Beam Characterization of a Materials Processing CO_2 Laser

Measurements show that traditional plano-convex lenses used in laser materials processing do not offer optimum performance

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ABSTRACT. The propagation of focused laser radiation has been characterized for 12 lenses using the laser propagation equation, yielding measurements of beam quality, spot size, and depth of focus. The beam quality of the laser places an intrinsic limit on the minimum focused spot size and was found to be $M^2 = 1.5 \pm 0.09$ ($M^2 = 1.0$ corresponds to an ideal beam) for the 1200-W CW CO_2 laser used in this study. As the lens focal length was decreased, measured values of spot size and M^2 were significantly increased over the values predicted for aberration-free lenses. This increase is believed to be due to spherical aberration introduced by the lenses. It was also found that at short focal lengths, aspheric lenses produce better results than plano-convex, meniscus, or diffractive lenses, at a laser power of 300 W. Equations were determined that accurately predict beam quality, spot size, and depth of focus under the influence of spherical aberration.

Introduction

Characterization of the propagation and focusing ability of a laser beam is essential in laser materials processing applications. This characterization is of particular importance in processes such as laser drilling and melting of metals, which exhibit a well-defined intensity threshold, below which the desired result is not obtained (Ref. 1). Indeed, in the interaction of metals with powerful light fluxes, it has been shown that the absorption of laser energy by metals is intensity dependent (Refs. 2, 3). As a result, processes such as laser cutting and drilling, which require removal of material through evaporation, and soldering and welding, which require melting, depend strongly on the characteristics of the materials processing laser. In many cases, the required intensity threshold for a material may be reached by focusing the laser radiation. Consequently, in materials processing applications, one should ask: 1) what parameter determines the intrinsic limit of the value to which a laser can be focused; 2) what limits the focusing ability of a high-quality laser lens; and 3) how does this limitation vary among different shapes of lenses? A requisite to an understanding of laser materials processing applications is therefore an understanding of the propagation of laser energy through optical systems, as well as knowledge of how the beam is affected by the system. Four important parameters that characterize a laser for materials processing are minimum spot size, beam quality, the minimum spot size location, and depth of focus.

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KEY WORDS

CO_2 Laser
Aspheric
Beam Quality
Depth of Focus
Diffractive
Meniscus
Spherical Aberration
Spot Size
Plano-Convex Lens

Spot Size and Beam Quality

In order to define spot size (the size of the laser beam at an arbitrary location along its axis of propagation), we first note that the beam profile of a laser operating in its fundamental mode has a Gaussian intensity distribution of the form (Ref. 4):

$$I(x,y,z) = I_0 \exp\left[\frac{-2\left(x^2+y^2\right)}{w^2(z)}\right] \quad (1)$$

where I_0 is the maximum intensity and w(z) is the spot size, or the radius of the beam at the point where the intensity has dropped to e^{-2} (13.5%) of the maximum intensity. Therefore, a cross-section of a Gaussian beam taken in a plane P perpendicular to the direction of propagation is a circle described by $x^2 + y^2 = w^2(z)$, where x and y are orthogonal coordinates in P. When the beam is focused by a lens with focal length, f, its divergence angle increases while the spot size decreases not to an infinitesimal point, but to a minimum value near the focal plane (the plane perpendicular to the optic axis at the focal point of the lens). The product of the divergence angle and the minimum spot size has a minimum value given by (Ref. 5):

$$w_0\theta = \frac{M^2\lambda}{\pi} \quad (2)$$

where w_0 is the minimum spot size, θ is the half-angle divergence of the beam,

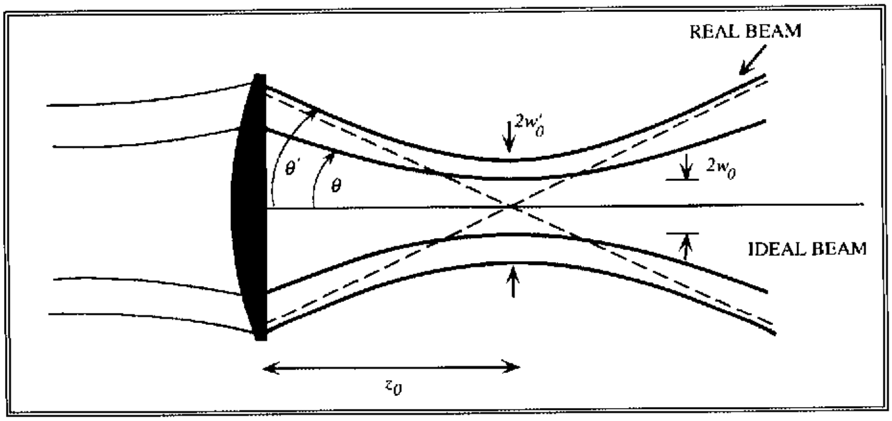

Fig. 1 — Propagation of real and ideal focused laser beams. The primes refer to the real beam.

M^2 is the beam quality, and λ is the wavelength of the laser radiation. The minimum possible value of this product (*i.e.*, $w_0\theta$) occurs when $M_2 = 1.0$.

A laser operating in the fundamental mode (TEM_{00}) will have the smallest allowed value of $w_0\theta = \lambda/\pi$ (*i.e.*, $M^2 = 1.0$). This limiting value is a result of diffraction of the laser beam, and is analogous to the diffraction of a bundle of rays passing through a circular aperture with a diameter equal to the diameter of the unfocused beam. Such a system is said to be diffraction limited. This however is an ideal case, and the beam quality of a real beam will always be greater than unity. Physically, the minimum product rule causes a real beam to be focused to a spot size which is larger than an ideal beam focused by the same lens — Fig. 1. Note that the cross-section of the beam along the propagation axis is a hyperbola and may be described by the equation

$$\frac{w^2}{a^2} - \frac{(z-z_0)^2}{b^2} = 1 \qquad (3)$$

where a and b are constants and z_0 is the location of the minimum spot size. The smallest value of w(z) corresponds to the minimum waist radius. The asymptotes are inclined to the propagation axis at an angle given by

$$\theta = \frac{\lambda}{\pi w_0} \qquad (4)$$

An expression for the variation of spot size along the axis of propagation may therefore be determined by solving for the constants a and b using the general conditions of a laser beam with an unfocused radius of W_0 focused by a lens of focal length f. A more mathematically rigorous derivation is given by Kogelnik and Li (Ref. 6). The first condition is that the laser is focused a distance z_0 from the lens. Therefore, at $z = z_0$, $w = w_0$. (One should note that the value of z_0 is not necessarily the focal length of the lens, since the laser has a finite divergence before entering the lens.) Substituting these values into Equation 3 yields

$$a^2 = w_0^2 \qquad (5a)$$

The second condition is that $w(z) = W_0$ at the lens. This gives

$$b^2 = \frac{w_0^2 z_0^2}{\left(W_0^2 - w_0^2\right)} \qquad (5b)$$

Substituting a and b into Equation 3 and using $W_0 \gg w_0$ gives

$$w(z) = w_0\sqrt{1+\frac{W_0^2}{w_0^2 z_0^2}(z-z_0)^2} \qquad (6)$$

Solving Equation 2 for M^2 and substituting $\theta = W_0/z_0$, the beam quality may be written as

$$M^2 = \frac{\pi w_0 W_0}{\lambda z_0} \qquad (7)$$

Rewriting Equation 6 to include the factor of $(M^2)^2$ yields

$$w(z) = w_0\sqrt{1+\frac{\pi^2 w_0^2 W_0^2 \lambda^2}{\lambda^2 z_0^2 \pi^2 w_0^4}(z-z_0)^2} \qquad (8a)$$

The equivalent expression in M^2 is therefore

$$w(z) = w_0\sqrt{1+\left(\frac{M^2\lambda}{\pi w_0^2}\right)^2(z-z_0)^2} \qquad (8b)$$

Equation 8b is the laser propagation equation and is identical to the expression given by Kogelnik and Li (Ref. 6).

Therefore, one can determine M^2 using Equation 7 by measuring W_0, locating z_0, the position of the beam waist, and making a single measurement of w_0. Alternatively, values for w_0, M^2, and z_0 may be determined simultaneously by making measurements of beam radius along the propagation direction and fitting to the data a curve of the form of Equation 8b, with w_0, M^2, and z_0 taken as the parameters of a nonlinear fit.

Spot Size and Spherical Aberration

The focusability of a laser beam is not only limited by the beam quality of the laser, but also by the optical element(s) used to transmit the beam. Specifically, the minimum spot size of a laser beam focused using a high-quality laser lens will be limited by third-order spherical aberration. Spherical aberration is defined as a variation of focus with aperture (Ref. 7), and is inherent in all simple lenses. The two lens parameters that contribute most to spherical aberration in simple lenses are the lens focal length and shape factor. As the lens focal length decreases, the curvature of the lens surface must necessarily increase. This increased curvature causes a ray in the outer portion of the laser beam (a marginal ray) to undergo

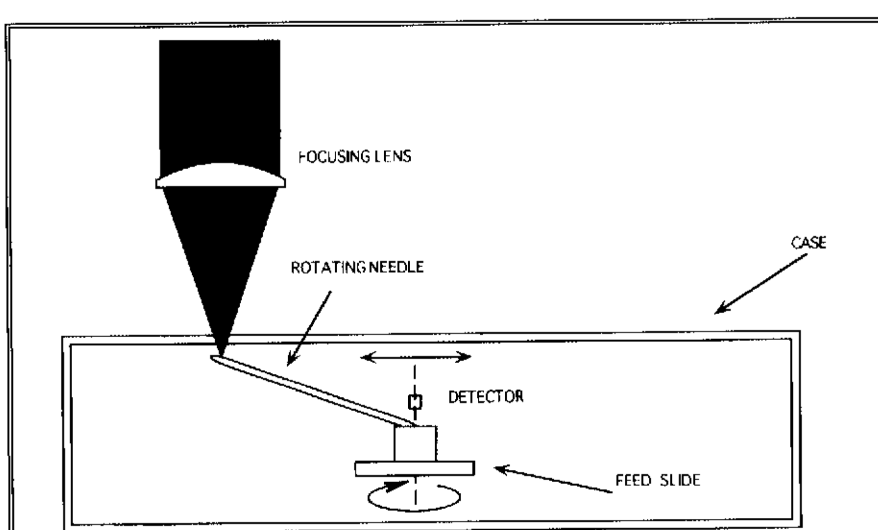

Fig. 2 — Schematic of the Laserscope scanning aperture system.

marginal ray) to undergo more refraction than a ray near the optic axis of the lens (paraxial ray). Consequently, marginal rays will be focused closer to the lens than paraxial rays. The result of this phenomenon is to increase the minimum spot size. The shape factor is also crucial in simple lenses since the amount of spherical aberration produced by a lens may be decreased by changing the shape of the lens. The four shapes or types of simple lenses tested in this work are plano-convex, meniscus, aspheric, and diffractive lenses. Plano-convex and meniscus lenses are spherical lenses, *i.e.*, both surfaces of the lenses are segments of spheres and can be defined by a constant radius of curvature. Aspheric lenses have at least one surface that has a varying radius of curvature, which is designed to minimize spherical aberration. The aspheric surface minimizes spherical aberration that would normally be present in a spherical lens. Diffractive lenses usually consist of spherical surfaces, one of which has been etched or placed in contact with a diffracting surface that reduces spherical aberration. Because of ease of fabrication, and therefore relatively low cost, plano-convex is the most common type of lens used in materials processing, but may suffer from excessive spherical aberration at short focal lengths.

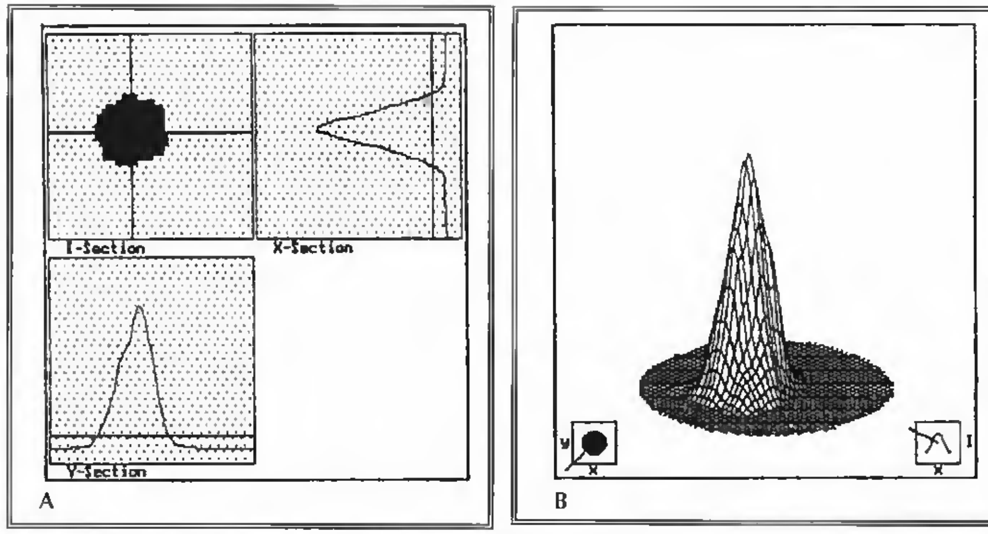

Fig. 3 — Intensity distribution of a CW CO_2 laser operating at 300 W. A — Contour and cross-sectional displays; B — isometric display. The laser radiation is focused by a 3.75-in. aspheric lens. The contour is taken at the plane, which corresponds to 86.5% of the total included power.

Spot Size and Depth of Focus

Another important parameter in laser materials processing is the depth of focus of the laser beam. Because the absorption of laser energy by the workpiece is dependent on the focused laser spot size (Ref. 3), it is very important to assure that the workpiece surface is located within the region of minimum spot size (*i.e.*, near z_0). In practice, this is accomplished by using the longest focal length lens that will produce the required depth of weld penetration or cut quality. Generally, depth of focus increases with the focal length of the lens. A practical definition has been given by Marshall (Ref. 8). Marshall arbitrarily defined depth of focus as the distance along the propagation direction at which the power density has decreased to 90% of its value at the position of the minimum spot size. This corresponds to an 11% increase in the area of the beam, which occurs when

$$w^2(z)=\frac{w_0^2}{0.9}$$

Rewriting Equation 8b as

$$w^2(z)=w_0^2\left[1+\left(\frac{M^2\lambda}{\pi w_0^2}\right)^2(z-z_0)^2\right] \tag{9}$$

and substituting $w^2(z)=\frac{w_0^2}{0.9}$ gives

$$\frac{10}{9}=\left[1+\left(\frac{M^2\lambda}{\pi w_0^2}\right)^2(z-z_0)^2\right] \tag{10}$$

Solving for the propagation distance z gives

$$z=z_0\pm\frac{\pi}{3}\left(\frac{w_0^2}{M^2\lambda}\right) \tag{11a}$$

The depth of focus (δ) is the distance within which the area A(z) is related to the area at the minimum waist, A_0, by

$$A(z)\le\frac{A_0}{0.9}$$

The length of this region is given by

$$\delta=\frac{2\pi w_0^2}{3M^2\lambda} \tag{11b}$$

Measurement of w_0, M^2, and therefore allows for a determination of the precision required for the positioning devices used in materials processing.

In this paper we present a method of determining beam quality, minimum spot size and its position, and depth of focus by performing measurements of beam spot size along the laser's propagation direction and then using a nonlinear curve fitting routine to obtain an expression relating the spot size of the laser beam to its propagation distance. A rotating aperture is used to make all measurements on a 1200-W continuous wave (CW) CO_2 laser. We present data to establish the relative performance of plano-convex, meniscus, aspheric, and diffractive lenses. A discussion of lens aberrations and their effects on beam quality is also presented.

Experiment

Diagnostic measurements were performed on a Photon Sources V1200 1.2-kW CW CO_2 laser. Measurements of the focused and unfocused spot size were made using a rotating aperture system (Prometec Laserscope) — Fig. 2. Laser radiation is detected by means of a pyroelectric detector mounted above a rotatable arm. The end of the arm has an aperture through which the laser radiation passes. The radiation is reflected down the length of the arm and then reflected to the detector. The entire assembly translates along the y axis and rotates about the z axis, so that the intensity distribution of the unfocused or focused beam is measured. Signals from the detector are sent to a computer, and stored on disk. The Laserscope therefore measures the cross-sectional area of the beam at a point along the z axis. Measurements are made independent of the laser mode, so that the technique may be used to perform beam radius measurements on beams consisting of higher-order modes. A ZnSe focusing lens is mounted on a linear translation stage and is accurately positioned along the laser propagation axis. The Laserscope is mounted on an x-y translation stage to facilitate positioning

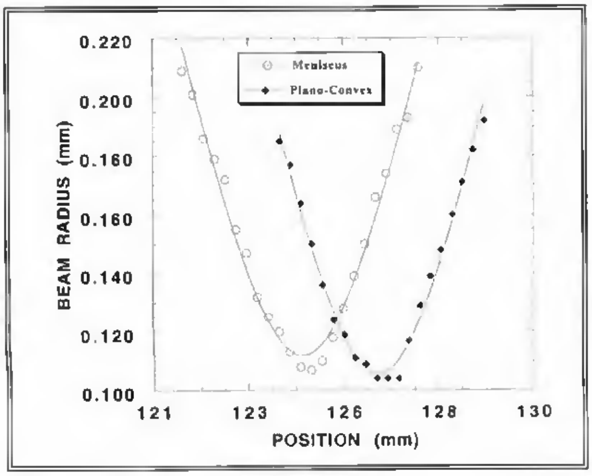

Fig. 4 — Beam radius vs. lens position for a CW CO_2 laser focused by 5-in. meniscus and plano-convex lenses.

of the focused beam onto the aperture.

Figure 3 shows a typical measurement of spot size. The Laserscope has been used to map the three-dimensional intensity distribution of the laser and determine the area of the beam at the plane above which 86% of the total power is included. The spot size radius is then taken to be the radius of a circle having the same area. The first figure is an isometric display of the intensity of the laser in a plane perpendicular to the direction of propagation of the laser, *i.e.*, in the x-y plane. This display type was used to view the overall shape of the beam and also indicated if the detector was saturated. The contour and cross-sectional displays facilitated alignment of the beam with the aperture and also indicated saturation. The contour plot represents the cross-section of the three-dimensional isometric intensity distribution taken at the plane corresponding to 86% of the included power. The x and y section plots represent cross-sectional views of the distribution and are taken in the x-z and y-z planes, respectively.

Measurements were made on 12 ZnSe lenses with nominal focal lengths ranging from 2.5 to 20.55 in. (63.5 to 522 mm). A list of the lenses used is given in Table 1. All measurements were made using approximately 300 W of laser power. To begin measurements, the lens was typically positioned so that the aperture of the Laserscope was a few millimeters above z_0. Determination of z_0 required iterative trial measurements, since nine of the 12 lenses focused the laser radiation at a position that was closer to the lens than the nominal focal length value. A 20-μm aperture was used to take all measurements of beam radius. Measurements were made on both sides of z_0 along the propagation direction, moving the lens in increments of 0.25 to 7 mm, depending on the focal length of the lens.

There are two major sources of error associated with measurements of spot radius. The first is due to temporal fluctuations in the spot radius of the unfocused beam, the second may result from an incorrect calculation of spot radius by the measurement apparatus. The temporal fluctuations of the laser were in effect averaged out by taking measurements along the propagation axis at different points in time and plotting the best-fit curve through the points. The included power technique is valid for beams that are rotationally symmetric and have no points of zero intensity (*e.g.* cold spots which occur at the center of the donut-shaped distribution of an unstable resonator). The Photon Sources laser exhibits no cold spots and any errors introduced as a result of a noncircular intensity distribution are also averaged out over the measurements taken along the propagation direction. Furthermore, incorrect measurements of beam radius are also prevented by holding the ratio of the area of the beam to the area scanned by the Laserscope (the fill factor) and the sensitivity of the instrument within the ranges recommended by the manufacturer. The fill factor was held between values of 0.40 and 0.80, and the sensitivity was also adjusted during each set of measurements so that the instrument was not saturated as the aperture was moved about z_0.

Table 1 — Lenses Tested

Nominal Focal Length	Lens type	Manufacturer
2.50 in. (63.5 mm)	aspheric	Laser Pwr. Optics
2.50 in. (63.5 mm)	meniscus	II-VI Inc.
2.50 in. (63.5 mm)	diffractive	Coherent
2.50 in. (63.5 mm)	plano-convex	II-VI Inc.
3.75 in. (95.2 mm)	aspheric	Laser Pwr. Optics
3.75 in. (95.2 mm)	meniscus	II-VI Inc.
3.75 in. (95.2 mm)	diffractive	Coherent
5.0 in. (127 mm)	meniscus	II-VI Inc.
5.0 in. (127 mm)	plano-convex	II-VI Inc.
7.5 in. (190.5 mm)	plano-convex	II-VI Inc.
10.0 in. (254 mm)	meniscus	II-VI Inc.
20.55 in. (522 mm)	meniscus	II-VI Inc.

Results and Discussion

Minimum Spot Size

Figures 4–6 show data sets of the lenses that typically have utility in materials processing applications (*i.e.*, $f \leq 5.0$ in., 127 mm). The data correspond to the spot size measurements made using a 20-μm-diameter Laserscope aperture. Measurements were taken approximately 3 mm above and below z_0 in increments of 0.25 to 7 mm, depending on the lens focal length. The beam radius was plotted as a function of propagation distance and a nonlinear curve-fitting algorithm was then employed to fit to the data a curve of the form of Equation 8b. The unfocused beam radius was found to be W_0 = 9.65 mm. Figures 4–6 show that with curve fitting it is possible to quickly describe the propagation of the focused laser beam along its propagation axis using Equation 8b. This curve fitting analysis is simple to perform on experimental data and provides a powerful method for analyzing laser spot size measurements (Ref. 9). A three-parameter curve fit (with parameters w_0, M^2, and z_0) such as shown in Figs. 4–6 was performed for all 12 of the lenses that were examined. The results are summarized in Figs. 7–9 and in Table 2.

Figure 7 shows the spot size as a function of focal length for the different lenses examined. The solid line shows the ideal spot size obtained using Equation 2, assuming that the 20.55-in. (522-mm) focal length meniscus lens introduces no spherical aberration. Equation 2 implies that, in the absence of spherical aberration, the product $w_0\theta$ is conserved as the lens focal length is changed. This yields an expression for minimum spot size given by

$$w_0 = w_{0(20.5)}\left(\frac{f}{f20.5}\right) \qquad (12)$$

where $w_{0\,(20.5)}$ is the spot size obtained using the 20.55-in. focal length lens, f, is

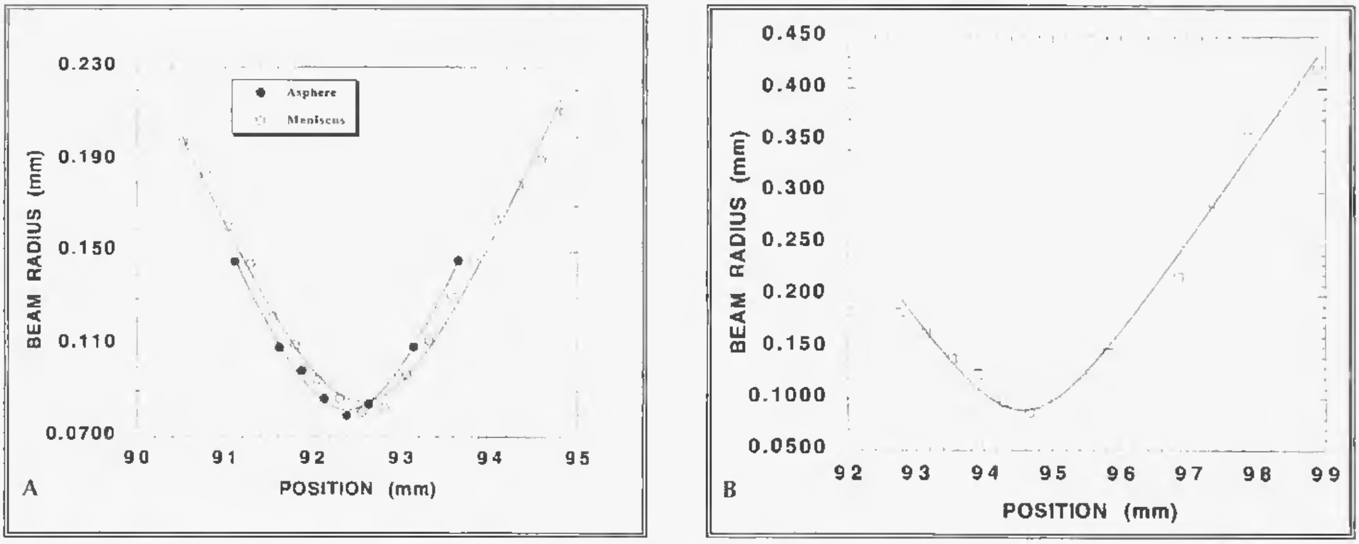

Fig. 5 — Beam radius of a CW CO_2 laser focused by 3.75-in. focal length lenses of various shapes. A — Aspheric and meniscus; B — diffractive.

an arbitrary focal length, and w_0 is the spot size at f. We suspect the dominant mechanism responsible for the deviation of the measured spot size from the ideal spot size is spherical aberration. Other third-order aberrations such as coma, astigmatism, and distortion are negligible when laser radiation is focused using high-quality lenses (Ref. 10).

At f = 2.5 in. (63.5 mm), the ability to focus the laser is highly dependent on the lens type. The plano-convex lens has the largest deviation from the ideal spot size, with a measured radius, which is 67% larger than the radius predicted for an aberration-free lens. However, for the 2.5-in. meniscus lens, the increase over the ideal spot size is less than 44%, and only 23% for the specially fabricated 2.5-in. aspheric lens. The performance of the plano-convex lens relative to the other lenses is expected since the plano-convex lens is uncorrected for spherical aberration. By using lenses that have been corrected for spherical aberration (aspheric, meniscus, and diffractive), rather than the less expensive plano-convex lenses, a significant increase in performance is obtained at short focal lengths. These results support the hypo thesis that at short focal lengths, spherical aberration limits the focused spot size even when high-quality laser lenses are used.

At f = 3.75 in. (95.2 mm), the aspheric lens again produced the smallest spot size, with a focused spot radius of 82 μm, while the meniscus and diffractive lens spot sizes were larger at 86 and 98 μm, respectively. At a laser power of 300 W, the spot size attained with the f = 2.5 in. diffractive lens is 60% larger than the ideal value. Like the aspheric lenses, the diffractive lenses are specially machined to eliminate spherical aberration and produce a small spot size. We postulate that the reason neither the diffractive nor the aspheric lenses achieved the predicted minimum spot size is because the shape correction used to fabricate these lenses is incorrect. The required shape correction is determined using computer lens design software that requires boundary conditions that include the laser beam characteristics. Since these lenses are produced for all CO_2 lasers, it is likely that the chosen shape correction is not optimum for the laser examined here. It should also be noted that the relative performance of the diffractive lens may im-

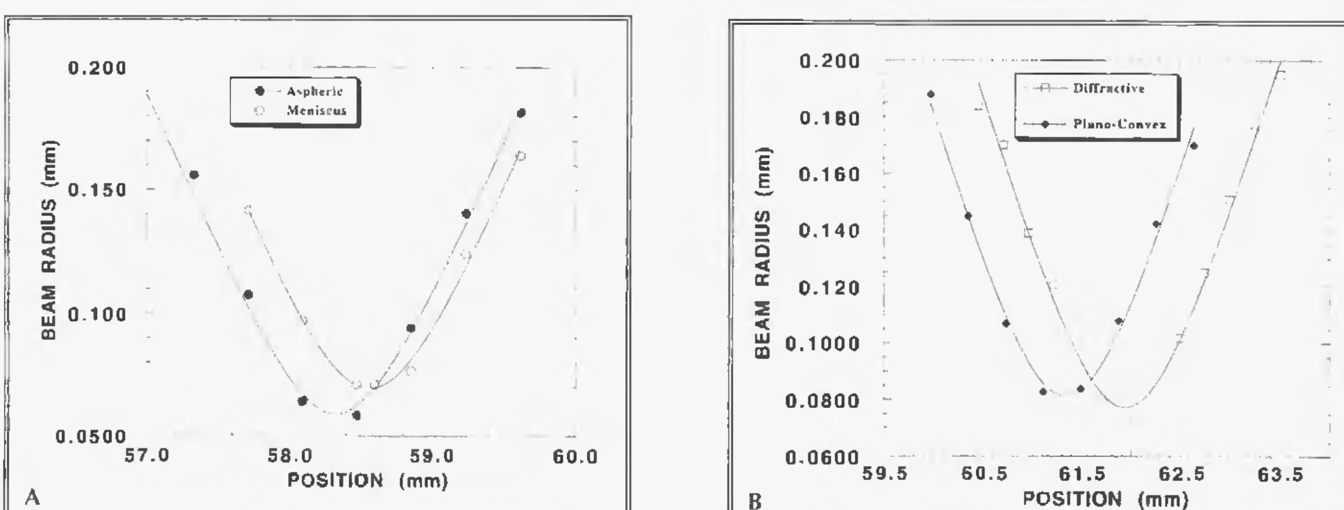

Fig. 6 — Beam radius vs. lens position for a CW CO_2 laser focused by a 2.5-in. focal length lens. A — Aspheric and meniscus lenses; B — diffractive and plano-convex lenses.

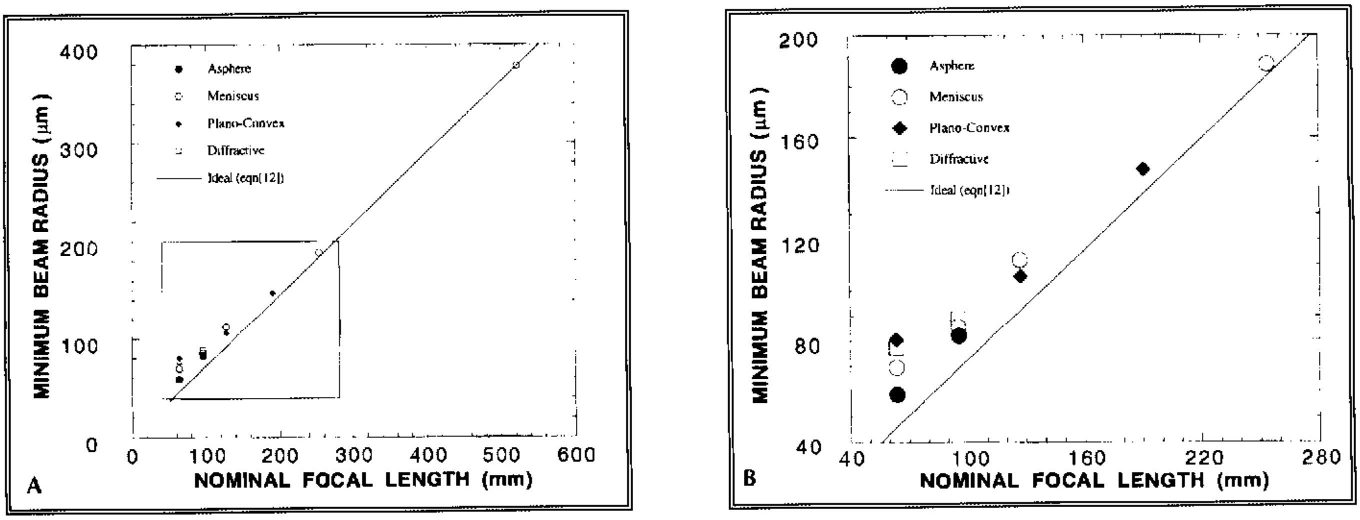

Fig. 7 — A — Spot size of a CW CO_2 laser as a function of lens focal length; B — boxed section of Fig. 7A.

prove at higher laser powers, as stated by the manufacturer, when thermal effects on the lens become appreciable.

Figure 7 shows that for all of the lenses that have utility in materials processing using this laser (*i.e.*, f ≤ 5.0 in., 127 mm), the ideal minimum spot size is not obtained using a single element lens, even if the lens is an aspheric or diffractive type. The only lenses shown to have insignificant spherical aberration are those that focus the laser to spot sizes too large to produce melting (i.e.f>5.0 in.) in most engineering alloys. Therefore, it is reasonable to conclude that the performance of this laser, and likely many other materials processing lasers, can be significantly improved with lens design that uses the proper boundary conditions to eliminate spherical aberration.

Beam Quality

Table 2 gives the measured beam quality for each focusing lens. Note that measured beam quality is inversely proportional to the focal length of the lens. This variation in beam-quality is likely due to spherical aberration, since beam quality is an intrinsic property of a materials processing laser and cannot be improved by the introduction of optical elements. As was the case for minimum spot radius, the best performance (beam quality) at short focal lengths was provided by the aspheric lenses, with beam quality measurements of M^2 = 2.4 at f = 2.5 in., and M^2 = 2.3 at f = 3.75 in.

For laser materials processing personnel, the utility of knowing beam quality is that one is able to estimate the spot size attainable with a given lens. However, since the measured beam quality is not consistent among lenses of differing shape and focal length, due to spherical aberration, one must take into account the effect of spherical aberration on beam quality in order to estimate spot size. Of course, the effect of spherical aberration on measured beam quality will depend on the type of focusing lens used. The meniscus shape was the shape most commonly tested in this study. A curve was fit through the data points of the meniscus lenses (Fig. 8) using an equation of the form

$$M^2 = M_0^2 + \frac{a}{f^2} \tag{13}$$

where M_0^2 is the intrinsic, aberration-free laser beam quality, a is a constant that depends on the lens shape and the beam profile, and f is the focal length of the lens. The term a/f^2 represents the increase in M^2 due to spherical aberration. This expression in combination with Equation 2 can be used to estimate minimum spot size for meniscus lenses based on the beam quality (M_0^2) and the focal length of the focusing lens. Substituting Equation 13 into Equation 2 and using $\theta \approx W_0/f$ yields an equation of the form

$$w_0 = c_1 M_0^2 f + \frac{c_2}{f} \tag{14}$$

where c_1 and c_2 are constants. The first term of Equation 14 represents the linear dependence of spot size on lens focal length in an aberration-free lens. The second term represents the increase in laser spot size due to spherical aberration. At long focal lengths, the spherical aberration term is negligible, and as predicted by Equation 12, the spot size varies linearly with f. However, at short focal lengths, the aberration term becomes nonnegligible and results in a nonlinear variation of spot size with focal length — Fig. 9. Therefore, the effect of the aberration term is to increase the deviation of the measured spot size from the ideal aberration-free spot size as the lens focal length decreases.

The smallest value of M^2 = 1.5 was measured using the 20.55-in. focal length meniscus lens. Assuming that this lens introduces no spherical aberration

Table 2 — Summary of the Focused Laser Parameters

Lens Type	(z_0) (mm)	δ (mm)	w_0 (µm)	M^2
asphere	58.3	0.286	59	2.4
meniscus	59.3	0.324	69	2.9
diffractive	61.1	0.434	77	2.7
plano-convex	61.3	0.468	80	2.7
asphere	92.4	0.578	82	2.3
meniscus	92.6	0.664	86	2.2
diffractive	94.6	0.730	98	2.6
meniscus	124.5	1.18	112	2.1
plano-convex	126.3	1.06	106	2.1
plano-convex	190.5	2.25	147	1.9
meniscus	254.0	4.41	189	1.6
meniscus	522.0	18.8	378	1.5

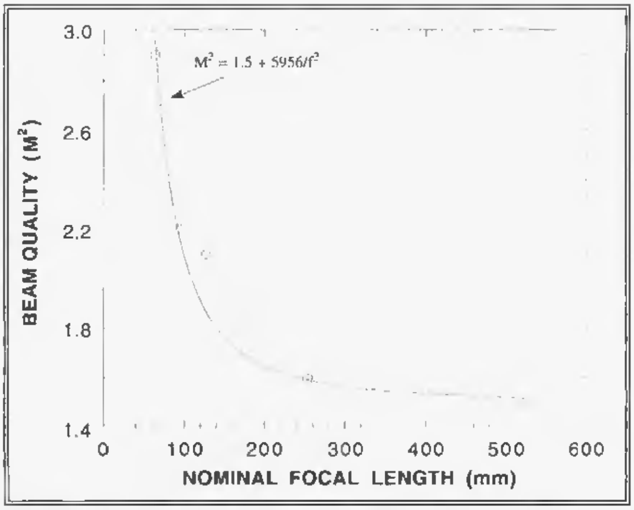

Fig. 8 — Beam quality of a CW CO_2 laser as a function of lens focal length. The data are for a 19.3-mm-diameter beam focused by meniscus lenses of various focal lengths.

($M_0^2 \gg a/f^2$), the beam quality of the laser is approximately $M_0^2 = 1.5$. The curve fit of Fig. 8 yielded $a = 5.96 \times 10^3$. This gives $a/f^2 \sim 0.02$, so that at long focal lengths, the increase in beam quality due to spherical aberration is on the order of the uncertainty in the measurement of beam quality. Taking the uncertainty in M^2 to be the same as the uncertainty in a measurement of the beam radius (~ 6%), we determine that the beam quality of the laser is $M_0^2 = 1.5 \pm 0.09$.

Figure 9 shows the fit of the spot size data for the meniscus lenses obtained using Equation 14. The fit yielded $c_1 = 4.8 \times 10^{-4}$ and $c_2 = 3.52 \times 10^3$ mm^2. From Fig. 9 it can be seen that Equation 14 accurately predicts the effect of spherical aberration on spot size at small focal lengths. The figure also shows that the effect of spherical aberration becomes negligible as the focal length increases, where the variation of spot size approaches the linear dependence predicted by the aberration-free model of Equation 12.

Position of Minimum Waist and Depth of Focus

The three-parameter curve fitting analysis also readily determines the position (z_0) of the minimum spot radius (w_0). The resulting z_0 values are given in Table 2. One can see that for most lenses the effective focal length is somewhat shorter than the nominal focal length. These results are consistent with the effect of spherical aberration in geometric optics, where nonparaxial rays are brought to a focus nearer the lens than are paraxial rays (Ref. 7). In materials processing applications, the effective shortening of t'e focal length of a lens results in less vorking distance between the workpiece and the lens. In addition, this variation in the position of the minimum spot radius also necessitates an empirical determination of z_0 by the laser operator, since use of the nominal focal length of the lens is inexact.

Depth of focus was also determined for each lens using Equation 11b. The results are given in Table 2. Typical values of depth of focus were approximately 0.5 and 1.0% of the nominal focal length for the 2.5- and 5.0- in. meniscus lenses, respectively. Note that as spherical aberration limits the minimum spot size obtainable at a given focal length, it results in an increased depth of focus. This effect is a demonstration of the principle of conservation of irradiance. When a laser beam is focused to a smaller spot, there is necessarily an increase in the divergence, and therefore, a smaller depth of focus. The values determined for the depth of focus provide an upper limit for the precision of the fixtures used to position the beam relative to the workpiece. Depth of focus also indicates the allowable dimensional variation of the parts to be processed in the direction perpendicular to the lens. Ideally, the precision should be no larger than half the value of the depth of focus of the lens. Substituting $w_0 = M^2\lambda/\pi\theta$ into Equation 11b and using $\theta = W_0/f$ gives

$$\delta = CM^2f^2 \tag{15}$$

where C is a constant. Substituting Equation 13 into Equation 15 yields

$$\delta = c_1'\left(c_2' + M_0 f^2\right) \tag{16}$$

where c_1' and c_2' are constants. By fitting a curve of the form of Equation 16 to the meniscus lens data, we determine $c_1' = 4.59 \times 10^{-5}$ mm^{-1} and $c_2' = 58$ mm^2. Therefore, using Equation 16, the depth of focus may now be determined for the laser used in this study, focused by a meniscus lens of any focal length.

Conclusions

1) The laser propagation equation was fitted to spot size measurements taken near the focal plane of a CW CO_2 laser for 12 different focusing lenses, with excellent agreement obtained for each lens.

2) Measured values of spot radius and

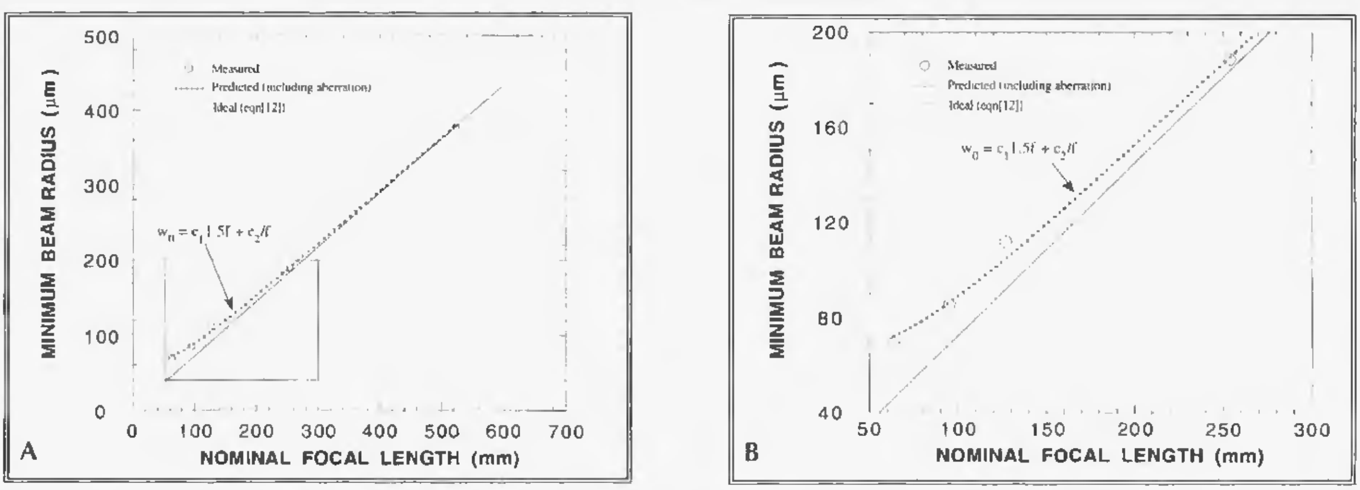

Fig. 9 — A — Minimum beam radius of a CW CO_2 laser as a function of lens focal length for five meniscus lenses; B — boxed section of Fig. 9A. The data points are fit with a curve of the form of Equation 14. The constants are $c_1 = 4.8e^{-4}$ and $c_2 = 3.52e^3$.

many of the lenses examined. These increases were judged to be due to spherical aberration by the focusing lens.

3) In general, lenses corrected for spherical aberration produced better results (smaller spot size and improved beam quality) than the plano-convex lenses. At short focal lengths, the best results were obtained using aspheric lenses.

4) Due to the nonoptimum performance of the lenses tested, an improved lens design that minimizes spherical aberration is expected to reduce focused spot size and thereby increase the processing capabilities of materials processing lasers.

5) The position of the minimum spot radius was determined for the lenses examined, and found to be nearer to the lens than the nominal focal length value.

6) Depth of focus was defined and calculated for the lenses examined in this work, and was found to be dependent on the beam quality of the laser and on the amount of spherical aberration produced by the focusing lens.

7) Equations have been determined for the meniscus lenses tested, which permit calculation of the minimum spot size and the depth of focus based on knowledge of the laser beam quality and the focal length of the lens.

8) The beam quality of a 1-kW CW CO_2 laser was determined to be $M^2 = 1.5 \pm 0.09$. This measurement was made using a long focal length lens (f = 20.55 in., 522 mm), so that contribution to M^2 from the lens due to spherical aberration was comparable to the uncertainty in a measurement of M^2.

Acknowledgments

The authors would like to acknowledge Fred Hooper for his technical assistance. We also would like to thank Charlie Robino for a careful review of the manuscript. This work performed at Sandia National Laboratories supported by the U.S. Dept. of Energy under contract number DE-AC04-94AL85000.

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