Development and Evaluation of an In-Situ Beam Measurement for Spot Welding Lasers

Comparative measurements demonstrate that multiple shots on Kapton™ film yield a focused laser beam diameter that is 99% of the actual beam diameter

BY P. W. FUERSCHBACH, J. T. NORRIS, R. C. DYKHUIZEN, AND A. R. MAHONEY

ABSTRACT. A straightforward and accurate method for measuring the laser beam diameter at focus is desired in order to develop fundamental understanding and for routine process control. These measurements are useful for laser materials processing by assuring laser performance consistency at the workpiece. By employing multiple-shot exposures on Kapton™ film, an unambiguous and precise measurement of the focused Nd:YAG laser beam diameter for spot welding lasers was obtained. A comparison of focused beam measurements produced with the Prometec laserscope and an ISO variable aperture method found that these two methods, which both measure the 86% energy contour, do closely agree. In contrast, Kapton film was found to measure the 99% beam energy contour and to diverge from measurements made with the other two methods. The divergence between Kapton and the other two methods was shown to be due to changes in the laser irradiance distribution that do not affect the location of the 99% energy contour. Since the 86% beam diameter was seen to not always be representative of the true beam diameter, the 99% Kapton film diameter can provide a more representative measurement of the focused laser for in-situ process control.

Introduction

Laser beam spot welding is widely used for electronics packaging, electrical interconnects, medical devices, and other high-value-added components. To develop predictive models of the process, maintain process control, and wisely choose optimized process parameters, measurement of the incident laser spot size at the workpiece is essential. Commercial instruments are available for this task but are often prohibitively large, too expensive, or too time consuming to be readily used. Moreover, the commercial instruments available do not have a NIST traceable calibration, despite the recent publication of an ISO standard for measurement of focused laser beams (Ref. 1).

Certainly the measurement task is problematic. The spot diameter at the focal plane of a typical pulsed Nd:YAG welding laser is only about 0.4 mm. With several joules of laser energy focused into such a small spot, the irradiance is easily sufficient to melt and vaporize most metals. Even instruments designed for this environment can be easily damaged if exposure to the focused beam is not carefully restricted. Measurement of this beam without attenuation can be a very difficult task. Attenuation of the incident laser beam with reflective optics using interference coatings can be effectively applied, but only for lasers with open beam paths and available working space. For many materials processing lasers, these methods are unworkable and a straightforward in-situ method is desired.

The placement of a thin foil of Kapton polyimide directly at the focal plane has been widely employed as an in-situ method to measure focal spot size. However, the accuracy of this technique is the subject of some discussion since focused-beam calibrations are still uncommon (Refs. 2–4). Kapton can be faulted since it cannot be used to determine the irradiance distribution or the spatial mode of the laser. These characteristics are important selling points in the more comprehensive commercial instruments (Ref. 5).

Nonetheless, this study furthers the development and evaluation of Kapton film because it is simply a very compelling method. The encouraging earlier study led to routine beam-characterization efforts at Sandia National Laboratories on several different lasers as a new element of process control. The results were insightful and informative, yet uncertainty remained because of the reported divergence in spot size between Kapton and the Prometec laserscope at high laser-pulse energy. The need for another comparative measurement technique became necessary in order to unequivocally verify the accuracy of the methods. Successful experiments with a variable aperture technique in the past (Ref. 6) pointed to a credible third method for comparison.

With the employment of a third calibration method as well as new Kapton measurement techniques, this study continues the qualification of Kapton film as an important in-situ instrument in laser spot welding process control.

KEYWORDS

Laser Beam Welding
Laser Focus
Spot Weld
Laserscope
ISO 11146
Beam Quality
Process Control

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Experimental

Transmittance through four thicknesses (25, 50, 75, 125 μm) of Type HN Kapton film was measured with a Cary 5E spectrophotometer. It was equipped with a Labsphere integrating sphere (150-mm diameter) as an optional accessory. The integrating sphere accessory enables the measurement of the total, normal, hemispherical transmittance, and total, near-normal, hemispherical reflectance, of the Kapton material at the laser wavelength λ. The measurement methods employed followed procedures outlined in ASTM standard test method E903-96 (Ref. 7).

Tests to determine Kapton hole enlargement and preferred number of laser shots were made with a Rofin/Baasel SWP5002 Nd:YAG spot welding laser with no fiber and a 120-mm focal length lens. Pulse energy was varied from 0.9 J to 2.9 J with a set 2-ms pulse duration.

In the evaluation testing, three distinct

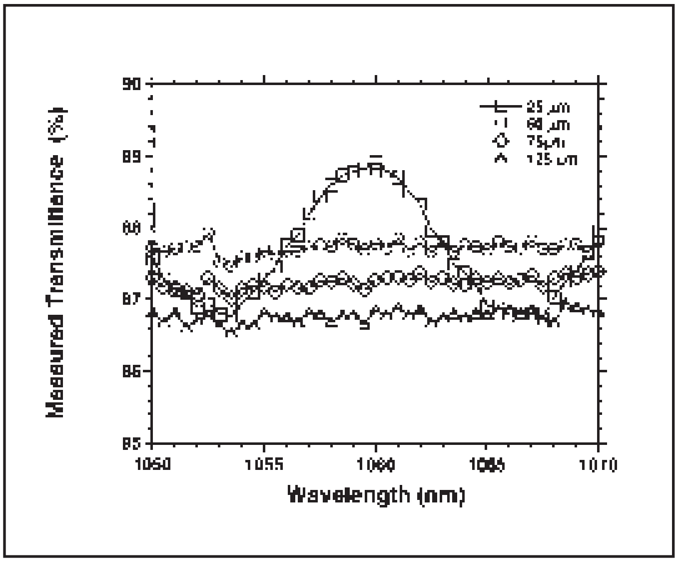

Fig. 1 — Transmittance through undamaged Kapton film for four thicknesses, measured with a spectrophotometer.

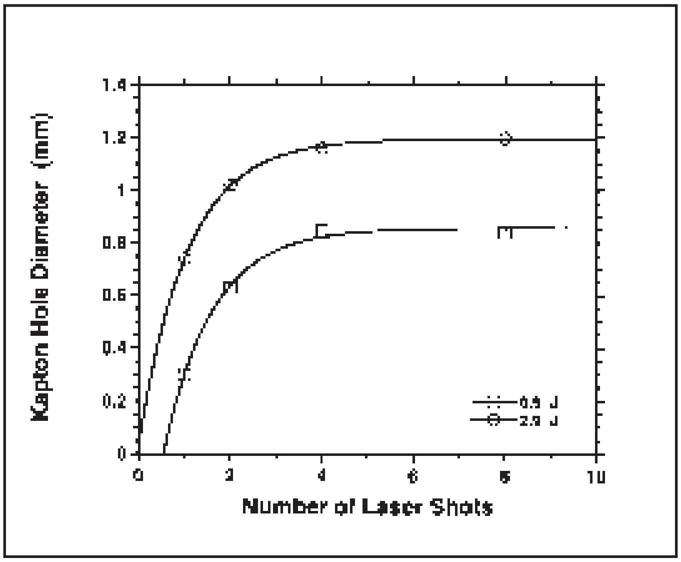

Fig. 2 — Dimensional change of burn-through hole after each shot in Kapton film for two Nd:YAG laser beam intensities. SWP5002 laser, 2-ms pulse.

methods were used to measure focused laser spot size, including Kapton film, the Prometec laserscope, and a variable-aperture method based on the international standard ISO11146 (Ref. 1). All comparative measurements were made with the same 250-W Raytheon SS525 pulsed Nd:YAG laser without fiber-optic delivery. The laser is designed for both spot welding and seam welding and includes variable pulse frequency from 1 to 200 pulses per second (pps). Pulse duration was set at 3 ms for all SS525 measurements. The Prometec laserscope outputs a 25-Hz synchronization pulse, which requires that all comparative measurements be made at this same frequency. Average power was varied from 33 to 315 W by adjusting the laser pulse energy from 1.3 to 12.6 J while maintaining the constant pulse frequency of 25 Hz. A 150-mm plano-convex focusing lens was used for these three-way comparative measurements. For the two-way comparison between Kapton film and variable apertures, a 100-mm focal length lens and 15-pps frequency were chosen in order to obtain a smaller beam diameter due to size limitations in the aperture set. For single-shot measurements on Kapton film, the control panel on the laser was set so that the shutter would allow from one to several pulses to be released from the laser cavity when the laser was fired. This was done by utilizing the laser's shutter/ramp timer.

Measurements of the unattenuated focused beam were made using the Prometec UFF100 laserscope. This instrument utilizes a rotating pinhole aperture and photodetector sensor, which scan and map the irradiance distribution. The resulting data files are processed with a personal computer to yield the beam cross-sectional area that includes 86% of the total beam power. The radius of the beam is determined by calculating the radius of a circle containing the same area. To synchronize hollow needle rotation of the laserscope with the laser pulsation required the construction of a timing circuit (Ref. 4), which assured that the laser fired at the same instant that the laserscope pinhole was located under the focused laser beam.

Beam diameter measurements of the unattenuated focused beam were also made with Type HN Kapton film. Based on results in the earlier study (Ref. 4) and evaluation of new beam transmittance data to be given later, film thickness for all beam diameter measurements was fixed at 50 μm. The Kapton film was cleaned with ethyl alcohol and placed into a 35-mm film slide mount to make the Kapton easy to handle and keep flat. The slide mount was rigidly attached to an x-y stage, which was positioned so that the Kapton film was directly in the focused beam's path. A CNC controlled the stage's motion. No inert shielding gas was used for the Kapton burn measurements. The diameters of the Kapton-burned holes were measured using an Olympus STM measuring microscope at a magnification of approximately 100×. Due to the irregularity of burns on the Kapton film, appropriate backlighting was used to help illuminate the through-hole. Two orthogonal measurements were taken for each spot and were then averaged to obtain an overall spot diameter.

A set of gold sputter-coated diamond wire dies in 25-µm increments were used to aperture the laser beam about the focal plane (Ref. 6). Diamond wire dies are ideal for this application, since diamond has a very high thermal conductivity and an extremely low thermal expansion coefficient. The gold coating assures that laser energy that is not transmitted through the aperture is reflected away, since the diamond is transparent to Nd:YAG radiation. To prevent damage to the apertures, the laser beam was attenuated with a beam splitter that delivered about 0.6% of the laser power to the focusing lens. The diamond apertures were placed over the entrance port of a Labsphere Model LIS-DG integrating sphere. The beam diameter was determined by first measuring the transmitted power using an aperture larger than the full laser beam diameter and then substituting smaller apertures to obtain two transmission values — one above and one below the 86% transmission value as specified in the ISO standard. To measure the laser power transmitted though the diamond apertures, a silicon photodiode detector was placed at one of the exit ports of the sphere. Beam power was measured with a LeCroy Waverunner digital oscilloscope, which was set to compute a 500-pulse average of the RMS value of each pulse waveform. Each aperture was centered on the sphere by adjusting an x-y stage and maximizing the oscilloscope pulse waveform.

$$w^2(z) = w_0^2 + M^4\left[\frac{\lambda^2}{\pi^2 w_0^2}\right](z - z_0)^2 \qquad (1)$$

For all the Kapton, laserscope, and variable aperture tests, multiple measurements about the focal plane were made at the same set of pulse energies and dura-

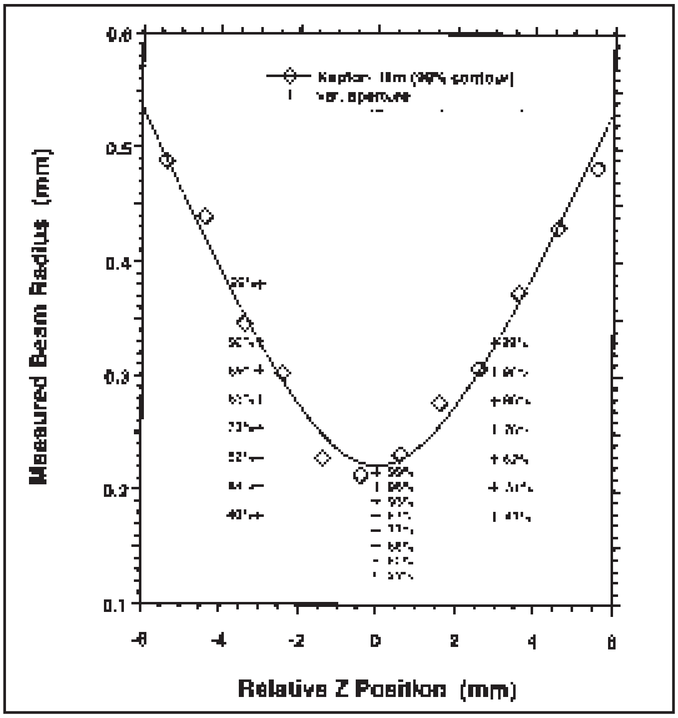

Fig. 3 — Hyperbolic curve-fit of Kapton-measured beam dimensions, along with aperture-measured beam transmission values for the same laser conditions at the same axial location and output power; f=100 mm, 4.0 J, 3 ms, 15 pps.

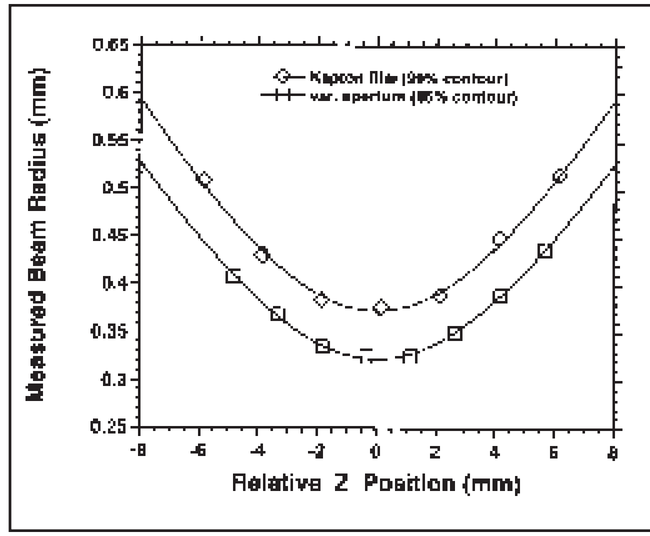

Fig. 4 — Hyperbolic curve-fit of Kapton- and aperture-measured beam radius for identical laser conditions; f=150 mm, 4.0 J, 3 ms, 25 pps.

tions, and usually with four to six spots above and below the focal plane. This typically resulted in a z-axis range of ~10 mm. The spot size measurements and focal plane position values for all three methods were fitted to the hyperbolic laser beam propagation Equation 1, where w_0 is the minimum spot radius at the focal plane, z_0 is the axial position of the focal plane relative to the lens, λ is the laser wavelength, and M^2 is a beam quality factor for the combined laser/optical system (Ref. 8). This approach to finding the minimum spot radius served to average the laser performance and more accurately estimate the minimum waist spot size and effective focal length. The curve-fits also provide a common method of comparison for the three experimental methods including statistical correlation coefficients.

Results and Discussion

Kapton Development

In the previous investigation (Ref. 4), a limitation to the largest beam diameter that could be measured with Kapton film was at times observed when the single-shot irradiance was insufficient to burn through the film. Measurements in that study and in trials with other lasers have indicated that it is often difficult to obtain cleanly burned holes in Kapton. To test whether a high reflectance or high transmittance was responsible for the robust behavior of Kapton, the optical properties were measured with a spectrophotometer. The results are given in Fig. 1. The high threshold irradiance of 50-µm Kapton can be understood when one considers that almost 88% of the laser beam passes through at the Nd:YAG (1060 nm) wavelength. The figure also shows that transmittance decreases as Kapton film thickness increases. This can be explained by absorptance in the film, which naturally increases as the thickness increases. It also is apparent in Fig. 1 that the 25-µm-thick Kapton has strong wavelength dependence that is thought to be due to constructive and destructive phase effects at the second surface during transmittance and reflectance. This thickness is exhibiting "thin film" behavior and probably should be avoided for beam diameter measurements. The pronounced variability observed for 25-µm-thick Kapton in Fig. 1 may account for the difference in beam diameters observed with 25 µm when compared with the other thicknesses examined in the earlier study (Ref. 4). Since the 50-µm Kapton film does not appear to show thin film behavior and has a low burn irradiance, it was chosen as the only thickness for use in subsequent tests in this study.

The transmittance data presented in Fig. 1 can be used to determine the optical properties of Kapton for the wavelength tested. The transmitted energy can be analytically expressed as a function of the surface reflectivity r and the material absorptance constant a:

$$T = \exp\left(-t/a\right)\left(\frac{1-r}{1+r}\right)\frac{1-r^2}{1-r^2\exp\left(-2t/a\right)} \quad (2)$$

where t is the material thickness (Ref. 9). A good fit to the data is obtained by using a material reflectivity of 0.06 and an absorptance constant of 0.6 mm.

The high transmittance of Kapton (see Fig. 1) makes it impractical for use with spot welding lasers when single low-irradiance laser pulses are selected. The high transmittance explains cases where Kapton is not burned through with a laser pulse that is otherwise sufficient to melt the surface of many metals. To expand the practical range of irradiance for Kapton film, a different measurement approach was conceived. Tests were made to determine the effect of multiple laser pulses on the measured beam diameter. Figure 2 shows the effect of multiple shots on Kapton hole diameter for two levels of irradiance. One can see that after about four shots, the hole diameter asymptotically reaches a maximum value. Since the maximum diameter is self limiting, and because shot-to-shot variability will be mitigated by the larger sample size, it is thought that a multiple-shot upper-limit diameter will be a more precise measurement than the single-shot measurements used in previous Kapton investigations (Refs. 3, 4). Figure 2 also shows that the single pulse diameter ranges from 61 to

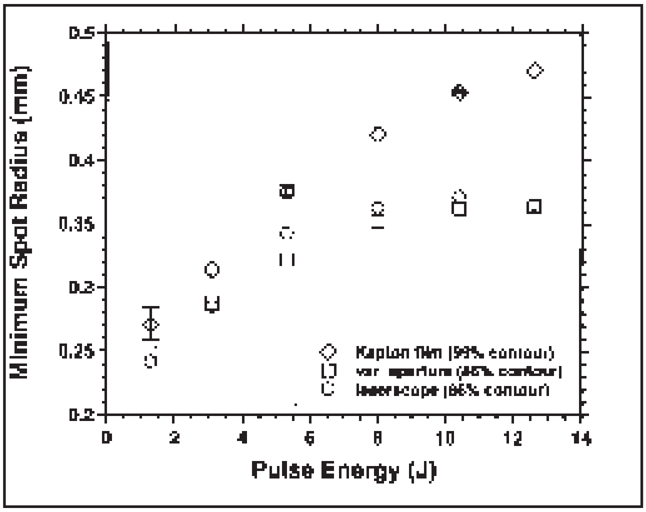

Fig. 5 — Minimum Nd:YAG spot radius for three focused-beam measurement methods. All at f=100 mm, 3 ms, 25 pps.

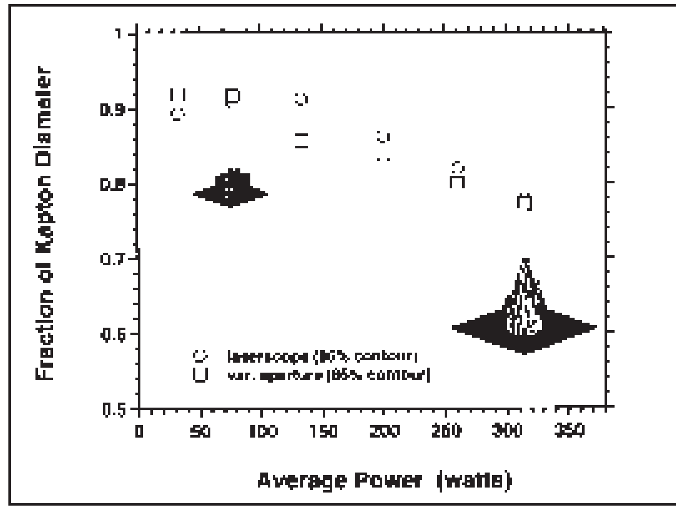

Fig. 6 — Ratio of the measured 86% beam diameter to the Kapton 99% beam diameter. Isometrics indicate significant change in beam mode as lamp power is increased. All at f=100 mm, 3 ms, 25 pps.

67% of the maximum beam diameter. Clearly the actual beam diameter is greater than this and must be close to the maximum diameter measured after repeated shots, but not significantly greater since a plateau is reached.

Because of Kapton's excellent transmittance at 1.06 μm, there is potential for a small fraction of the beam energy to pass beyond the outer edge of the largest hole diameters in Fig. 2. In other words, the actual beam diameter could be somewhat larger than the diameter measured with multiple shots on Kapton. Consequently, indirect measurements were made to try to determine the actual percentage of laser pulse energy transmitted through a Kapton-burned hole after exposure to five shots. Kapton-measured beam radius as well as aperture-measured transmission results for a 100-mm focal length lens are given in Fig. 3. The figure contains the hyperbolic curve-fit for Kapton film measurements about the focal plane for a 4.0-J pulse. By subsequently placing sequential diamond apertures of a known radius in the path of the same power beam at the same axial position, measurements of beam transmission were made that directly correlate with the Kapton-measured radius.

One can see in the figure that the hyperbolic fit intersects with the transmission measurements at values of approximately 99%. At focus, the aperture and Kapton values are nearly identical and a 99% beam transmission is a valid hypothesis for these results. In addition, separate curve-fits that are not shown estimate the minimum spot radius for the Kapton and the 99% aperture in Fig. 3 to be within 4% of each other with values of 222 and 213 μm, respectively. It is thought that experimental error may account for the relatively low 92% (–3 mm, converging beam) transmission measurement in Fig. 3.

For a slightly different set of conditions, a comparison of the 86% aperture-measured radius and the Kapton-measured radius is shown in Fig. 4. In this higher average power case (100 W vs. 60 W), the Kapton diameter measurements closely match the theoretical hyperbolic curve-fit. It should be noted that this laser design is often more stable at higher power levels. The 99% value obtained by the Kapton measurements is shown to be offset by a nearly constant amount from the 86% value obtained from the variable aperture measurements. This is not consistent with a Gaussian profile where the offset would grow as the beam size grows. Indirectly, Fig. 4 shows that the beam profile is not Gaussian.

It is evident from Fig. 4 that the Kapton measurement is always larger than the 86% contour and certainly very close to the maximum beam contour. The high transmission of 99% indicates that the multiple-shot Kapton-measured diameter represents the very outer edge of the bell-shaped laser beam. Since the outer edge of the laser beam is excluded, the diameter does not include low-irradiance azimuthal ring modes near the periphery that likely have little effect on welding. The transmittance values in Fig. 3 also indicate that the Kapton hole is not burning beyond the outer edge where the last percent is contained.

To understand why the laser-burned hole is not greater than the actual beam diameter, heat conduction in the Kapton can be examined. We can estimate the importance of thermal conduction during the laser pulse by evaluating the distance the heat is conducted for a single laser pulse. Kapton has a heat capacity (C_p) of 1.09 J/g/K, a thermal conductivity (k) of 0.12 W/m/K and a density (ρ) of 1.4 g/cc. The heat conductance distance can be estimated from the following equation:

$$x = \sqrt{\frac{kt}{\rho C_p}} \tag{3}$$

This results in a distance of 15 μm for a 3-ms pulse. This is reasonably small when compared to the spot diameter, so conduction into the surrounding Kapton is probably minimal. It is also evident from Equation 3 that the use of short-duration laser pulses can be effective in minimizing conduction into the Kapton film and preventing a misleading enlargement of the hole.

Kapton Evaluation

A direct comparison of the three measurement methods is given in Fig. 5. The spot weld beam irradiance examined ranged from 0.23 to 1.0 MW/cm^2. One can see that the multiple-exposure Kapton measurements have a larger diameter than both the laserscope and the variable aperture methods for all laser conditions. This result is expected, since the Kapton measurement indicates the diameter where approximately 99% of the laser energy is contained within (see Fig. 3). In contrast, both the laserscope and the aperture methods compute the diameter within which only 86% of the laser beam energy is contained. Not surprisingly, the laserscope and the aperture results in Fig. 5 are very close in magnitude. Clearly, both methods can be used equally as well to obtain the 86% contour for a large range of laser conditions. The close correlation between these two methods is in fact a calibration of both, and a validation of the laserscope's utility. Concerns in Ref. 4 about the reliability of the laserscope measurements are now alleviated with these new results.

The error bars included on three of the Kapton data points in Fig. 5 indicate the variability that was observed for conditions where replicates were made. In one case, the error bar is less than the data point symbol. Replicates were not required for the laserscope or aperture methods since each value given is in fact an average of many hundreds of laser pulses. The variability at low power shown in Fig. 5 is probably due to laser instability at low power more than to Kapton variability at low irradiance. If shot-to-shot variability in laser beam diameter is expected with a lamp-pumped Nd:YAG laser, then multiple exposures of Kapton film should be made in order to obtain a more accurate measurement.

The strong correspondence between the laserscope and aperture measurements in Fig. 5 also reveals an apparent swing away from the Kapton values. The divergence between Kapton and the other two methods in Fig. 5 appears to occur at average powers greater than 100 W. The divergence is likely due to a change in laser beam mode that results in a larger beam that does not produce a corresponding increase in the 86% contour. Pulsed Nd:YAG materials-processing lasers without fiber delivery typically will change in transverse mode as the pumping power increases (Ref. 10). The change in mode shape is apparent in Fig. 6 where irradiance distributions are presented for the 3-J and 12-J pulses. The isometrics were obtained from the laserscope output files at locations near the beam minimum waist. Since more of the beam energy is concentrated near the center for the 12-J beam, it is understandable that the 86% beam diameter does not increase in the same proportion as the 99% Kapton diameter does in Fig. 5.

To compare the 86% values with the Kapton 99% values, it is useful to examine the standard Gaussian beam profile. The irradiance distribution of the single-mode Gaussian laser beam is given (Ref. 11) as:

$$I(r,\theta) = I_0 \exp -2\left(\frac{r}{w}\right)^2 \tag{4}$$

where I_0 is the irradiance at the center of the beam, r is the radial coordinate, and w is the Gaussian beam waist (radius), which is a constant. If we integrate the irradiance distribution, we can find the power contained within a circle of radius r_1:

$$P = \int_0^{2\pi}\int_0^{r_1} I_0 \exp -2\left(\frac{r}{w}\right)^2 r\ dr\ d\theta \tag{5}$$

For the total power, we have

$$P_0^\infty = \frac{\pi}{2} w^2 I_0 \tag{6}$$

For the power contained within the Gaussian beam radius w,

$$P_0^w = \frac{\pi}{2} w^2 I_0 (0.865) \tag{7}$$

For the power contained within any aperture r,

$$P_0^r = \frac{\pi}{2} w^2 I_0 \left[1 - \exp -2\left(\frac{r}{w}\right)^2\right] \tag{8}$$

The ratio of the power passing through the Gaussian beam radius w to the total power gives the familiar 86% beam transmission, T_w.

$$T_w = \frac{P_0^w}{P_0^\infty} = 0.865 \tag{9}$$

For the Kapton transmission of 0.99 established in Fig. 3, we have

$$T = \frac{P_0^r}{P_0^\infty} = 1 - \exp -2\left(\frac{r}{w}\right)^2 = 0.99 \tag{10}$$

which can be rearranged to yield the theoretical ratio of Gaussian radius to the 0.99 transmission Kapton radius:

$$\frac{w}{r_{.99}} = 0.66 \tag{11}$$

In other words, the 86% beam diameters (or radii) should be 66% of the 99% beam diameter if we are comparing true Gaussian beams.

Figure 6 shows the ratio of the measured beam diameter to the Kapton-measured beam diameter for both the laserscope and the variable aperture methods. The fraction of Kapton diameter varies from about 0.77 to 0.92. At high energies, the measured diameters become closer in magnitude to the 0.66 theoretical value for Gaussian beams in Equation 11. The more Gaussian-like isometric in Fig. 6 at high energy is also consistent with the decreased value of the ratio.

If we accept that the Kapton measured contour is representative of the actual beam dimension, then the pronounced variations in the 86% contour shown in Fig. 6 further indicate how subjective the universal measurement truly is. In contrast, the 99% Kapton contour is unbiased and unambiguous as laser conditions change.

Notwithstanding substantive differences in measurement technique, both the laserscope and aperture methods describe a fundamentally different characteristic of the focused laser beam than that measured with Kapton. For both methods, the 86% energy contour is used to designate the $1/e^2$ beam diameter. It is the value referenced universally for characterizing laser beams in science and industry as well as in the ISO standard. Yet the 86% energy contour really only indicates the $1/e^2$ beam diameter for single-mode beams, which by definition exhibit a Gaussian irradiance distribution. In practice, the 86% contour provides an effective measure for beam comparison purposes, since it represents a circle that contains a very large fraction of the laser energy. Nonetheless, it is clearly an arbitrary measure. There is no body of evidence to suggest that an 86% diameter is any more or less significant than a 99% diameter for laser materials processing. While there may be subtle differences in processing for laser beams with different irradiance distributions, an accurate measurement of the beam at either the 86% or 99% diameter will likely yield the most desired first-order effects.

For process control purposes, the 99% Kapton diameter may be preferred since it can be measured in-situ, it represents the entire laser beam, and as shown in Figs. 3 and 4, it can be both precise and accurate. Since the 99% diameter represents the very outer edge of the laser beam, significant changes in beam diameter, as shown in Fig. 5, will always be apparent in the Kapton measurement. Moreover for fiber-delivered beams where mixed beam modes result in a top-hat distribution, the 99% diameter may be a more useful indicator of laser performance. Finally, the Kapton burn represents an actual physical process. It is a functional measure, somewhat similar to spot welds on thin metal sheets that are often used to check irradiance. But since Kapton yields the 99% beam diameter, the values are independent of laser energy and provide a focused laser beam measurement that is both fundamental and useful in providing a high degree of confidence in laser performance at the workpiece.

Conclusions

1) Multiple shots on Kapton film have been shown to give an unambiguous and precise measurement of an unattenuated spot welding laser beam at focus.

2) Direct comparisons of the focused laser beam diameter have been given based on measurements obtained from Kapton film, the Prometec laserscope, and an ISO standard established variable aperture method.

3) Unlike the laserscope and the variable aperture methods, which locate the 86% energy contour, Kapton film locates the contour that contains 99% of the laser energy.

4) The Prometec laserscope and the ISO variable aperture method have been shown to closely correlate for laser beam irradiance that ranges from 0.23 to 1.0 MW/cm^2.

5) Divergence between the Kapton-measured beam diameter and the laserscope 86% beam diameter has been shown to be due to changes in the laser beam mode at high lamp power.

6) Transmittance measurements with a spectrophotometer at the 1.06-µm laser wavelength found that 88% of the incident energy passed through 50-µm-thick Kapton film.

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