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Case Studies

A Field Evaluation of the Effect of Pulsed Arc Welding Technique on Reducing Worker Exposures

Dawn Tharr, Column Editor

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Researchers from the National Institute for Occupational Safety and Health (NIOSH) conducted an in-depth study of the gas metal arc welding operations at an agricultural and construction equipment manufacturer. The company produces heavy machinery such as trenchers, tractors, hay balers, tree-handling equipment, and directional boring systems. Approximately 475 welders are employed in seven independently operated plants located at the site. In the past, worker exposures to welding fumes were controlled through a combination of general and local exhaust ventilation. Recently, plant management changed from conventional power sources to pulsed inverter power sources for their welding operations. Research has shown that under laboratory conditions gas metal arc welding with pulsed arc can reduce fume generation.[1,2] This fume reduction is due to the ability of pulsed current to transfer metal droplets from the wire, through the arc, to the work piece, with minimum heat. The purpose of this study was to evaluate whether the welding fumes generated during pulsed arc welding in the production environment are indeed significantly less than that of conventional arc welding, given similar process parameters.

Process Description

Gas metal arc welding (GMAW) is a welding process that uses an arc between a continuous filler metal electrode (wire) and the weld pool. The process is used with shielding from an externally supplied gas, and without the application of pressure.[3] Conventional GMAW has three distinct modes in which the metal from the wire is transferred to the work piece: short circuit, globular, and axial spray.[4,5] Short circuit transfer is associated with low average currents and voltage levels, and occurs when the wire actually touches the molten weld pool. This creates a short circuit, causing an increase in the current, which subsequently melts the wire tip. Globular transfer occurs at higher voltages and amperages. During this type of transfer, the wire melts before touching the molten pool, and the metal is transferred across the arc through gravity. Melted droplets may be up to four times larger than the wire diameter and may be transferred in an irregular pattern. Spray transfer occurs with increasing currents and voltages, using argon-rich shielding gas mixtures. During spray transfer, the magnetic field from the arc surrounds the wire, and the high magnetic force from that field pinches the wire down from the end. The resulting molten droplets are smaller than the wire diameter and are transferred across the arc to the work piece in a constricted, axial column. This results in reduced spatter (metal particles expelled during welding, which do not form part of the weld),[6] compared to short circuit and globular transfer modes. However, the temperature of the surface of the molten-forming droplet during spray transfer can be in excess of 10,000°F, which is well above the vaporization temperature of steel. It is this high temperature that causes most of the welding fumes during spray transfer.

Short circuit transfer has applications in light gauge sheet metal welding. Due to the low heat input of short circuit transfer, use on heavier (thicker) metal can cause non-fusion and is, therefore, not desirable. The concern of non-fusion is reduced during globular transfer because of the increased heat input. However the dramatic increase in spatter from this mode of metal transfer prevents it from being a viable production method. Axial spray transfer has a high heat input which virtually eliminates the concern of non-fusion. Spray transfer also has low spatter and the highest deposition rate of the three modes of metal transfer for conventional GMAW. In general terms, at the survey site, the conventional GMAW process can change from short-circuit, through globular, to axial spray transfer by increasing the arc energy (an increase of voltage and amperage). Because of the above-mentioned advantages, most of the conventional GMAW at this site used the axial spray arc transfer.

Pulsed power welding, or pulsed spray transfer, is an arc welding process variation in which the power is cyclically programmed to pulse so that effective, but short, duration values of power can be utilized. Such short duration values are significantly greater than the average value of power. When pulsed power welding is used with the GMAW process, small metal droplets are transferred directly through the arc to the work piece. The current alternates from a low background current, which begins to melt the wire while maintaining the arc, to a high peak current during which spray transfer occurs. One droplet is formed during each high peak current pulse. As the wire is advanced, the current pulses again and transfers the next droplet. The average arc energy during this pulsed process is significantly lower than during conventional axial spray transfer, thus, reducing the amount of welding wire that is vaporized. With the reduction of weld wire vaporization, welding fume generation is reduced. Some laboratory research indicates that a reduction in welding fume during pulsed arc welding is only attainable for certain ranges of voltages for each wire feed speed. If the pulsed technique is to be an effective engineering control, the voltage parameter must be controlled to an optimum setting for the welding operation. Voltages that are too low may result in spatter, while voltages that are too high will increase the fume generation.

Project Parameters

At this site, welding was primarily of low carbon steel using solid wire GMAW conventional and pulsed processes. A 95 percent argon/5 percent oxygen shielding gas was also used. During approximately 70 percent of the welding, 0.045-inch diameter ER70S-3 wire (Lincoln L50, Cleveland, OH) was used; approximately 20 percent of the work was completed using 0.035-inch diameter ER70S-6 wire (Lincoln L56); and 5 percent using 0.052-inch diameter ER70S-3 wire (Lincoln L50); with the balance of the welding using other diameters and wire types. The two wires, ER70S-3 and ER70S-6, have slightly different additives. For 0.035-inch diameter wire, the manufacturer's suggested current range was 40 amps to 225 amps, and the suggested voltage range was 15 volts to 24 volts. For 0.045-inch diameter wire, a suggested current range of 100 amps to 325 amps was given, and 17 volts to 35 volts was the suggested voltage range; for 0.052-inch diameter wire, the current range was 200 amps to 400 amps, and the voltage range was 19 volts to 36 volts. Welders primarily work in the down hand (flat) position, and approximately 95 percent of the work was fillet welds. Fillet welds join two parts that are approximately at right angles to each other, in a lap joint (parts overlap), corner joint, or T-joint.[7] The cross section of a fillet weld approximates a triangle. The welders at the site used four primary types of steels in their work: 572 Grade 50, 1045, A36, and 1018. The metal was dry pickled and descaled prior to welding. Base metal thickness ranged from 1/16 to 2 inches.

Welders in Plants 7, 4, and 1 were included in this study. Plant 7 produced rubber tire trenchers and directional boring equipment; Plant 4 produced tree-handling equipment; and Plant 1 produced special order equipment. In Plant 7, each of the sampled welders worked separately at their own workstations. In Plant 1, the sampled welders worked in pairs on the same part. In Plant 4, the sampled welders worked separately, except for one pair, who worked on the same part. The welders did not use local exhaust ventilation; however, heated make-up air was provided in the plants. Many of the welders used small portable fans in their work areas. The plants were under negative pressure. Plant sizes were 300 feet × 450 feet × 18 feet for Plant 1 and 320 feet × 600 feet × 22 feet (to a 24-feet ceiling peak) for Plants 4 and 7. Employees took a 30-minute lunch break at the work site and two 10-minute rest breaks during the 10-hour workday. Welders worked a 50-hour workweek at the time of the study.

The power sources used during the study were the Power Wave 450 from the Lincoln Electric Company (Plants 1 and 4) and the Maxtron 450 from Miller Electric Manufacturing Company (Plant 7). These power sources can be used for both pulsed spray transfer as well as conventional GMAW. Wire feeds ranged from 200 to 600 inches per minute (ipm), amperage levels ranged from 140 to 400 amps, and voltages ranged from 18 to 30 volts. Welders in Plant 1 typically used larger diameter wires (0.052 inch) at a faster rate (600 ipm) than welders in Plants 7 and 4, who typically used 0.045-inch diameter wire at a rate of 400 ipm. During this study, all the welders sampled in Plants 1 and 4, and 60 percent of the welders in Plant 7, used Lincoln L50 wire. The remaining 40 percent of sampled welders in Plant 7 used Lincoln L56 wire.

Sampling Methodology

Data were collected on total welding fume emissions using personal sampling pumps and filters on the welders, over the 10-hour workday. Nineteen welders were sampled in Plant 7, six welders in Plant 4, and four welders in Plant 1. A 37-mm diameter filter cassette, containing a tared, 5 μm pore-size polyvinyl chloride filter, was placed in the breathing zone of the welders, with an attempt to situate the filter high on the welder's lapel, under the welding helmet. At lunchtime, all the personal filters were removed and immediately replaced with new filters. During each day, half of the welders in each plant used conventional GMAW, while the other half used pulsed GMAW. The selection of which welders used which techniques was randomized. On the second day of sampling, the welders switched to the other welding technique. On the third day of sampling, the majority of welders returned to the technique they had used during the first day. This strategy allowed each welder to be sampled during both pulsed and conventional welding, thus accounting for exposure variations from individual work practices. Area samples were also collected in the plants. The sampling pumps were calibrated and operated at 2 liters/minute (lpm). Filters were analyzed by DataChem Laboratories (Salt Lake City, UT) according to the NIOSH Method 0500 for total particulate.[8] The same filters were subsequently analyzed for elements using the NIOSH Method 7300.

Ozone data were collected in the welders' breathing zones, using passive samplers (Ogawa, Pompano Beach, FL). Because of a limited number of passive samplers (50), data could not be collected on all the welders during all three days of sampling, and no area samples were collected. In Plant 7, all 19 welders were sampled on Day 1, and seven were randomly sampled on Day 2, providing a total of 26 full-shift samples. In Plant 1, all four welders were sampled on both Days 1 and 2, resulting in 8 full-shift samples. In Plant 4, all six welders were sampled on both Days 1 and 2, resulting in 12 full-shift samples. All 50 of the passive samplers, including four blanks, were submitted to the Research Triangle Institute Laboratory (Research Triangle

TABLE I
Personal total welding fume data

	Total # half-shift samples			Resulting # full-shift samples		
	Plant 7	Plant 4	Plant 1	Plant 7	Plant 4	Plant 1
Pulsed	53	20	12	26	10	6
Conventional	54	16	12	27	8	6
Total	107	36	24	53	18	12
Pulsed > 5 mg/m^3	4	3	2	1	0	2
Conv > 5 mg/m^3	14	7	10	4	4	4
Total	18	10	12	5	4	6

Park, NC) to be analyzed by ion chromatography.

Air currents in the welding area were assessed with a hot wire anemometer (TSI VelociCalc, St. Paul, MN), which measured air velocities in feet per minute (fpm). Arc timers were used to measure the total amount of time each welder's arc was on during the sampling periods. The Miller power sources in Plant 7 already had the capability to measure arc time; however, the Lincoln power sources did not. To measure arc times for these welders, a plant technician designed an arc timer that could be clipped to the welding power cable or ground lead. DC current through the cable magnetized and closed the loop in the mechanism, turning the counter on. Arc time was measured in 1/100 of an hour.

Data Results and Analyses

Total Welding Fume

The total welding fume data collected on the welders' personal sample filters, and on the area sample filters, were all below the Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) for total particulate of 15 milligrams per cubic meter (mg/m^3).[9] A total of 167 personal half-shift samples were collected; 51 percent were during pulsed GMAW, and 49 percent were during conventional GMAW. Twenty-four percent of the personal half-shift samples (40 of 167) were greater than 5 mg/m^3 (Table I). Of these 40 samples, 31 were collected during conventional welding, and nine were collected during pulsed welding. The highest concentration detected was 10 mg/m^3, collected on a conventional welder in Plant 7. When the morning and afternoon filter data were combined to determine the time weighted average (TWA) concentration for each welder, 15 of the personal full-shift concentrations were found to be greater than the American Conference of Governmental Industrial Hygienists (ACGIH®) threshold limit value (TLV®) of 5 mg/m^3 for welding fume (Table I).[10] Of these samples, 12 were collected during conventional GMAW and 3 were collected during pulsed GMAW. The conventional welder in Plant 7 who had the highest half-shift concentration also had the highest TWA concentration, calculated as 8 mg/m^3. A repeated measures model was used to interpret the data, and analyses of variance (ANOVA) were performed to evaluate response variables.

The statistical analysis of the personal half-shift data showed a 24 percent significant reduction overall in total welding fume levels when using pulsed arc welding versus conventional welding. The pulsed technique resulted in personal total welding fume exposure reductions of 21 percent in Plant 7, 33 percent in Plant 4, and 25 percent in Plant 1 (Figure 1). No significant interaction was found between welding technique and plant. An evaluation of the overall workers' exposures to total welding fume found that Plant 7 welders were exposed to significantly lower total welding fume levels than welders in Plants 1 and 4. Exposure differences between Plants 1 and 4 were insignificant. The lower levels of Plant 7 could be attributed to the plant's lower arc times; less welding results in less fume (Table II).

Welding Fume Constituents

The elemental analysis of the filter data found no concentrations over the applicable OSHA PELs. Analysis of full-shift manganese exposures for the welders found almost half were greater than the ACGIH TLV for manganese of 0.2 mg/m^3 as a TWA. The exposures occurred almost evenly between pulsed and conventional welding operations. Manganese concentrations ranged from 0.05 mg/m^3 to 0.60 mg/m^3. The highest personal sample concentration collected, 0.60 mg/m^3, was for a

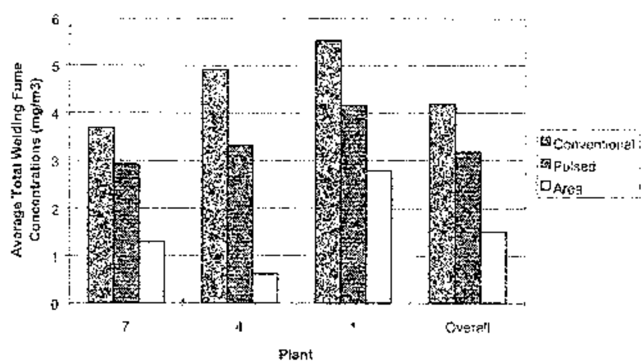

FIGURE 1
Average total welding fume concentrations during pulsed and conventional welding operations, measured on the welders in each plant and overall. Area concentrations are also depicted. Fume levels were significantly lower for pulsed welding in all plants.

TABLE II
Arc time data

Plant	Welding technique	Average arc time (min)	Percent sample time actually welding
7	Conventional	37	14
7	Pulsed	45	12
4	Conventional	51	23
4	Pulsed	59	22
1	Conventional	98	38
1	Pulsed	103	40
Overall	Conventional	62	25
Overall	Pulsed	69	25

conventional welder in Plant 7. Twelve of the full-shift personal samples had arsenic concentrations greater than the NIOSH Recommended Exposure Limit (REL) of 0.002 mg/m^3 (ceiling value).[11] These exposures were split evenly between pulsed and conventional welding operations. Arsenic concentrations on the welders ranged from not detected to 0.01 mg/m^3.

A multiple comparison test was performed on several elements (including aluminum, barium, chromium, copper, iron, magnesium, manganese, and zinc) that had measurable quantities for many of the samples. The statistical analysis for these 10 elements indicated exposures generated during conventional GMAW were significantly higher than exposures during pulsed GMAW ($p < 0.01$). Overall, it was shown that Plant 7 had significantly lower exposure levels ($p < 0.01$) than Plants 1 and 4.

Ozone

A regression analysis of the ozone sampling data did not find the difference between the pulsed and conventional welders to be significant due to the large variation of results. The average ozone concentration for pulsed arc welders was 40 percent higher overall than that of the conventional welders (Figure 2). This increase in ozone can be understood because although the average arc energy of pulsed GMAW is lower than that of conventional GMAW, the peak amperage is higher. Ultraviolet radiation increases roughly proportional to the square of the current,[12] and the rate of formation of ozone depends upon the intensity of the ultraviolet radiation. Thus, higher current peaks result in increased ultraviolet radiation, which, in turn, increases the amount of ozone generated.

Breaking the data down by plant showed a 41 percent increase in average ozone concentration for pulsed arc welders in Plant 7 and a 63 percent increase for Plant 4 when compared to conventional welders. Pulsed arc welders in Plant 1 had a 16 percent drop in their ozone levels compared to the conventional welders. No explanation was found for this result. Statistical analyses again did not find any of these differences to be significant ($p < 0.05$). The majority of ozone samplers measured low concentrations; only four of the ozone samplers were above 50 parts per billion (ppb) (the TLV during heavy work). Three of these were during pulsed arc welding (out of 24), and one was during conventional welding (out of 22). The highest ozone concentration measured occurred during a pulsed welding operation in Plant 4 (150 ppb).

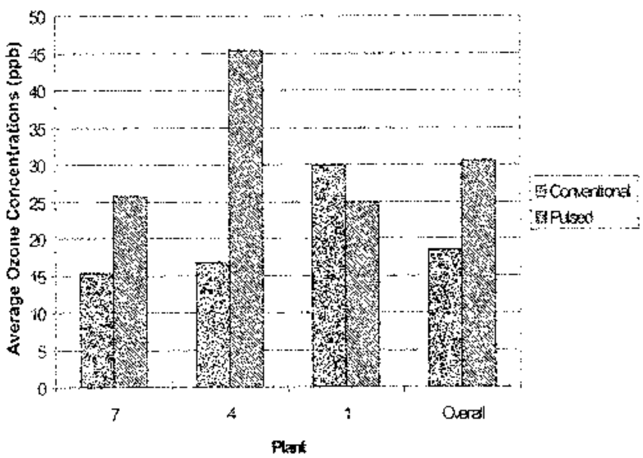

FIGURE 2
Average ozone concentrations during pulsed and conventional welding operations, measured on the welders in each plant and overall. Ozone levels were not significantly different between the two techniques.

Other Factors

A regression analysis of the amperage, voltage, humidity, and temperature data established that these factors did not significantly affect the amount of fume generated or the arc time. It is possible no effect was found since the parameters were only recorded at one point during the sampling period. It is likely that the parameters changed throughout the day, particularly amperages and voltages which may have increased or decreased depending on what the welder was working on. Amperage levels were found to be significantly higher in Plant 1 than in Plants 7 and 4 due to the use of larger diameter wires at higher wire feed speeds in Plant 1. Temperatures in the three plants ranged from 64°F to 80°F, and humidity levels were around 20 percent. Air velocities in the vicinity of the welders varied, depending on their proximity to man-cooling fans. For those welders who had the fans on, the average air velocity at the fan was 1128 fpm, but where the welder actually worked, the average air velocity was only 27 fpm. Due to the low air velocities, it is unlikely the fans had much impact on the welders' exposures to fumes. In addition, many of the welders frequently moved around their work pieces which would have placed them both upwind and downwind of the welding fumes.

Conclusions

Research under laboratory conditions has shown a reduction in welding fume generation from pulsed arc transfer during gas metal arc welding. The results of this research show similar reductions in worker exposures in a production environment. Thus, replacing conventional gas metal arc welding with pulsed arc techniques can lead to a reduction in welding fume emissions. This process modification is particularly useful because the welding fumes are controlled at the source, as opposed to being exhausted from the welder's breathing zone when using a more typical ventilation control method. In some cases, optimum fume control might be achieved by combining pulsed gas metal arc welding with properly designed local exhaust ventilation, particularly if welding fume exposures or ozone concentration exceed OSHA PELs.

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