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Ozone: a critical contaminant produced during gas metal arc welding (GMAW) on aluminum alloys—resolving the short- versus long-duration sampling discrepancy

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Abstract

Ozone is one of the gases produced during argon-shielded arc welding on aluminum alloys. Arc welding superimposes multiple episodes of intense emission of short duration onto the background level during the work shift. Short-duration exposures during welding were measured using colorimetric detector tubes and long-duration exposures, by colorimetric badges utilizing similar chemistry. Both devices were positioned on the lapel in the breathing zone. Many of the short-duration samples exceeded the 8-h TLV–TWA (threshold limit value–time-weighted average) of 0.08 ppm for moderate work during argon-shielded gas metal arc welding (GMAW) also known as metal inert gas (MIG) welding. Some short-duration samples exceeded the transient limit of 0.24 ppm (3× the TLV–TWA), and several exceeded the maximum of 0.40 ppm (5× the TLV–TWA). Exceedance of the maximum in jurisdictions using TLVs as exposure limits necessitates control measures including effective local exhaust ventilation and respiratory protection. Ozone was undetectable (< 0.04 ppm) during gas tungsten arc welding (GTAW) also known as tungsten inert gas (TIG) welding. During long-duration sampling, almost all levels during GMAW were ≤ 0.08 ppm h (≤ 0.01 ppm averaged over 8 h), the limit of detection of the sampling device. As a result, ozone is a critical gaseous contaminant (requiring control measures) during GMAW (MIG welding). Protection of the eyes against irritation in sensitive individuals dominates other considerations.

Keywords Aluminum alloys · Arc welding · Critical gaseous contaminant · GMAW (MIG welding) · GTAW (TIG welding) · Ozone · Personal exposure assessment

Introduction

Arc welding creates many hazardous conditions that can impact the health and safety of workers (NIOSH 1988). This article is one of a series that addresses these concerns during arc welding on aluminum alloys in a shipbuilding environment (McManus and Haddad 2013, 2014, 2015a, b, 2016). The strategy followed by these authors in the studies described in these articles highlights one of the most important concepts in the practice of industrial/occupational hygiene: identifying the critical contaminant generated or present during a process.

Typically, in any process, one air contaminant (critical contaminant) dominates assessment of exposure and the type and extent of response necessitated by occupational health and safety regulations. Dominate in this context has the meaning of the highest fraction of the relevant exposure limit of the jurisdiction having authority over the employer performing the work. The critical contaminant is neither necessarily obvious nor apparent through inspection of reference documents such as Safety Data Sheets or specification sheets or reports on material analysis. Identification often requires air and, sometimes, other types of sampling. Once identification of the critical contaminant does occur, effort involved in surveillance of exposure and control can focus on reduction of exposure to

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that substance to levels as far below the relevant exposure limit as needed to ensure worker protection. This is especially important when initial exposure monitoring indicates that exceedance of the exposure limit can occur or is occurring.

By necessity, the activity described here is ongoing because exposure limits are not static in time and usually decrease when change does occur. When decrease does occur, the relative position of contaminants in the hierarchy of importance of exposure can change. Provided that formulations and operating conditions remain constant with time, the relative importance in the hierarchy of exposure of individual contaminants present or produced in a process depends on the fraction of the relevant exposure limit.

Assessing exposure to ozone in a welding environment is difficult as described in a companion article [article submitted for publication, not cited]. This difficulty arises, in part, from the presence of NO_2 (refer to previous discussion about mechanism of formation). NO_2 acts as a positive interferent in the chemistry used to measure ozone. (NO_2 causes false high readings in almost all technologies used in measurement of ozone.) This reaction is demonstrable in the depression in the level of ozone measured in emissions measured downwind from thermal power stations (White 2009). Additional factors include slowness of response of electrochemical detectors and duration of sample time and the inability of ozone-monitoring equipment to function in an industrial environment containing airborne particulates. Complicating this situation further is the transient and unpredictable nature of arc welding as occurs in the aluminum shipbuilding and many other environments. A conservative strategy for assessing exposure employs both short- and long-duration sampling. Sources of exposure to ozone include the welding plume and background levels that exist and develop in the building. Background levels exist because of ozone in ambient air and develop because of inadequate ventilation. Ozone in ambient air can be an important consideration in this type of project because of the contribution to measured levels. Recent studies show that ozone levels in ambient air can range from 0.025 to 0.040 ppm for measurements made worldwide (Reid et al. 2008).

Safety and protection of the welder during sampling are paramount considerations. These considerations limit the type of equipment that is suitable for this type of sampling. Welding superimposes an essentially off-on-off signal of considerable magnitude onto a possibly non-zero baseline. As a result, assessment of exposure necessitates integration of measurements during exposure to the welding plume and during total daily activity. Another article in this series (submitted for publication, not yet cited) determined that personal exposure to ozone in this situation was best determined using colorimetric technology.

Welding activity during fabrication of ship structures is described as “tacking and fitting” and “production welding.” Tacking and fitting occurred manually and involved one worker to position the piece and the other to weld it. Tacking involved short welds. Production welding involved filling in seams between tack welds. Production welding occurred manually and by machine. Machines were used extensively during welding of seams on horizontally oriented sheets and pieces of metal. The operator watched the operation from a very close distance. Reduction in exposure occurred once they modified the machine to collect and remove the plume. The data show the effectiveness of the design.

Participants in this study used different types and levels of respiratory protection ranging from half-facepiece respirators to supplied-air welding helmets. Welders who used the former also used a welding helmet, an essential piece of equipment during this work. The air-supplied welding helmet contains built-in eye and skin protection.

The source of air for front-mounted cartridges is the space under the welding helmet. The lapel on the coveralls or the balaclava/bib combination is close to the source of contaminated air that is drawn into the welding helmet for breathing. The lapel-balaclava/bib combination also is the closest position to the face that is common to all types of respiratory and other welding-related protection (Fig. 1). The supplied air welding helmet provides air from another source to the welder’s face.

The lapel-balaclava/bib combination likely does not receive the highest concentration of ozone that is measurable. Higher concentrations likely would occur at locations on the front and side of the welding helmet since the welder often positions the helmet in the path of the plume. The important consideration here is what the welder could breathe in the absence of a respirator, not the welding helmet. The welding helmet is an essential part of welding equipment. Welding cannot occur safely without it. That being the case, a welder always will use face protection of this type, but not necessarily a respirator.

An important function of the welding helmet that is not often recognized is the barrier afforded to deflect the plume away from the face. The concentration of contaminants outside the welding helmet is about 1.4× the level inside (Goller and Paik 1985). Observation suggests that this occurs because of the surface aerodynamics of the helmet. This appears to be similar to what occurs above the wing of an aircraft. One can see this separation sometimes during take-off. The air above the wing does not contact the surface of the wing. There is a separation. This separation is also visible in wind tunnels in studies involving vehicles. This information shows that position of the welding helmet on the face and torso is critical and that distortion of the “fit” by sampling devices is not acceptable. Distortion of the relationship between the head, face, and torso and the welding helmet could admit the plume and exacerbate exposure.

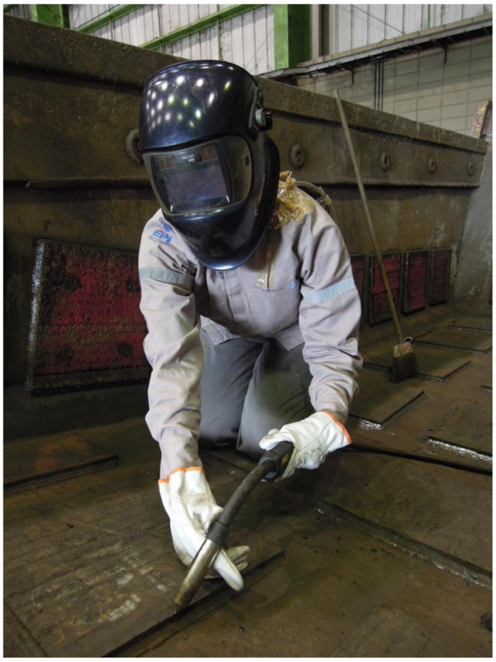

Fig. 1 Mock-up showing position of the sampling tube on the lapel of a welder. This position provides the best compromise of position for welders wearing various types of respiratory protection

The intent in choosing the location on the lapel-balaclava/bib combination was to ensure that the sample represented at least what was presented to the nose under the welding helmet.

Methods

The detector tube used for short-duration sampling (Dräger no. 6733181 ozone 0.05b, Dräger Safety Inc., Pittsburgh, PA) was attached to the front lapel of the participant (Fig. 1) using duct tape. Duct tape provides reliable and secure attachment to the coveralls and protects the tube against damage and protects the wearer from contact with the broken glass at the end of the tube. A short section of thick-walled tubing (about 1.5 m) connected the detector tube to the pump (Fig. 2). This length did not interfere with the speed of obtaining a pump stroke or normal movement of the welder. During this study, the sample taker remained behind the welder. This type of sampling is hazardous to anyone in the immediate vicinity of the welder (including the sampler shown in Fig. 2). The sampler requires complete protection for welding because of possible exposure to hazardous levels of UV radiation reflecting off every shiny surface in the work area. Reflection of UV radiation to the back side of the welder is a known hazard during this type of welding.

In the case of production welding, sampling occurred only during active generation of the plume. In other words, when welding stopped, sampling stopped. This avoided the possibility of sampling air containing ozone at levels less than experienced during welding. In the case of tacking, sampling also occurred only during the period of exposure to the plume. The heated plume rises rapidly toward the roof space of the building and associated ozone disappears soon after welding stops.

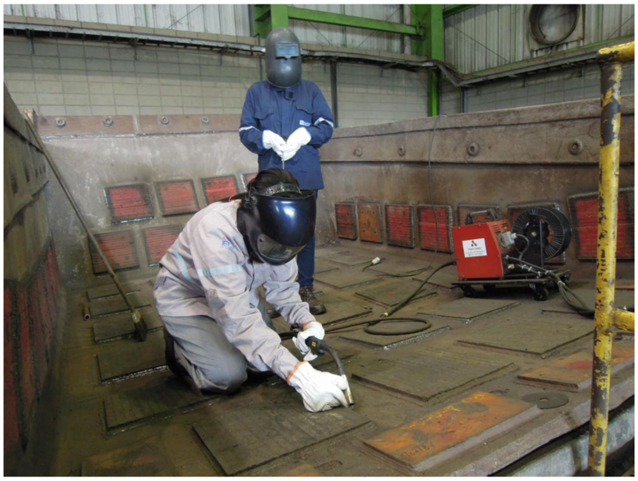

Fig. 2 Mock-up showing the relative positions of the welder and the sample taker who operates the bellows pump. The plastic tube connects the bellows pump to the sample tube. The geometry provides flexibility to the welder for rapid movement to avoid unexpected safety risks such as spatter of molten metal

The mechanics of welding sometimes necessitated sampling during two or more separate welds. The samples reported here required four or five pump strokes. The sample period required approximately 75 s. Hence, the result from short-duration sampling is a time-weighted average during the sample period.

The diffusion badge used for long-duration sampling (ChromAir Number 380010, Morphix Technologies, Virginia Beach, VA) was mounted onto the front lapel of the participant in the same location as the detector tube using duct tape. Duct tape in this application provided more secure attachment that afforded by metal clips and prevented exposure of the UV-sensitive back side of the badge to UV irradiating from the arc.

Colorimetric products utilize similar chemistry and suffer from similar interferences [article not cited]. The color reaction utilized in these tests, while complex, is not specific to ozone. Nitrogen dioxide is an acknowledged interferent in the use of these products. Dräger Safety Inc. indicates that 1 ppm of NO_2 does not interfere with the reading of ozone. Higher concentrations change the indicating layer to a diffuse white or gray (Dräger 2011). Morphix Technologies indicates that nitrogen dioxide produces no interference up to 0.3 ppm (Morphix Technologies 2017). Exposure to 0.5 ppm of NO_2 for 5 h produces a reading equivalent to 0.04 ppm of ozone.

Exposure to 1 ppm of NO_2 for 3 h produces a reading equivalent to 0.04 ppm of ozone.

Calculations were performed using IHDataAnalyst Lite Version 1.29 (Exposure Assessment Solutions, Inc., Morgantown, WV, www.OESH.com). IHDataAnalyst Lite Version is a software package used in the practice of industrial hygiene.

Results

Table 1 provides information concerning welding parameters utilized during this work. Welding occurring during short-duration sampling included gas metal arc welding (GMAW) also known as metal inert gas (MIG) welding (Table 2) and gas tungsten arc welding (GTAW) also known as tungsten inert gas (TIG) welding (Table 3) (Althouse et al. 1988). The shield gas was argon.

Tables 2 and 3 contain results from short-duration sampling for ozone during arc welding. Results are arranged in order of increasing concentration, rather than occurrence, for ease of examination. Separated groups of results within a category represent testing of more than one welder. Results presented in Table 2 indicate that ozone levels encountered during production welding (GMAW) can exceed the TLV–TWA of 0.08 ppm for moderate work and peak exposures (the transient limit of 0.24 ppm (3× the TLV–TWA) and the maximum of 0.40 ppm (5× the TLV–TWA) during the duration of the sample). The data from individual workers are log-normally distributed as are the geometric mean values. The geometric means are distributed log-normally.

Ozone was undetectable during GTAW under similar conditions (Table 3). None of the tubes used during GTAW exhibited any change in color and, therefore, no evidence of exposure to ozone.

Levels of ozone measured on an individual who performed a specific task varied considerably. The statistical distribution of values within a category appears to be consistent with the log-normal distribution of data typically obtained in industrial hygiene (Leidel et al. 1977). That is, while most of the numbers are small, high values occur as well. Values obtained during this study were presented in ascending manner in order to highlight this distribution.

The distribution of ozone levels between individuals who performed the same or a similar task varied considerably. This suggests considerable variation in individual work style and spatial relationship between the torso, the arc, and the plume. The data suggest that no single posture or orientation produced consistently lower or higher exposures. That is, high levels occurred when the welder hunched over the arc on horizontal surfaces, as well as when work occurred overhead and on vertical surfaces. The data also suggest that ozone levels were no higher during work in the structure than in the open shop. What created the exposure was the spatial relationship between the position of the arc, the torso, and the bounding surfaces, such as side sheets and frame structures.

Tables 4 and 5 present results from long-duration sampling for ozone. Samples are listed by job title and activity. All of the samples reported on exposure to ozone during GMAW (MIG welding). GTAW (TIG welding) was not sampled because of absence of detectable ozone during short-duration sampling. That is, only the GMAW samples had measured levels above the level of detection and the GTAW samples all had values below the level of detection. Long-duration samples on production welders (GMAW) covered various structural geometries and welding orientations. The vast majority of long duration samples showed no color change or color change, indicating a reading at or below the integrated level of detection of 0.08 ppm x h, the minimum quantifiable integrated exposure specified by the manufacturer.

When converted to concentration averaged over the duration of the sample, none of the exposures equalled or exceeded the TLV–TWA of 0.08 ppm. The highest concentration averaged over the duration of the sample was 0.03 ppm. Levels of ozone

Table 1 Welding parameters during sampling for ozone

Parameter	Current Amperes	Voltage Volts
GMAW (MIG welding)		
Horizontal fillet weld (5083 base material, ER-5183 wire, 1.2 mm diameter)	190 to 240	24 to 25
Vertical up fillet weld (5083 base material, ER-5183 wire, 1.2 mm diameter)	160 to 190	24 to 25
Overhead fillet weld (5083 base material, ER-5183 wire, 1.2 mm diameter)	180 to 220	24 to 25
GTAW (TIG welding)		
Horizontal fillet weld (5083 base material, filler rod 2.5 mm, 5083 base material)	235	26
Vertical up fillet weld (5083 base material, filler rod 2.5 mm, 5083 base material)	212	25
Overhead fillet weld (5083 base material, filler rod 2.5 mm, 5083 base material)	240	25

Current shall not vary more than ± 15% for both processes. Voltage shall not vary more than ± 10% for both processes. When using 6061 base material, current and voltage are higher. CSA-CWB W47.2 Aluminum [CSA Group 2011)] was followed during this work

Table 2 Short-duration sampling for ozone during GMAW (MIG welding)

	Concentration		
Location/description	Measured levels (ppm)	Geometric mean (ppm)	Geometric standard deviation
Production welding, GMAW (MIG welding)			
A2 automated welding machine, no ventilation	< 0.02, 0.04, 0.12, 0.14, 0.14	0.07	2.4
	< 0.02, < 0.02, 0.02, 0.04, 0.06, 0.12, 0.14, 0.16	0.05	2.5
A2 automated welding machine, local exhaust ventilation	0.03, 0.05, 0.06, 0.06, 0.12, 0.14	0.07	1.8
	< 0.02, 0.02, 0.03, 0.10, 0.13	0.04	2.5
"Bug" automated welding machine, no ventilation	0.46, 0.94	0.66	Not applicable
	0.16, 0.24, 0.36, 0.60, 0.64	0.35	1.8
	0.16, 0.28, 0.36, 0.60, 0.60	0.36	1.8
"Bug" automated welding machine, local exhaust ventilation	0.10, 0.14, 0.14, 0.15, 0.30, 0.30	0.17	1.6
	0.04, 0.10, 0.24, 0.24, 0.24, 0.30, 0.40, 0.50	0.21	2.3
Horizontal welding on frames at floor level	0.1, 0.2, 0.3	0.18	1.7
Horizontal welding on frames at waist level	< 0.04, < 0.04, < 0.04	< 0.04	Not applicable
	0.3, 0.3	0.3	Not applicable
Horizontal welding on deck surface (floor level)	0.3, 0.5	0.4	Not applicable
	0.1, 0.2, 0.2	0.16	1.5
Horizontal welding overhead on seam between the keel and side sheet	0.2, 0.3, 0.3, 0.4, 0.4	0.31	1.3
Horizontal welding overhead inside engine bed on bottom sheet	< 0.02, < 0.02, < 0.02, 0.04, 0.04, 0.06	0.03	1.6
	< 0.02, 0.03, 0.04, 0.06, 0.10, 0.13	0.05	2.1
Horizontal welding on side sheet under splash rail	< 0.04, 0.2	0.12	Not applicable
	< 0.04, < 0.04	< 0.04	Not applicable
Horizontal welding on side sheet inside frames (inside the structure)	< 0.04, < 0.04, 0.2, 0.2, 0.2, 0.3	0.13	2.5, not applicable
Vertical welding on side sheet	< 0.04, 0.06, 0.1, 0.1, 0.1, 0.4, 0.6	0.13	2.7
Summary		0.12	2.8

The lower level of detection < 0.02 ppm versus < 0.04 ppm reflected the number of pump strokes. The comment in the Abstract refers to terms used in the TLV booklet for peak exposures (excursion and maximum). These values apply where the TLV does not contain a ceiling limit. As explained in the text, ACGIH states that these values, in the context in which they are applied, are not to be exceeded. This means that exceedance of a TLV–TWA could occur because of exceedance of values corresponding to terms described in the section on peak exposures and not because of exceedance of the TWA itself. Peak exposures carry weight in workplace regulations (for example, WorkSafeBC in British Columbia, Canada) where they are specifically identified in the OH&S Regulation

expressed as time-weighted average exposures (during the duration of the sample period) were the same irrespective of orientation of the welder to the arc or extent of confinement of the space.

Discussion

Measurement of exposure of welders and workers involved in related tasks to ozone is difficult, complex, and frustrating. This occurs because of superimposition of a highly discontinuous process involving high-level production of ozone of short duration onto a long-duration, possibly non-zero baseline.

There is a necessity to reconcile the seeming inconsistency between measurements obtained during welding using short-duration sampling devices with those obtained during long-duration sampling. The integrated limit of detection of the long-duration sampling device is 0.08 ppm x h (Morphix Technologies 2017). This value corresponds to 0.08 ppm x h × 60 min/h = 4.8 ppm x min. Similarly, exposure at the level of the TLV–TWA of 0.08 ppm of ozone during the work shift of 8 h would produce a reading of 0.08 ppm × 8 h = 0.64 ppm x h or 38.4 ppm x min. The geometric mean of

Table 3 Short-duration sampling for ozone during GTAW (TIG welding)

Location/description	Concentration (ppm) Measured levels	Geometric mean	Geometric standard deviation
Touch-up welding, GTAW (TIG welding)			
Horizontal welding overhead inside frames (inside structure)	< 0.04, < 0.04, < 0.04, < 0.04, < 0.04	< 0.04	Not applicable
Horizontal welding on bottom surfaces inside frames (inside structure)	< 0.04	Not applicable	Not applicable
Horizontal welding on side sheet inside frames (inside structure)	< 0.04, < 0.04, < 0.04, < 0.04, < 0.04	< 0.04	Not applicable

The lower level of detection < 0.02 ppm versus < 0.04 ppm reflected the number of pump strokes

the exposures (0.12 ppm) in Table 2 and duration of exposure of 75 s (1.25 min) per weld contribute a mean integrated exposure of 0.12 ppm × 1.25 min/weld = 0.15 (ppm x min)/weld to the long-duration sampler. To reach the integrated limit of detection would require exposure to ozone from 4.8 ppm x min × (weld/0.15 ppm x min) = 32 welds.

The preceding calculation provides the way to show that integrated exposure (concentration × time) measured using short-duration sampling devices such as detector tubes can fit within the envelope of 4.8 ppm x min without detection by the long-duration sampler. This situation potentially can explain the lack of detectability of ozone during assessment using long-duration sampling technologies such as the ChromAir badge. The number and duration of welds occurring during the sampling period determine the response. Maximizing the number of welds during the sampling period is critical to the success of this strategy.

Long-duration occurred on average for 410 min during this investigation. This period covered the work performed by welders and other workers in this shipyard. Obtaining coverage of all welds performed during the sampling day was critical to maximizing potential for achieving the integrated limit of detection of the badge. Sampling for fewer than the total number of welds required to achieve the integrated limit of detection would compromise the value of the sample because of the accompanying uncertainty.

Ozone levels in ambient air ranging from 0.025 to 0.040 ppm in measurements made worldwide (Reid et al. 2008) could complicate this situation. Without measurement of ozone in ambient air, the question then becomes what is the origin of ozone in measurements provided by the badge, ambient air, or welding activity? A background level of 0.025 ppm of ozone for sampling time averaging 410 min as occurred during this study would contribute 0.025 ppm × 410 min = 10.25 ppm x min to the loading on the badge. This would exceed the loading (4.8 ppm x min) at which ozone is detectable on the badge.

Detector tubes can measure airborne concentration in short-term samples that are not detected on the diffusion badges. Some of this discrepancy also may result from active sample collection produced by the detector tube–pump combination versus passive sample collection by the diffusion badge. Another possible aspect is the integrating nature of the diffusion process in what essentially is an instant-on—high-level—instant-off type of signal.

Although none of the exposures measured as a time-weighted average over the duration of the sample exceeded the TLV–TWA (Tables 4 and 5), many of the short-duration samples measured during welding (Tables 2 and 3) did so. Coincident with adoption of the TLVs informally as guidelines or as regulatory limits is adoption of the transient and maximum (ACGIH 2018). ACGIH indicates that peak values may exceed 3× the TLV–TWA for no more than 30 min or 5× at any time, in both cases provided that the TLV–TWA is not exceeded. In the case of ozone, the transient (30 min) is 0.24 ppm and the maximum, 0.4 ppm, for moderate work.

In the first case, the level on the long-duration sample during the total of all peak exposures would be 30 min × 0.24 ppm = 7.2 ppm min or 0.12 ppm h. As discussed, the vast majority of long duration samples (Tables 3 and 4) read at or below the threshold level of 0.08 ppm x h over the duration of the sample. The two samples that exceeded 0.08 ppm x h read 0.2 ppm x h. These levels correspond to average concentrations of 0.01 ppm to 0.03 ppm during the duration of the sample. These results suggest that welding occurred during the period of the sample in small amounts. The likelihood that the work occurred during the period of 30 min within the considerably longer duration of the sample was very small.

Some of the readings contained in Tables 2 and 3 for short-duration sampling exceeded the transient limit of 0.24 ppm and the maximum of 0.4 ppm. These exceedances occurred primarily during overhead work and operation of the automated welding machine. Installation of local exhaust ventilation on the “bug” greatly reduced exposure of the operator to ozone produced by this equipment. Failure of the long-duration samples to exceed the 8-h TLV–TWA of 0.08 ppm during the sampling period (< 8 h) suggests that exceedance of the TLV because of exceedance of the

Table 4 Long-duration sampling for ozone: tasks unrelated to welding and automated production welding (GMAW or MIG welding)

Location/description	Duration (min)	Color change	Loading (ppm x h)	Average concentration (ppm)
Tasks unrelated to welding				
Clean-up labourer	404	None	< 0.08	< 0.01
Ventilation provider	392	None	< 0.08	< 0.01
Fabricator (milling, grinding)	437	None	< 0.08	< 0.01
	442	None	< 0.08	< 0.01
Fitter				
Various weld orientations	384	None	< 0.08	< 0.01
	360	None	< 0.08	< 0.01
	389	None	< 0.08	< 0.01
	376	None	< 0.08	< 0.01
	388	None	< 0.08	< 0.01
	391	None	< 0.08	< 0.01
	390	None	< 0.08	< 0.01
Tacker				
Various weld orientations	407	None	< 0.08	< 0.01
	392	None	< 0.08	< 0.01
	418	None	< 0.08	< 0.01
	412	None	< 0.08	< 0.01
	371	None	< 0.08	< 0.01
	417	None	< 0.08	< 0.01
Automated welding machine operator (horizontal surfaces)				
Digi-pulse	360	Threshold	0.2	0.03
	470	None	< 0.08	< 0.01
	300	None	< 0.08	< 0.02
"Bug"	435	Threshold	0.08	0.01
	305	Light	< 0.08	< 0.02
	370	Threshold	0.08	0.01
	441	Threshold	0.08	0.01
A2	423	Trace	< 0.08	< 0.01
	435	Light	< 0.08	< 0.01
	432	Trace	< 0.08	< 0.01
	445	Threshold	0.08	0.01
Average (*n* = 28)	400			

The lower level of detection < 0.01 ppm versus < 0.02 ppm reflected the duration of the sample

transient limit of 0.24 ppm in some measurements would be difficult to prove using current technology.

Exceedance of the maximum although occurring in only a limited number of situations is a greater concern because of the necessity to use respiratory protection and local exhaust ventilation. Use of respiratory protection and effective use of local exhaust ventilation are mandatory during work in these situations when the regulator having jurisdiction adopts TLVs in their entirety as exposure limits. NIOSH (National Institute for Occupational Safety and Health) recommends use of a supplied-air respirator in exposures up to 1 ppm of ozone (NIOSH 2007). NIOSH does not approve use of a cartridge for fear of a risk of fire. Cartridges containing charcoal were used in photocopiers to adsorb and to destroy ozone and in some instruments for the same purpose (Thermo Electron 2004). Some manufacturers utilize cartridges containing charcoal. Given this knowledge and testing of charcoal respirator cartridges after exposure to welding plumes, one manufacturer of respirators has recommended use of charcoal in cartridges for protection against ozone to 10× the exposure limit (in the case of the TLV for moderate work, 0.8 ppm) (3M 2009). In this respect, ozone is a critical contaminant during GMAW (MIG welding).

Coincident with investigation of the work discussed here, experience showed the importance of another consideration, namely eye irritation. As discussed previously, the

Table 5 Long-duration sampling for ozone: manual production welding (GMAW or MIG welding)

Location/description	Duration (min)	Color change	Loading (ppm x h)	Average concentration (ppm)
Downward welding				
Horizontal surfaces, open area	440	Threshold	0.08	0.01
	436	Threshold	0.08	0.01
	403	Light	0.08	0.01
	403	Light	0.08	0.01
Horizontal welding				
Vertical surface, open top	407	Trace	0.08	0.01
	427	Trace	0.08	0.01
	417	Trace	0.08	0.01
	391	Trace	< 0.08	< 0.01
	395	Trace	< 0.08	< 0.01
Vertical surface, closed top	418	None	< 0.08	< 0.01
	455	Trace	< 0.08	< 0.01
	443	None	< 0.08	< 0.01
	430	Trace	< 0.08	< 0.01
	388	None	< 0.08	< 0.01
	455	None	< 0.08	< 0.01
	410	None	< 0.08	< 0.01
	400	Trace	< 0.08	< 0.01
	385	Trace	< 0.08	< 0.01
Vertical welding				
Vertical surface, void space	460	Threshold	0.08	0.01
Vertical surface, void space	490	Light	< 0.08	< 0.01
Vertical surface, void space	480	Trace	< 0.08	< 0.01
	483	Threshold	0.08	0.01
Vertical surface, wet deck	470	Threshold	0.08	0.01
	480	Trace	< 0.08	< 0.01
Overhead welding				
Jet tube	225	Trace	< 0.08	< 0.02
	403	Light	0.08	0.01
	380	Light	0.08	0.01
Spaces formed by bottom sheet and girders in inverted engine bed	440	Trace	< 0.08	< 0.01
	420	Trace	< 0.08	< 0.01
	423	Threshold	0.08	0.01
	395	Light	0.2	0.03
	395	None	< 0.08	< 0.01
Average (*n* = 32)	420			

The lower level of detection < 0.01 ppm versus < 0.02 ppm reflected the duration of the sample

conjunctival membranes in the eye are susceptible to attack as are mucus membranes in the respiratory system (ACGIH 2001). On a practical level, eye irritation from exposure to ozone is as much a reason for taking protective action as is provision of respiratory protection based on exceedance of the TLV–TWA and the maximum. Eye irritation appears to reflect individual susceptibility. Hence, eye irritation can occur at levels of ozone that may not exceed the TLV–TWA. Eye irritation at the concentration of exposure could be the deciding factor in determining the appropriate type of respiratory protection for some individuals.

The options for protecting the eyes from exposure to ozone in a welding environment are limited. These include tight-fitting chemical splash goggles and full-facepiece respirators. Chemical splash goggles are difficult to wear under a welding helmet as an additional item of personal protection and may not provide a gas-tight seal and may impair protection afforded by the welding helmet. Manufacturers market full-facepiece respirators combined with eye protection for welding to address this situation.

NIOSH recommends the use of full facepiece respirators, helmets, or hoods for routine exposure to contaminants that cause any irritation of the mucus membranes of the conjunctiva (transparent membrane that covers the white of the eye and underside of eyelids) or the cornea (outer transparent surface of eye) or causes any reflex tearing (Bollinger 2004). Eye protection also is required for contaminants that cause minor subjective effects, as well as those that cause damage. Damage includes disintegration and sloughing of the conjunctival or corneal epithelium, as well as edema (swelling) or ulceration. NIOSH also recommends against the use of goggles in this application.

Conclusion

Assessing exposure to ozone during welding is complicated and poses complex issues. Compounding these issues are the short-duration bursts of ozone production superimposed onto long periods of exposure at background levels. Short- and long-duration samplings are needed to enable understanding about exposure to ozone during arc welding on aluminum alloys. Integration of short- and long-duration measurements is possible through calculation that compares the response of the sampling devices. Ozone is a critical contaminant during GMAW (MIG welding). As such, ozone may control the type and level of measures needed to satisfy requirements for regulatory compliance during GMAW (MIG welding). Ozone was undetectable during GTAW (TIG welding).

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

3M (Minnesota Mining and Manufacturing) (2009) 2009 Respirator selection guide. 3M, Occupational Health and Environmental Safety Division, St Paul

ACGIH (American Conference of Governmental Industrial Hygienists) (2001) Ozone. In Documentation of the TLVs[7] and BEIs[7]. American Conference of Governmental Industrial Hygienists, Cincinnati, [CD-ROM]

ACGIH (American Conference of Governmental Industrial Hygienists) (2018) TLVs and BEIs for chemical substances and physical agents & biological exposure indices. American Conference of Governmental Industrial Hygienists, Cincinnati

Althouse AD, Turnquist CH, Bowditch WA, Bowditch KE (1988) Modern welding. Goodheart-Willock Company, Inc., South Holland

Bollinger N (2004) NIOSH respirator selection logic (DHHS (NIOSH) Publication No. 2005-100). Department of Health and Human Services (US), Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, Cincinnati

CSA Group (2011) Certification of companies for fusion welding of aluminum (CAN/CSA W47.2-11). CSA Group, Mississauga

Dräger (2011) Dräger—tubes & CMS—handbook. Dräger Safety, Lubeck

Goller JW, Paik NW (1985) A comparison of iron oxide fume inside and outside of welding helmets. Am Ind Hyg Assoc J 46:89–93

Leidel NA, Busch KA, Lynch JR (1977) Occupational exposure sampling manual (DHEW (NIOSH) Publication No. 77-173). Department of Health, Education, and Welfare (US), Public Health Service, Center for Disease Control, National Institute for Occupational Safety and Health, Cincinnati

McManus TN, Haddad AN (2013) UV and blue light exposures in an aluminum shipbuilding environment. Int J Open Scient Res 1(6): 15–27

McManus TN, Haddad AN (2014) Use of methanol as a coolant during machining of aluminum in a shipbuilding environment: a failure to assess and manage risk. Adv Mater Res 955-959:1061–1064. https://doi.org/10.4028/www.scientific.net/AMR.955-959.1061

McManus N, Haddad AN (2015a) Oxygen levels during welding assessment in an aluminum shipbuilding environment. Prof Saf 60(7):26–32

McManus N, Haddad AN (2015b) Argon-related fatigue: an investigation in an aluminum shipbuilding environment. Prof Saf 60(10):47–55

McManus TN, Haddad AN (2016) Chromium emissions during welding in an aluminum shipbuilding environment. Weld J 95(03):86-s–92-s

Morphix Technologies (2017) ChromAir System. Operating instructions for ozone monitor (Part Number 380010). Morphix Technologies, Virginia Beach

NIOSH (National Institute for Occupational Safety and Health) (1988) Criteria for a recommended standard, welding, brazing, and thermal cutting (DHHS (NIOSH) publication no. 88–110). Department of Health and Human Services (US), Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, Cincinnati

NIOSH (National Institute for Occupational Safety and Health) (2007) NIOSH pocket guide to chemical hazards (DHHS (NIOSH) Publication No. 2005-149, August 2006 with minor technical changes, September 2007, with minor technical changes). Department of Health and Human Services (US), Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health, Cincinnati

Reid N, Yap D, Bloxam R (2008) The potential role of background ozone on current and emerging air issues: an overview. Air Qual Atmos Health 1:19–29

Seinfeld JH, Pandis SN (1998) Atmospheric chemistry and physics—from air pollution to climate change. Wiley, New York

Thermo Electron (2004) Model 42C, chemiluminescence NO-NO_2-NO_x analyzer. Thermo Electron Corporation, Franklin

White WH (2009) Considerations in the use of ozone and $PM_{2.5}$ data for exposure assessment. Air Qual Atmos Health 2:223–230

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