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Fume emissions during gas metal arc welding

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Abstract

The control of exposure to welding fumes is of increasing importance in promoting a healthy, safe and productive work environment. This article describes the effects of shielding gas composition on the amount and composition of welding fumes produced during gas metal arc welding (GMAW). The amount of fumes generated during welding was measured for steady current over a range of wire-feed speeds and arc voltages using the standard procedures contained in ANSI/AWS F1.2 [American Welding Society. ANSI/AWS F1.2. Laboratory method for measuring fume generation rates and total fume emission of welding and allied processes. Miami, Florida; 1992]. Results of these measurements show that the fume formation rates (FFRs) increase with CO_2 and O_2 in the shielding gas mixture. The lowest FFRs were obtained with the mixtures of $Ar + 2\%CO_2$ and $Ar + 3\%CO_2 + 1\%O_2$. The highest FFRs were obtained with the mixtures of $Ar + 18\%CO_2$ and $Ar + 5\%CO_2 + 4\%O_2$. The welding fumes contains mainly iron, manganese, silicon, titanium and sodium under oxide forms. The fume cluster particles have dimensions between 0.5 and 2 μm. The FFR was found to be governed by the transfer modes of molten metal, i.e. the current intensity and arc voltage, as well as by the shielding gas mixtures composition. Thus these parameters have to be taken into consideration before designing a welding process. Whenever possible, users of GMAW should use the lowest current intensity. However, when this is not possible, due to the constraints of process productivity, welders should use higher currents, but with $Ar + 2\%CO_2$ and $Ar + 3\%CO_2 + 1\%O_2$ shielding mixtures, which will lead to smaller fume emissions.

Keywords: *Shielding gas mixtures, fume formation rate, fume particle size, fume particles composition, metal transfer modes*

Introduction

Welding is the principal industrial process used for joining metals. However, it can produce dangerous fumes that may be hazardous to the welder's health. Presently, 1–2% of workers from different professional backgrounds (some 3 million persons) are subjected to welding

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fume and gas action. In confined spaces, welding can be deadly, as without proper ventilation, toxic fumes and gases can be much more intense, and possibly over the respective limits for toxic substances [2].

With the advent of new types of welding procedures and consumables, the number of welders exposed to welding fumes is growing constantly in spite of the mechanisation and automation of the process. Simultaneously, the number of publications on epidemiological studies [3,4], and the devices for welders' protection is also increasing. Also, the concern of companies to reduce the costs related to the workers' sick leave (both short and long terms) and the need to increase the workers' productivity are also gaining significance nowadays.

Welding fumes consist of metal oxide particles and gases that are formed during welding. The particles are small enough to become and remain airborne and are easily inhaled. Although it is almost impossible to consume enough iron oxide to cause a toxic effect [5], steel contains alloying elements that, in their pure forms, could be hazardous to the worker's health. For example, steel contains manganese, an element recognised to be responsible for Parkinson's disease [3].

New environmental legislations, both health and safety legislations, in the EU and in the United States are driving the need for the study of welding mechanisms and the selection of the operational procedures that will reduce the fume emissions [6–8].

The revision of exposure limits in recent years has resulted in even lower limits on the release of toxic substances during welding, and this downward trend can be expected to continue in the coming years, as a way to reduce the incidence of work-related diseases in welders.

The chemical composition of the particles and the amount of fumes produced during welding depend on the welding procedures, the chemical composition of the shielding gases (necessary to protect the weld bead and weld pool), the filler and the base material, the presence of coatings and the time and severity of the exposure [9,10].

The fumes produced during gas metal arc welding (GMAW) are composed of oxides and metal vapours that originate predominately from the welding wire, while the base metal usually contributes less than 10% to the total fumes [11].

In order to protect the weld pool and the hot parent metal from contact with the atmospheric environment, shielding gas or mixtures of gases are used. These gas mixtures also affect metal transfer modes, due to their different physical properties, namely thermal conductivity and ionisation potential.

The fumes released during GMAW is the result of the hot welding wire, droplets that are transferred from the wire tip to the weld pool, the weld pool itself, the hot parent metal and the molten particles that are projected by the wire 'explosion', to the region outside the influence of the shielding gas protection.

In spite of knowing the sources of fumes, it is difficult to separate the individual effect of each factor, as many of them are in a way interrelated [12]. However, depending on the welding procedures, different solutions can be found by lowering the droplet temperature during GMAW welding, by using more 'friendly' consumables with special coatings in combination with more effective shielding gases [12–14]. Therefore, it is necessary to study the influence of welding parameters and shielding gases on the fumes emitted, and hence solutions can be found and welders can work in a healthier environment.

Control of fumes at the source, by modification of procedures and/or consumables, can be used to complement the existing control strategies. A systematic approach to fume control by process modification contributes to the clarification of fume emission characteristics and to support the decision making on actions to provide a healthier environment for the welders.

Experimental

A detailed study of the influence of the chemical composition of shielding gas mixtures on the fume produced during GMAW process was performed aiming at:

- Analysing the fume formation rate (FFR), the chemical composition and the size of the emitted fume particles for each of the shielding gas mixtures;
- Characterising the mechanisms responsible for the fume formation.

The shielding gas mixtures are used to protect the welding area from the deleterious effects of atmospheric gases. The mixtures under study were: $Ar + 2\%CO_2$, $Ar + 8\%CO_2$, $Ar + 18\%CO_2$, $Ar + 5\%O_2$, $Ar + 8\%O_2$, $Ar + 3\%CO_2 + 1\%O_2$ and $Ar + 5\%CO_2 + 4\%O_2$.

In order to study the influence of shielding gas mixtures on the fumes produced during welding, bead-on-plate welds were made in steel plates (see composition in Table I), within a range of welding current intensity from 150 to 280 A and a voltage between 15 and 35 V. Within this range, the parameters were chosen so that the acceptable quality welds could be obtained for each of the studied mixtures, thus allowing the comparison between the mixtures. The test conditions are shown in Table II.

A conventional power supply, *ESAB LAN 400* was used to conduct the study. The torch was maintained on a simple mechanised system. A computer equipped with an analogue-to-digital (A/D) conversion board was used to sample the current, voltage and the wire-feed speed during the welding (Figure 1). A sampling rate of 5 kHz was selected for the present work.

The FFR was measured using the standard procedures described in ANSI/AWS F1.2. [1]. For this, a fume chamber was built (Figure 2). A turntable was used, upon which the plates were fixed.

The fumes emitted were collected on pre-weighted glass fibre filters (Whatman GF/A) which were then re-weighted to give the total weight of fumes produced. The weight was then used along with the arc time to calculate the FFR. In these experiments, the arc time employed was 15 s. In this work, the FFR is defined as the weight of fume generated

Table I. Parent metal composition.

	C (%)	Si (%)	Mn (%)	P (%)	Cr (%)	Ni (%)
Parent metal	0.1	0.13	0.35	0.012	0.02	0.03

Table II. Parameters used during the experimental welding tests.

Parameters	
Electrode type	AWS E 70 S-6
Electrode extension (mm)	16
Electrode diameter (mm)	1.2
Gas flow ($l\,min^{-1}$)	15
Parent metal thickness (mm)	8
Extraction rate ($l\,min^{-1}$)	800
Welding speed ($mm\,min^{-1}$)	350
Wire-feed speed ($m\,min^{-1}$)	5, 6, 7, 9,10

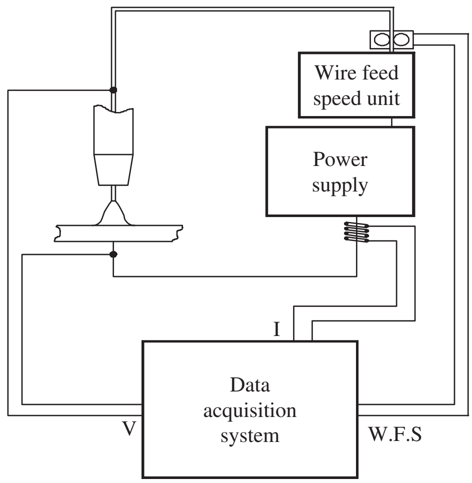

Figure 1. Scheme of the welding monitoring system [2], which illustrates the torch, the arc welding, the power supply and wire feed speed (e.g. welding machine) and the data acquisition system, which acquires the arc voltage, current intensity and wire feed speed during welding.

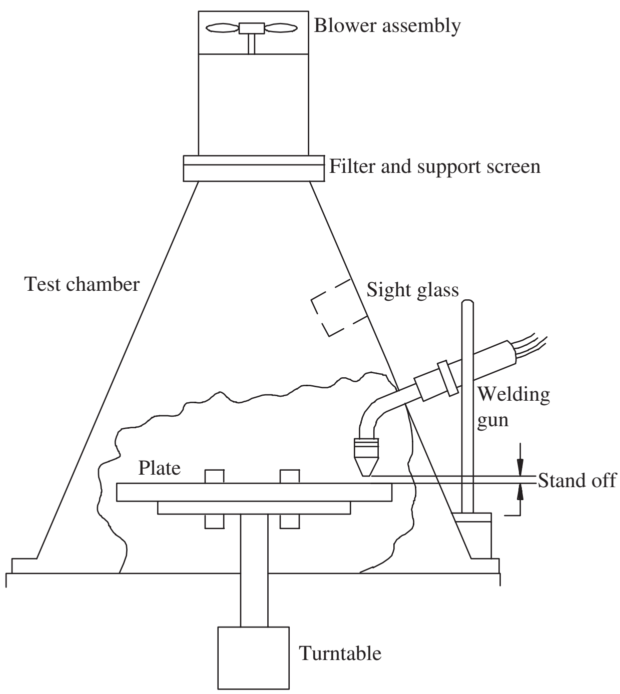

Figure 2. Fume chamber used in the experimental procedure [1].

per unit of arcing time and is expressed in term of grams per minute. Before being used, the filters were heated for 1 h at 150°C, for complete dryness.

Selected samples of fumes were inspected under scanning electron microscopy (SEM) to evaluate the shape and the dimensions of the particles. Energy dispersive X-ray (EDX) analysis was used to determine their chemical composition. To obtain a more accurate and consistent result, each test was made three times, and the results presented are the average of these measurements.

Results and discussion

Fume formation rate

The reduction of fume emissions at the source is of extreme importance since the effective control of fumes emitted during welding, through general and local extraction is not always adequate. The magnitude of the hazards created by the welding fumes depends on the composition and the concentration of the fumes and on the exposure time.

Figure 3 represents the evolution of the FFR with the current intensity for each of the gas mixtures studied. The course of the curves is similar for all mixtures, which can be related with the metal transfer modes. Globally, the figure indicates that the FFR increases with the current intensity, as a result of the higher arc temperature. However, this increase is not linear, due to the different arc welding behaviours, namely the metal transfer modes. These modes are intrinsically related to both the current intensity and the voltage at the tip of the electrode, and when these increase, the mode transfer changes from short circuit to globular and then to spray with a corresponding increase in molten droplet transfer by time unit.

From Figure 3, it can also be seen that as the CO_2 and O_2 content in the shielding gas mixture increases, the FFR also increases, both in the ternary and in the binary gas mixtures. It should also be noted, that the oxidising component of the shielding gas (Table III) also has an important role on the amount of fumes produced during welding, especially for low contents in CO_2.

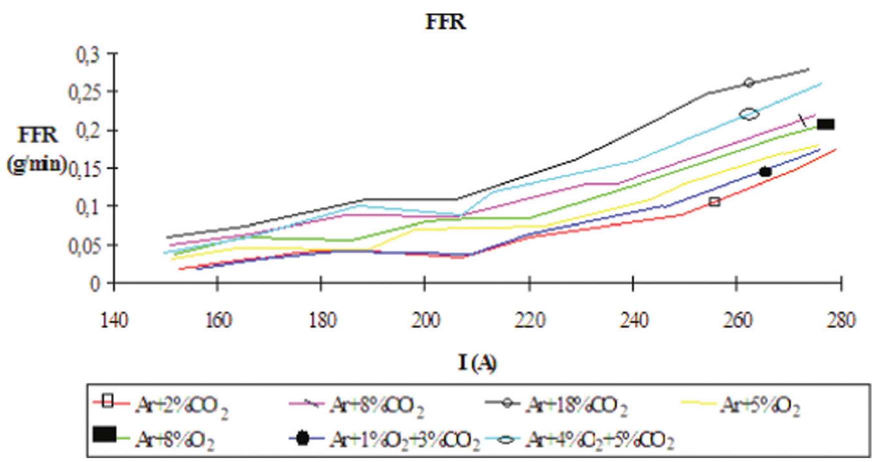

Figure 3. Variation of the FFR with the current intensity for the different gas shielding mixtures studied.

Table III. Equivalent O_2 for each shielding gas mixture.

Gas mixtures	Equivalent O_2 (%)
$Ar+2\%CO_2$	0.8
$Ar+8\%CO_2$	3.0
$Ar+18\%CO_2$	7.2
$Ar+5\%O_2$	5.0
$Ar+8\%O_2$	8.0
$Ar+3\%CO_2+1\%O_2$	2.2
$Ar+5\%CO_2+4\%O_2$	6.0

Table IV. Values of the limits of the FFR for the different gas mixtures.

Gas mixtures	Minimum FFR ($g\,min^{-1}$)	Maximum FFR ($g\,min^{-1}$)
$Ar+2\%CO_2$	0.02	0.17
$Ar+8\%CO_2$	0.05	0.22
$Ar+18\%CO_2$	0.06	0.28
$Ar+5\%O_2$	0.03	0.19
$Ar+8\%O_2$	0.04	0.21
$Ar+3\%CO_2+1\%O_2$	0.02	0.18
$Ar+5\%CO_2+4\%O_2$	0.04	0.26

These results give an indication about the shielding mixture and the parameters that lead to fewer fumes during welding. In general, the FFR increases with:

(1) A decrease of arc stability – higher amounts of spatter are released during welding, which is projected on regions outside the influence of the shielding gas, and are oxidised and vaporised.
(2) An increase in the thermal conductivity of the mixture – which promotes a reduction of the conduction zone, being almost all the generated heat, concentrated in that region. Therefore, there is a local and intense heating of the molten droplet that enters rapidly in ebullition.
(3) An increase in the molten metal droplet size – increases the time period over which the droplets are exposed to a high temperature.
(4) An increase in the active (CO_2) content of the mixture – when the amount of CO_2 in the mixture increases, the reaction rate that occurs in the weld pool also increases, as a result of the decomposition of CO_2 into CO and O_2.
(5) The oxidising content of the mixture – increases the arc temperature as a result of the exothermic reactions between the oxidising elements and the weld pool elements.

Table IV presents the limit values (maximum and minimum) of the FFR for the different shielding gas mixtures under study in the range of current intensity and voltage tested.

It can be noted that of all the mixtures studied, $Ar+2\%CO_2$ exhibited the lowest FFR, followed by $Ar+3\%CO_2+1\%O_2$, while $Ar+18\%CO_2$ and $Ar+5\%CO_2+4\%O_2$ produced the highest FFRs. The majority of the particles have diameters lesser than 0.25 μm and are cluster-shaped. Thus, toxicity will be controlled by the size of the clusters and not by the size of the individual particles, as they are not bound to interact individually with the affected organisms.

Fume particles' size

The SEM analysis of the filters clearly shows an increase in the FFR with an increase in Ar/CO_2 content of the mixture, as can be observed in Figures 4–6, respectively.

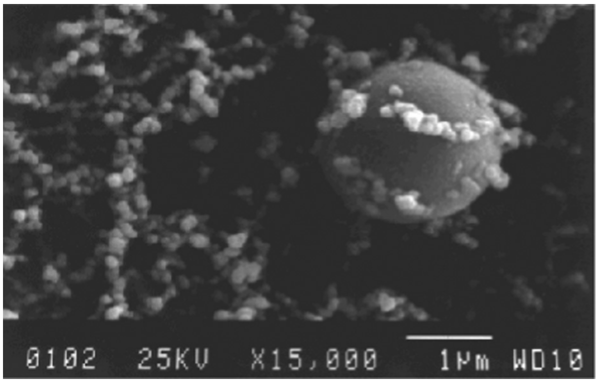

Figure 4. Fume particles obtained with $Ar + 2\%CO_2$ mixture.

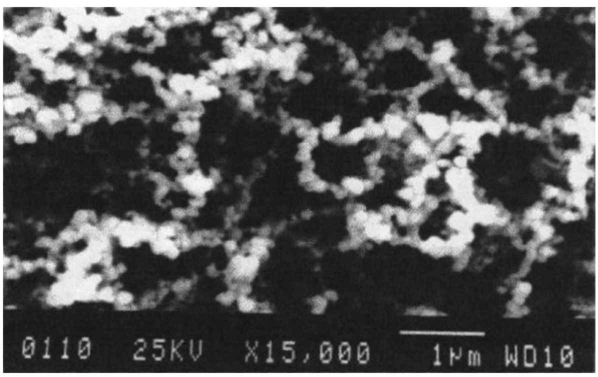

Figure 5. Fume particles obtained with $Ar + 8\%CO_2$ mixture.

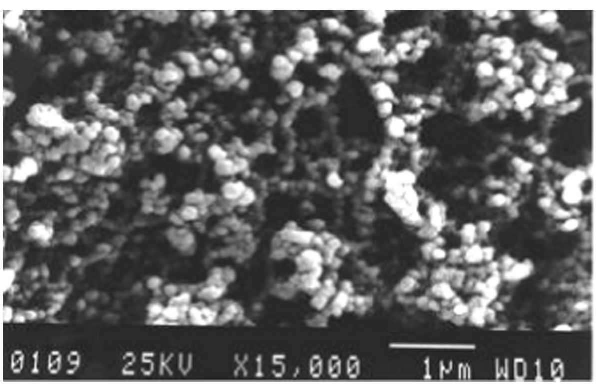

Figure 6. Fume particles obtained with $Ar + 18\%CO_2$ mixture.

An increase in the cluster particle size with the increase of the CO_2 in the mixture can also be noted, with values ~1.5 μm for the Ar + 18%CO_2 mixtures, and values ~0.25 and 0.5 μm for the mixtures with Ar + 2%CO_2 and Ar + 8%CO_2, respectively.

In Figure 4, a particle with dimensions of ~2 μm is also visible. However, this is not so prejudicial for the welders' health, because it is less breathable. The particles that deposit in the alveolar passages of the lung, when inhaled, are predominantly smaller than 0.1 μm, while the inhaled particles that deposit in the nose and throat are generally larger than 2.5 μm [14].

In Figure 7, an evident increase in the particle size can be seen with the increase of CO_2 and O_2 content of the mixture. The amount of deposited and agglomerated particles in the fibres after welding with the Ar + 3%CO_2 + 1%O_2 shielding gas mixture is relatively small in comparison with all other mixtures, the exception being the Ar + 2%CO_2 mixture.

Since the fume particles are deposited in the respiratory organs in cluster shape, it is easy to understand that mixtures with high thermal conductivity and high active content are more detrimental. However, welding parameters, such as current intensity, can be adjusted to reduce the FFR and the amount of cluster fume particles.

It should be noted, however, that this is not always the best option, since there are situations where there is the need to weld materials with high thickness and, consequently, to use parameters that will lead to higher penetration weld beads and deposition rates. In these cases, a mixture leading to a lower fume generation, still providing a high quality weld and meeting the required specifications, should be used.

Chemical composition of the fume particles

Besides understanding the changes in the FFR with welding current intensity and voltage, and the particles' fume size resultant from the different mixtures, it is also important to evaluate their chemical composition when considering the fume toxicity.

Pure manganese is a neurotoxin that can cause manganese poisoning in large doses. Chromium and nickel can be carcinogenic. Although the other elements can cause some respiratory diseases, they have less hazardous effects when compared with manganese [14].

Table V summarises the results of the EDX analysis of the welding fumes. It can be observed that the silicon fume content increases with the increase of the oxidising potential of the gas mixture.

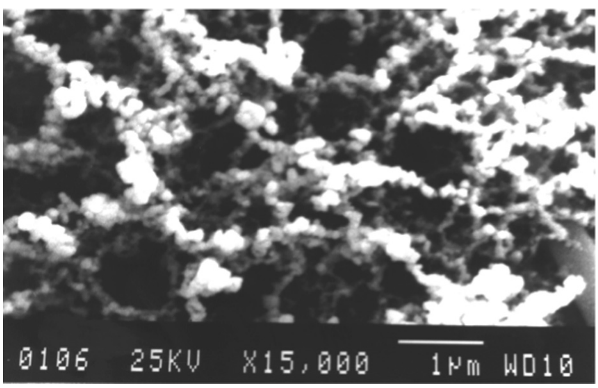

Figure 7. Fume particles obtained with Ar + 5%CO_2 + 4%O_2 mixture.

Table V. Chemical composition of the fume particles produced with different shielding gas mixtures, and for two values of current intensity, obtained by EDX. The remaining weight percentage, corresponds to 'other elements'.

Current intensity (A)	Shielding mixtures	Si (wt%)	Na (wt%)	Mn (wt%)	Fe (wt%)
180	$Ar + 2\%CO_2$	14.02	7.90	9.70	65.67
	$Ar + 8\%CO_2$	15.26	7.21	9.32	65.31
	$Ar + 18\%CO_2$	24.20	7.00	8.90	56.78
	$Ar + 5\%O_2$	16.30	7.20	9.60	63.87
	$Ar + 8\%O_2$	25.30	8.10	9.78	53.53
	$Ar + 3\%CO_2 + 1\%O_2$	14.90	7.36	9.12	65.76
	$Ar + 5\%CO_2 + 4\%O_2$	17.04	7.87	9.40	62.61
270	$Ar + 2\%CO_2$	16.02	8.35	12.41	60.44
	$Ar + 8\%CO_2$	18.34	7.45	11.43	59.88
	$Ar + 18\%CO_2$	26.25	7.20	11.23	52.20
	$Ar + 5\%O_2$	19.84	7.46	11.93	57.61
	$Ar + 8\%O_2$	26.40	8.23	12.26	49.91
	$Ar + 3\%CO_2 + 1\%O_2$	17.51	8.00	11.23	60.41
	$Ar + 5\%CO_2 + 4\%O_2$	25.38	8.12	11.76	51.64

The $Ar + 18\%CO_2$ mixture presents a high content of silicon in the fumes. This fact is related, not only with the oxidant content of the mixture, but also with the lower arc stability, that gives rise to a higher amount of projected particles. This projection has two effects: it increases the weld pool turbulence, which increases the total area available for vaporisation, and second, it promotes more oxide formation, as these particles are projected in regions outside the shielding gas protection area like air environment. This means that the mechanism responsible for silicon fume content is the oxidation and subsequent vaporisation, as these oxides have low vaporisation temperatures.

The Mn and Na fume contents decrease with an increase of CO_2 in the mixture, contrary to the effect of O_2. This behaviour is related to the arc temperature, which decreases with the increase in the CO_2 and with the decrease of the O_2 in the gas mixture.

It should be noted, however, that the differences in Mn and Na fume contents are more noticeable with an increase in the current intensity, and hence with the arc temperature, than with the oxidising content of the mixture. This means that the direct vaporisation of Mn and Na is the mechanism responsible for the presence of these elements in the fumes generated during the GMAW.

Conclusions

The mechanisms responsible for the fume formation are complex. However, this article attempts to point out that a clear and precise understanding of the parameters that affect the fume formation can assist in developing practical actions to reduce the fume emissions at the source. The data presented here gives a summary of the differences in GMAW metal transfer modes and their relations to the fume generation rates for gas mixtures with different Ar, CO_2 and O_2 contents. The results obtained have shown that:

(1) The FFR is closely dependent on the molten metal transfer mode. By selecting the right welding parameters, viz. the welding current intensity and voltage, the FFR can be reduced.

(2) The FFR increases with the increase of arc temperature and arc instability, with the active component and the thermal conductivity of the mixture and with the volume of the droplets.
(3) The shielding gas mixtures also affect the FFR due to the effect of the ionisation potential of the gas in the molten metal transfer mode. The FFR increases with the increase of CO_2 and O_2 content in the gas mixture.
(4) The amount of fumes released during welding is higher for mixtures with CO_2 than the ones with O_2 with the same oxidising potential.
(5) The mechanism responsible for the presence of Si in the fume is oxidation and the subsequent vaporisation, while the direct vaporisation of Mn and Na is the mechanism responsible for the presence of these elements in the fume.
(6) The high percentages of elements like Si and Mn in the fumes points out the necessity of designing, installing, and operating newer and increasingly efficient welder protection systems, both individual protection and extraction system to be used in welding stations and workshops.
(7) Whenever possible, users of GMAW should use the lowest current intensity possible. However, when it becomes possible, due to constraints of the parts to be welded, namely their thickness and the process productivity, users should use higher currents, but with $Ar + 2\%CO_2$ and $Ar + 3\%CO_2 + 1\%O_2$ shielding mixtures, which lead to less fume emissions.

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