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Title: An analysis of welding fume generation during GMAW: A comparison with previous research results

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Abstract

The formation of welding fumes during gas metal arc welding (GMAW) has been extensively researched, particularly since Germany classified them as hazardous substances in 2005 under the Hazardous Substances Ordinance. This classification has increased focus on measures to reduce welding fumes. Correctly interpreting the processes within the arc is essential for selecting effective measures, as fume emissions result from complex interactions influenced by factors such as electrical power, wire feed speed, and the synergy characteristic curve stored in the welding power source based on shielding gas and filler material. These parameters affect both arc characteristics and material transfer, with alloy component evaporation contributing to fume formation. Various explanations for this phenomenon have emerged, often derived from simulations. This study aims to compile these explanations and evaluate their consistency with existing findings, focusing on fundamental similarities between theoretical approaches and experimental results while critically assessing simplified simulation models.

Keywords

Gas Metal Arc Welding, Welding Parameters, Welding Fume Generation, Comparison

1 Introduction

Gas metal arc welding (GMAW) is an arc welding process using a consumable electrode. The use of the arc as a heat source causes components from the wire electrode to overheat and vaporize. The oxidation of these components outside the shielding gas produces fine particles which agglomerate and are carried into the surrounding air by convection. This is perceived as welding fumes escaping from the process [Pires06, Deam00]. Since 2005, welding fumes have been classified as a hazardous substance, as the fine particles can penetrate deep into the lungs when inhaled [Rose11, Keane14]. In addition, various alloy components are carcinogenic or are suspected of leading to Parkinson's-like sickness [Keane14]. To protect staff, it is therefore essential to keep exposure to a minimum and to reduce welding fume emissions as much as possible. To achieve this, various explanatory approaches have been pursued in the past, describing the formation of welding fumes depending on the material interface. To this end, both experimental and simulation-based approaches have been employed [Pires06, Deam00, Rose11, Boselli13, Tashiro18].

2 Aim of the Investigation

This paper aims to discuss and contextualize theoretical models of various material transitions relating to welding fume emissions in the light of current research findings. To this end, high-speed footage of different process variants will be analyzed on the basis of these theoretical approaches and compared with findings on welding fume emissions. The current findings will be used to review existing assumptions and, where necessary, to supplement them.

3 Materials and Experimental Details

The high-speed images were recorded using a camera manufactured by Photron. The backlighting for the images was generated using a mercury vapor lamp, and the images were illuminated using a laser light source manufactured by Cavilux. The welding fume emission rates were determined in accordance with DIN EN ISO 15011. To this end, the welding fumes are collected on a glass fiber filter and measured gravimetrically. Relative to the welding time, this yields the fume emission rate (FER), which can subsequently be evaluated together with calculated parameters. The parameters are calculated on the basis of current and voltage waveforms, which are measured and recorded at high resolution during welding. Table 1 shows general materials, which are identical for all tests, whilst Table 2 contains the specific process parameters for the different process variants.

Table 1: General used materials for weldments

Filler wire (diameter)	ISO 14341-A-G 3Si1 (1.2 mm)
Shielding gas (flow rate)	ISO 14175-M21-ArC-18 (15 l/min)
Base metal	EN 10277-S235JR, mild steel

Table 2: Welding parameters for investigated process variations

	Spray transfer mode (STM)	Pulsed arc (PA)	Short circuit mode (SCM)
Wire feed speed (wfs) [m/min]	12	10	4
Welding speed (ws) [cm/min]	45	40	20
Contact tip to weldpiece distance (CTWD) [mm]	17	16	12
Mean Power [kW]	Low FER: 8.2 High FER: 13.5	Low FER: 9.2 High FER: 7.0	Low FER: 2.2 High FER: 2.2

4 Results and Discussion

Scientific papers published to date on the physical mechanisms of welding fume formation have focused on different aspects. Furthermore, various approaches have been used to arrive at the results. In addition to experimental methods, semi-empirical, analytical and numerical approaches have been employed. However, when describing the origin of welding fumes, all authors describe similar mechanisms. The studies distinguish between material transfer in short-circuit welding, material transfer in pulsed arc welding and material transfer in spray arc welding [Pires06, Rose11, Chae06]. Apart from this, the same physical conditions apply to all process variants, meaning that welding fumes are primarily generated by the evaporation of metal. When the vapor pressure is exceeded, nucleation and growth of metal vapor droplets occur. This process is described in more detail by Tashiro et al. [Tashiro18]. Oxidation by CO2 or O2 in the shielding gas or atmospheric oxygen leads to the formation of fumes, which are emitted into the environment. Furthermore, according to Pires et al., the active gas content increases the arc temperature and accelerates the evaporation of the droplet [Pires06]. The three main sources of metal vapor are the melting wire end, the free-falling droplet in the arc and the molten pool. However, evaporation from the molten pool is the lowest and, according to Pires et al., amounts to approximately 10 % [Pires06, Pires10]. Consequently, the same particle formation chain applies to the formation of welding fumes for all material interfaces, comprising the following steps:

Evaporation → Supersaturation → Nucleation → Condensation → Coagulation → Oxidation

In addition to the formation of welding fumes from the arc as a direct source, welding spatter has been identified as a further secondary source [Jenkins05]. This is particularly important to note when processes are unstable, and the amount of spatter consequently increases.

Short-arc processes are characterized by the fact that material transfer takes place under short-circuit conditions. The transition occurs periodically and is initiated by the constriction of the melting wire end caused by the rising current after immersion in the molten pool. The arc ignites when the free end of the wire is severed from the molten pool. This keeps the molten pool liquid and melts the free end of the wire. The wire feed ensures that the molten wire end dips into the melt and the cycle repeats. Consequently, at no point is a single free droplet exposed to the high temperature of the arc. Nevertheless, there are specific mechanisms that can lead to increased smoke emission. Deam et al. describe the breakdown of the short circuit caused by a rapid rise in current. [Deam00] In this process, the molten bridge between the wire end and the molten pool bursts, leading to spatter and turbulence in the process. Scotti describes that an increase in FER can also be observed when the short-circuit current, arc length or droplet diameter is increased [Meneses14]. Accordingly, the conclusion drawn from the literature sources considered is that the material transfer during a short circuit generally yields low FER results, as this process condition is achieved at low current [Pires06]. Furthermore, however, the FER can be reduced further if the current is reduced during short-circuit resolution in order to suppress the bursting of the molten bridge.

Pulsed arc processes are characterized by the fact that the current is specifically modulated over time. In conventional pulsed arc processes, there is a periodic alternation between a pulse phase and a base current phase. The material transfer occurs through the detachment of a droplet from the free end of the wire during the pulse phase. The driving force for the constriction above the droplet is the Lorentz force, which is particularly strong during the pulse phase. Gravity[MO1] ensures transfer into the melt. According to Boselli et al., a 2D model specifically for the pulsed metal-shielding-gas process has shown that the metal vapor emanates mainly from the wire tip during the pulse phase. Smoke formation subsequently occurs at the edge of the arc, where the oxygen partial pressure is higher [Boselli13]. Individual large droplets, which are detached in each period, result in a higher volumetric heat capacity. Consequently, metal evaporation is lower during the pulse phase despite a higher peak current [Rose12, Nemchinsky97]. Nevertheless, there is a risk that, if the current rise rate is too low and the pulse frequency too high, the free-flying droplet will re-enter the pulse phase, causing significant metal evaporation [Rose 2012; Nemchinsky 1997].

Spray arc processes are characterized by high power and a quasi-steady state. These processes are operated at high wire feed rates and thus at high current. Due to the high power and the continuous melting of the wire, a comparatively long arc forms, in which small droplets detach from the end of the wire and fall into the molten pool. As the droplets have a higher surface-to-volume ratio and lower heat capacity, they heat up faster than larger droplets and metal can evaporate more rapidly [Bosworth00, Deam00]. Added to this is the greater distance the droplets must travel within the arc and the high average current at which the process is operated [Rose12]. In this process, the arc length and process power are the parameters that significantly influence the FER. Due to these conditions, the spray arc process is classified as a high-emission process.

In recent studies, the three material transitions described were examined in relation to welding fume emissions under various parameter variations. To this end, high-speed footage of the processes was captured, and current and voltage waveforms were recorded. The data were analyzed synchronously in order to interpret all aspects of the process behavior.

For the material transition during short-circuit welding, various sources have identified the current flow during short-circuit resolution as the primary source of welding fumes. In the experimental investigations, two SCM processes were compared with regard to FER. Figure 1 shows four process phases for a conventional process. The waveform plot shows a triangular current curve. The voltage responds to the different process states. The short-circuit resolution, which was identified as the main source, occurs at high current and a brief voltage rise. This releases spatter, which in turn releases welding fumes (b). This process, using the settings from Tables 1 and 2, shows an FER of 1.9 mg/s.

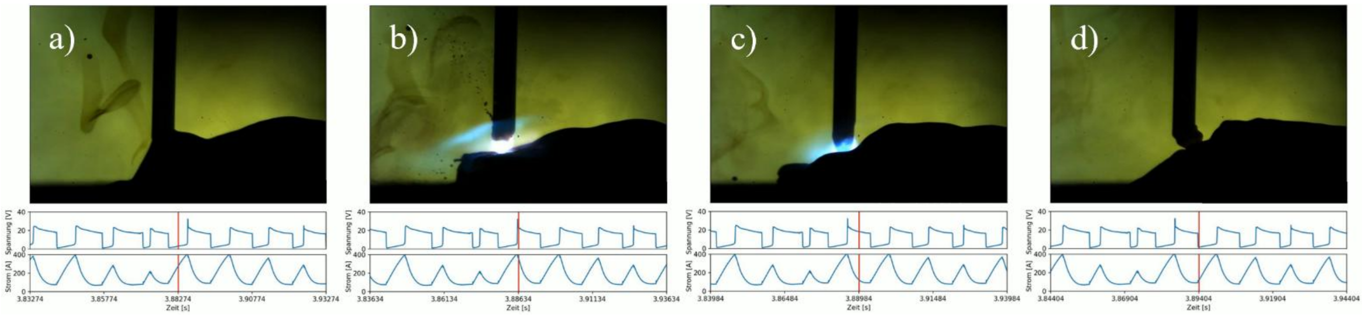

Figure 1: High-speed recording of a conventional SCM process. a) Short-circuit phase, b) Short-circuit resolution, c) Arc burning phase, d) Begin of short circuit

In comparison, short-circuit resolution can be precisely controlled by reducing the current. Various process variants from different manufacturers have already incorporated this control mechanism. Figure 2 also shows four process phases, with the difference that short-circuit resolution occurs at a lower current and the current profile has otherwise been adjusted (b). To enable a comparison between the processes, both were carried out at the same wire feed rate and power. The FER for this process was measured at 0.4 mg/s, which is around 80 % lower than that of a comparable conventional process. Accordingly, the results of the previous studies can be confirmed here.

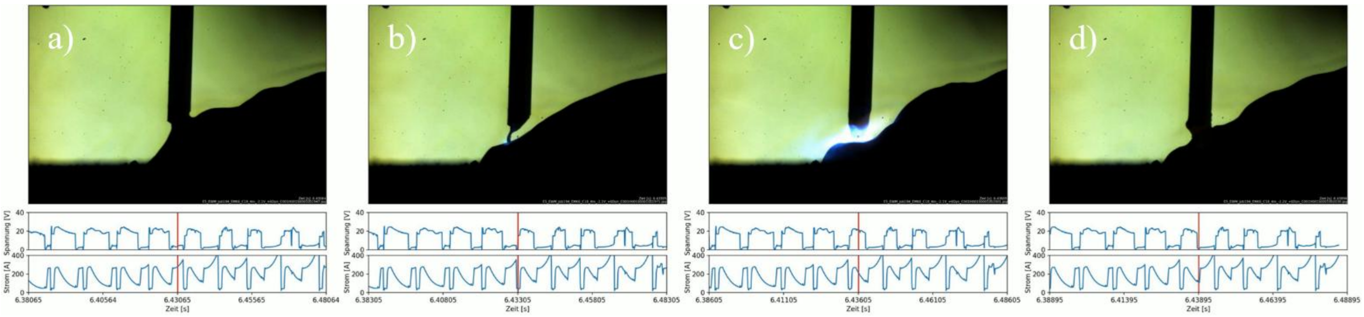

Figure 2: High-speed recording of a energy-reduced SCM process. a) Short-circuit phase, b) Short-circuit resolution, c) Arc burning phase, d) Onset of short circuit

When set appropriately, the pulsed process emits little welding fume, even though very high pulse currents are achieved. Nevertheless, some process conditions were identified as critical in the studies mentioned. If droplet detachment is not fully complete or the droplet is still in free fall, the high pulse current can lead to excessive evaporation. Figure 3 illustrates such a process condition. Process adjustments reduced the pulse current and slightly reduced the pulse frequency. Consequently, the current-induced Lorentz force is insufficient to detach the droplet. The result is an uneven process, which repeatedly exhibits disturbances in the material transfer. This results in a FER of 4.4 mg/s for this process. In the event of more severe disturbances, the FER may rise even further.

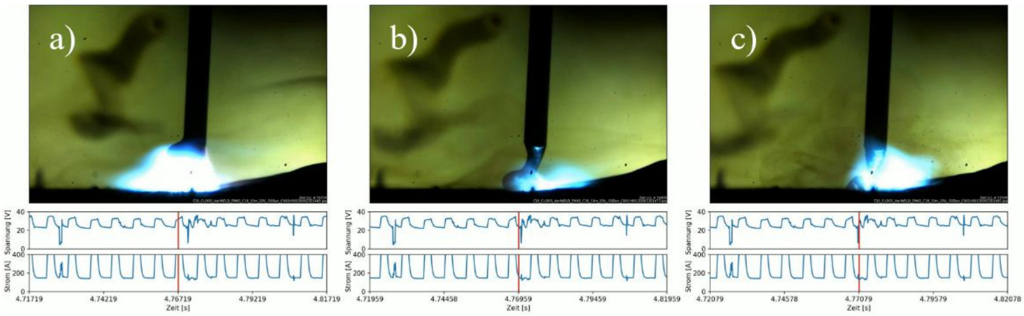

Figure 3: High-speed recording of a conventional PA process with reduced pulse-current. a) Pulse phase, b) Droplet constriction, c) Droplet detachment

The images in Figure 4 show the same process with a higher pulse current and a slightly increased frequency. The result is that droplet detachment occurs at the end of the pulse phase and the droplet flight is completed during the base current phase. The droplet is therefore not exposed to the high energy of the pulse phase. In this process, a FER of 1.5 mg/s was achieved. Consequently, welding fume emissions have been positively influenced by the trouble-free process behavior.

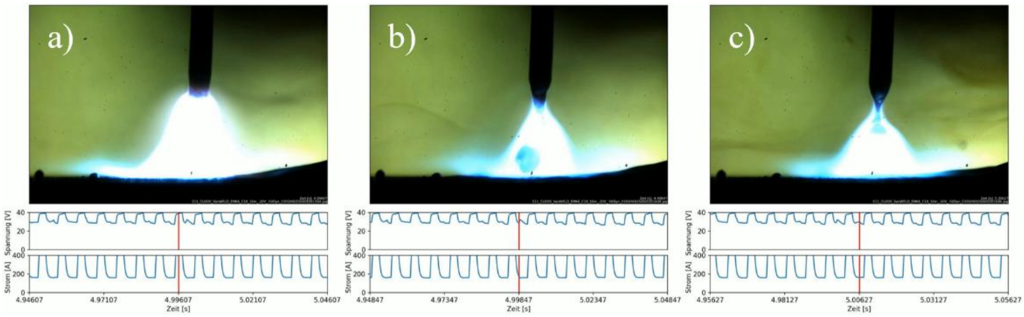

Figure 4: High-speed recording of a conventional PA process with standard parameters. a) Pulse phase, b) Droplet constriction, c) Droplet detachment

Due to the consistently high-power output in the spray arc process, the main factors influencing welding fume emissions are the arc length and droplet size. Figure 5 illustrates two process conditions. In (a), the process was carried out at a reduced voltage. A FER of 2.7 mg/s was measured. On the right-hand side (b), the process is shown with a slightly increased voltage compared to the zero point of the characteristic curve. Here, a FER of 6.6 mg/s was measured. The findings from the studies therefore correspond with the results. However, the investigations reveal further peculiarities that were not taken into account in the reviewed studies. Firstly, in process a) with a low FER, an increased number of micro-short circuits can be observed, which are an indicator of a short arc. When setting up the process, care can be taken to keep the arc length for the droplet as short as possible. Accordingly, it is possible in SCM to significantly reduce the FER at high melting rates, which makes the SCM process particularly stand out.

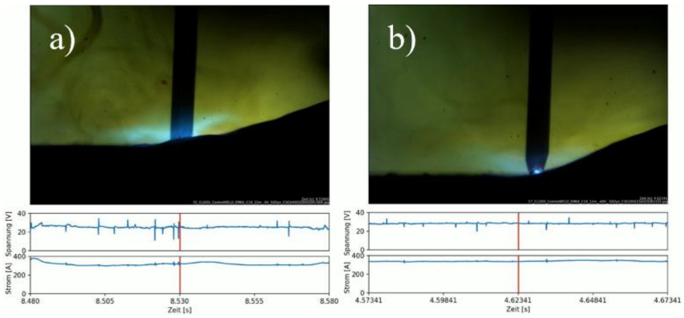

Figure 5: High-speed recording of a conventional STM process. a) reduced voltage, b) increased voltage

Another point is that reducing the voltage results in a particularly narrow and deep penetration. This effect is shown more clearly in Figure 6. This could provide a further explanation for the low FER. The high arc pressure at reduced arc voltage pushes the molten metal to the side and forms a cavity. The altered surface conditions of the melt can have a positive effect on the condensation of the metal vapor during the process. Thus, the metal vapor is not forced out of the process zone, but is absorbed by the molten pool.

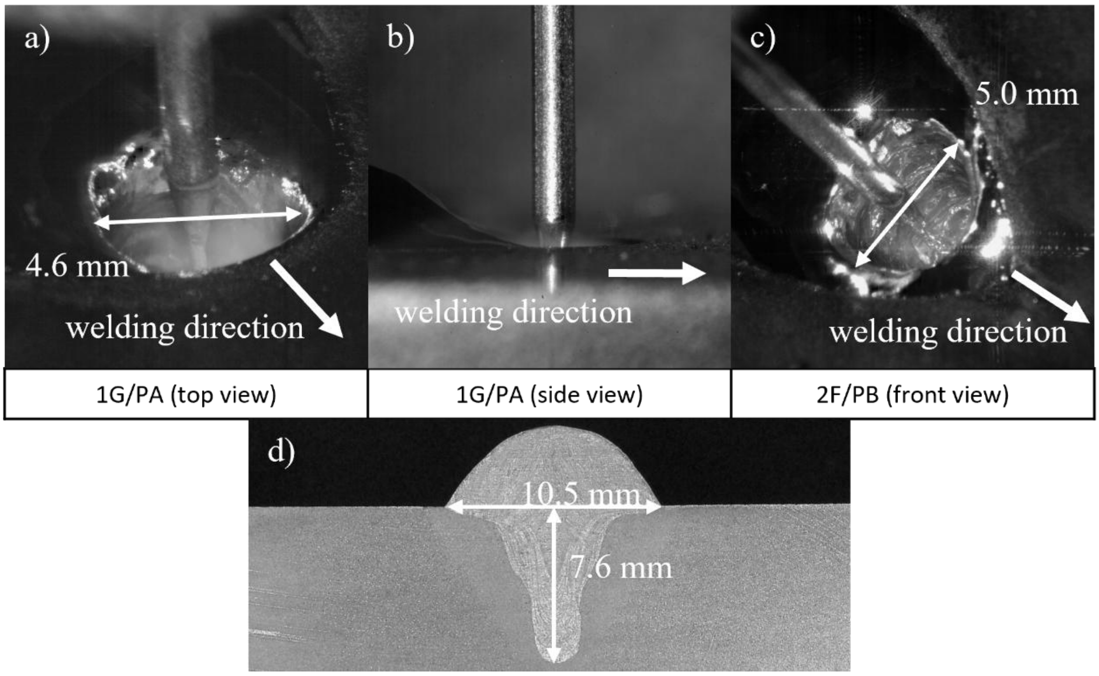

Figure 6: High-speed recording of a conventional STM process. a) Top view, b) Side view, c) Front view, d) Cross-section

5 Summary

This study investigated fume generation mechanisms during gas metal arc welding (GMAW) for three metal transfer modes: short circuit mode (SCM), pulsed arc (PA), and spray transfer mode (STM). Theoretical explanations from previous research were reviewed and compared with experimental high-speed camera recordings and fume emission rate (FER) measurements conducted in accordance with DIN EN ISO 15011. For all transfer modes, metal evaporation from the wire tip, the free droplet, and the weld pool were identified as the common primary source of fume formation, following the particle formation chain. Weld spatter was confirmed as a secondary fume source, particularly under unstable process conditions. For the SCM, the current level during short circuit dissolution was identified as the dominant driver of fume emission. A conventional

SCM process yielded a FER of 1.9 mg/s, while an energy-reduced variant achieved a FER of only 0.4 mg/s, representing a reduction of approximately 80 %. These results are in good agreement with findings from earlier investigations. For the PA process, stable operation with complete droplet detachment prior to the subsequent pulse phase yielded a FER of 1.5 mg/s. An unstable variant with insufficient pulse current, which prevented regular droplet detachment, resulted in a FER of 4.4 mg/s. This confirms that the timing of droplet transfer relative to the pulse phase is critical for minimizing fume emissions. For the STM, arc length and droplet size were confirmed as the dominant parameters governing fume emission. A reduced arc voltage setting yielded a FER of 2.7 mg/s, while an elevated voltage resulted in 6.6 mg/s. Additionally, a previously unreported mechanism was observed: low arc voltage produced a narrow, deep penetration cavity under high arc pressure. This geometry may promote re-absorption of metal vapor into the weld pool, thereby further reducing fume emissions.

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Conflict of Interest

The author declares no conflict of interest.

Data Availability Statement

Data available on request.

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