., a Photon Sources 1-kW CO₂ laser system has been hardening the power-steering housings for all GM automobiles in the last four years. Don Sutherland, manager of process development, metal forming and casting at the GM Technical Center in Warren, Mich., says: "We've increased the reliability and lifetime of automobile steering-gear housings significantly as a result of the laser's use." The company is also using a GTE Sylvania 5-kW CO₂ laser to harden railroad-engine cylinder liners at its Electro-Motive Div. in La Grange, Ill.

According to Roger A. Heimbuch, senior staff engineer for process development at the GM Technical Center, the company is also looking at developing other automotive applications, including the hardening of gears, transmission parts, camshafts, and engine valve seats.

Seam-welding of electronic components and packages is another growing application. Medtronic Inc., a major manufacturer of heart pacemakers, is using both CO₂ and Nd:YAG lasers at its plants in Minneapolis and Mississauga, Ontario, to weld the pacemaker's circumferential seal. Another popular seam-welding application is that of batteries, like the lithium ones being welded by a Nd:YAG laser at Honeywell in Minneapolis.

A testimonial to the laser's superior performance can be observed at the Gould Industrial Battery Div., Fort Smith, Ark., and C&D Battery Co., Leola, Pa., where computer-controlled CO₂ laser systems, supplied by United Technologies Research Center, East Hartford, Conn., have been seam-welding thousands of lead-acid batteries used by the Bell System's power reserve grid. According to Western Electric spokesmen, the laser's weld quality is superior to that of other techniques, besides the obvious advantages of higher-welding speed. Each of the laser systems in the Gould plant zips through a battery with 106 welding junctions in about six minutes, or about one-ninth the time it takes a conventional three-headed bonder to do the same task. Electrical and visual weld failures, which had averaged about 12 per battery, have been cut by more than one-half.

Western Electric has 25 Nd:YAG laser systems in its Hawthorne, Ill., plant for the manufacture of RC (resistor-capacitor) networks. A laser beam cuts 1 to 1.5-mil-wide lines in capacitor foil material, thereby creating resistance paths.

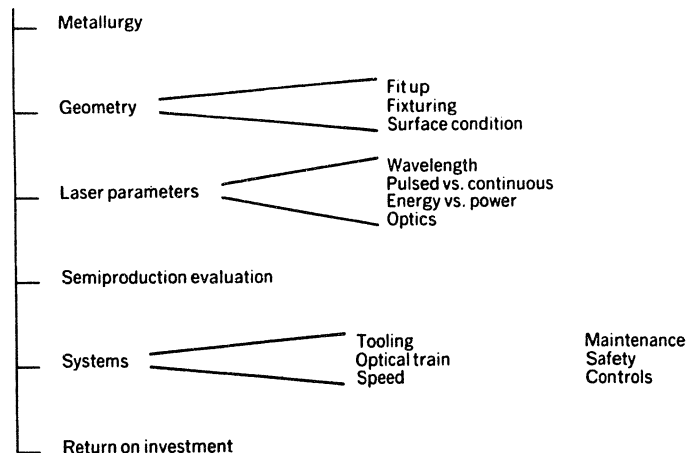
Materials either too difficult or impossible to cut, weld or harden with precision by conventional means submit readily to the laser's beam. Examples include aerospace composites, such as boron, titanium, waspaloy, and graphite. One of the most common aerospace applications of lasers is the drilling by ruby, Nd:YAG and Nd:Glass lasers of very fine, intricate holes in aircraft turbine blades.

Lettering, engraving, and marking

For products that are either too fragile or too small or that cannot be marked fast enough by conventional stamping, engraving, printing, and scribing methods, the laser is a solution. At Medtronic, for example, the company needed a marking system to identify its pacemakers

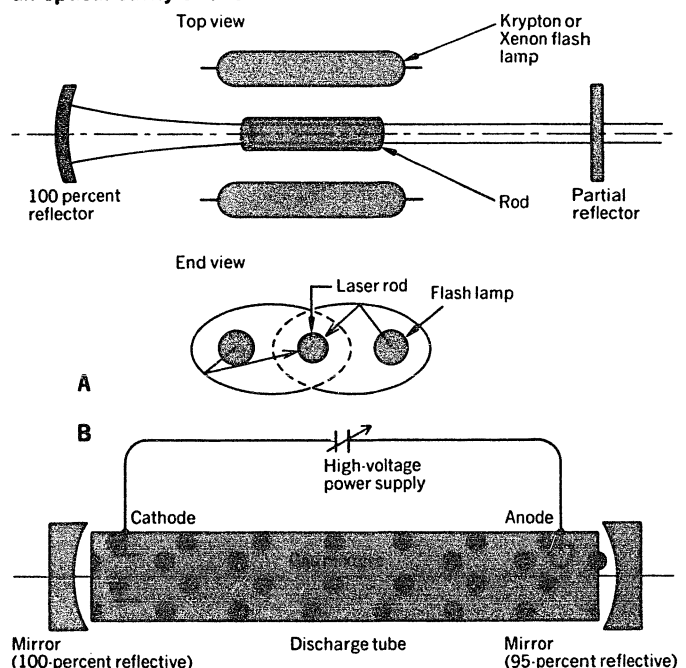
after they had been sealed. Formerly conventional marking of the pacemaker covers had to be performed before the covers were sealed, because the material was too fragile and marking it after sealing would have disturbed critical internal parts in the pacemakers. A Nd:YAG laser, with pinpoint depth control of the beam, solved the problem.

Hundreds of marking, engraving and lettering applications for tool steels, automotive parts, aircraft-wire insulations, and the like are springing up. Marking Universal Product Codes on food containers is one of the newest applications. GM is looking into installing a computer-controlled Nd:YAG laser system to mark vehicle iden-



[1] Considerations in evaluating laser-processing techniques extend from the type of material to be processed to maintenance requirements and safety considerations.

[2] A basic solid-state or Nd:YAG laser (A) consists of a crystal rod as the lasing medium, an arc or flash lamp as the excitation source, and an optical cavity made up of a pair of reflector mirrors. A basic CO₂ laser (B) consists of a gas mixture in a discharge tube as the lasing medium, a high-voltage power supply as the excitation source, and an optical cavity of two mirrors.



tification numbers on different parts of its automobiles (hoods, doors, trunk lids, engines, etc.) as they roll off the production line. The advantage of laser marking over conventional methods is that computer control of the marking process ensures faster, more accurate, and more flexible operation.

Marking is generally performed in two ways. In the more popular method, the computer-controlled laser beam scans the material to be marked, turning on over specified locations to vaporize the material where marking is needed. The other technique, not computer-controlled and much less costly, is micromachining. Here a high-power TEA CO₂ laser beam is flooded over a stencil or mask that contains all of the alphanumerics to be marked on the material. The mask or stencil is placed between the laser-beam delivery system and the material to be marked. All marking locations are thus vaporized

simultaneously. This method is, of course, less flexible than the computer-controlled one.

One beneficial fallout of laser lettering results from its precision. When alphanumerics are cut out in a plastic or plexiglass material, the removed material is not wasted, as it would be with other techniques; it can be used for lettering purposes elsewhere.

Laser-cut suits and graded shoe patterns

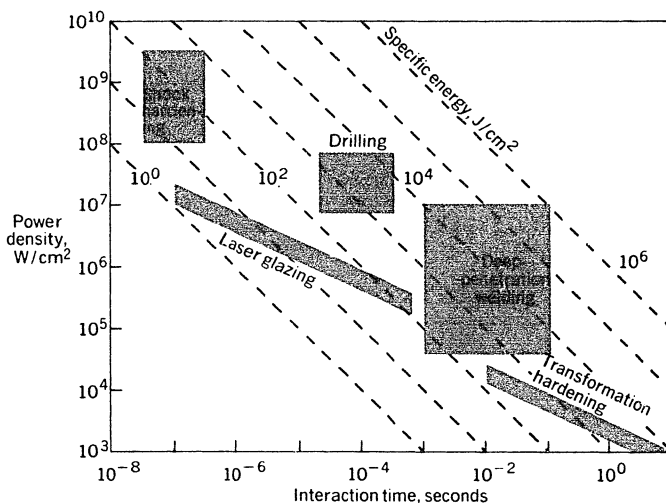
The use of lasers to cut fabrics and graded cardboard patterns is popular worldwide. CO₂ laser systems can be observed cutting complex patterns in fabrics for men's suits at such places as Richman Brothers, Cleveland; the Carroll Manufacturing Co., Westminster, Md.; Virginia Cutting Co., Fredericksburg, Va.; and Shinso, Renown and D'Urban in Japan. Graded cardboard shoe patterns are cut at the General Shoe Manufacturing Co., Nashville; Brown Shoe Co., St. Louis; and Florsheim Shoe Co., Chicago, to name a few. Hughes Aircraft Co., Industrial Products Div., Carlsbad, Calif., is the world's major producer of flat-stock laser-cutting systems.

There is more to a laser-cutting system than meets the eye (Fig. 7). Tens of thousands of master pattern shapes are entered into an automatic marker-making system such as the Hughes Model AM-1 via a digitizing process. This process transforms geometric shapes into digital data that is graded and stored on a disk memory resident in the marker-making system.

The marker system has a fast refresh CRT that displays the geometric apparel patterns. An operator utilizes a series of complex software piece-placement instructions to create interactively markers on nests of men's suit pieces. An electromagnetic cursor allows the operator to move pieces easily, in real time, to create markers.

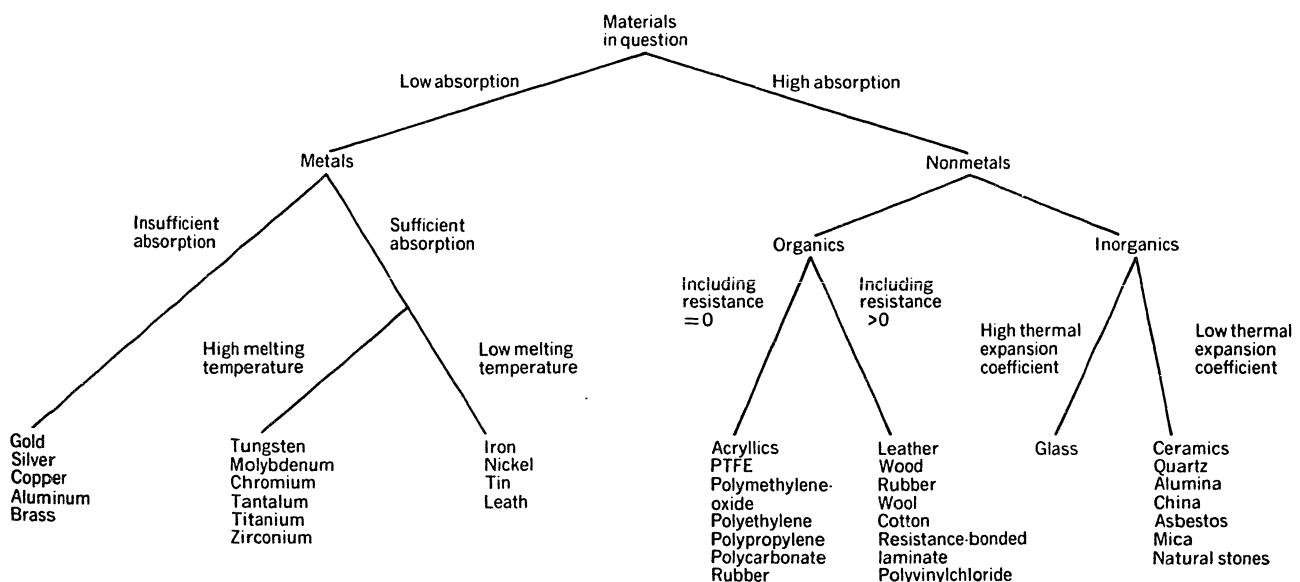
Coupled with material-size data and specific production information, a magnetic tape is generated by the AM-1 system with enough cutting data to keep the laser-cutting system operating for two to three shifts. The information is fed into the cutting system's controller via magnetic tape.

The next step is to load the system's conveyor with the fabric. Cutting then commences under computer control, with the conveyor moving the fabric into the cut zone. The laser's head, delivering a constant beam, is moved



[3] Operational areas for laser materials processing. Depending on the power density as a function of interaction time, applications can range from glazing to transformation hardening.

[4] How metals and nonmetals absorb the energy of a CO₂ laser beam. Many materials with low thermal absorption to the CO₂'s laser beam energy can be readily processed with Nd:YAG lasers.



over those spots to be cut. The conveyor then increments to the next cutting position.

Most cloth laser-cutting systems cut what is known in the apparel industry as "one-high," or one-layer-high of material. The laser beam is usually focused to a small spot size on the material's top. Material fuses together at cut lines and gas separates layers during cutting. This is why most such systems are used to cut men's rather than women's clothing, because women's clothing is manufactured in such large volumes that multilayered cutting is needed.

Trimming and scribing—earliest applications

As far back as the early 1960s, lasers were recognized as excellent tools for trimming resistor and capacitor hybrid networks. Repetitively pulsed Nd:YAG lasers, with pulses of short duration, trim thin-film and thick-film resistor materials by vaporizing lines part way into the resistor

area and monitoring in real time the changing resistance value as the trimming is performed. By providing feedback control from the measurement system to the laser, the laser's output can be controlled to provide resistance tolerances of better than 0.1 percent. An additional advantage over earlier sandblasting techniques is cleaner operation. This application has extended into the trimming of components in hybrid and monolithic ICs.

Scribing of IC wafers is another early electronic application. Most silicon wafers are scribed with Nd:YAG lasers, while alumina and ceramic substrates require the higher-output-power CO₂ laser. Alumina and ceramics substrates can also be scribed with Nd:YAG lasers. Smoother and narrower kerf widths are possible than with CO₂ lasers, but throughput rates are lower.

Another material-removal application is wire-stripping of insulation. Although conventional tool or chemical methods suffice in a vast majority of cases, certain tough types of insulation require material removal by laser, to avoid nicking of the wires. Kapton insulation, used often in aerospace applications, is an example.

One of the most exotic laser material-removal applications involves making precision holes in cigarette filter-tip paper. The greater precision control over hole sizes that the CO₂ laser beam makes possible gives a more accurate determination of a filter cigarette's final tar and nicotine content.

Processing nonmetals with the CO₂ laser

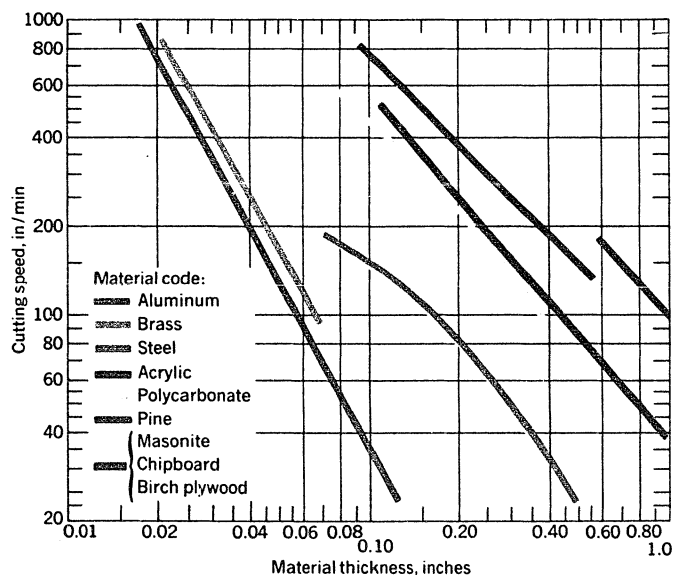
Because most nonmetals absorb energy from the 10.6- μ m wavelength CO₂ laser beam, a host of organic and inorganic material applications has opened up—from acrylics, polyethelenes, wood, rubber, and wool to diamonds. Hole drilling in plastics and rubber materials is one of the fastest-growing applications. Both of these materials respond extremely well to CO₂ laser energy. Examples in plastics include hole drilling in aerosol valves, contact lenses, pipes, tubing, and wire insulations. Rubber examples include hole drilling in baby-bottle nipples and rubber seals. Plastic materials have been welded with CO₂ laser beams.

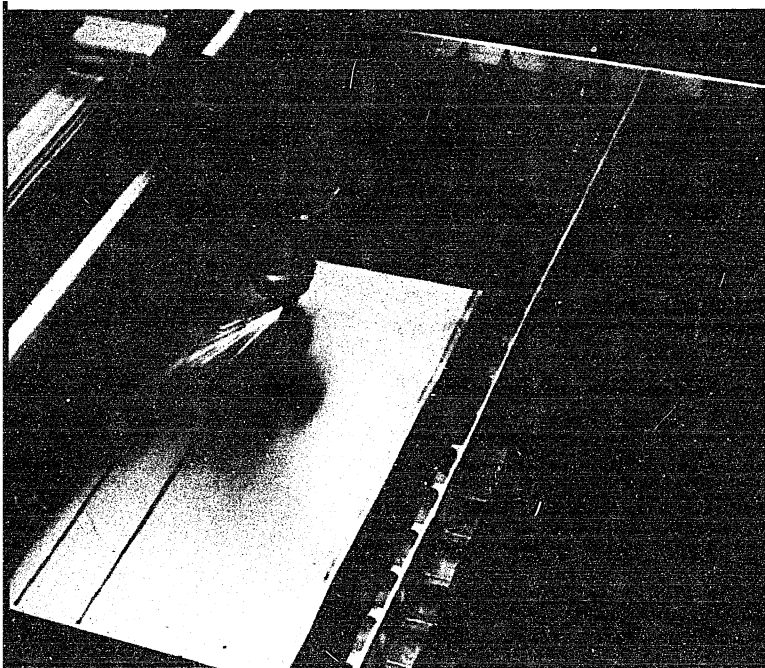
The pros and cons of industrial lasers

Compared with other materials-processing applications, the laser offers the following advantages:

- No contact is made with the workpiece, reducing contamination problems. The laser beam operates at a distance.
 - Localized heating minimizes the spread of heat around the work area.
 - No vacuum is needed.
 - The laser beam can process materials either too difficult or impossible to do by other means.
 - Very tiny holes can be drilled.
 - Systems operate rapidly, typically faster than conventional methods.
 - Processing of materials in inaccessible areas is possible.
 - With computer control, the system can be adapted to automation.
 - Extremely small welds can be made on delicate materials.
 - The highest power densities are available with laser beams.
- But there are some disadvantages as well. They include:
- Equipment and operating costs, including the need for periodic maintenance and replenishment or replacement of consumables (gas in CO₂ lasers and arc pump lamps in Nd:YAG lasers), are high. Newer high-power CO₂ lasers with gas recirculators reduce gas consumption considerably, however.
 - The depth of penetration in laser-produced holes is limited, although repeated application of the laser's beam to the same spot helps increase this somewhat.
 - Material that is vaporized by a laser beam tends to recondense on the walls and lips of drilled-out holes, forming a raised rim at the hole entrance.
 - The walls of drilled-out and cut surfaces are generally rough (32 to 250- μ m finish).
 - Control of size and tolerances for laser-produced holes is difficult.
 - Material surfaces must sometimes be chemically coated to increase laser-beam energy absorption.
 - For welding applications, the size of the work piece is limited, and careful control of pulse parameters must be maintained.
 - Laser systems, particularly multi-kilowatt CO₂ types, occupy very large areas of space. On the other hand, the optical beam-delivery system can be placed remotely in small areas.

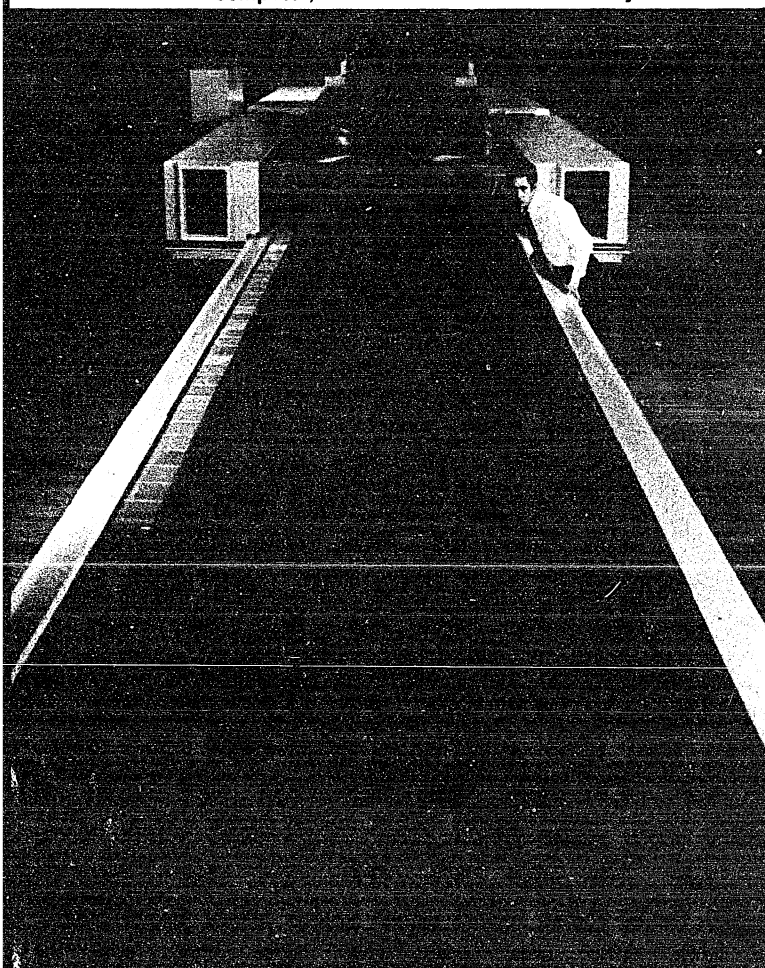
[5] The cutting speed of a laser can be increased by operating on thinner materials. The above data is for a 1200-W CO₂ laser operating in the TEM₀₀ mode.





[6] Laser beams can cut through metals that are often difficult, if not impossible, to process by other means.

[7] Multiple patterns of clothing material are cut by laser in this Hughes CO₂ system. The patterns are fed into a computer, which also controls the laser system.



The leading laser suppliers

About a dozen companies supply Nd:YAG and CO₂ laser systems, some of whom do not manufacture the basic laser component (they buy it elsewhere and sell a system built around it). Roughly a third of the companies supply Nd:YAG systems and the remainder CO₂ systems.

Major Nd:YAG laser-system suppliers are:

General Photonics, 2255F Martin Ave., Santa Clara, Calif. 95050. (408) 244-4030.

GTE Sylvania, Laser Products Dept., P.O. Box 188, 430 Ferguson Dr., Mountain View, Calif., 94042. (415) 969-4900.

HDE Systems, 615 N. Mary Ave., Sunnyvale, Calif., 94086. (408) 735-7272.

Holobeam Laser Inc., a subsidiary of Control Laser Corp., 11222 Astronaut Blvd., Orlando, Fla., 32809. (305) 851-2540.

International Laser Systems, 3404 N. Orange Blossom Trail, Orlando, Fla., 32804. (305) 295-4010.

Korad Div. of Hadron Inc., 2520 Colorado Ave., Santa Monica, Calif. 90404. (213) 829-3377.

Quantronix Corp., 225 Engineers Rd., Smithtown, N.Y. 11787. (516) 273-6900.

Raytheon Co., Laser Center, Fourth Avenue, Burlington, Mass., 01803. (617) 272-6402.

Major suppliers of CO₂ laser systems are:

Apollo Lasers Inc., 6357 Arizona Circle, Los Angeles, Calif. 90045. (213) 776-3343.

Avco Everett Metalworking Lasers, 32 Cobble Hill Rd., Somerville, Mass., 02143 (617) 389-3000.

British Oxygen Co. Ltd. (BOC) Hammersmith House, London W69DX, England, 01-7482020.

Coherent, 3210 Porter Dr., Palo Alto, Calif., 94304. (415) 493-2111.

Ferranti Ltd., Ferry Road, Edinburgh, Scotland, EH5 2XS. 031-3322411.

GTE Sylvania, Laser Products Dept., P.O. Box 188, 430 Ferguson Dr., Mountain View, Calif., 94042. (415) 969-4900.

Hughes Aircraft Co., Industrial Products Div., 6155 El Camino Real, Carlsbad, Calif. 92008. (714) 438-9191.

Lasermark Div. of Lumonics Research Ltd., 105 Schneider Rd., Kanata, Ontario, K2K1Y3, Canada. (613) 592-1460

Photon Sources Inc., 37100 Plymouth Rd., Livonia, Mich., 48150. (313) 591-0101

United Technologies Research Center, East Hartford, Conn., 06108. (203) 727-7330.

For both drilling and welding, medium power levels of 50 to 500 W suffice. And throughput rates can be quite high. A 250-W CO₂ laser can perforate a polyethylene plastic tubing with 0.020-inch (0.5-mm) holes spaced 6 to 24 inches (15 to 61 cm) apart, at 300 ft/min (90 m/min).

One of the more interesting applications for Nd:YAG lasers is the removal of imperfections from natural diamonds. Drilling with conventional tools, if not done carefully, can make the flaws more pronounced.

Meeting the production-line challenge

In many cases a laser can be shown to do the job well, yet its high cost can be a serious drawback. Or, even more common, the industrial environment may not be suited to laser use. Figure 8 shows the punishment a typical laser system delivery head takes in an industrial environment. It must endure the mechanical vibrations of such massive production-line machinery as punch presses and stamping

Principles of Nd:YAG and CO₂ lasers

There are three methods for operating Nd:YAG lasers: continuous, repetitively Q-switched and continuously pumped, and pulse-pumped. They operate as follows:

Continuous method. The YAG material is excited by an arc lamp with continuous power. Output power levels of about 10 W are possible through the use of xenon arc lamps, and about 100 W through the use of krypton arc lamps. In either case the lamp (or pump) remains on continuously.

Repetitively Q-switched and continuously pumped method. The lamp or pump remains on continuously, and an optical shutter in the laser cavity is opened for brief intervals to allow pulses of high peak power to exit. One type of optical shutter for partial laser-beam exiting is known as acousto-optic Q switching. Its typical repetition rate is 20 000 per second, and average output power is 75 W. Typically repetition rates of 1 to 10 kHz (for pulse widths of 100 to 300 ns) yield peak output powers of 1 to 10 kW. This type of operation is suitable for drilling, scribing and some cutting.

Pulse-pumped method. The laser's power supply is pulsed, usually with a pulse-forming network, resulting in a flash-lamp output. Peak power outputs of 10 kW are typical for pulses from 0.5 to 10-ms wide at repetition rates up to 200 per second. This type of operation is suitable for welding.

There are two common methods for operating

CO₂ lasers: continuous, and repetitively pulsed. They work as follows:

Continuous method: The lasing gas medium (a mixture of CO₂, He, and N₂ in a 5:1:1 ratio) is excited by a high-voltage supply connected to electrodes in the laser's discharge tube. A continuous output from the laser cavity results. Output powers of up to 20 kW (average) are possible. This type of operation is suitable for welding metal seams and cutting.

Repetitively pulsed method: The high-voltage power supply output is pulsed to produce beams at about 100 pulses per second with average powers of about 100 W. Output energy levels of about 1 J, with pulse lengths of 10 to 100 ms, are typical. This type of laser can work metals more effectively than continuous CO₂ lasers of equal average power. It is used for welding, drilling, and some cutting.

One type of pulsed CO₂ laser is the TEA (transversely excited atmospheric) laser. Its gas medium is energized by megavolt pulses. This is generally done by a bank of capacitors that are charged up, in parallel, to a voltage that does not exceed the breakdown voltage of the CO₂ laser tube. A spark is then triggered to discharge the capacitor bank across the laser tube. Output laser pulses of several joules at microsecond durations are possible. Peak powers of 10⁷ W have been obtained. Besides its use for hole drilling of metals, this laser is useful for marking of materials.

machines, showers of sparks that fly off the material being cut or drilled, extremes of heat and dust that accumulate constantly, and through it all the laser must operate within tight tolerances. In addition, unlike laboratory models, production-line laser systems must be designed with multitudes of interlock and safety features that even the most careless worker cannot defeat, and be easily serviceable at minimum downtimes.

GM's Sutherland observes: "We look at lasers enthusiastically but realize that they have limitations. For example, variations in the surface reflectivity of different materials—even within the same material—can cause variations in the quality of the workpiece. This can be controlled through the use of surface preparations before laser-beam treatment, but this then adds to the costs. Competitive techniques do not have these problems."

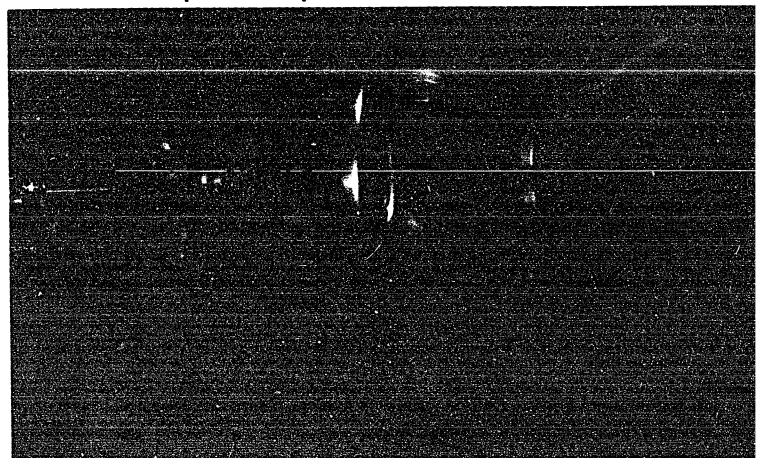
The Ford Motor Co. pioneered the integration of multi-kilowatt lasers and numerically controlled machine tools in 1974 by laser welding automotive underbodies. A 6-kW CO₂ laser with a five-axis numerically controlled positioning system, delivered by United Technologies Research Center, was used in a program to fusion-weld continuously a variety of underbodies and hopefully to replace resistance spot-welding methods. The laser system (Fig. 9) demonstrates a 24-hour output stability of better than ± 3 percent and a deep-penetration welding capability in 1/18-inch-thick rimmed steel of 188 inch/min. The laser's beam-positioning system was capable of contouring speeds in excess of 500 inch/min. with accuracies within ± 0.002 inch.

Problems developed later when Ford attempted to use the system in a production environment. Since the weld joint configuration was a partial-penetration burnthrough lap weld, it was essential that the gap between the parts be

less than 0.035 inch. Repeated semiproduction runs indicated that such fit-up tolerances could not be maintained routinely on the large unsupported structures being welded. The structures are also shipped over hundreds of miles to Ford's assembly plants. The result was a postponement of the laser system's production application. Ford is now using it as a test system for other potential laser-processing applications.

Simon Engel, president of HDE Systems Inc. in Sunnyvale, Calif., believes that laser manufacturers should have on their engineering staffs more individuals familiar

[8] The red and blue metallic assembly is a Photon Sources precision laser-beam delivery head that has undergone harsh industrial-environment treatment on the production line. Under conditions like these, industrial lasers must still operate with precision.



with production-line and industrial problems than with the theoretical and scientific aspects of laser design. Concentrating on his expertise in materials as well as his laser experience from his previous employer, he has successfully sold many dedicated Nd:YAG laser systems designed for welding and drilling metals.

Other laser makers, however, differ with Mr. Engel, believing that some of the problems that laser manufacturers have encountered while attempting to serve the in-

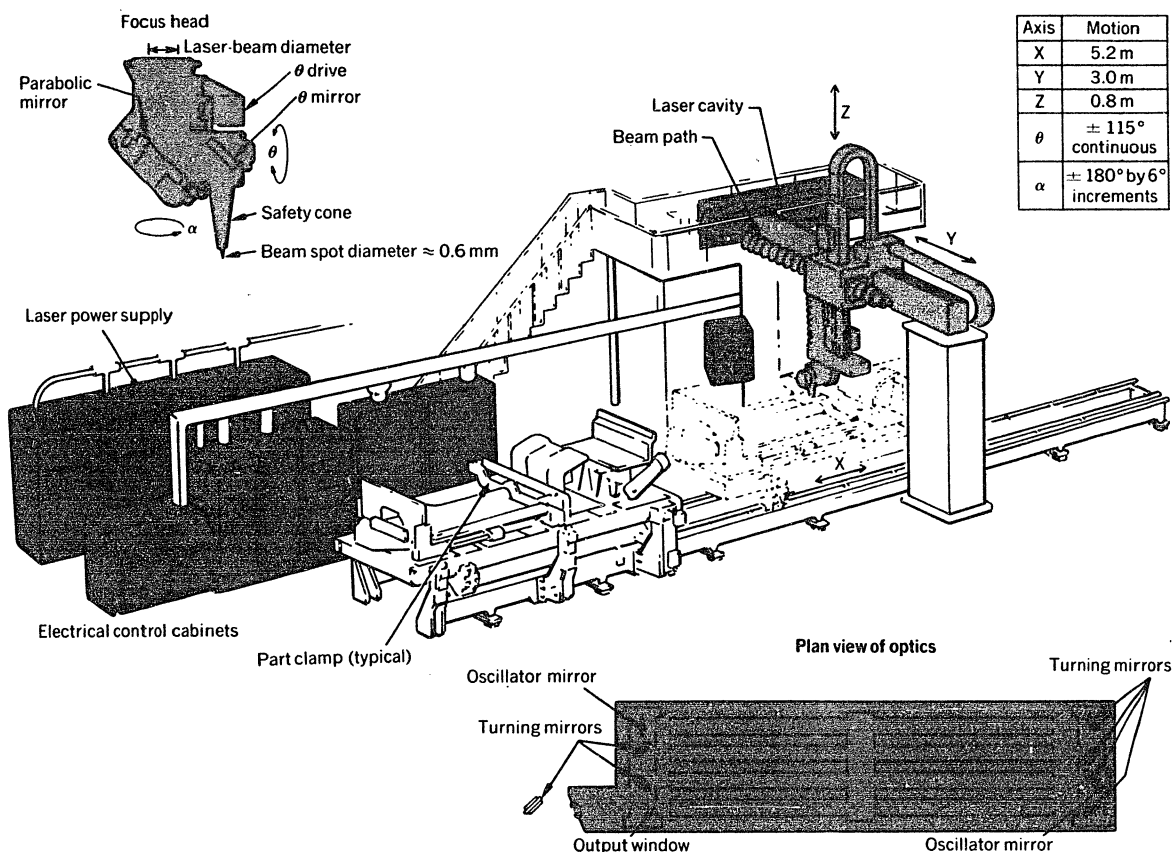
dustrial materials-treatment market were part of a natural evolution of the equipment. Their belief is that the fruits of earlier work on better-engineered industrial designs are just beginning to be enjoyed.

A look ahead

Many designers of industrial lasers believe that the next step is total or near-total closed-loop control of laser systems. Such systems would make use of low-cost micro-

I. Characteristics of Common Lasers and Their Applications

Class	Type	Wavelength, μm	Average Output Power	Mode of Operation	Pulse Repetition Rate, per second	Pulse Length	Applications
Neutral gas	Helium-Neon (He-Ne)	0.6328, 1.15, 3.39	0.5-50 mW	Continuous	—	—	Interferometry, alignment, educational, demonstrations, display projection
Ionized gas	Argon	0.4880, 0.5145	2-18 W	Continuous	—	—	Graphics, display projection, holography, pattern generation, pollution detection, spectroscopy, semiconductor annealing, photochemical, dye-laser pumping
Ionized gas	Krypton	0.6471, 0.5682	0.5-1 W	Continuous	—	—	Display projection
Ionized gas	Helium-Cadmium (He-Cd)	0.4416, 0.3250	0.5-50 mW	Continuous	—	—	Pollution detection
Molecular gas	Carbon-Dioxide (CO_2)	9.6, 10.6	100 W-20 kW	Continuous	—	—	Materials welding, hardening, cutting
Molecular gas	Carbon-Dioxide (CO_2)	9.6, 10.6	50-100 W	Repetitively pulsed	100	100 μs	Materials welding, hardening, cutting, drilling
Molecular gas	Carbon-Dioxide (CO_2)	9.6, 10.6	(Up to 10^7 W peak)	Transversely excited atmospheric (TEA)	Up to 100	10 μs	Materials drilling, marking
Molecular gas	Nitrogen (N_2)	0.3371	0.1 to 1 W (up to 10^8 W peak)	Repetitively pulsed	100	10 ns	Materials processing, dye-laser pumping
Solid state	Ruby	0.6943	50 W (up to 10^5 W peak)	Pulsed	1	0.2-5 ms	Materials welding, drilling, satellite ranging, plasma diagnostics in fusion experiments, semiconductor annealing, marking
Solid state	Neodymium-YAG (Nd:YAG)	1.06	Up to 1 kW	Continuous	—	—	Materials welding, drilling
Solid state	Neodymium-YAG (Nd:YAG)	1.06	75 W (up to 10 kW peak)	Repetitively Q-switched, continuously pumped	25 000	200 ns	Materials welding, trimming, scribing, drilling, semiconductor annealing, dye-laser pumping, marking, component fabrication
Solid state	Neodymium-YAG (Nd:YAG)	1.06	500 W (up to 10 kW peak)	Pulse pumped	200	0.5-10 ms	Materials welding, drilling, marking
Solid state	Neodymium glass (Nd:glass)	1.06	Up to 10 W	Pulsed	1	0.5-10 ms	Materials welding, drilling, nuclear fusion
Semiconductor	Gallium-Arsenide (GaAs)	0.85-0.905	20 mW-1 W	Continuous	—	—	Range finding
Semiconductor	Gallium-Arsenide (GaAs)	0.85-0.905	6 mW	Current pulsed	Up to 5000	0.1 μs	Communications
Liquid organic dye	Various	1-0.4 (tunable)	Up to 5 W (depending on dye)	Laser pumped	—	—	Process control, photochemistry, Raman spectroscopy



[9] This 6-kW, CO₂ laser system was installed in the Ford Motor Co. Weld Development Center to weld the underbodies of a wide range of vehicles on the production line. The system is computer-controlled and can provide five axes of motion for the laser-beam delivery head.

processor and pattern-recognition ICs to provide better control and operating economies. These systems would either eliminate or greatly minimize the need for special operator training.

In one step toward such a system, Vanzetti Infrared & Computer Systems Inc. of Canton, Mass., has developed a technique for Fiat, the Italian automobile manufacturer, to control welds from an Avco CO₂ laser beam. Control is accomplished by monitoring the temperature of the metal being worked on. A fiberoptic cable, embedded in the welding probe, carries the infrared radiation from the hot metal surface to two detectors. Each cable/detector system is sensitive to a different spectral region (for surface-radiated, not reflected laser-beam infrared energy). The ratio of the two detectors' outputs determines the blackbody temperature of the metal to within 1 percent, thus allowing precision laser-beam application through an appropriate electronic feedback circuit.

One area of intense scientific interest is in use of the laser to anneal silicon semiconductors and solar cells, instead of the conventional oven-annealing. An indication of the magnitude of this interest can be gleaned from the recent meeting of the Materials Research Society in Boston. Ten sessions were devoted to technical papers on laser annealing, many from other countries, such as Italy, Japan, Britain, and the Soviet Union.

At present a number of semiconductor manufacturers

For further reading

Following are sources of further information on the use of lasers in industry:

- *Industrial Applications of Lasers*, a 1978 book by John F. Ready of Honeywell Corporate Research Center, Bloomington, Minn., covers the subject of industrial lasers extensively. Starting with fundamentals of laser operation, the book carefully examines related topics, like laser safety, optics, alignment and tooling, and closely looks at a host of materials-processing applications. The emphasis is on practical lasers that are on the market. The book is published by Academic Press, New York, N.Y.

- *Guide for Material Processing by Lasers*, a handbook put out by the Laser Institute of America, has excellent information on metals processing. It is published by the Paul M. Harrod Co., Baltimore.

- Many technical papers on laser processing are available from the Society of Manufacturing Engineers, 20501 Ford Rd., P.O. Box 930, Dearborn, Mich. 48128, and from the Society of Automotive Engineers, 400 Commonwealth Dr., Warrendale, Pa. 15096.

are experimenting with ruby, argon, and Nd:YAG lasers for annealing. Although no production systems exist, successful results indicate that this may not be too far off.

Laser annealing is more precise than oven annealing in repairing the damaged areas of silicon, and oven annealing may also cause wafer warping. ♦

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