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The Choice: Welding with CO_2 or Nd:YAG Lasers

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Introduction

The recent commercial availability of multi-kilowatt Nd:YAG lasers has opened new avenues for rapid laser processing as well as intensified the competition (cost effectiveness) between CO_2 and Nd:YAG laser systems. Vendors offering Nd:YAG laser systems may claim lower operating costs (than CO_2) and fiberoptic beam delivery flexibility while CO_2 systems vendors may emphasize lower capital cost and well established processing requirements and experience.

The capital and operating costs of a laser system are impacted by demand and supply economics and technological advances. Frequently the total cost of a workcell using a laser for processing has to be considered rather than the laser system alone. Consequently it is not very practical to approach the selection of a laser system based on its capital cost and estimated operating cost only.

This presentation describes a more pragmatic approach to aid the user in the selection of the optimal multi-kilowatt laser system for a particular processing requirement with emphasis on welding. CO_2 laser systems are well established on the factory floor. Consequently, emphasis is given to the comparative application of Nd:YAG lasers, process requirements and performance. Requirements for the laser welding of different metals are examined in the context of hardware (laser system and beam delivery) selection and examples of welding speeds that can be achieved using CO_2 and Nd:YAG lasers are examined.

CO_2 Laser Systems

Many laser users are familiar with CO_2 lasers. Consequently, only a brief review is given with the focus on recent technology advancements. The major suppliers/manufacturers of CO_2 lasers are listed in Table 1. The cost of multi-kilowatt power CO_2 laser systems without external cooling and beam delivery varies from <$100/W for a 1 kW output to <$50/W for >5kW output. A number of excitation methods and geometries are used by various CO_2 laser manufacturers. The major characteristics of these methods are listed in Table 2. Original designs were DC excited slow flow providing high beam quality ($M^2<1.3$). Increased power could be obtained by increasing the cavity length with a consequent size increase. Electrode wear tends to be a problem with service needed after several hundred hours of operation. The transverse or cross flow system with substantially higher gas flow enabled substantial increase in power levels. Systems with fast axial flow and RF excitation appeared with more compact size and no electrode wear but with

consequent increase in cost and complexity. Higher power is generally obtained at the expense of beam quality. However, some manufacturers use deformable and folded mirrors (Laser Ecosse) to maintain high beam quality or aperture the cavity to extract a lower power, higher quality beam (Rofin-Sinar). Further advancement in technology has led to fast axial flow systems using turboflow compressors in place of blowers. Noise and maintenance requirements are substantially decreased. Hybrid systems using AC (kHz) excitation instead of RF (MHZ) and ceramic electrodes now have less complex power supplies and electrode service intervals of over 10,000 hours.

TABLE 1. List of manufacturers supplying multi-kilowatt CO_2 laser systems in USA.

Manufacturer	Telephone #	Excitation Method	Beam Characteristics	Output Power (kW)
Convergent Energy	(508) 347-2681	DC cross flow	cw	1-45
		DC slow flow	cw, pulse, superpulse	
		DC fast flow	cw, pulse	
Laser Ecosse	(606)586-6900	DC slow flow	cw, pulse	1-8
		DC fast axial flow	cw, pulse	
PRC	(201)347-0100	DC fast axial flow	cw, pulse superpulse, hyperpulse	1-5
Rofin-Sinar	(313) 455-5400	DC transverse flow	cw	1-22
		AC transverse flow	cw, pulse	
		RF fast axial flow	cw, pulse, superpulse	
		Slab (diffusion cooled)	cw, pulse	
Trumpf	(203) 677-9741	RF fast axial flow	cw, pulse	1-12

TABLE 2. Characteristics of CO_2 laser excitation methods

Excitation Method/Geometry	Characteristics
DC	lower complexity and cost for power supply, high electrode degradation
RF	higher complexity and cost, no electrode degradation
AC (kHz) and ceramic electrode	lower complexity and electrode degradation
slow flow	higher beam quality, lower power
transverse or cross flow	lower beam quality, higher power
fast axial flow	lower beam quality, higher power
no flow/low flow (slab geometry)	high beam quality, simple, compact

Low power (100W) sealed CO_2 lasers have been used for a number of years. The operating life for a single charge are now in the 20,000 hours range. These sealed lasers eliminate the gas requirements of conventional units. Consequently, gas supply costs and its associated problems are completely eliminated. The recent introduction of the compact slab CO_2 laser with 2 kW of output power is a significant advancement in the technology of CO_2 lasers. The electrodes are two closely separated parallel plates and RF excited. The laser essentially operates as a sealed system. A telescope/beam shaping optics system transforms the rectangular output from the parallel plates discharge to a high quality circular beam. The high power mode of operation requires a fresh charge (of gas) after approximately 2 days of operation. Consequently, the result is an effective low flow (1 L/hr) gas requirement. The elimination of blowers and the tuned RF power supply leads to a very compact head (170x80x85 mm) and low noise operation. A vacuum pump is still required for pump down when recharging. Another significant improvement is the nearly instantaneous (minutes for RF power stability) stable output from turnon compared to 1-2 hours for conventional fast axial flow RF excited designs. A premixed gas bottle supplies gas for up to a year's operation. At a listed price of \$77/W, an expected operating life of >15,000 hours of the slab, beam quality of $M^2 \approx 1.4$, the slab CO_2 laser can be considered a technological breakthrough.

Nd:YAG Laser Systems

Low power ($\leq$ 500W), Nd:YAG lasers have been deployed on the factory floor for a number of decades. These solid state lasers using flash lamps to pump ceramic rods are more compact in size than CO_2 lasers and required no lasing gas. The multi-kilowatt Nd:YAG systems offered today (see Table 3) are basically oscillator-amplifier designs of previous years but using additional or bigger rods. The advancement in crystal growing technology has allowed the availability of better priced larger diameter and longer rods. Most models offered are multimode, continuous wave (cw) output with beam quality in the $M^2 = 100$ range. A 2 kW system normally costs >\$100/W.

TABLE 3. List of manufacturers supplying multi-kilowatt Nd:YAG laser systems in USA

Manufacturer	Telephone #	Beam Characteristics	Output Power (kW)
Electrox	(317) 248-2632	pseudo cw, pulse	1.6 - 2.4
Haas (Trumpf)	(203) 677-9741	cw, pulse	1 - 2
Hobart Laser	(810) 588-8812	cw	1 - 3
Lee Laser	(407) 422-2476	cw	1 - 2
Lumonics	(313) 591-0101	cw, pulse	1 - 2, 5(peak)
Rofin-Sinar	(313) 455-5400	cw, pulse, hyperpulse	1 - 2, 5(peak)
US Laser	(201) 848-9200	cw	1 - 2

The cw mode is optimal for high speed welding. The Electrox Nd:YAG is a pulsed laser using multiple oscillators to control the duty cycle. The 6 head 2.6 kW model allows full control of duty cycle while the 4 head 1.6 kW model can only achieve 66% duty cycle. Consequently, the 6 head model can generate pseudo cw output for high speed processing and low duty cycle pulsed high peak power for deep penetration. Most high power Nd:YAG lasers available have cw mode output with some having pulse or hyperpulse operation (pulse on top of DC level) to achieve higher peak powers.

An alternative to the standard rod is the slab design that holds the promise of a high quality beam at high power levels. Although a 500W slab laser with high beam quality has been in operation at General Electric for over a decade, the problem of thermal management has not been resolved without significant beam quality degradation for high power cw output even with diode pumping. Another alternative design that offers a very compact and efficient package is the end pumping of rods with diode lasers (Lawrence Livermore Laboratory). Low power outputs have been demonstrated and increased power levels are expected soon.

Beam Delivery

Laser systems require power and cooling to operate and optics for delivering the appropriate beam to the workpiece. With diamond turning and diffractive optics, a wide range of optics is available for beam shaping although cost may become prohibitive for complex systems. Conventional beam delivery for CO_2 beams includes transmissive (ZnSe) and reflective (Cu, Mo) optics. The latter is preferred in production applications because of its resistance to damage by splatter and the ease of cleanup. Longer standoff (focal lengths) are preferred to minimize splatter but at the expense of larger spot sizes. Although larger spot sizes allow poorer fitup requirements, the lower irradiance result in shallower penetration or slower processing speeds. Cross flow systems are now available to prevent splatter on lenses. Optics used for multi-kilowatt CO_2 beams require water cooling.

For Nd:YAG beams, transmissive (glass, quartz) optics is the norm and cooling is unnecessary. A flat cover glass is usually used as a lens protector. Lenses with BK 7 glass are substantially lower cost than the ZnSe lenses for CO_2 beams.

An alternative to fixed optics beam delivery is fiberoptic or waveguide beam delivery systems. The capability of flexible fiberoptic beam delivery is often cited as the unique advantage of high power Nd:YAG lasers. High power fiberoptic beam delivery with robotic manipulation of the focusing head allows 3-D processing with the laser source at a remote location. Power levels of over 3 kW have been delivered through 600 μm diameter hard clad quartz fibers. Recent improvements in beam launching and fiberoptics have minimized total losses to <5%. The use of a fiber for beam delivery has a significant drawback, i.e. the beam quality is degraded substantially depending on fiber size. For example, the initial beam quality entering a 600 μm fiber may have $M^2 = 100$ but the output from the fiber will tend to degrade M^2 to ≤ 200. The beam quality of multimode high power Nd:YAG beams is poor compared to CO_2 beams ($M^2 \leq 5$) of similar powers. Consequently processing speed and penetration will be lower.

Fiberoptic or waveguide beam delivery for CO_2 beams have been proven feasible in the low power range. Recent advancements have enabled the launching of kilowatt high quality CO_2 beams through several meters of millimeter size hollow waveguides with less than 30% of power loss[2,3]. For the case of the CO_2 (10.6 μm) wavelength, the propagation of the photons is through reflection at the fiber wall where a small loss is encountered at each reflection. Consequently, power losses are manifest in the fiber itself as opposed to the case of the silica fiber for Nd:YAG beams where the property of total internal reflection is used. Irrespective of the losses, the quality of a beam transmitted through a fiber will be constrained by the fiber size and the presence of bends. Consequently, a substantial degradation of the beam quality will result for the initial high quality CO_2 beams.

In essence, fiberoptic/waveguide beam delivery is feasible for both kilowatt CO_2 and Nd:YAG beams although the generation of heat along the CO_2 beam delivery fiber will require more engineering complexity in the system for heat removal. The substantial beam quality degradation for the CO_2 case makes the choice undesirable. However, this does not preclude a ruggedized CO_2 fiber system available in the near future from being attractive for niche applications.

Processing Requirements

In the cutting of cotton fabrics, plastics and synthetics, CO_2 is preferred over the Nd:YAG laser because such materials absorb CO_2 wavelengths but are transparent for the Nd:YAG. For metals, the Nd:YAG wavelength absorption is significantly higher. However, high beam quality is preferred for cutting. With high power and high beam quality, the CO_2 is the laser of choice.

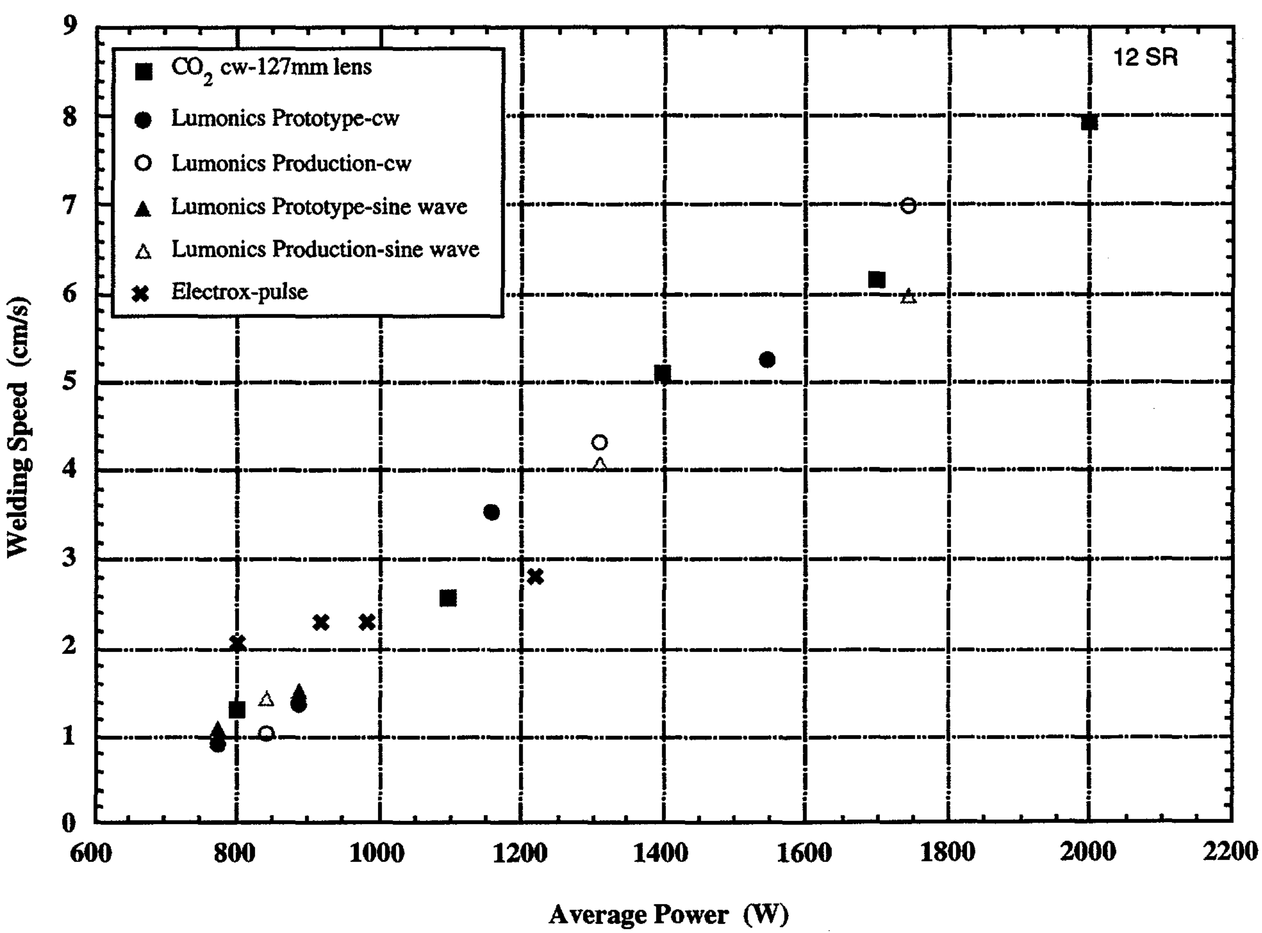

Figure 1. Weld speeds obtained as a function of delivered beam power for CO_2 and Nd:YAG lasers. The duty cycle for the pulsed Nd:YAG beam varied from 33% to 45% and peak power from 3 to 4 kW. This figure is Figure 1 from Industrial Laser Review, June 1994, p.14.

For welding, beam quality is not as crucial as long as sufficient power and irradiance (power density) are achieved. Consequently, the misconception has been that given similar conditions of power and irradiance the better coupling of the 1.06 μm Nd:YAG wavelength to metals, particularly reflective metals (e.g., copper or aluminum) would result in improved processing over CO_2. Better absorptivity or lower reflectivity would certainly imply a lower threshold beam irradiance to form a weld pool. However, once the weld pool is formed, the geometry of the weld pool, vapor and plasma would result in substantially increased coupling for both CO_2 and Nd:YAG. As a result, for adequate beam irradiance to achieve a required penetration, process speeds are very similar for a given power[1]. This situation is illustrated in Figure 1 for full penetration lap welds (1.5 mm) of aluminum bearing stainless steel (SR 12). The spot sizes were 300 μm and 600 μm for the CO_2 beam with the 127 mm and 254 mm focusing lens respectively, and 500 μm and 600 μm for the cw and pulsed Nd:YAG beams respectively. The data in Figure 2 for 409 stainless steel (full penetration lap welds, 3 mm) illustrates the advantage of using a smaller spot size with higher beam intensities as well as indicating again that similar process speeds are obtained for the same beam irradiance and power level irrespective of wavelength when threshold irradiances are exceeded.

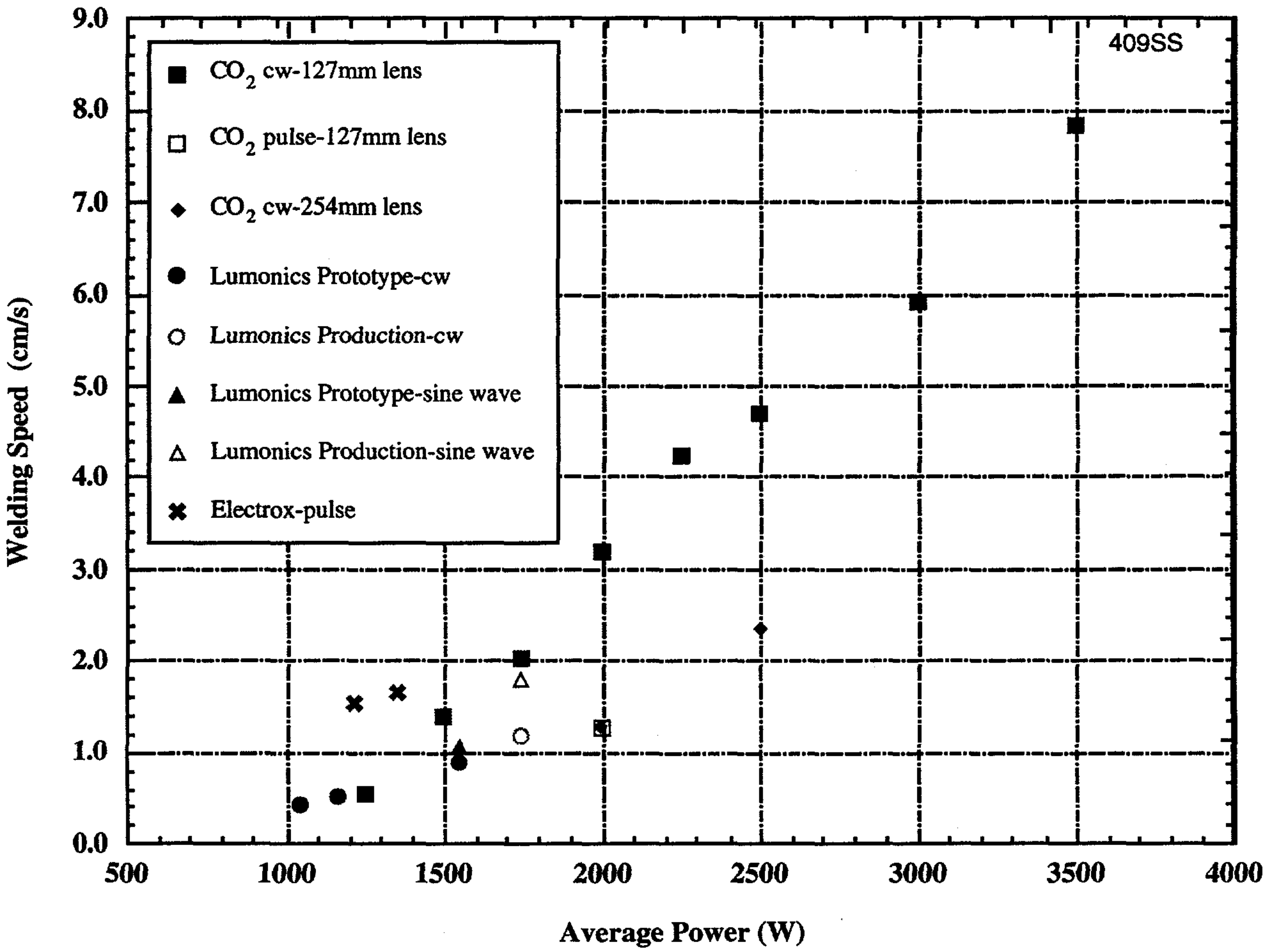

Figure 2 Weld speeds obtained as a function of delivered beam power for CO_2 and Nd:YAG lasers. The duty cycle for the pulsed Nd:YAG beam was 40% and the peak power was 4 kW. This figure is an expansion of Figure 2 from Industrial Laser Review, June 1994, p.15.

In the past, laser power is often used as the essential parameter for specifying process needs. However, process results are impacted by the spot size of the beam used. Consequently, beam irradiance should be specified. In many applications, such as the processing of reflective metals, beam irradiance is the crucial parameter. Beam irradiances above the threshold value that is dependent on reflectivity /absorptivity and thermal conductivity, are required. The penetration is also controlled substantially by beam irradiance whereas process speed is controlled by power when threshold irradiances are exceeded. A list of threshold beam irradiances are listed in Table 4 for steel and aluminum.

TABLE 4. Threshold beam irradiances for steel and aluminum with cw CO_2 and Nd:YAG laser beams[4,5,6,7]

Material	Wavelength	Threshold Irradiance (Wcm^{-2})
Steel	CO_2	~ 7 x 10^5
	Nd:YAG	~ 3 x 10^5
Aluminum	CO_2	~ 2 x 10^6
	Nd:YAG	~ 1 x 10^6

Laser Selection

A common tendency in considering laser beam welding to replace arc welding is to specify the laser system without changing the joint geometry and fitup requirements. The process results obtained will frequently be far from optimal. In other words, the process should be designed for laser beam welding to take advantage of its characteristic precision and high speed. Specifying the weld geometry and fitup leads to a requirement on the laser beam spot size. For a particular material, the threshold beam irradiance (see Table 4) and process speed specifies the minimum power required for the laser.

For example, the threshold beam irradiance requirements for steel or aluminum is higher for the CO_2 wavelength compared to Nd:YAG because of the lower absorptivity. However, less than 2 kW of a high quality ($M^2 \approx 1.4$) CO_2 beam is required to process aluminum at a standoff (focal length) of 177 mm (5 in.) compared to a requirement of approximately 3kW of Nd:YAG power for a 600 μm fiber delivered beam using 1:1 imaging optics at a substantially shorter standoff distance. For pulsed beams, the threshold irradiance values are higher because of the heat dissipation between pulses.

The technical process requirements are rather straight forward compared to the selection of an optimal laser system. If adequate beam irradiance and power are available, the choice of CO_2 or Nd:YAG would depend on workcell and fixturing considerations. The fiberoptic beam delivery of Nd:YAG lasers does offer a significant advantage in flexibility. If fiberoptic beam delivery is not necessary, the new slab CO_2 laser offers many advantages that bear consideration. The laser should be designed for the factory floor environment. Although components are designed to have a long life, repair and maintenance are inevitable. Consequently, ease in maintenance and downtime in addition to system robustness and performance are significant considerations.

Frequently, new and advanced systems with the promise of substantial processing gains become available but with sparse performance data. The user then is faced with weighing the risk of established system uptime versus potential increased performance. Perhaps, the increase in user input or collaboration in the development of a new and improved system will increase the acceptance of the new system.

The selection process for an optimal laser system is incomplete without a discussion on the cooling and beam delivery systems necessary to implement laser processing. The fact that most lasers perform well (subject to maintenance requirements) but frequent problems are encountered with cooling systems, beam delivery and overall integration are well known.

Laser cutting systems are often customized. The use of a system integrator experienced in laser systems will ensure a reliable beam delivery system. Cooling is usually not part of an integrated system and frequently becomes the weakest link resulting in significant downtime. Coolant requirements need to be considered carefully for either a building chiller system or a custom system.

Closing Remarks

The choice of a particular laser system is impacted by a number of parameters that includes process, fixturing and workcell requirements and cost. Hardware cost is not the major consideration in many applications; otherwise, the CO_2 laser would be the optimal candidate.

The text of this paper is intended to give the reader an introduction to the basic requirements of selecting the optimal laser system with emphasis on welding. The presentation will focus on examples of current multikilowatt laser systems with a discussion on the parameters for laser system selection.

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