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Pulse Shaping Effects on Weld Porosity in Laser Beam Spot Welds: Contrast of Long- & Short- Pulse Welds

J. T. Norris, M. J. Perricone; Sandia National Laboratories, Albuquerque

K. M. Faraone, C. M. Ellison; Honeywell FM&T, Kansas City

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Pulse Shaping Effects on Weld Porosity in Laser Beam Spot Welds: Contrast of Long- & Short-Pulse Welds

J. T. Norris[1], M. J. Perricone[2], C.M. Ellison[3], & K.M. Faraone[4]

[1]Material Sciences and Engineering Center, Sandia National Laboratories
P.O. Box 5800, Albuquerque, NM 87185
[2]formerly with Sandia, presently with R.J. Lee Group, Inc.
350 Hochberg Rd., Monroeville, PA 15146
[3]Honeywell FM&T, *2000 E 95th St, Kansas City, MO 64131*
[4]formerly with Honeywell, presently with BWX Technologies, Inc
1570 Mount Athos Rd, Lynchburg, VA 24504

Abstract

Weld porosity is being investigated for *long-pulse* spot welds produced by high power continuous output lasers. *Short-pulse* spot welds (made with a pulsed laser system) are also being studied but to a much small extent. Given that weld area of a spot weld is commensurate with weld strength, the loss of weld area due to an undefined or unexpected pore results in undefined or unexpected loss in strength. For this reason, a better understanding of spot weld porosity is sought.

Long-pulse spot welds are defined and limited by the slow shutter speed of most high output power continuous lasers. Continuous lasers typically ramp up to a simmer power before reaching the high power needed to produce the desired weld. A post-pulse ramp down time is usually present as well. The result is a pulse length tenths of a second long as oppose to the typical millisecond regime of the short-pulse pulsed laser. This study will employ a Lumonics JK802 Nd:YAG laser with Super Modulation pulse shaping capability and a Lasag SLS C16 40 W pulsed Nd:YAG laser. Pulse shaping will include square wave modulation of various peak powers for long-pulse welds and square (or top hat) and constant ramp down pulses for short-pulse welds. Characterization of weld porosity will be performed for both pulse welding methods.

Acknowledgments

The authors would like to thank the many people at Sandia National Laboratories that contributed to various aspects of this study. The assistance of A. Kilgo and her colleagues in the Metallography Lab (1822) are greatly appreciated, as are the efforts of J. Sena in radiography (1522). Many thanks to E. Vernon and R. A. Roach for their recognition of the fundamental need for work in this area that made funding of this project possible. Finally, thanks to Danny MacCallum for his careful review of this document.

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Nomenclature

CW	Continuous wave (or un-modulated) long pulse spot weld
EDM	Electric Discharge Machining
Nd:YAG	Neodymium-doped Yttrium Aluminum Garnet
SQW	Square Wave (Modulation)

1. Introduction

This study seeks to characterize weld porosity for long- and short- pulse laser beam spot welds. Long-pulse spot welds are typically produced by a continuous output laser where shutter response time is slow. Continuous lasers also usually ramp up to a simmer power before reaching the programmed high output power. The addition of ramp-up and simmer time before and after reaching high power results in pulse times of tenths of a second in duration. Although only a relatively short high output power time may be programmed, the result is a long-pulse weld. Figure 1 shows a temporal measurement of a programmed 25 ms double pulse spot weld made with a Lumonics JK802 having sinusoidal modulation. Total pulse time is 375 ms. With a pulsed laser, spot welds on the order of milliseconds are produced and with a shutter response time of microseconds. The two different pulsing methods are likely to generate different behaviors in weld porosity. Characterization of both should direct how best to operate within the two different processes. Multiple focal length lenses, pulse shapes, and heat inputs are explored and contrasted to identify optimal processing conditions. The Lumonics JK802 laser offers additional capability through modulation of the output power in a sinusoidal or square wave manner. In continuous seam welds, Kuo et.al. (ref. 1) demonstrated high peak power modulation as means to reducing porosity occurrence and size. In producing long-pulse spot welds, this will allow for pulse shaping to be investigated beyond just pulse time and magnitude.

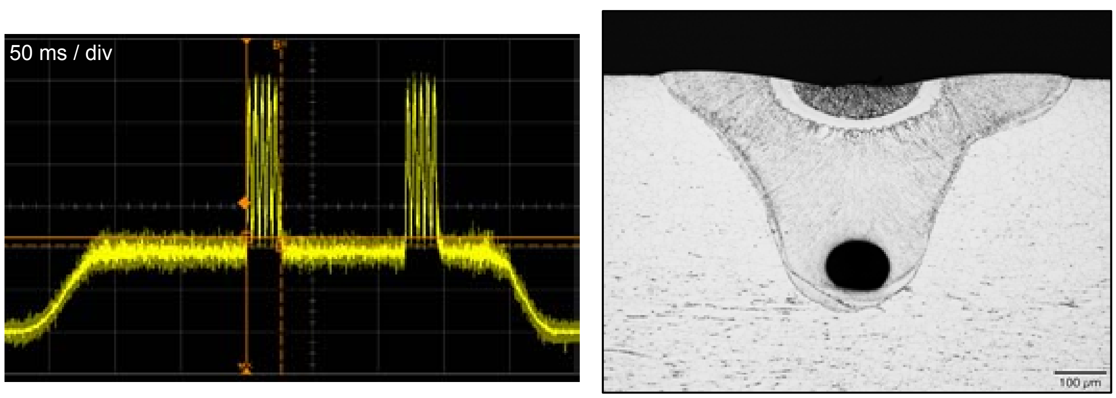

Figure 1: Temporal measurement of a sinusoidal modulated double pulse (left). Total pulse time approximately 375 ms. Corresponding metallographic cross-section (right). Hemispherical feature at weld surface believed to be re-melt due to long post-pulse simmer time.

2. Experimental Setup

Two lasers were employed to produce the long- and short- pulse spot welds examined in this study. Long-pulse spot welds were generated with a Lumonics JK802 Nd:YAG fiber delivered laser. This laser offered the added capability of Square Wave Modulation (SQW). Pulse shapes examined included continuous wave (CW, or un-modulated), 75% SQW and 150% SQW; each were tested at 25, 75, and 125 ms *set* pulse times. Short-pulse spot welds were made with a Lasag SLS 200 C16 40 W fiber delivered pulsed Nd:YAG laser. Here, square (or top-hat) and constant ramp-down pulses were investigated. The constant ramp-down pulse was generated such to be consistent with the pulse times (3, 6, 9 ms) and peak powers (800-1850 W) used for the square pulse welds. The difference being the ramp-down pulse contained half the pulse energy as that of a square pulse (Figure 2). Pulse energy used in this study ranged from 1.2 – 16.5 J.

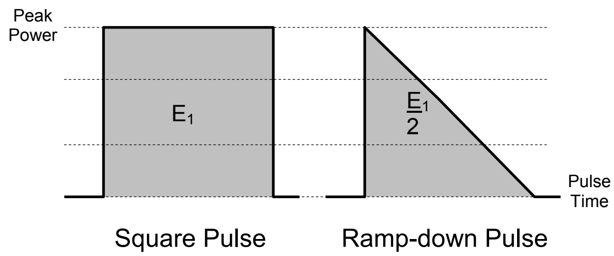

Figure 2: Illustration of pulse shaping used in short-pulse spot welds.

All welds in this investigation were produced at sharp focus determined either through the use of Kapton film (ref. 2) or by examination of metallographic sections welded at varying offset distances (ref. 3). A total of 5 different focal length lenses were evaluated. Output power, in the case of the long-pulse conditions, and pulse energy, for short-pulse spot welds, were measured prior to testing with either an Ophir Nova II power meter or with a Scientech AC50HD pulse energy detector. All welds were made under UHP argon gas shielding. Weld samples were wire cut (electric discharge machining, EDM) from 304L stainless steel and dimensioned to 4 X 0.5 X 0.048". Positioned to produce a standing-edge weld joint, 15-18 spot welds were made at each condition per sample (Figure 3). Time was allotted between pulses to avoid pre-heating of the weld sample. The standing edge geometry was chosen for its ease in x-ray radiography from which weld porosity was characterized.

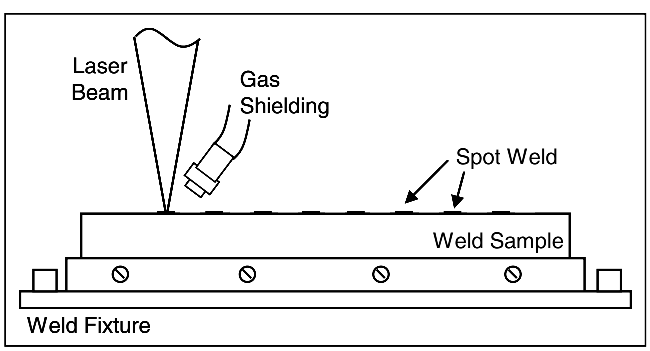

Figure 3: Illustration of pulse shapes used in short-pulse spot welds (top). Weld setup schematic identifying fixturing and shield gas orientation relative to the laser beam (bottom). Coaxial gas shielding used on long- pulse welds.

Since the Lumonics JK802 is a continuous output laser not specifically intended for spot welding, fast shutter control in not inherent in the system. As such, the long-pulse spot welds required standardizing of the pre- and post- pulse times. This includes a ramp-up, pre-pulse simmer, post-pulse simmer, and a ramp-down time. This was evaluated through an integrating sphere notch filtered for the 1064 nm wavelength. Programming of the weld pulse was defined to minimize pulse-to-pulse variation and reduce differences in pre- and post- pulse times for the three different tested durations: 25, 75, 125 ms. Figure 4-left shows the temporal output of a *set* 25 ms CW (un-modulated) pulse. On average, pre- and post- pulse time measured from 200 – 225 ms with longer set times producing the longer pre- and post- pulse time.

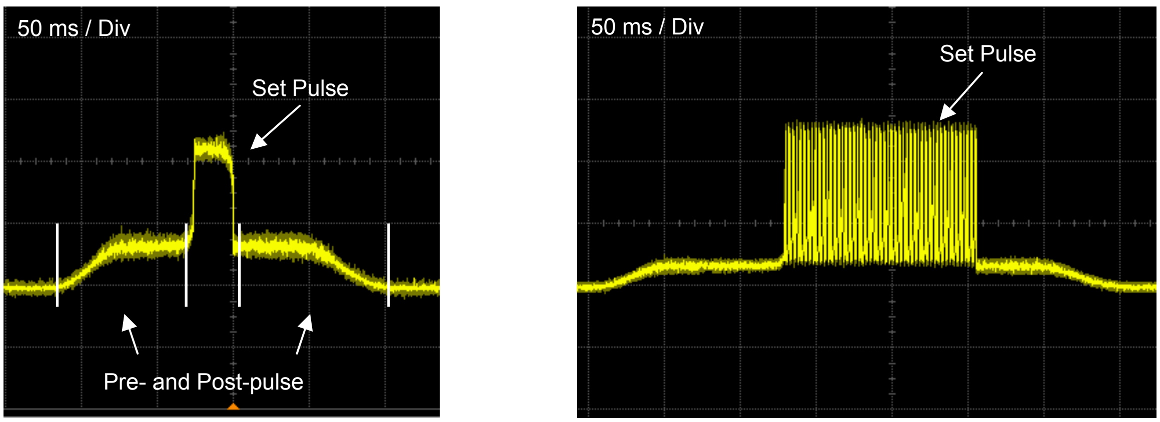

Figure 4: Lumonics JK802 long-pulse temporal measurements. Un-modulated (left), 150% SQW (right). Pre- and post- time inherent to the long-pulse process.

Pulse shaping of a long-pulse with the Lumonic's JK802 is described by *percent peak power*, *percent mean power*, and *frequency* (in this study, frequency was held constant at 400 Hz). Both the peak and mean power settings are defined as a percentage of the laser's total output power, or 800 W. As such, a 150% SQW setting will produce ~1200 W peak power. The duty cycle experienced during modulation is set by the mean power. As percent mean power approaches the set peak power, duty cycle approaches one (1) allowing for a smooth transition between a modulated pulse and a CW (or un-modulated) pulse. The effects of modulation greatly reduced with increasing duty cycle. These interrelated parameters are illustrated in figure 5. It is important to note that modulation of the long-pulse is only experienced during the *set* pulse time (Figure 4-right) and not during the pre- and post- pulse time.

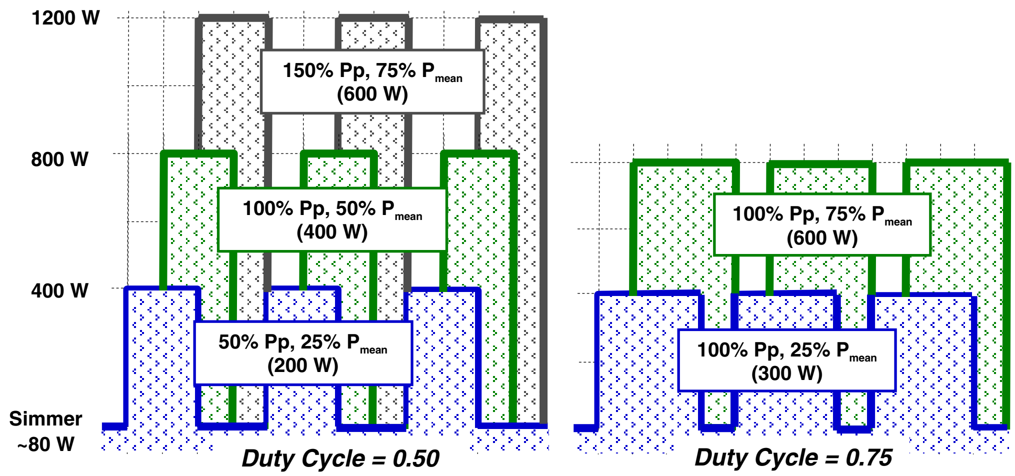

Figure 5: Schematic of SQW modulation operator defined parameters.

3. Results & Discussion

3.1 **Long-pulse Evaluation of Weld Parameters on Penetration:** Presented are two penetration maps described by percent output power; one as a function of pulse time (Figure 6A), and the other, as a function of pulse shape (Figure 6B). Map A identifies, as expected, that as power and/or pulse length is increased, so is weld penetration. The transition between conduction and keyhole mode welding is very distinct. This is differentiated by the sharp rise in penetration at approximately 50% output power (or ~500 W). In map B where power mode is contrasted for a constant 75 ms pulse time, the improved coupling effects of SQW modulation are presented. At an output power setting where CW pulses only produced conduction mode welds (being wide in contrast to their depth), employing SQW modulation promoted keyholing, providing a more efficient weld with greater penetration. These welds, even at shallow penetrations, exhibit a champagne glass or nail head weld profile and generally (for comparable penetrations) are smaller in diameter to those of a CW spot weld. In all, these data agree with our expectations of the effect of SQW modulation as it relates to weld penetration and shape.

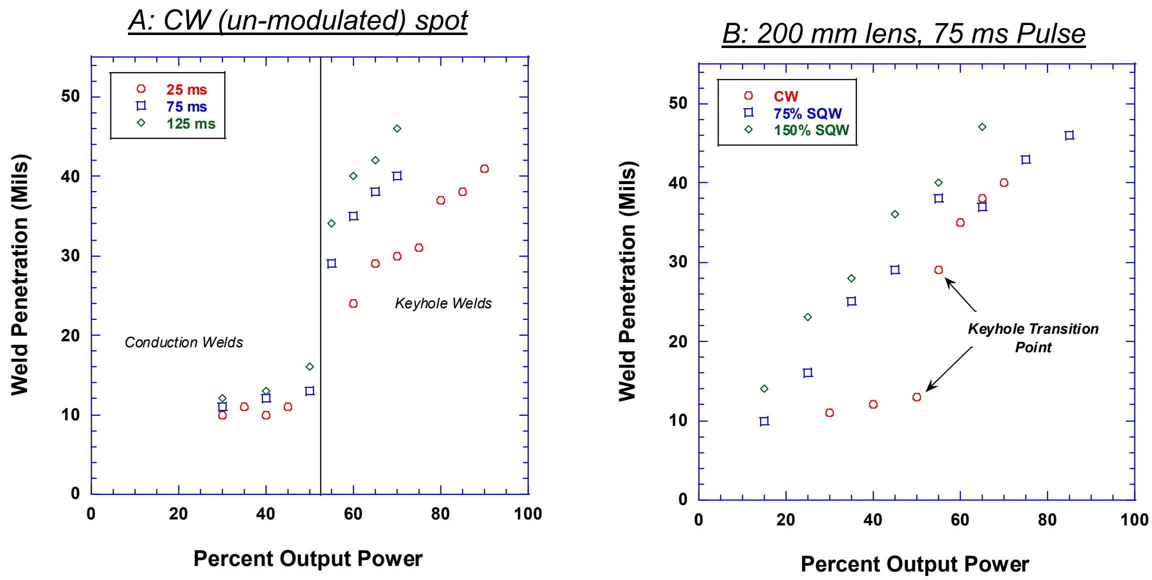

Figure 6: Penetration-power maps for long-pulse spot welds.

3.2 Long-pulse Evaluation of Porosity and Focal Length: Weld porosity was assessed through x-ray radiography. For each weld parameter 15 replicate spot welds were made. If any pores were identified, the weld parameter was said to be pore forming, or *porous*. Of those with pores, the tendency to form a pore was defined by the percent of welds (out of the 15 replicates) containing pores. This is identified as the *pore percent*. Since the strength of a spot weld depends upon cross-sectional weld area of the joined faying surfaces, the *area percent loss* by the pore was calculated by the area percent of the pore relative to its weld area. As such, the effect of porosity for welds of varying size is standardized so their effects may be described. Figure 7A maps the presence of pores for CW long pulse welds by focal length lens to weld depth. For the two plots illustrated within, porous and pore free welds are represented by blue squares and red circles, respectively. The onset of porosity with respect to penetration is identified and it is found that greater weld penetration can be achieved without the presence of pores with long local length lenses. This trend in porosity formation was also seen in continuous laser beam seam welds – for both SQW modulated and Continuous Wave laser modes (ref. 4). The porosity map of Figure 7B illustrates the influence of modulating the long pulse. At 75% SQW modulation, the boundary between porous and pore free welds is shifted downwards generating pores at shallower penetrations. The before noted effect of focal length (with respects to porosity) remains consistent for SQW modulated spot welds. Although not presented, 150% SQW modulation produced the same effects creating pores at even shallower depths of penetration.

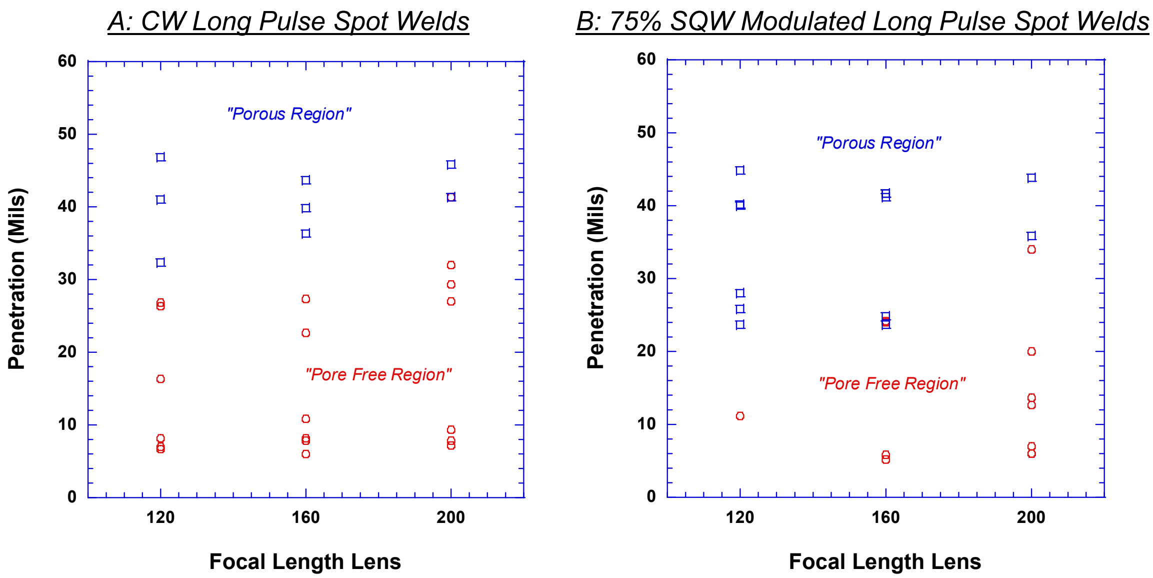

Figure 7: Porosity maps illustrating the effect of focal length lens and pulse shape.

3.3 Area Loss of Long-pulse Welds by Focal Length and Pulse Shape: In characterizing the effect of pores, beyond merely noting their presence, their impact relative to weld size is of considerable consequence - after all, equal size pores in a large and small weld do not influence weld functionality equally. In Figure 8, weld size is normalized by the *area percent loss* enabling a contrast of lens focal length and pulse shape. The results continue to imply modulating of the long pulse as unfavorable. Not only were pores produced at shallower penetrations by SQW modulation (over that of a CW pulse) but here, pores are also seen to make up a larger percent of the overall weld size subsequently producing a greater area percent loss. The greater the percent modulation, the higher the area percent loss. Of the parameters tested, pores for high modulated welds were shown to reduce weld area by as much as 23%. Lens focal length continued to show an appreciable role in pore reduction. With a 200 mm lens, the area percent loss even with 150% SQW modulation stayed below 10% area loss for the parameters tested. Longer focal length lenses reduce both the occurrence of pores and their size. This is particularly germane if modulation is necessary to achieve small weld diameters.

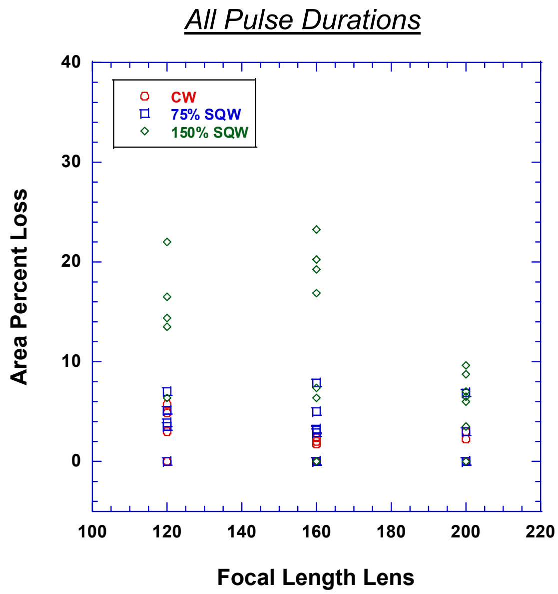

Figure 8: Lumonics JK802 long-pulse spot welds.

3.4 Effect of Pulse Duration in Long-pulse Welds: Little literature was found relating long pulse spot welds and weld porosity; however it has been stipulated for GTA welds that if the weld pool's condition is such that the pore is able to outgas, then porosity can be reduced and possibly avoided (ref. 5 & 6). For this reason, pulse duration was varied from 25 to 125 ms for a total long-pulse time of 225 – 350 ms. Analysis of the 200 mm lens data set showed pulse duration to have no distinguishable effect on pore formation (Figure 9A). Pores were just as prevalent at 25 ms as with 125 ms. This trend was observed for all three focal length lenses tested. This is further characterized by Figure 9B where the pore forming tendency (the percent of welds containing pores under a constant condition) show no preference with respect to pulse time. In this plot, both the 200 and 120 mm lens data are presented; solid and hollow symbols, respectively. The intermixed symbols representing the three varied pulse times reveal no particular time to have a higher tendency to form porosity. Continued analysis did however show pulse time affecting pore size. Figure 9C demonstrates that the area percent loss due to pores is much less at 25 ms in contrast to longer pulse times. Note that all pulse times covered the same penetration range (up to ~45 mils). Once again, all three lenses demonstrate the same behavior.

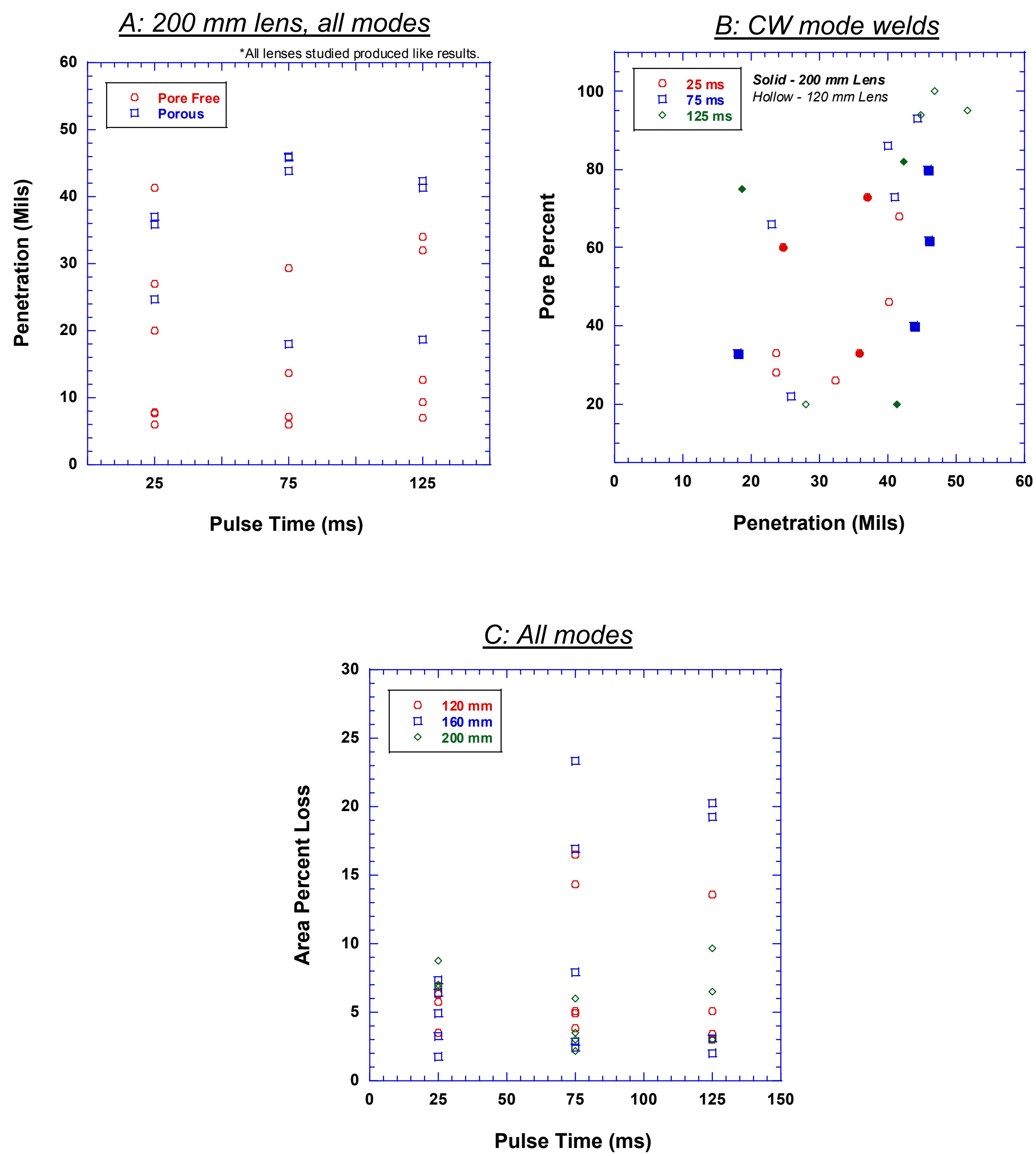

Figure 9: Porosity characterization as a function of pulse time for Lumonics JK802 long-pulse spot welds.

In addition to the aforementioned trends, it should be noted that although it extends beyond the intent of this study, welds of shallow penetration (<10 mils) having long pulse times (75 and 125 ms) showed weld center cracking (Figure 10). This behavior has been witnessed in production spot welds when made with the long-pulse process - its extent appears to be closely tied to the Cr/Ni ratio of the joining stainless steel and the length of post-pulse simmer time. Weld concavity due to spatter appears to accentuate this phenomenon. Metallography shows what is believed to be a re-melt region (hemispherical feature at the weld's center – Figure 10) where cracking primarily takes place. Recall that temporal measurements showed pre- and post- pulse times to increase with longer set times. It is likely the weld cracking is not necessarily the result of the longer set time but is due to the increased post-pulse time inherent in the longer set pulse time condition.

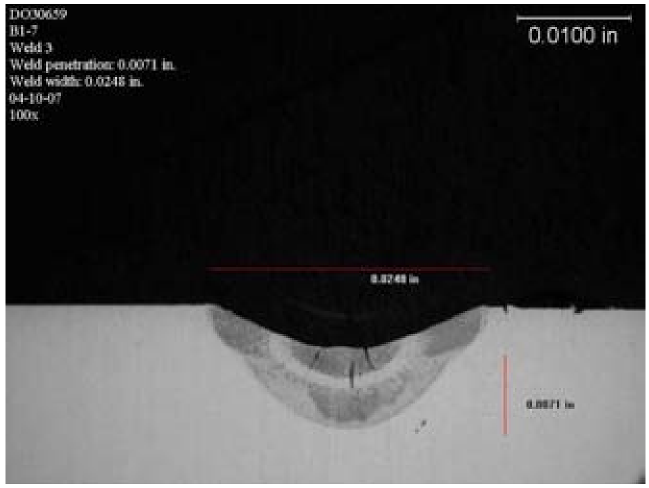

Figure 10: Metallographic cross-section of a 125 ms long-pulse spot weld. Center weld cracks primarily limited to re-melt region (hemispherical feature at welds surface).

3.5 Pore Size Relative to Weld Area: For continuous laser beam seam welds, nominal pore diameter showed a strong linear relationship to weld cross-sectional area (Figure 11B – from ref. 4). If this behavior holds true for spot welds, high aspect ratio smaller area welds would be preferred in effort to minimize pore size. Given that the strength of a weld is proportional to its area, larger welds would be necessary for high strength applications. This could prove problematic in that a balance, or compromise, between weld size and the *area percent loss* due to a pore would have to be met. Fortunately, this study showed no such correlation for the range of parameters tested (Figure 11A). Large and small area welds produce both large and small pores. In this study, *predicting* nominal pore size in spot welds is unresolved and appears to be chaotic. Unlike a continuous seam weld where a quasi steady state in the weld pool can be obtained (ref. 6), this unpredictable formation of pore size may be symptomatic of the frenetic nature of a keyhole mode spot weld.

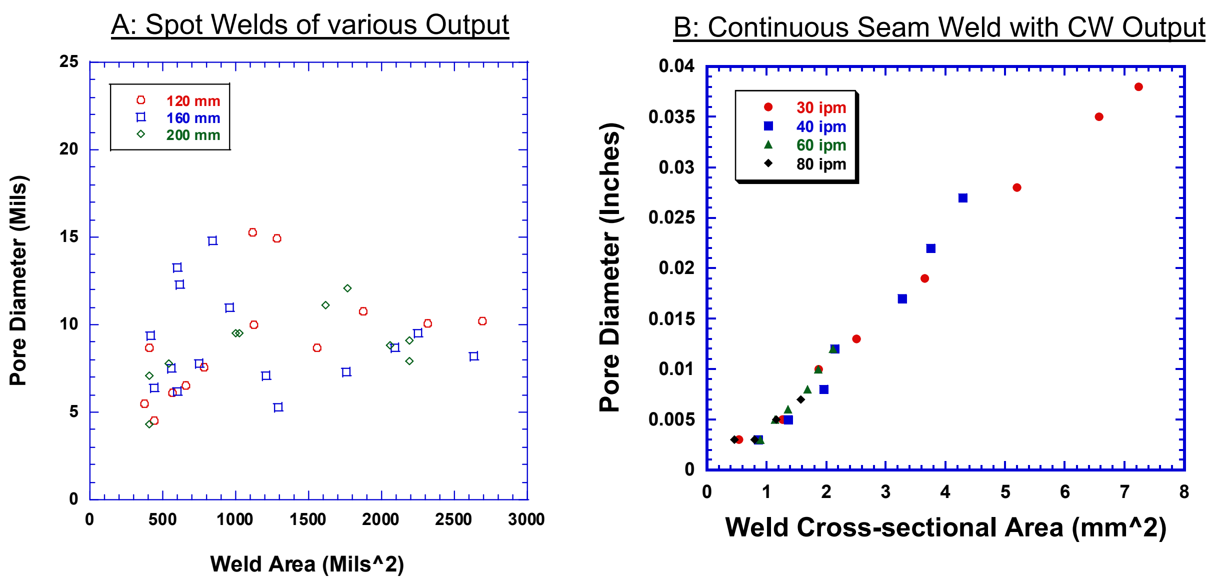

Figure 11: Contrasting relationship between weld area and pore diameter for long-pulse spot welds and continuous seam welds .

3.6 Short-Pulse Spot Weld Analysis: Primarily for the purpose of contrast, short-pulse spot welds were also examined. The parameters studied held either pulse time (t_p) or peak power (P_p) constant. The small matrix study resulted in only a partial characterization of weld porosity. Selected weld conditions included pulse shape (square and constant ramp-down) and focal length lens (100 and 150 mm) covering various penetration ranges depending upon weld parameter (t_p, P_p); 18 replicate welds were examined for each parameter.

Figure 12A describes the effect of focal length lens and penetration on weld porosity for a square pulse spot weld. Spot welds produced with a 150 mm focal length lens showed a transition from pore free to porous welds at ~ 25 mils penetration. The 160 mm lens used with the long-pulse process was moderately better in that porosity formed around 30 mils penetration. All parameters tested with a 100 mm focal length lens had pores and ranged in penetration from 25 – 55 mils. Shallower penetration welds were not captured by this matrix. As such, the transition point with respects to penetration from pore free to porous welds was not captured. However it is expected, or may be extrapolated from the long-pulse data set and results identified for continuous seam welds (ref. 4), that the transition between porous and pore free welds is less than that identified for the 150 mm lens.

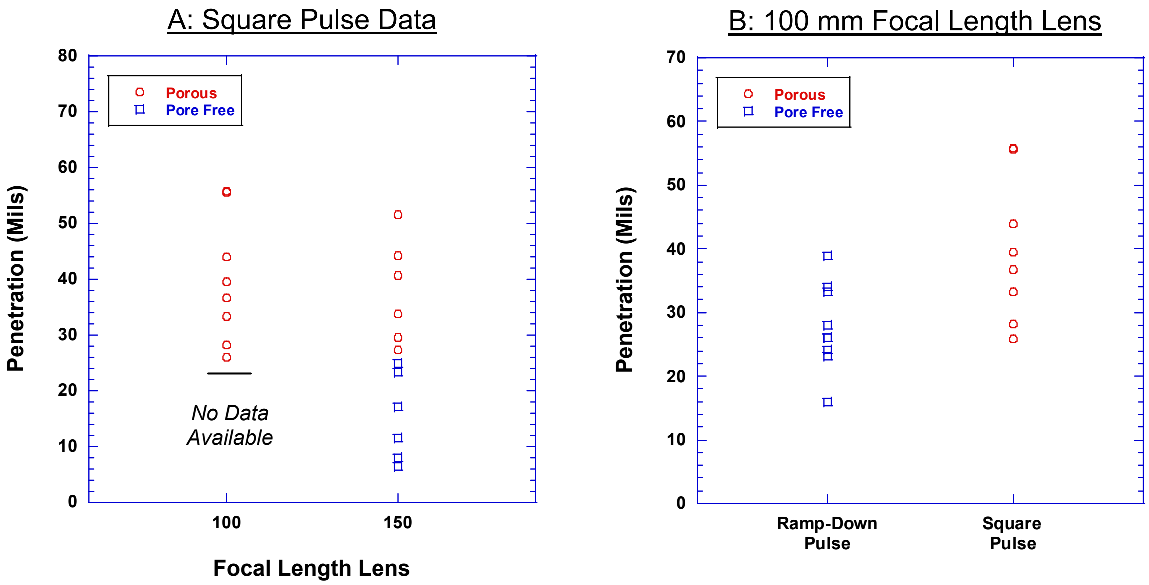

Figure 12: Porosity map illustrating effects of focal length and pulse shape for short-pulse spot welds.

Distinguishing the effect of pulse shape in short-pulse spot welds is identified by Figure 12B. Under the constant ramp-down pulse variable, it is the 150 mm lens that was limited in that only conduction mode welds of shallow penetration were created (no porosity would be expected). The 100 mm lens constant ramp down pulse data (Figure 12B) generated welds as great as 40 mils penetration. No porosity was seen in these welds. This is a considerable change in porosity given all parameters made with a square pulse at comparable penetration produced pores. Since weld functionality (most commonly, strength) is tied more closely to fused area as opposed to penetration, porosity as a function of weld area and pulse shape needs to be analyzed if equivalent welds are to be compared; this is presented in Figure 13 where in fact the parameters tested for the two different pulse shapes are of equal magnitude. It can therefore be concluded that continuous ramp-down pulses are advantageous in minimizing weld porosity over those made with a square pulse. It should be noted however, that the 100 mm lens constant ramp down welds when examined through metallography (instead of x-ray radiography having a resolution of only ~5 mils), micro porosity was present at greater penetrations but exhibited pores measuring only a few mils in diameter.

Although some trends in weld porosity have been revealed for short-pulse spot welds, a more extensive study is merited to better understand and capture the extent of weld porosity, particularly in contrast to that of the long-pulse process. Note that short-pulse processing does offer reduced heat input and superior control in weld aspect ratio over that of the long-pulse process. A thorough understanding of both processes is needed.

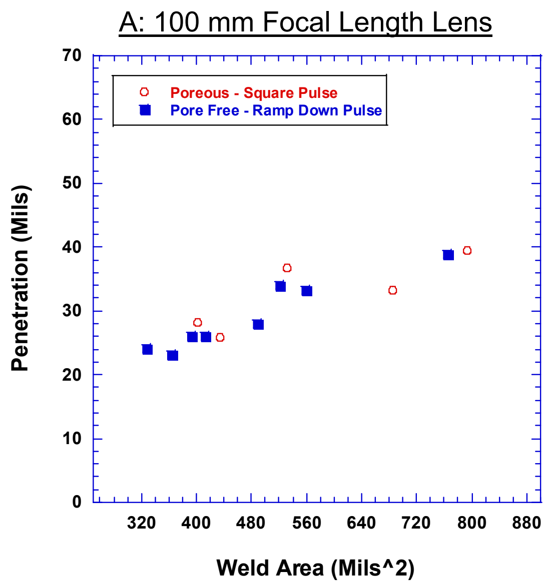

Figure 13: Contrasting weld area for continuous ramp-down and square pulse welds.

4. Conclusions

This study has demonstrated that porosity in both long- and short- pulse spot welds can be minimized, if not avoided, through informed selection of processing parameters. The following conclusions can be drawn from the experiments detailed in this report:

1) Square wave modulation of a long-pulse can produce keyhole mode welds even at shallow penetrations. These welds also provide a smaller weld spot diameter in contrast to un-modulated (CW) long-pulse welds.

2) Porosity-penetration maps developed in this study illustrated longer focal length lenses to be capable of greater weld penetration before the onset of porosity compared to shorter focal length lenses.

3) The use of high peak power square wave modulation in long-pulse spot welds tended to create larger weld pores relative to un-modulated pulses concomitantly reducing weld area and strength. The effect is minimized with longer focal length lenses.

4) Although the programmed pulse time of a long-pulse showed no effect on the *occurrence of pores* or *pore percent*, the *area percent loss* due to a pore was considerably less for the 25 ms programmed time.

5) Constant ramp-down pulse shaping for short-pulse spot welds proved effective in reducing weld porosity.

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