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Performance of Three-Crystal 1800 Watt CW Nd:YAG Laser

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Abstract

The goal of this project was to develop a laser system that would combine some of the favorable characteristics of the two most commonly used lasers for seam welding of heat sensitive assemblies. A multirod (3) symmetrical resonator CW Nd:YAG laser has been developed that is rated at 1800 watts output power. By utilizing the symmetrical resonator design, beam characteristics are not significantly compromised compared to that of single rod systems. The laser is capable of producing acceptable welds in aluminum and copper alloys and also has sufficient power to produce welds in steels and nickel base alloys at high welding speeds.

A Different Laser Needed

Sandia began studying lasers as welding heat sources in the early 1970's. Since the mid-70's, the emphasis has been on the use of pulsed Nd:YAG lasers to produce hermetic seam welds on heat sensitive components. Also, medium powered CO_2 lasers have been used extensively, primarily operated in the CW mode. Pulsed Nd:YAG lasers, typically commercially rated at 150 watts in the early years and at 400 watts during the 1980's, have found important applications for welding near heat sensitive glass-to-metal seals, pyrotechnics, and polymer materials. However, the multiple melt-freeze cycles associated with pulsing exacerbate hot cracking problems in many engineering alloys. Consequently, alloy selection to avoid hot cracking can become very demanding, particularly in the case of dissimilar welds.

The propensity for hot cracking can be reduced by use of continuous heat sources, such as CW CO_2 lasers. However, due to the greater characteristic wave length of CO_2 laser light compared to that of Nd:YAG lasers (10.6 μm vs. 1.06 μm), adsorption of energy from a CO_2 laser beam is less efficient, particularly for conduction mode welding of highly reflective metals such as copper and aluminum.

Our selection of a laser for a given welding application generally has involved an engineering compromise that considers the reflectivity of the alloys to be welded, the heat sensitivity of the assembly, and the hot-cracking tendency of the alloys.

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The goal of this project was to develop a laser system that would combine some of the favorable characteristics of the two most commonly used lasers for seam welding of heat sensitive assemblies. Specific objectives were to produce a Nd:YAG laser that: 1) is capable of welding aluminum and copper alloys, 2) operates in the continuous wave mode so as to reduce the propensity for hot cracking, and 3) has sufficient average power to compete with medium-powered CO_2 lasers and provide high weld speeds.

An 1800 watt CW Nd:YAG system has been developed and subjected to preliminary characterization. All experiments were conducted at the manufacturers' facility and more thorough characterization, particularly of beam quality will be made once the system is installed in Sandia's research facility.

Design Approach

The laser resonator design was based on evolutionary improvements over earlier designs. The designer, Larry Marshall of Martek, Inc, had designed Sandia's first high pulse rate Nd:YAG laser (150 watt) in the early 70's and also was the principal designer for a widely used 400 watt pulsed Nd:YAG laser of U.S. manufacture. The laser head for this new laser, though designed for CW operation, is based on Marshall's design experience for efficient pulsed Nd:YAG systems.

The primary design approach was to improve efficiency compared to earlier designs through very careful heat management. This included highly efficient cooling and control of the energy spectra delivered to the laser rods. Unlike earlier high-powered CW Nd:YAG systems based on 5 to 8 rods, this system was specified to utilize a maximum of 3 laser rods so as to minimize assembly and alignment problems. The designer concluded that a symmetric periodic resonator was optimum for our design goals. The three cylindrical laser rods were equally spaced between the resonator's mirrors. Each rod was pumped by two arc lamps placed in a close-coupled, dual-elliptical cavity. This design approach provides stable operation over wide power ranges and high efficiency, because of the large mode volumes created within the laser rods [1].

System Packaging

The three rod symmetric periodic resonator is housed along with a water cooled beam dump and shutter, and a helium-neon alignment laser in a space not substantially larger than that for some 400 to 600 watt lasers. The dimensions of the enclosure are 10 x 18 x 59 inches. A schematic representation of the three-rod symmetric periodic resonator is shown in Fig. 1. The head design also incorporates a number of "user friendly features" such as easy replacement of O-rings or arc lamps without disassembly of the elliptical enclosures and remote mirror alignment. Consequently, this "fourth generation" design is easier to maintain than lasers of earlier designs.

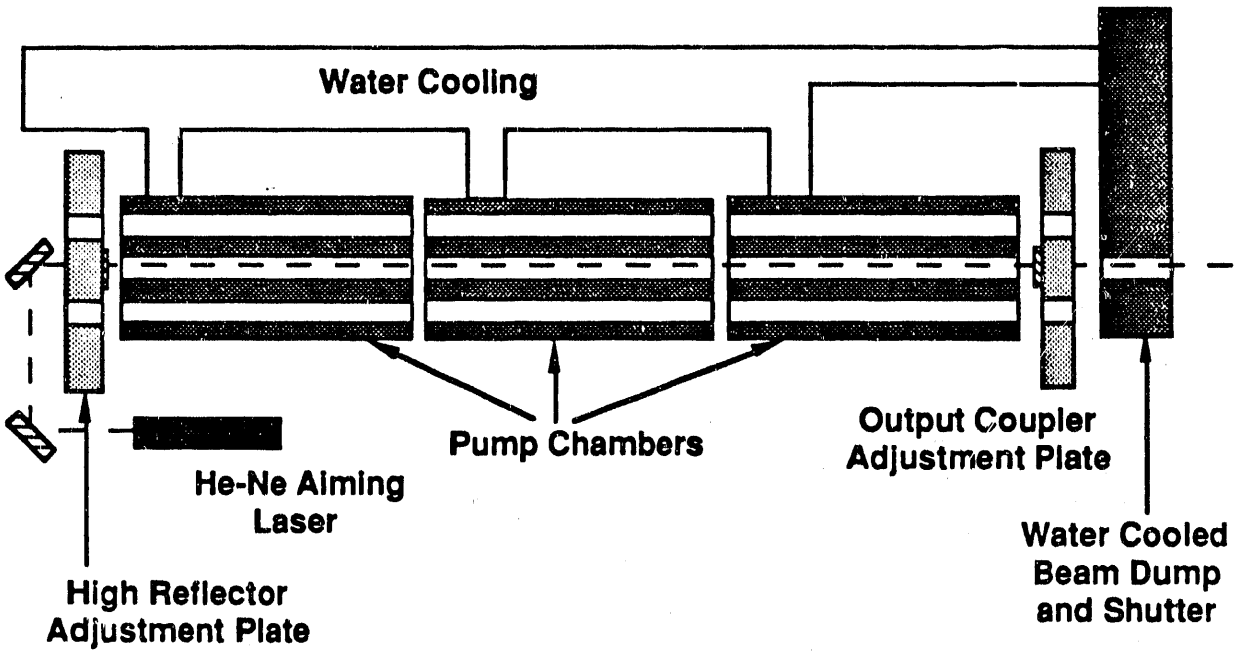

Figure 1. Schematic representation of three-rod symmetric periodic resonator.

Power to the arc lamps is provided by a modular, rack-mounted power supplies of state-of-the-art switching design. Each arc lamp is powered by its own individual power supply. Switching power supplies are electrically highly efficient and generate little heat energy. Advantages to the user afforded by these power supplies include compact size, light weight, programmability, high speed, quiet operation, and highly stable output. The switching power supply rectifies the input signal which is then passed through a series of buck convertors to reduce the voltage amplitude. This voltage is then modulated at 20 kHz and filtered to achieve a highly stable output signal. Since the voltage is modulated at a high frequency, the need for large transformers to store energy is eliminated. The switching power supply derives it's compact size from the ability to use small transformers since the energy being stored is small compared to normal 60 Hz operation. Also, because of the relatively small heat dissipation, the required cooling fans generate little noise. An additional advantage of the modular design is the ability to replace a defective module. The entire power supply, including electronic controls, is packaged in a 24 x 29 x 68 inches (height) rack cabinet.

The modular power supply is amenable to a number of control strategies. For example, the multiple power supplies can all be slaved to one power supply or controlled independently. This power supply is particularly adaptable to computer-based control strategies. Adaptive control based on electrical, thermal, and/or light sensors is feasible.

Laser Performance

The three-rod laser has produced in excess of 2000 watts output power and has been conservatively rated at 1800 watts maximum output power. Nominal laser extraction efficiency is 4.3% with a slope efficiency of 5.6 %, which is approximately 50% higher than most state-of-the-art systems. Many commercial Nd:YAG lasers operate in the 2-3% efficiency range.

Although a high mode order laser, the spatial distribution of energy for this laser during high power operation is approximately Gaussian, with positive deviations from Gaussian seen in the tails of the distribution (see Figure 2). This spatial distribution of energy was measured with a slot scan profiler using a 5 μm aperture and 1 Hz scan rate. As a function of power level, beam quality of the laser is compared with that of other commercial lasers on the basis of the number of times diffraction limited, as measured (see Figure 3).

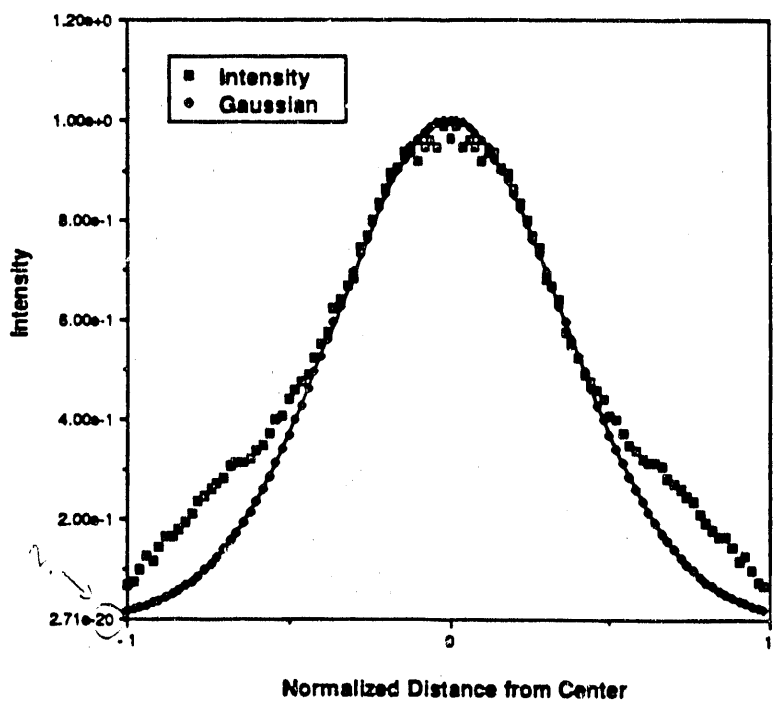

Figure 2. Normalized cross-sectional energy distribution of CW Nd:YAG laser measured at high power.

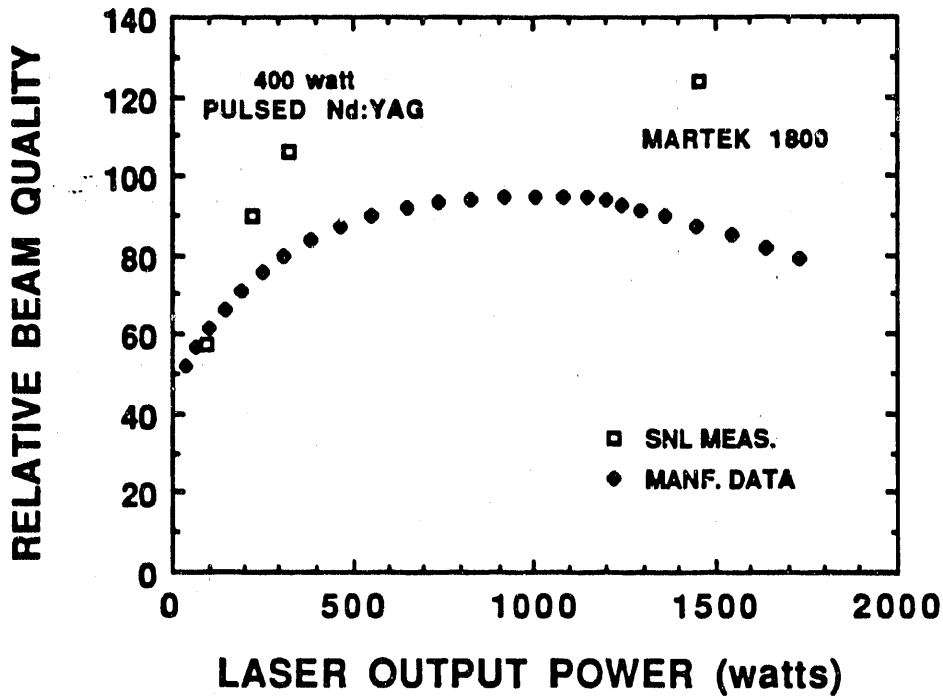

Figure 3. Manufacturers laser beam quality of 1800 Watt CW Nd:YAG compared to SNL measured data for CW laser and a pulsed Nd:YAG system.

Beam quality was measured in the far field by measuring the 1/e spot size at the focal plane of a four inch focal length plano-convex lens and by measuring the divergence angle below the focal plane. The laser beam incident on the focusing lens was expanded to an approx. 1.7 inch diameter producing an effective F# of 2.35. Spherical aberration was not expected to be significant using this laser at this relatively low F#.

The spot size was measured using an apparatus described in [2], by centering a series of gold coated diamond apertures in the focal plane and measuring the transmission with a silicon photodetector. The 63% transmission (1/e) diameter was estimated to be 0.0168 inch. 1/e diameters were measured because a better measurement was obtained at this diameter since it is easier to detect a small change in beam transmission at this point on the gaussian like distribution.

The beam divergence from this waist diameter was measured by exposing photosensitive paper at a series of four locations below the focal plane. The full angle was determined to be 22.4 degrees. The product of the waist radius and the half angle divergence is then: $W\emptyset$ = 41.8 rad. µm and $W\emptyset_{min} = \lambda/\pi$ = 0.337 rad µm times differential = 41.8/.337 = 124. Also included are experimental values for M^2 as reported by the manufacture of the laser.

Some modifications in the resonator design were made between the measurement of the Sandia values and the manufacture values. Also, differences in experimental technique may account for some of the disagreement between the two sets of data. Additional beam characterization by Sandia is planned. Both sets of data show that the beam quality of this laser is comparable to that of some single rod lasers of 1/4 to 1/3 the power of this laser. The ability to increase output power without altering beam quality by means of symmetrical multirod resonators has been discussed by Kushnir et al.[3] and was recently investigated experimentally by Driedger et al.[4]. Driedger et al. confirmed that the beam quality remains virtually unchanged as second and third rods are added to a resonator so long as the rod/mirror geometry is optimized. Consequently, the power can be multiplied by the number of rods without sacrificing beam quality. Depending on whose data is used in the comparison, these data suggest that the beam quality of this laser at full rated power (1800 watts) is comparable or somewhat better than Sandia's present commercial 400 watt Nd:YAG laser. If further characterization supports this tentative conclusion, we will conclude that the refinements in the design have achieved approximately the same beam quality performance for 600 watts/rod as has previously been accomplished for 400 watts/rod.

Table 1. Examples of Welding Performance*

Alloy	Thickness Inches	Weld Type	Welding Speed in/min	Weld Penetration inches
304 ss	0.062	Butt	90	0.062
316 ss	0.125	Butt	60	0.125
Inconel 718	0.125	Bead	75	0.125
1010 Carbon St	0.040	Butt	400	0.040
5456 Al	0.032	Edge	90	0.056
DHP Cu	0.032	Edge	80	0.056
Titanium	0.250	Butt	30	0.118
Monel 400	0.100	Bead	60	0.100

* All welds made at 1800 watts except for edge welds, which were made at 1500 watts.

Welding Performance

Initial welding trials have been made on a variety of alloys. These include steels, high alloy steels, nickel base alloys, aluminum alloys, and copper. A sample of the results is presented in Table 1. Importantly, these welding trials have confirmed that aluminum alloys and copper can be welded at moderately high weld speeds, which is a primary design goal. A metallographic section of an edge weld made on aluminum alloy 5456 is shown in Figure 4. This weld was produced with 1500 watts average power at a weld speed of .0381 m/s (90 in./min). Welds in both alloys 5456 and 6061 appear to be relatively free of cracks.

A penetration mode butt weld in austenitic stainless steel is illustrated in Figure 5. To produce this weld, the laser was operated at 1040 watts average power and the weldment was translated at .0106 m/s (25 in./min). Although, this weld is not as narrow as many penetration mode welds produced by other processes (e.g., electron beam welding and some very high power density pulsed Nd:YAG laser welds), the aspect ratio is sufficiently high to assure high efficiency welding. This weld was made at an estimated 7×10^9 watts/m^2 power density, whereas many penetration mode welds are made at factors of two to three higher power density. Further improvements in the ability to make penetration mode welds are possible. Only moderate reductions (less than 30%) in the incident beam diameter would be required to double the power density. This may well be achievable with further refinements in upcollimation and output optics.

Figure 4. Metallographic cross section of edge weld on 5456 aluminum, 1500 Watts, 0.0381 m/s (90 in/min).

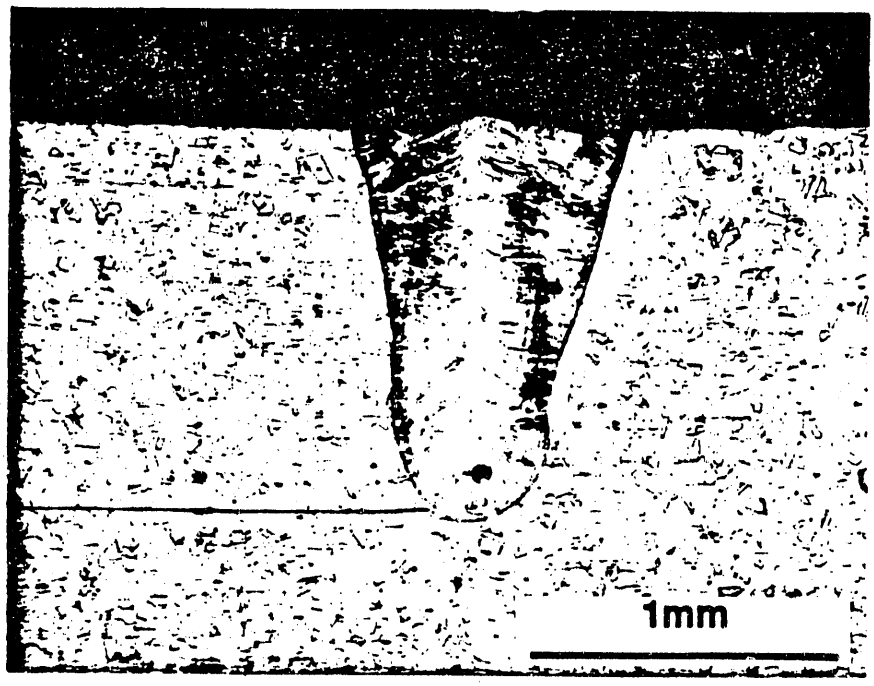

Figure 5. Metallographic cross section of butt weld in austenitic stainless steel, 1040 Watts, 0.0106 m/s (25 in/min).

Summary and Possible Further System Evolution

The development of a three-rod high powered CW Nd:YAG following an evolutionary approach has been successful in meeting the objectives of this system development project. The laser is capable of producing acceptable welds in aluminum and copper alloys and also has sufficient power to produce welds in steels and nickel base alloys at high welding speeds.

Further evolution of the design can be anticipated to extend the capabilities of the present system. Still higher powers might be achieved by increasing the length of the active medium, either by an additional rod or by longer rods. This would be of interest both for producing welds with: 1) greater penetration, 2) at higher speeds, and/or 3) higher aspect ratios (i.e., penetration mode welding achieved by higher power density).

Another direction for evolution of this system would be to develop high power pulsed Nd:YAG systems. This could be achieved by replacement of the arc lamps by flash lamps and development of electronic pulse forming power supply. Because a pulsed system would probably prove to be more efficient than the present CW system, average output power levels of 1400 and 2100 watts should be

achievable for 2 and 3 rod systems, respectively. At the high peak power densities and high duty cycles that these systems would afford, penetration mode welding should prove to be very achievable. Also, high duty cycles might in some cases mitigate the hot-cracking problems normally experienced when welding with pulsed systems on many common complex alloys.

Acknowledgments

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