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Profiling Mild Steel Welding Processes to Reduce Fume Emissions and Costs in the Workplace

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Abstract

To provide quantitative information to choose the best welding processes for minimizing workplace emissions, nine gas metal arc welding (GMAW) processes for mild steel were assessed for fume generation rates, normalized fume generation rates (milligram fume per gram of electrode consumed), and normalized generation rates for elemental manganese, nickel, and iron. Shielded metal arc welding (SMAW) and flux-cored arc-welding (FCAW) processes were also profiled. The fumes were collected quantitatively in an American Welding Society-type fume chamber and weighed, recovered, homogenized, and analyzed by inductively coupled atomic emission spectroscopy for total metals. The processes included GMAW with short circuit, globular transfer, axial spray, pulsed spray, Surface Tension Transfer™, Regulated Metal Deposition™, and Cold Metal Transfer™ (CMT) modes. Flux-cored welding was gas shielded, and SMAW was a single rod type. Results indicate a wide range of fume emission factors for the process variations studied. Fume emission rates per gram of electrode consumed were highest for SMAW (~13 mg fume g^{-1} electrode) and lowest for GMAW processes such as pulsed spray (~1.5 mg g^{-1}) and CMT (~1 mg g^{-1}). Manganese emission rates per gram of electrode consumed ranged from 0.45 mg g^{-1} (SMAW) to 0.08 mg g^{-1} (CMT). Nickel emission rates were generally low and ranged from ~0.09 (GMAW short circuit) to 0.004 mg g^{-1} (CMT). Iron emission rates ranged from 3.7 (spray-mode GMAW) to 0.49 mg g^{-1} (CMT). The processes studied have significantly different costs, and cost factors are presented based on a case study to allow comparisons between processes in specific cost categories. Costs per linear meter of weld were $31.07 (SMAW), $12.37 (GMAW short circuit), and $10.89 (FCAW). Although no single process is the best for minimizing fume emissions and costs while satisfying the weld requirements, there are several processes that can minimize emissions. This study provides information to aid in those choices. Suggestions for overcoming barriers to utilizing new and less hazardous welding processes are also discussed.

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Keywords

flux-cored arc welding; fume emissions reduction; fume generation rates; gas metal arc welding; manganese generation; nickel generation; welding costs; welding fumes

INTRODUCTION

Welding is an important occupational activity in the USA and worldwide and includes workers in many industries, especially in the manufacturing, construction, energy, and transportation sectors. The US Bureau of Labor Statistics (2006) estimated that in excess of 330 000 US workers do welding as part of their jobs. About two-thirds of those workers were in manufacturing industries. Welding produces multiple hazards during operation, including fumes, gases, and physical agents such as extreme heat and ultraviolet radiation. A review by Antonini (2003) detailed a number of occupationally related adverse health effects in welders, such as lung disease and possible neurological disease. The National Institute for Occupational Safety and Health (NIOSH, 2007) Work-Related Lung Disease Surveillance Report indicates proportionate mortality ratios of 1.58 for pneumoconiosis and 1.21 for lung cancers for welders.

Common welding configurations

Welding-based hazard analysis is dependent on an understanding of the range of welding processes and conditions. NIOSH (1988) lists >80 different welding processes, but most welding is done with electrical arc-welding processes. The most prevalently used variations, based on materials consumed, are shielded metal arc welding (SMAW or stick welding or manual metal arc welding) ~45%, gas metal arc welding (GMAW) ~34%, and flux-cored arc welding (FCAW) ~17%, according to a US Environmental Protection Agency review (1994).

SMAW has minimal equipment needs: a power supply, an electrode holder, welding rods, and a ground clamp. The welding rods have a coating over the filler metal rod that provides a shielding environment to minimize degradation of the weld by atmospheric gases. The SMAW flux not only shields the weld but also removes impurities and solidifies as a slag on top of the weld bead, which then must be removed after welding. GMAW uses more complex equipment; besides a power supply, it uses a gas-shielded torch or gun, and the electrode is a consumable wire of the desired filler metal fed by a motorized feeder. The shield gas is supplied from cylinders. Shield gases range from the completely inert [argon (Ar), helium (He), and their mixtures] to active gases, which include carbon dioxide (CO_2), Ar mixtures with CO_2 or oxygen (O_2), and other gas mixtures; these gases may have chemical interactions with the weld or fume. FCAW uses equipment similar to GMAW, but the wire electrode has an internal flux material for weld shielding; the process may be used with or without shield gas. The slag from FCAW is generally a smooth coating on the weld bead that is easily removed, while SMAW slags are generally removed with a chipping hammer, wire brush, or grinder. Both SMAW and FCAW have significant advantages when welding on painted, coated, or contaminated surfaces, relative to other processes.

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Metal transfer modes in GMAW

GMAW differs from other arc-welding processes in that more than one mode of metal transfer from the electrode into the weld pool is possible. At low voltages, the process is called short circuit (SC) GMAW. The electrode wire is in direct contact with the weld pool, and a portion melts and is transferred into the weld pool. The melting breaks the SC, starting the arc. The arc is intermittent (up to hundreds of times per second) and not perfectly stable, which may generate spatter, where relatively large droplets are deposited outside the weld bead. During the SC phase, the magnetic field surrounding the wire creates a force inward, proportional to the voltage, which squeezes the molten wire to a smaller diameter and decreases its cross section, increasing its resistance. At the same time, inductance in the welding unit increases the voltage to keep the current constant. This is an unstable system with positive feedback that quickly 'pinches off' the molten wire and initiates the arc. Several techniques have been developed to tightly regulate pinch off, including Surface Tension Transfer™ (STT; Lincoln Electric, Cleveland, OH, USA), Regulated Metal Deposition™ (RMD; Miller Electric, Appleton, WI, USA), and Cold Metal Transfer™ (CMT; Fronius USA LLC, Brighton, MI, USA). STT and RMD precisely control the current until conditions are optimal for transfer of the molten metal drop into the weld pool, and CMT uses current control and a backward wire movement to achieve similar results.

When the voltage is increased above SC conditions, another mode of operation known as globular transfer (GT) occurs. The wire end melts, forming large drops that are larger than the wire diameter. The droplets fall by gravity into the weld pool, which limits usage to flat welding positions; this mode is generally avoided because of severe spatter problems.

As the applied voltage is further increased and when using shield gases contain high percentages of Ar, there is a transition to axial spray (AXS) transfer mode. Metal leaves the electrode wire tip and is transferred as a very fine spray into the weld pool, producing a high-quality weld with lower spatter. The technique is used primarily in flat or horizontal situations; overhead or vertical use may have drip problems. A modification of axial spray transfer is pulsed spray transfer (AX-P), where current pulses are added to a steady-state background current; this allows the total current to transiently exceed the required transition current and permit spray mode. This produces high-quality welds in any position with lower heat and a low fume generation rate.

A number of welding process emission studies have been done for various welding types, such as SMAW (Tandon *et al.*, 1984), flux-cored (Moreton *et al.*, 1981), and gas metal arc (Quimby and Ulrich, 1999; Keane et al., 2009, 2012), but methodologies and data content varied considerably. The objectives of this study were to assess a wide spectrum of arc-welding processes for fume generation rates and identify the best choice or choices one could select to minimize fume emissions at the source and to compare costs of the processes studied.

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MATERIALS AND METHODS

Plate preparation, welding operation, and fume generation

Welding was done in a conical chamber based on an American Welding Society (2006) design for a chamber to measure fume generation rates and met the performance criteria. Welding wire was ER70S-3, 1.14 mm (0.045 in) diameter, fed from a 15 kg (33 lb) reel for all GMAW processes except CMT, which used 0.89 mm (0.035 in) wire. FCAW used E71T-1C wire, while SMAW generation used 7018 H4R 4.8 mm (3/16 in) rods; this rod diameter was chosen to provide metal feed rates comparable with the other processes.

The basic welding system for GMAW processes (SC, GT, AXS, and AX-P) used a multiprocess welder (350MP, Lincoln Electric). RMD used a Miller Electric Pipeworx™ welder, and CMT used a Fronius TPS 2700. STT welding used a Lincoln Electric PowerWave™ 455M with a Powerfeed™ 10M wire feeder with STT capability.

Shield gas was taken from cylinders at a flow rate of 19 l min^{-1}. The welding baseplates were 12.7 mm (0.5 in) thick A36 steel, 56 cm (22 in) diameter disks; mill scale was removed by acid treatment followed by grinding to leave a bright surface finish. Operation with all shield gases and welding process types used similar conditions but was adapted to good welding practice, within the ranges recommended by welding consumables manufacturers. All welding operations were adjusted for good bead appearance with good penetration of the baseplates and good toe wetting and no undercut. Baseplates were rotated at the desired rotary speed to provide a travel rate consistent with good welds. A welding turntable was modified for external control by Labview (National Instruments, Austin, TX, USA) program. Rotary speed was measured by an encoder on the output shaft and input to the program and the travel rate displayed continuously during operation. Welder operation was done under program control to precisely control arc time. Operating variables are shown in Table 1 below.

Sampling strategies

Fumes from the weld area were sampled through a 102 mm filter at the top of the chamber at 200 l min^{-1}. This high flow rate sampling was applied to collect welding fume particles as fresh as possible so that potential effects due to aging can be avoided and did not appear to affect the weld. The potential aging effects include an increase in particle size due to potential thermal coagulation and a reduction of particle concentration as a result of wall loss due to diffusion, which in turn would provide inadequate information for fume particle characterization. The approximate chamber aerosol concentration was monitored with a Data RAM 4000 (Thermo Electron, Franklin, MA, USA). The filter material was Hollingsworth and Vose (East Walpole, MA, USA) electrostatic medium (PE 13060NA), cut to fit the filter housing. The flow was measured with a mass flow meter (TSI, Shoreview, MN, USA) before sampling. After sampling was completed, filters were removed from the housing, folded inward, weighed to the nearest 0.1 mg, and kept in sealed antistatic polyethylene bags. Fume generation rates were calculated by dividing the net mass of fume collected by the sampling duration in minutes. In order to allow comparison of processes on an equal mass basis, however, fume generation rates need to be normalized with respect to

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the mass consumption rates, which is the product of the wire feed rate (inch per minute) and measured wire or rod density (gram per inch).

Sample recovery and processing

Welding fume was recovered from the filters by gentle suction onto a 47 mm, 0.8 μm polycarbonate filter. The stainless steel filter housing had a short piece of 6 mm ID silicone tubing, cut at 45° on the inlet end, and house vacuum was connected to the outlet. Using a gentle blotting action, most of the fume was removed from the filter. Sufficient quantity from the sample was collected for metals analysis. After collection, the polycarbonate filter was removed from the housing over a tared 75 × 75 mm weighing boat, and material brushed from the filter and housing interior with a #3 artist's brush. The fume was treated with an antistatic device (Zerostat™, Fisher Scientific) at this point to prevent losses. The fume was added to a disposable 13 mm diameter × 25 mm long polyethylene vial with two 3.2 mm silicon-nitride-coated ceramic balls and shaken for 30 s in a Wig-L-Bug™ grinder. After grinding, the material was antistatic treated again and weighed into 20 ml scintillation vials with polytetrafluoroethylene (PTFE)-lined caps. Storage in the vials was at room temperature, in air, and vials remained closed unless samples were removed for analysis; a previous study (Keane *et al.*, 2009) indicated that samples were stable after 3-month storage using this procedure.

Metal analysis

For metals analysis, 5.0 mg of each welding fume sample was weighed in a 15 ml centrifuge tube, and 3 ml of ultrapure HNO_3 (Optima, Fisher Scientific, Pittsburgh, PA, USA) were added, the tube was vortexed, and poured into 55 ml PTFE digestion tubes (CEM, Matthews, NC). The process was repeated with 3 ml, then 4 ml, bringing the total to 10 ml in the digestion tubes. The PTFE tubes were sealed and heated 20 min at 200°C in a MARS microwave digester (CEM, Matthews, NC) and cooled, and the contents transferred to 25 ml volumetric flasks. After filling to 25 ml with 18 MΩ cm H_2O and mixing, samples were diluted 1:100 with 18 MΩ cm H_2O, mixed, and analyzed at Bureau Veritas (Novi, MI) for manganese, nickel, iron, and chromium by inductively coupled plasma atomic emission spectroscopy (ICP-AES). The microwave digestion procedure was effective in solubilizing difficult fume samples in earlier studies (Keane *et al.*, 2012) and also yielded excellent results when used for analysis of reference welding fume samples. All samples were also analyzed for hexavalent chromium, using an ion chromatography method from earlier studies (Keane *et al.*, 2012), because chromium metal is often found at very low levels in plates, wires, and rods from recycling steel.

Relative costs of welding processes

Computation of costs for various processes is usually difficult in absolute terms, but comparisons on a relative basis are often possible. Costs will be considered primarily in three areas: consumables, labor, and equipment. Consumables would include welding rods and wire, shield gases, and other items such as contact tips and nozzles. Labor costs are best computed in relative terms and would include not only actual welding (hot work) time but also preparation, scaling, re-welding, etc. and are often computed as cost per linear meter or

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feet. of weld; labor costs should include wages, benefits and contractor's overhead, etc. Since some welds require multiple passes, such as a root pass as well as multiple fill passes, cost comparisons need to be done on the same types of welds. Equipment costs (welding machines and associated wire feeders) are more difficult to compute since the welding equipment may be acquired, financed, and depreciated in many different ways, or can often be leased. The labor and consumables cost estimates in this study were done on a boiler seal trough plate weld that was divided into three equal lengths of 4.6 m. This job had sufficient scope and adequate space for cost analysis. The weld was an overhead fillet weld on 6.3 mm thick carbon steel. The SMAW required a root pass, one fill pass, slag removal, and grinding for completion. The FCAW weld was a single pass followed by slag removal, and the GMAW was a SC single pass weld with no postwelding work. The overall travel rates (including any postwelding slag removal and grinding) for the three types of welding were 2.5 cm min^{-1} for SMAW, 11.7 cm min^{-1} for FCAW, and 10.4 cm min^{-1} for GMAW (SC).

Statistical issues and data quality

Previous studies in this laboratory (Keane *et al.*, 2012) yielded typical variances for replicate welding runs that assured that four replicates of each welding trial would have more than sufficient statistical power for assuring good quality results.

RESULTS

Results are shown below in Figs 1–5; all results are presented as arithmetic means of four replicate welding runs with the error bars representing the standard error of the means. Total fume generation rates are shown in Fig. 1; results range from 35 (CMT) to almost 400 mg min^{-1} (AXS). As Fig. 2 shows, the normalization has the effect of changing the relative rankings of the processes studied because results are lowered for high wire feed rate processes such as spray, pulsed spray, and FCAW processes, while low wire feed rate processes such as SMAW and SC are increased on a relative basis. Normalized fume generation rates were calculated as the product of the fume generation rate (from Fig. 1 or Table 2), the reciprocal of the wire feed rate (Table 1), and the reciprocal of the wire or rod linear density in gram per meter (measured). As an example, for STT: [88 mg fume min^{-1} × (1 min 125 in^{-1} wire) × (39.37 in m^{-1}) × (1 m wire 7.97 g^{-1} wire) = 3.48 mg fume g^{-1} wire]. Results normalized for mass of electrode consumed ranged from 0.8 (CMT) to 12.5 mg min^{-1} (SMAW). Some studies relate results to amounts of metal deposited rather than consumed; data for percentages of metal deposition are often provided by welding consumables suppliers to allow that calculation. Fume generation rates can also be normalized with respect to weld lengths; results are shown in Table 2 in terms of milligram per meter. Fume generation rates normalized for weld length were calculated as the product of the fume generation rate (Fig. 1 or Table 2) and the reciprocal of the welding travel rate (Table 1); e.g. for STT: [88 mg fume min^{-1} × (1 min 10 in^{-1}) × (39.37 in m^{-1}) = 346 mg fume m^{-1}].

In addition to fume generation and normalized fume generation rates, generation rates of specific metals are also important for estimating exposures and health risk. This information also removes the non-metal components of welding fume, such as fluxes from SMAW and

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FCAW processes, which are major constituents of welding fume for those processes. Figs 3–5 display the normalized generation rates of manganese, nickel, and iron for each process in terms of microgram metal per gram of welding consumable. Metals-normalized generation rates were calculated as the product of the normalized fume generation rate (Fig. 2 or Table 2) and the mass fraction of that metal in the fume, as measured by ICP-AES; e.g. for STT: [3.48 mg fume g^{-1} × 0.06 mg Mn mg^{-1} fume × 1000 μg 1 mg^{-1} = 209 μg Mn g^{-1}].

Samples were also analyzed for chromium (data not shown), but none were above the limit of detection (~0.01 μg); the manufacturer's specified that both Cr and Ni were <0.15% in the welding consumables; small amounts of Cr and Ni are typical from steel recycling. Traces of hexavalent chromium were seen for most samples but at levels very far below the quantitation limit.

Results of fume generation rates, normalized generation rates, and metals generation rates were tightly grouped for all of the processes; in most cases, standard errors were a few percent of the means of the four replicate welding trials.

Labor costs were computed in the course of this study for the overhead fillet weld described above, using SMAW, GMAW, and FCAW welding processes. Labor and consumables costs per linear meter of weld were $31.07 (SMAW), $12.37 (GMAW SC), and $10.89 (FCAW). The only GMAW process used in the cost analysis was SC, but projected costs per meter of weld length for the other GMAW processes in this study can be calculated by correcting by the relative travel rates. Fume generation rates normalized for travel rate can also be calculated, yielding values of milligram fume per meter of weld length. In the case of GT and AXS, these processes could not be used on overhead welds and are purely hypothetical examples. Results are shown in Table 2, with estimated quantities and hypothetical quantities identified.

Equipment costs (low to high) range from SMAW to GMAW and FCAW to pulsed GMAW; the complex-waveform processes (STT, RMD, and CMT) are the most expensive; these capabilities are usually available only on dedicated units or top of the line models. Typical equipment cost ratios compared with a 250 amp capacity SMAW unit are the following: GMAW ~ 1.74; GMAW-pulsed ~ 2.1; STT ~ 2.9; RMD ~ 3.5 and CMT ~ 4.9, but these types of comparisons are at best limited, due to the vastly different features of available welding machines.

DISCUSSION

Fume generation rates spanned a wide range, from ~390 mg min^{-1} for spray-mode GMAW to <40 mg min^{-1} for CMT, an 11:1 ratio overall. Normalized rates covered a 14:1 range, ranging from >12 mg fume g^{-1} of wire consumed (SMAW) to <2 mg g^{-1} for AX-P and CMT, demonstrating there are several good choices for minimizing total fume emissions. For mild steel, SMAW had twice the normalized fume generation rate as the next highest process, and substituting a GMAW process would be a major improvement in situations where high fume exposures would be expected and/or difficult to reduce by engineering controls such as local exhaust ventilation. Normalized generation rates for manganese also

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showed a broad range of values, from 450 μg g^{-1} to ~80 μg g^{-1}. While the SMAW Mn generation rate was the highest, just as for normalized fume rates, and CMT and AX-P likewise the lowest, Mn generation rates for FCAW and AXS were much higher on a relative basis, only slightly less than SMAW. Nickel normalized generation rates were much lower than manganese rates, all were <100 μg g^{-1}. Iron was the dominant metal in the fumes; normalized generation rates ranged from ~3700 to <500 μg g^{-1} wire.

Fume generation rates were generally comparable with other studies. The US Environmental Protection Agency (1994) average emission factors were 18.4 mg g^{-1} for SMAW versus 12.6 in this study and ~12 mg g^{-1} for FCAW versus 4.7 mg g^{-1} found in this study; GMAW (transfer mode(s) unspecified) was 5.2 mg g^{-1}, while the results for the 9 GMAW types studied here ranged from 1 to 6.4 mg g^{-1}. Fume generation rates were also similar although somewhat greater than results from a recent study from this laboratory on stainless steel welding (Keane *et al.*, 2012).

Selecting the best welding process

While the Figures show the various generation rates for fumes and metals, the choices are not as simple as choosing the lowest generation rates for the hazardous agent of interest. First, the process selected needs to be able to produce a competent weld for the specific task. In some cases, there may be severe limitations on what processes can be used, such as in chemical plants, power plants, or nuclear facilities. Certain welds may have a single specified process for certification. Some welding techniques have limitations on thicknesses of the materials, or the welding unit may have special input power requirements, such as three-phase only power. After eliminating unsuitable choices, one can then select the best process to minimize the problem of highest priority, such as total fume or manganese, and further narrow the list. Analysis of costs will further narrow the list of possibilities. Cost estimates may be significantly different, depending on how the equipment is acquired or leased, but the cost estimates for labor and consumables presented in the Results section should be usable for most situations. All of the process choices would need labor costs normalized to equivalent linear travel rates for comparisons.

Barriers to adopting new process choices

Most welders have completed testing and certification for multiple types of SMAW applications and are familiar with overcoming difficulties, while this may not be the case for GMAW and similar processes. Also, the work sequence is different between SMAW and any of the GMAW techniques. A typical SMAW pattern would be to prepare the area for welding, weld until the rod is consumed, go back and chip off the slag from the weld, inspect the weld, and prepare any questionable areas for re-welding. Typically they would then mount a new rod and repeat the sequence. GMAW typically include preparation and then welding continuously as long as the torch cable can reach, unless obstacles are present. This may cause more fatigue, especially for vertical and overhead positions. Training and testing may be necessary, but most GMAW processes, including AX-P, STT, CMT, and RMD, are not especially difficult to learn or use. In some cases, local welding supply outlets or manufacturer's representatives may be able to provide demonstrations or training, or welders with the required training may be able to train other welders. A suggestion for

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easing adoption would be to keep the timing intervals of current practice and keep welding rates (time for completion of a typical weld) similar at the outset even though GMAW processes are often easier and faster than SMAW. Likewise, management may be reluctant to change processes, but demonstration of significantly reduced costs on an ongoing basis can be an effective argument for change.

CONCLUSIONS

For minimizing fume generation rate, fume generation rate per gram of wire, and manganese generation rate per gram of wire, there are several attractive choices shown in this study, including CMT, pulsed spray GMAW, and other GMAW types. This has already been demonstrated in a study covering multiple farm machinery manufacturing plants; industrial hygiene surveys showed consistently lower fume exposures in those facilities when using pulsed spray welding (Wallace *et al.*, 2001). A recent study in power plant shops confirmed that fume and hexavalent chromium exposures from GMAW processes were substantially lower than SMAW and FCAW (Keane *et al.*, 2012). CMT, pulsed spray, STT, and RMD have multiple practical advantages besides low total fume generation rates; they are usable in any position, have low heat input that minimizes warping, and have labor costs per weld significantly lower than SMAW. While there will be situations where they may not be suitable, both would be good choices in many applications, especially where fume may be difficult to reduce by local exhaust ventilation, or similar measures. Compared with SMAW, the most commonly used welding type, any of the GMAW processes examined in this study have a substantial advantage with respect to fume or Mn reduction.

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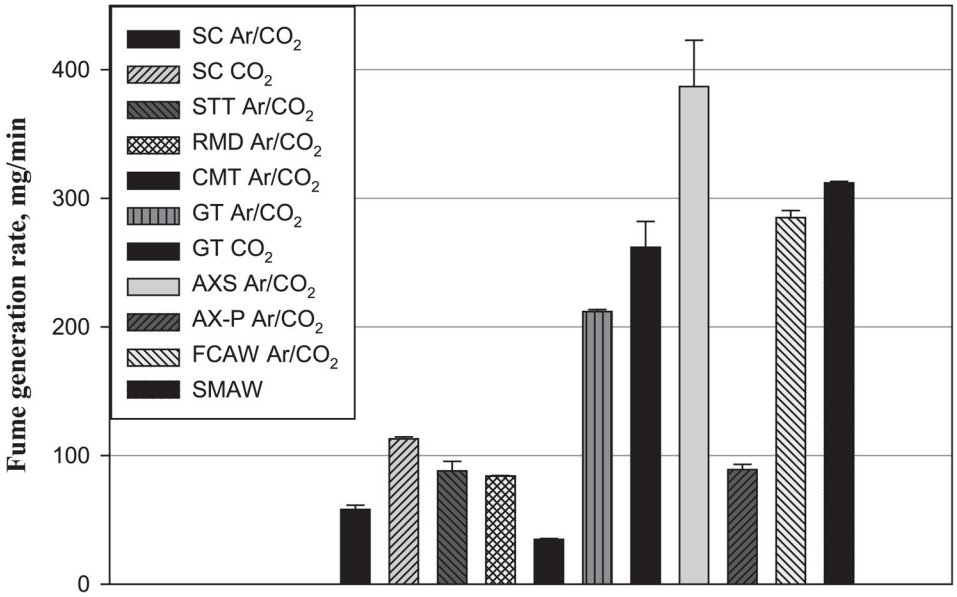

Fig. 1.

Total welding fume generation rates in milligram per minute for 11 processes. (SC: short-circuit; STT: Surface Tension Transfer™; RMD: Regulated Metal Deposition™; CMT: Cold Metal Transfer™; GT: globular transfer; AXS: axial spray; AX-P: pulsed axial spray; FCAW: flux-cored arc welding; SMAW: shielded metal arc welding).

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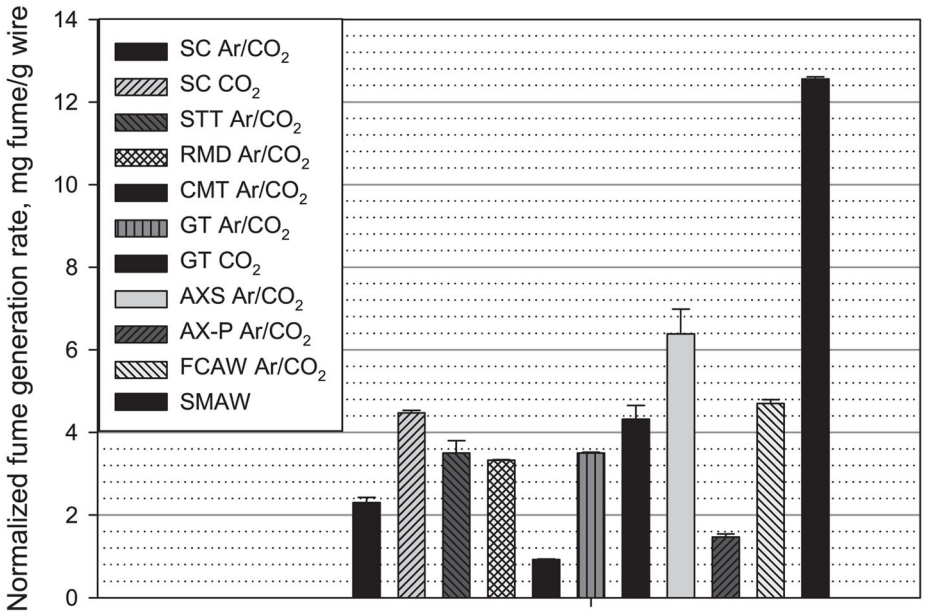

Fig. 2.

Normalized total welding fume generation rates in milligram fume per gram of metal consumed for 11 processes. Normalized fume generation rates were calculated as the product as the fume generation rate, the reciprocal of the wire feed rate, and the reciprocal of the wire or rod linear density in gram per meter.

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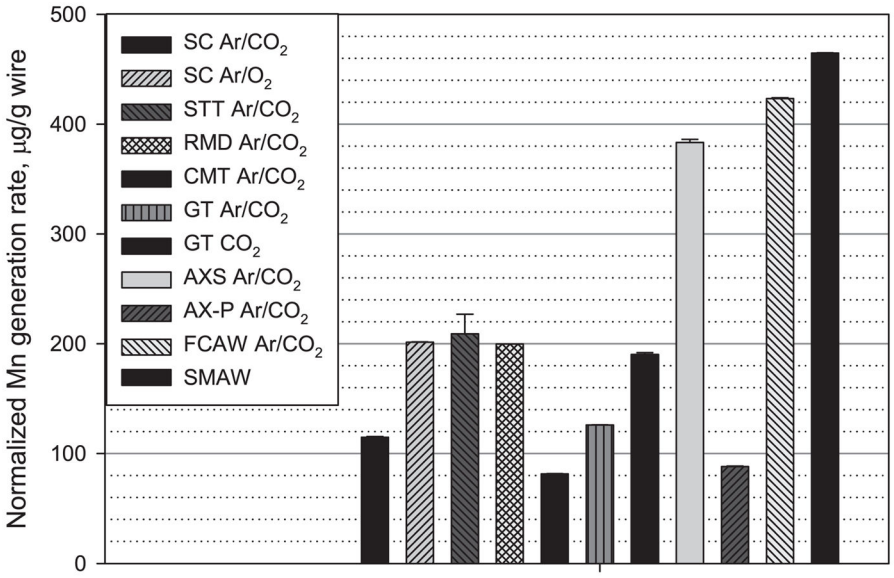

Fig. 3.

Normalized total manganese generation rates in microgram Mn per gram of metal consumed for 11 processes. Metals-normalized generation rates were calculated as the product of the normalized fume generation rate and the mass fraction of that metal in the fume, as measured by ICP-AES.

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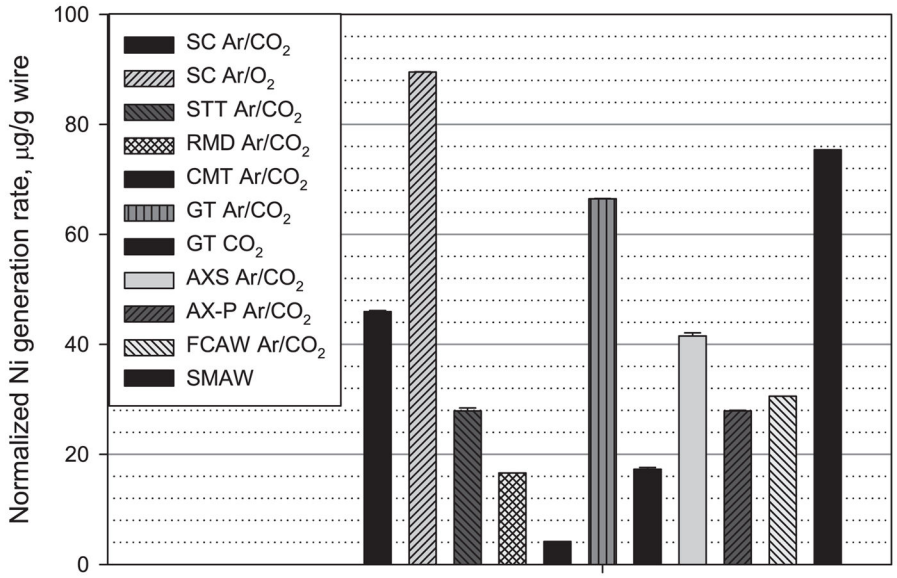

Fig. 4.

Normalized total nickel generation rates in microgram Ni per gram of metal consumed for 11 processes.

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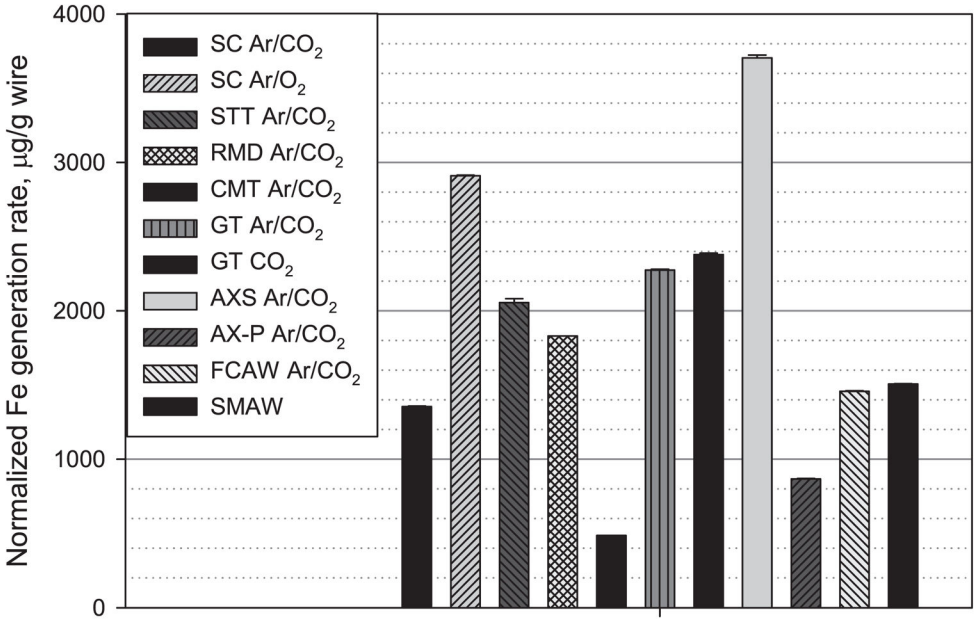

Fig. 5.

Normalized total iron generation rates in microgram Fe per gram of metal consumed for 11 processes.

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Table 1

Operating conditions for welding in the study

Process	Shield gas	Wire feed rate (mm min^{-1}) [in min^{-1}]	Travel rate (mm min^{-1}) [in min^{-1}]	Voltage (V)	Current (A)
GMAW SC	Ar/CO_2 75/25%	3175 [125]	381 [15]	14–16	140–150
GMAW SC	CO_2 100%	3175 [125]	381 [15]	14–16	140–150
GMAW STT	Ar/CO_2 75/25%	3175 [125]	254 [10]	19	130–150
GMAW RMD	Ar/CO_2 75/25%	3175 [125]	381 [15]	19	130
GMAW CMT	Ar/CO_2 75/25%	4775 [188]	381 [15]	11–18	150–160
GMAW AXS	Ar/CO_2 90/10%	7620 [300]	508 [20]	24–26	230–260
GMAW GT	Ar/CO_2 75/25%	7620 [300]	508 [20]	25–26	250–260
GMAW GT	CO_2 100%	7620 [300]	508 [20]	25	250–260
GMAW AX-P	Ar/CO_2 75/25%	7620 [300]	508 [20]	1.1[a]	240
FCAW	Ar/CO_2 75/25%	7620 [300]	508 [20]	26	160
SMAW	N/A	3124 [123]	356 [14]	20	125–150

[a]Voltage trim.

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Table 2

Fume generation rates, normalized fume generation rates, and costs per linear meter of weld and fume generation rates in milligram fume per linear meter for 11 welding processes

Process	Shield gas	Fume generation rate (FGR) (mg min^{-1})	Normalized FGR (mg g^{-1})	Cost ($ linear m^{-1})	FGR (mg linear m^{-1})
Short circuit	Ar/CO_2 75/25%	58	2.3	12.37	152
Short circuit	CO_2 100%	113	4.5	12.37	297
Surface tension transfer	Ar/CO_2 75/25%	88	3.5	18.55[a]	346
Regulated metal deposition	Ar/CO_2 75/25%	84	3.3	12.37[a]	220
Cold metal transfer	Ar/CO_2 75/25%	34.8	0.92	12.37[a]	91
Axial spray	Ar/CO_2 90/10%	212	3.5	9.27[a,b]	417
Globular transfer	Ar/CO_2 75/25%	262	4.3	9.27[a,b]	516
Globular transfer	CO_2 100%	387	6.4	9.27[a,b]	762
Pulsed spray	Ar/CO_2 90/10%	89	1.5	9.27[a]	175
Flux cored	Ar/CO_2 75/25%	285	4.7	10.89	561
Shielded metal arc	N/A	312	12.6	31.07	876

[a] Estimated.

[b] Hypothetical only.