Laser Welding Beam Quality Calibration

Federal Manufacturing & Technologies

L. R. Foulk

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LASER WELDING BEAM QUALITY CALIBRATION

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Published June 1997

Final Report
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ABSTRACT

The relationship of beam quality and weld depth of penetration was studied to attempt to better quantify the operation of CO₂ laser beam welders. Equipment to measure laser beam quality was obtained. The equipment was calibrated using standard apertures. To relate weld penetration and beam quality measurements, it was necessary to force changes in the CO₂ laser welder's operation. The chosen experimental variables were laser gas mixture and the use of a group of focusing lenses that had been used in production.

SUMMARY

The measuring equipment was chosen from state-of-the-art equipment that was available at the time and that could be placed directly in both the focused and unfocused laser beam. The calibration of beam diameter was performed by the use of dimensionally calibrated, sharp edge apertures placed directly above the measuring equipment. Assistance in designing the experiments came from the FM&T Statistical Services department. The gas mixture experiments were three-factor, fully designed experiments, and the analysis techniques were analysis of variance and regression analysis. The weld coupons were cross sectioned, and measurements were made on the weld nuggets by the FM&T Analytical Science Laboratory.

DISCUSSION

SCOPE AND PURPOSE

Four objectives were established for this study:

1. Choose the best equipment for making measurements of laser beam quality on high power CO₂ laser beam welders.
2. Develop a calibration process for the beam quality measuring equipment.
3. Determine what laser beam parameters affect beam quality and how they should be controlled.
4. Determine if beam quality can be used to quantify weld quality.

Welding with CO₂ laser beams is presently controlled with daily weld samples. It would enhance process control if laser beam quality could be routinely measured and related directly to the quality of the weld.

ACTIVITY

Existing Method

CO₂ laser welders are used in many modern manufacturing processes. The use of the lasers at AlliedSignal Federal Manufacturing & Technologies (FM&T) involves the daily check of welder performance with 0.037 and 0.062 in. thick bead-on-plate (B-O-P) weld samples. Welding these samples brackets the machine performance via a functional test that is easily evaluated. The laser is required to penetrate through the thin (0.037 in.) plate but not penetrate through the thick (0.067 in.) plate. This daily, before-use, functional check of the laser is done at a specified constant feed rate and laser power. The method has produced satisfactory results, but it would be desirable to further quantify the laser's performance in terms of beam focusability and how that focusability affects weld parameters (most specifically, weld penetration).

Proposed Method

One very important factor that affects a laser's beam spot diameter is the inherent focusability, or quality, of the raw beam. The formula for this quality factor is

$$Q = \frac{f\lambda}{\pi w w_0}$$

where f is the focal length of the focusing optics, λ is the wavelength of the laser, w is the radius of the raw beam, and w_0 is the radius of the focused laser beam (see Figure 1). A more

commonly used term is M^2 which is the inverse of Q . M^2 is a dimensionless number and is a measure of how close the actual beam is to a diffraction-limited Gaussian single mode beam. The ideal M^2 is equal to 1. In practice, however, it will always be greater than 1. Essentially, for a given laser welder, all parameters in the above equation are constant except for focused spot size, w_0 , and therefore, M^2 is proportional to w_0 .

An alternative method for calculating M^2 is the use of a curve fit equation of the form

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

where w is the beam radius at a distance z from the focusing lens. At a distance z_0 from the lens, the beam radius is a minimum w_0 . Measurements of the focused beam radius are made at various distances from the focusing lens. The equation is then fit to the data using M^2 , w_0 , and z_0 as the parameters (Ref. 1). Use of the curve fit equation would result in a time savings during actual measurements, as it requires measurements to be made on only the focused beam.

Figure 1. Focusability of Real and Ideal Laser Beam

Equipment Selection

A search was performed to find the best equipment to measure M^2 . It was most desirable to find equipment that could accept the beam directly so that additional optics did not have to be used to split the beam. The additional optics would add to the alignment of the setup and would necessitate a beam absorber for the remainder of the beam.

At the time, the only device that could be found that would meet our needs was the Prometec Laserscope. It had the capability of directly accepting the entire beam, both focused and unfocused (see Figure 2). The Laserscope uses the principle of sampling the beam with a pinhole. The pinhole is drilled near the end of a hollow needle. The needle is mounted on a rotating carrier that steps the rotating needle through the laser beam, thereby scanning the entire cross-sectional area of the beam with a total of 41 scans. A pyroelectric detector is mounted at the axis of the hollow needle, and the sampled beam is reflected through the needle and up to the detector (see Figure 3). The detector signals are amplified, digitized, and then transferred to the computer that is also used to control the monitor.

The Laserscope can accept an unfocused beam with a diameter as large as 50 mm or as small as 5 mm. (Most of the CO₂ welding lasers in the plant have beam diameters of 25 mm or less.) It can accept focused beams with diameters from 4 mm to < 100 μ m. A coarse adjustment of the Laserscope to the beam intensity can be made by changing the pinhole size of the needle, which means a physical change of the rotating needle. Fine adjustment is made by changing the internal gain factor. The size of the square measuring window is adjustable so that laser beams of various diameters can be displayed with the best possible resolution.

Modifications to the Equipment

Once the beam passes through the Laserscope, it has to be dissipated to avoid heating the surface that it contacts. A fixture was made from 1/2 inch aluminum (see Figure 4). The beam is diffused by the thin aluminum plate that is mounted at a 53 degree angle. The plate was vapor blasted to provide better diffusion characteristics. During use to make measurements on focused beams, the focal point is at the level of the top of the needle so the diameter of the beam at the plate is great enough that no damage is done to the plate. The plate gets warm with continuous use and a small fan is used under those conditions to cool the plate.

Calibration of the Equipment

By definition, for Gaussian TEM₀₀ mode, the beam radius of a laser is determined where the intensity has decreased by $1/e^2$. The Laserscope calculates beam radius in terms of 86% ($1 - 1/e^2$) of the laser power. Figure 5a shows an intensity distribution projection. The volume of the distribution is proportional to the power of the laser. The beam cross-sectional area is established by taking into account those measuring points in the intensity distribution whose sum amounts to 86% of the total for all measuring points and therefore represents a variable proportional to the beam power (Figure 5b). Figure 5c shows a projection, and Figure 5d shows a contour line display of the cross-sectional area.

Figure 2. Laserscope Operation in Raw Beam and Focused Beam Modes

The radius is determined by treating the calculated area as a circle. This method is useful only if the beam is rotationally symmetrical, which was a reasonable assumption for the lasers measured in this study.

Figure 3. Construction of the Hollow Needle

Calibration of the Laserscope was performed using sharp-edged apertures that had been previously measured by dimensional methods. The apertures were placed on the top edge of the beam entrance port of the equipment. So that the beam was much larger than the aperture, an unfocused laser beam was directed through the aperture and the beam radius was measured using the *combination* mode of the equipment.

Figure 6 shows this combination mode measurement result, and Figure 7 shows the corresponding *isometric* mode. Six different apertures were used. The laser beam radius was measured at the 86% point as defined above. The aperture radius, however, is greater and so, the measured beam radius must be divided by some factor to account for the remainder of the beam that passed through the aperture. The factor was found to be approximately equal to $1-1/e^2$. Using this factor, the agreement of the calibrated apertures to the instrument data ranged from 0.8% to 8%.

Figure 4. Laserscope and Mounting Fixture

Implementation of Experiment

Four studies were performed using two different laser welding systems; these studies are identified as follows:

1. Weld System #1, Study A, was a two-level, three-factor, fully designed experiment (or eight distinct settings). The factors were gas flows of He, CO₂, and N₂. The levels were 60 and 140 for He, 50 and 110 for CO₂, and 60 and 100 for N₂. These levels represent relative gas flows of the approximate minimum and maximum limits of practical adjustment. The power was held constant at 600 Watts by adjusting resonator current to offset the power change caused by the gas flow change. Weld speed was held constant at 60 in/min. Eight stainless steel coupons were obtained from one sheet of stainless steel. This sheet of stainless steel was used for all coupons throughout the study. One coupon was used for each of the eight gas settings, and four B-O-P

welds were made on each coupon. Before each coupon was welded, the average M^2 value was obtained.

2. Weld System #2, Study B, was a two-level, three-factor, fully designed experiment (eight distinct settings) and one at the normal settings. The factors were gas flows of He, CO₂, and N₂. The levels were 40 and 80 for He, 50 and 110 for CO₂, and 60 and 100 for N₂. The normal settings are 52, 79, and 92 for He, CO₂, and N₂, respectively. The power was held constant at 600 Watts by adjusting resonator current, and weld speed was held constant at 60 in/min. Nine stainless steel coupons were used in this study. One coupon was used for each of the nine different gas settings, and three B-O-P welds were made on each coupon. Before each coupon was welded, the average M^2 value was obtained.

3. Weld System #2, Study C, was a two-level, three factor, fully designed experiment (eight distinct settings) and one at the normal settings. The factors were gas flows of He, CO₂, and N₂. The levels were 40 and 80 for He, 50 and 110 for CO₂, and 60 and 100 for N₂. The normal settings are 52, 79, and 92 for He, CO₂, and N₂, respectively. The weld speed was held constant at 60 in/min. The power was set at 600 Watts at normal setting and was not adjusted when gas settings were changed, but power was recorded when the gas settings were changed. Nine stainless steel coupons were used in this study. One coupon was used for each of the nine different gas settings, and three B-O-P welds were made on each coupon. Before each coupon was welded, the average M^2 value was obtained.

4. Weld System #2, Study D, used seven different lenses. Six lenses had been used and rejected from the production line, and one was a new and acceptable lens. The gasses were set at normal settings (52, 79, and 92 for He, CO₂, and N₂, respectively), power was set at 600 Watts, and weld speed was set at 60 in/min. Seven stainless steel coupons were used in this study. One coupon was used for each of the seven different lenses, and three B-O-P welds were made on each coupon. Before each coupon was welded, the average M^2 value was obtained for each lens.

The welded coupons were taken to the FM&T Analytical Science Laboratory. The coupons were sectioned, polished, etched, and each weld was measured for depth and width using a calibrated optical comparator. Photographs of some of the weld sections were taken with a magnification of 50X (see Figure 8). The data was used to first calculate the average and standard deviation of weld depth for each coupon. The results were sorted by study and average depth and are listed in Table 1 in the Appendix. The results also were sorted by study and M^2 ; those results are listed in Table 2.

Figure 5. Determination of Beam Radius by Laserscope

Figure 6. Combination Mode

Figure 7. Isometric Mode

Conclusions

The data was analyzed to determine if gasses have an effect on either average weld penetration depth or M^2 , for Studies A, B, and C. The analysis technique is called analysis of variance. The analysis indicated the following:

1. The analysis did not detect a significant effect due to gasses on depth for studies A and B. N_2 indicated an effect on depth for Study C. If you look at Table 1, Study C, high values of N_2 and power give larger values for depth. The effect is due to power, not N_2 . The results are summarized in Table 3.
2. The analysis detected significant effects due to gasses on M^2 for studies A and C but not on Study B. These results are summarized in Table 3. Studies A and B were similar studies but on different weld systems. Why one shows effect on M^2 due to gasses and the other no effect could mean there is another factor(s) effecting M^2 .

Regression analysis was performed on the average weld penetration depth and M^2 on Studies A, B, and D, to determine if there is significant correlation. These analyses did not detect

significant correlation between depth and M^2 on any of the studies. The results are given in Table 4.

Analysis of variance was performed on Study C to determine if the gasses have a significant effect on the power reading. This analysis failed to detect a significant effect. The results are displayed in Table 5.

Regression analysis was performed on the average weld depth and M^2 versus power, on Study C, to determine if there is significant correlation. This analysis indicated there is significant correlation between power and weld depth but not between M^2 and power. The results are given in Table 6.

Analysis of variance was performed on Study D to determine if there is a significant difference between type of lens (new and old lens) on weld depth and M^2 . This analysis failed to detect a significant difference in type of lens for either weld depth or M^2 . These results are listed in Table 7.

A plot of the average weld depth as a function of M^2 for data from all the studies on the two different laser welders is shown in Figure 9. The two different lasers generated two clusters of data that appear to show a relationship between weld depth and M^2 , although no relationship was substantiated by statistical analysis.

ACCOMPLISHMENTS

The analyses of data indicate the following:

1. There is not a significant effect on average weld penetration depth due to gas settings. This supports the concept that laser is a robust process for welding application with respect to gas settings.
2. There may be an effect on M^2 readings due to gas settings; results are inconclusive.
3. There is not a significant relationship between average weld penetration depth and M^2 .
4. As gas settings are changed, the power will change, but we could not find a relationship between gas settings and power change.
5. There is a strong relationship between power and weld penetration depth.
6. There is no relationship between power and M^2 .
7. There was no difference between new and old lenses with respect to weld penetration depth and M^2 value.

Although a significant relationship between weld penetration and M^2 could not be found, an obvious use for the Laserscope is in the monitoring of the general state of optimization of a laser weld system. The Laserscope can be used to document laser beam profile changes with time and will be a valuable tool in bringing a laser weld system back on line after required maintenance.

Figure 8. Typical Weld Sections

Figure 9. Average Weld Penetration Versus Beam Quality
(power was 600 W for both lasers)

FUTURE WORK

Additional measurements of M^2 on laser weld systems other than the two that were available for this study would yield more data which may show a relationship to weld penetration. An alternative study which might be possible would be to change the beam quality by using lenses with varying focal lengths, suggested by Ref. 1, and observing the effects on weld penetration.

REFERENCE

1. M. Essien and P. W. Fuerschbach, Beam Characterization of a Materials Processing CO₂ Laser. *Welding Journal*, February 1996, pp. 47-54.

APPENDIX

Experimental Data

Table 1. Experimental Data From Four Studies -- Sorted by Average Weld Penetration Depth for Each Study

Study	Lens	He	CO ₂	N ₂	Power	M ²	<u>Weld Depth</u>		No.
							XBAR	Sigma	
A	NEW	60	50	60	600	3.21	0.0394	0.0016	4
A	NEW	140	110	60	600	3.08	0.0399	0.0015	4
A	NEW	60	110	60	600	2.95	0.0408	0.0017	4
A	NEW	60	110	100	600	2.77	0.0411	0.0019	4
A	NEW	140	110	100	600	2.82	0.0414	0.0012	4
A	NEW	140	50	100	600	2.78	0.0426	0.0013	4
A	NEW	60	50	100	600	2.97	0.0429	0.0010	4
A	NEW	140	50	60	600	3.09	0.0434	0.0032	4
B	NEW	80	110	100	600	1.66	0.0514	0.0009	3
B	NEW	40	110	100	600	1.67	0.0523	0.0017	3
B	NEW	40	50	100	600	1.70	0.0523	0.0018	3
B	NEW	40	50	60	600	1.82	0.0525	0.0006	3
B	NEW	80	50	60	600	1.74	0.0527	0.0015	3
B	NEW	80	110	60	600	1.68	0.0527	0.0006	3
B	NEW	40	110	60	600	1.70	0.0533	0.0003	3
B	NEW	52	79	92	600	1.64	0.0543	0.0007	3
B	NEW	80	50	100	600	1.62	0.0554	0.0018	3
C	NEW	40	110	60	480	1.62	0.0429	0.0012	3
C	NEW	40	50	60	490	1.84	0.0435	0.0023	3
C	NEW	80	50	60	530	1.74	0.0473	0.0007	3
C	NEW	80	110	60	520	1.60	0.0481	0.0018	3
C	NEW	40	110	100	560	1.73	0.0509	0.0005	3
C	NEW	52	79	92	600	1.73	0.0520	0.0010	3
C	NEW	40	50	100	600	1.75	0.0533	0.0014	3
C	NEW	80	110	100	620	1.77	0.0543	0.0021	3
C	NEW	80	50	100	640	1.74	0.0557	0.0025	3
D	OLD2	52	79	92	600	2.15	0.0498	0.0009	3
D	NEW	52	79	92	600	1.72	0.0499	0.0013	3
D	OLD1	52	79	92	600	1.76	0.0507	0.0016	3
D	OLD3	52	79	92	600	1.69	0.0534	0.0027	3
D	OLD6	52	79	92	600	1.80	0.0545	0.0034	3
D	OLD4	52	79	92	600	1.67	0.0547	0.0035	3
D	OLD5	52	79	92	600	1.73	0.0551	0.0039	3

Table 2. Experimental Data From Four Studies -- Sorted by M^2 for Each Study

Weld Depth									
Study	Lens	He	CO ₂	N ₂	Power	M ²	XBAR	Sigma	No.
A	NEW	60	110	100	600	2.77	0.0411	0.0019	4
A	NEW	140	50	100	600	2.78	0.0426	0.0013	4
A	NEW	140	110	100	600	2.82	0.0414	0.0012	4
A	NEW	60	110	60	600	2.95	0.0408	0.0017	4
A	NEW	60	50	100	600	2.97	0.0429	0.0010	4
A	NEW	140	110	60	600	3.08	0.0399	0.0015	4
A	NEW	140	50	60	600	3.09	0.0434	0.0032	4
A	NEW	60	50	60	600	3.21	0.0394	0.0016	4
B	NEW	80	50	100	600	1.62	0.0554	0.0018	3
B	NEW	52	79	92	600	1.64	0.0543	0.0007	3
B	NEW	80	110	100	600	1.66	0.0514	0.0009	3
B	NEW	40	110	100	600	1.67	0.0523	0.0017	3
B	NEW	80	110	60	600	1.68	0.0527	0.0006	3
B	NEW	40	50	100	600	1.70	0.0523	0.0018	3
B	NEW	40	110	60	600	1.70	0.0533	0.0003	3
B	NEW	80	50	60	600	1.74	0.0527	0.0015	3
B	NEW	40	50	60	600	1.82	0.0525	0.0006	3
C	NEW	80	110	60	520	1.60	0.0481	0.0018	3
C	NEW	40	110	60	480	1.62	0.0429	0.0012	3
C	NEW	40	110	100	560	1.73	0.0509	0.0005	3
C	NEW	52	79	92	600	1.73	0.0520	0.0010	3
C	NEW	80	50	60	530	1.74	0.0473	0.0007	3
C	NEW	80	50	100	640	1.74	0.0557	0.0025	3
C	NEW	40	50	100	600	1.75	0.0533	0.0014	3
C	NEW	80	110	100	620	1.77	0.0543	0.0021	3
C	NEW	40	50	60	490	1.84	0.0435	0.0023	3
D	OLD4	52	79	92	600	1.67	0.0547	0.0035	3
D	OLD3	52	79	92	600	1.69	0.0534	0.0027	3
D	NEW	52	79	92	600	1.72	0.0499	0.0013	3
D	OLD5	52	79	92	600	1.73	0.0551	0.0039	3
D	OLD1	52	79	92	600	1.76	0.0507	0.0016	3
D	OLD6	52	79	92	600	1.80	0.0545	0.0034	3
D	OLD2	52	79	92	600	2.15	0.0498	0.0009	3

Table 3. Analysis of Variance, Gasses vs. Weld Penetration Depth and M²

* means interaction term

Yes means significant effect at 5% level; No means did not detect significant effect.

	Study A			Study B			Study C	
	Depth	M ²		Depth	M ²		Depth	M ²
He	No	Yes		No	No		No	Yes
CO ₂	No	Yes		No	No		No	Yes
N ₂	No	Yes		No	No		Yes	Yes
He*CO ₂	No	Yes		No	No		No	Yes
He*N ₂	No	Yes		No	No		No	Yes
CO ₂ *N ₂	No	No		No	No		No	Yes

Table 4. Regression Analysis, M² vs. Weld Penetration Depth

No means there is not significant correlation.											
	Study A				Study B				Study C		
	Depth				Depth				Depth		
M ²	No				No				No		

Table 5. Analysis of Variance, Gasses vs. Power

<p>* means interaction term Yes means significant effect at 5% level; No means did not detect significant effect.</p>	
	Study C
	Power
He	No
CO ₂	No
N ₂	No
He*CO ₂	No
He*N ₂	No
CO ₂ *N ₂	No

Table 6. Regression Analysis, Power vs. Weld Penetration Depth and M^2

Yes, there was significant correlation; No, there is not significant correlation.		
Study C		
	Depth	M^2
Power	Yes	No

Table 7. Analysis of Variance, Type of Lens (New and Used) vs. Weld Penetration Depth and M^2

No means did not detect significant effect at the 5% level.		
Study D		
	Depth	M^2
Type	No	No

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