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Analysis of the influence of shielding gas mixtures on the gas metal arc welding metal transfer modes and fume formation rate

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Abstract

The development of shielding gases for welding applications has been of increasing interest for two main reasons: to improve the productivity and the operating characteristics of the process and to reduce the healthy and safety problems due to fume and particle emissions.

The present paper outlines some of the most important features of seven shielding gas mixtures used and gives information about the influence of these mixtures on the process characteristics, namely on the metal transfer modes and fume emissions.

The focus of this work is an experimental study of shielding gases aimed at analysing arc stability and transfer modes, as well as, fume formation, having in view the achievement of a better working environment for welders.

Keywords: D. Shielding gas mixtures; Metal transfer modes; Fume formation rate

1. Introduction

The gas metal arc welding (GMAW) process has been dominating the welding construction world for several years now. This fact is related to its high flexibility, which allows the welding of a great variety of materials and thickness, and to its considerable potential for automation and robotization [1].

Nevertheless, applications of the process lack scientific background and are often based on empirical approaches, which can solve some specific problems, but do not result in more general solutions. The need to improve the process performance requires a clear and detailed study of the basic phenomenon and of the mechanisms involved in this process.

The physical phenomena involved in this welding process are of complex nature, requiring knowledge of electricity, magnetism, hydrostatics and fluid and gas dynamics [2].

The development of welding shielding gas mixtures in recent years has been based on the need to establish a stable arc, to obtain a smooth molten metal transfer and to reduced fume emissions, which will improve process performance, productivity and control, and will reduce the risk of fusion defects.

Process productivity and quality, essential factors when considering automation and robotization, are strongly dependent of the shielding gases and mixtures used.

It is well known that the chemical composition and the amount of the fumes produced depend on the welding process, filler and shielding gas composition, and of the welding parameters.

2. Background

2.1. Metal transfer modes

The metal transfer mode is influenced by the type of the filler wire, voltages and current intensities range, electrode polarity and shielding gas. For a better understanding of

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the effects of the several factors it is necessary to consider the physics of the transfer process [3,4].

There are, basically, two theories to describe the metal transfer: *static force balance theory* and *pinch instability theory* [5–8]. *Pinch instability theory* only explains the general tendency for the decrease of the droplet size with the increase of the current intensity and the conditions for the instability of the molten metal column. The s*tatic force balance theory* allows a better explanation of arc phenomena, and is the one that will be considered in this work [5].

The *static force balance theory* claims that the droplet detaches from the electrode tip when the detaching forces on the drop exceed the retention forces. Detaching forces include: gravitational, electromagnetic and plasma drag forces, while the surface tension and the vaporisation forces are retention forces.

The gravitational force, F_g, is due to the mass of the droplet. When welding in a flat position is given by:

$$F_g = \frac{4}{3}\pi R^3 \rho_d g \quad (1)$$

where R is the droplet radius, ρ_d is the metal drop density and g the gravitational constant [9].

The electromagnetic force results from the divergence or convergence of the current flow within the electrode. When the current lines diverge, e.g., when the conduction zone is large enough, the *Lorenz* force, that acts in planes perpendicular to these current lines, becomes a detaching force. When the current lines converge, this force becomes a retention one. The electromagnetic force, F_{em}, is given by:

$$F_{em} = \frac{\mu_0 I^2}{4\pi} \ln\left[\frac{r_a}{R}\right] \quad (2)$$

where I, is the current intensity, r_a, the radius of the arc, μ_0, the permeability of free space [5].

The vaporisation force, F_v, is given as follows:

$$F_v = \frac{\dot{m} I J}{\rho v} \quad (3)$$

where v, is the vapour velocity, $\dot{m}$, the total mass vaporised per unit time per unit current, ρ, the vapour density and J the current density [5].

The plasma drag force is given by:

$$F_d = C_d R\left(\frac{\rho_f v_f^2}{2}\right) \quad (4)$$

where C_d, is the drag coefficient, R, the droplet radius, ρ_f, the fluid density and v_f is the velocity of the fluid [5].

Finally, surface tension resultant force, which acts to retain the liquid drop on the electrode, is given by:

$$F_\gamma = 2\pi R \gamma \quad (5)$$

where R, is the electrode radius and γ, the surface tension of liquid metal [5].

In 1983, Waszink [10] investigated the amplitudes of the forces responsible for droplet detachment, finding a good agreement between the theoretical and the experimental results in the case of repelled transfer. However, for spray transfer, this theory deviates significantly from experimental results. In addition to the limitations mentioned above, the static force balance theory has some difficulties in explaining much of the metal transfer phenomena that occur during GMAW process. First, the effect of electrode extension in the metal transfer is difficult to explain. Second, this analysis has been performed for steel electrodes and argon as shielding gas. Other cases that produce a repelled transfer, as observed with CO_2, cannot be explained by this theory.

2.2. Sources of fume

New environmental, healthy and safety legislation, both in the EU and in the United States, drove the need for the study of welding mechanisms and the selection of the operational procedures in order to reduce fume emissions [11].

Despite the advances in welding automation and control technology, welders are still exposed to the welding fumes and gases hazardous. The chemical composition of the particles in these fumes and gases depend on the welding procedure, the chemical composition of the shielding gas, filler metal and the base material, the presence of coatings, time and severity of exposure and ventilation [12,13].

Any material is a potential source of fume when heated to a high temperature. The fume released during GMAW is the result of the hot welding wire, droplets that are transferred from the wire tip to the weld pool, weld pool and hot parent metal and molten particles that are projected by the wire "explosion".

It is difficult to separate the individual effect of each factor. Many of them are somehow interrelated [14]. However, depending on the welding process, different solutions are being investigated to lower the emission of welding gases and fumes [15] or to reduce physical demands. Solutions can be found by lowering the droplet temperature during GMAW welding, by using "green" consumables with special coatings in combination with more effective shielding gases. Therefore, it is necessary to study the influence of welding parameters on the fumes released, so welders could work in a healthier environment.

3. Experimental procedure

A detailed study of the influence of seven gas mixtures ($Ar + 2\%CO_2$, $Ar + 8\%CO_2$, $Ar + 18\%CO_2$, $Ar + 5\%O_2$, $Ar + 8\%O_2$, $Ar + 3\%CO_2 + 1\%O_2$ and $Ar + 5\%CO_2 + 4\%O_2$) on the features of GMAW process was performed aiming at:

- Analysing the transfer modes with the different shielding gases.
- Analysing the fume formation rate.
- Characterising the mechanisms responsible for the fume formation.

For this purpose several welding tests were made, in steel plates (see composition in Table 1), using a mild steel electrode wire (AWS ER 70 S-6) with a diameter of 1.2 mm. This is a common consumable, widely used in industry for carbon steel welded construction.

Table 1
Parent metal composition

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

3.1. Metal transfer modes

To establish the parameter range where the different metal transfer modes occur for each of the 7 shielding gas mixtures, bead-on-plate welds were made covering the voltage range of 10–38 V and current range from 100 to 375 A.

During the tests, the mean values of current and voltage, corresponding to each type of transfer, were registered and transfer mode maps for each mixture were developed. These are charts that allow the identification of the current and voltage range where the different transfer modes occur (short circuit, globular, repelled and spray).

The experimental procedure was identical for all the shielding gas mixtures: for each wire feed speed, the arc voltage was varied to allow the determination of the boundaries of arc instability and the transfer modes that occur between those boundaries. The parameters used during the tests are illustrated in Table 2.

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, the voltage and the wire feed speed during welding (Fig. 1). A sampling rate of 5 kHz was selected for this work.

The determination of metal transfer modes and the definition of the mode boundaries were made with the help of signal data analysis, visual inspection and arc sound.

Table 2
Parameters used during the experimental tests

Parameters	
Electrode	AWS E 70 S-6
Electrode diameter (mm)	1.2
Electrode extension (mm)	16
Gas flow (l/min)	15
Parent metal thickness (mm)	8
Welding speed (mm/min)	350
Wire feed speed (m/min)	2, 5, 6, 7, 9, 10

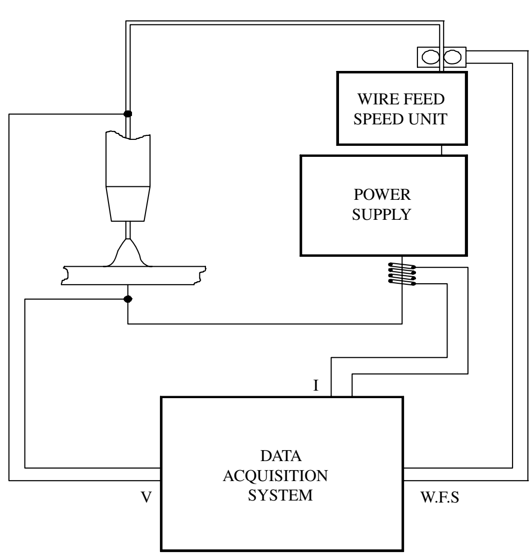

Fig. 1. Scheme of the welding monitoring system [1].

3.2. Fume emissions

In order to study the influence of shielding gas mixtures on the fumes produced during welding, bead-on-plate welds were made within a range of current from 150 to 280 A and a voltage between 15 and 35 V. Within this range, the parameters were chosen so that acceptable welds could be obtained for all studied mixtures, thus allowing comparison between mixtures. Test conditions were identical to the ones shown in Table 1.

Fume formation rate (FFR) was measured using the standard procedures contained in ANSI/AWS F1.2. For this, a fume chamber was built (Fig. 2). A turntable was used, upon which the plates were fixed. The extraction rate used was of 800 l/min.

The fumes emitted were collected on pre-weighted glass fibre filters (Whatman GF/A), which were then reweighted to give the total weight of fumes produced. The weight was then used along with the arc time to calculate fume formation rate (FFR). In these experiments, arc time employed was 15 s. For the purpose of this work, the FFR is defined as the weight of fume generated per unit of arcing time and is quoted in g/min.

4. Results and discussion

4.1. Metal transfer modes

The effect of shielding gas mixtures on the metal transfer mode is a phenomenon which is not completely understood. For that reason transfer mode maps, which represent the V/I relation for different transfer modes, were made with the results obtained experimentally for each mixture. With these maps some assumptions were undertaken, concerning the phenomena that occur and its influence on metal transfer modes.

In this analysis the ionisation energy of the different mixtures was not taken in consideration, due to its reduced influence [1].

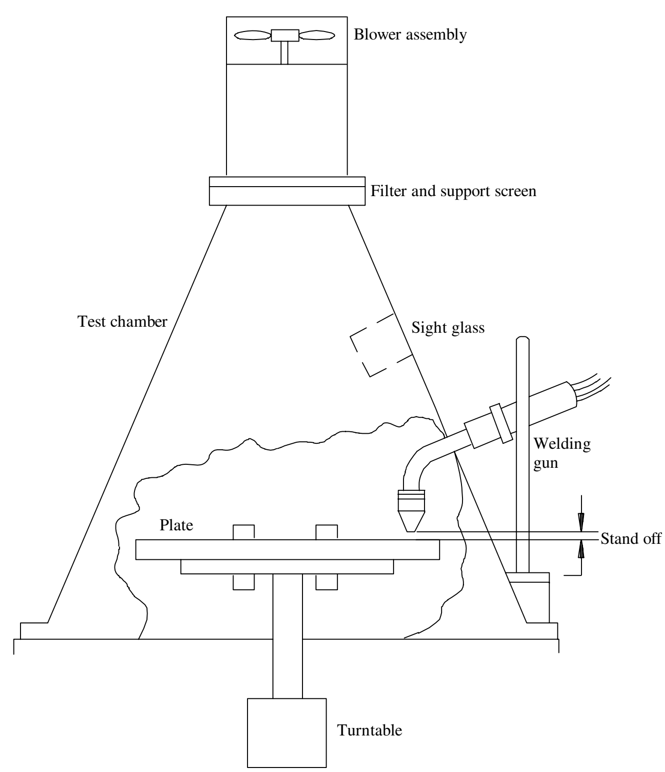

Fig. 2. Fume chamber used in the experimental procedure [16].

4.1.1. Binary argon/CO_2 mixtures

Through the analysis of the transfer mode maps for the Ar + 2%CO_2 and Ar + 18%CO_2 mixtures (Figs. 3 and 4, respectively) it is possible to verify that the necessary voltages to obtain a stable metal transfer increase as the CO_2 content of the mixture increases. This indicates that the arc stability decreases with the increase of carbon dioxide content in the mixture. This fact is related to the high thermal conductivity of CO_2, which gives rise to more heat loses by conduction and thus the necessity to use higher voltages, for the same current intensity, to initiate and stabilise the arc.

Fig. 5 illustrates a simplified scheme of the possible arc shape resulting from mixtures with low quantities of CO_2 (left) and with high content of CO_2 (right) showing a longer arc length and thinner isothermal distribution for lower CO_2 contents.

Due to the higher heat flow associated with gas mixtures with higher content of CO_2, the radial distribution of the arc temperature is more uniform and its length is shorter for the same current intensity. On the contrary, mixtures with less CO_2 have an inner zone, that is much hotter than the peripheral zone.

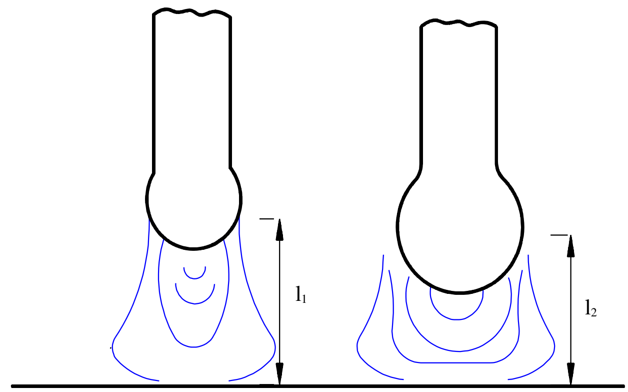

Fig. 5. Exemplifying scheme of the possible arc temperatures distribution and its shape for mixtures with a higher content of CO_2 (right) and low (left), for the same current and voltage, l_1 is higher than l_2 [1].

It was also observed that the extension of the spray transfer region decreases with increased CO_2 content. This phenomenon is also related to the increase of thermal conductivity of the mixture, with increasing CO_2 content.

As the thermal conductivity of the mixture increases, the arc stops enveloping the droplet, producing an anodic spot contraction and, as a result, a shorter electric conduction

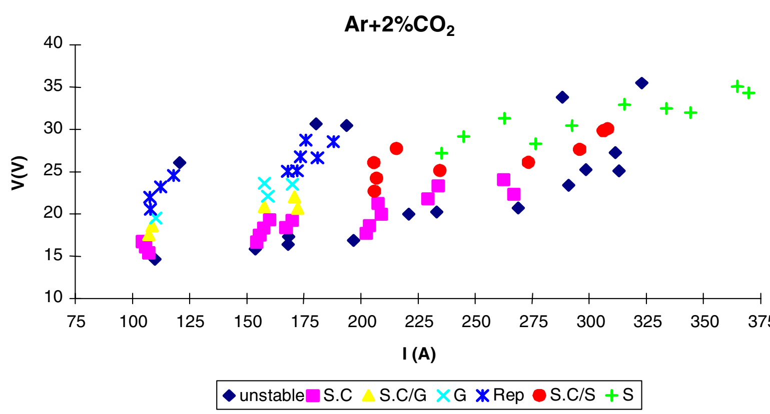

Fig. 3. Transfer mode map for Ar + 2%CO_2 shielding gas mixture. Where SC, short circuit transfer; G, globular transfer; R, repelled transfer; S, spray transfer; SC/G, transfer mode between short circuit and globular and; SC/S, transfer mode between short circuit and spray.

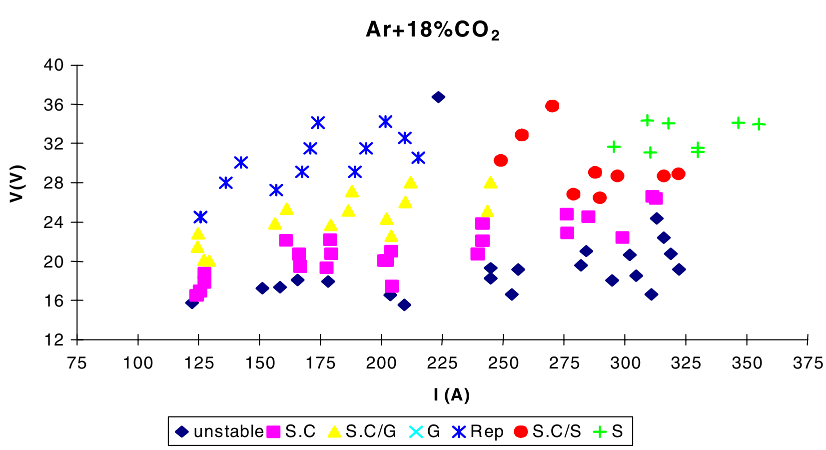

Fig. 4. Transfer mode map for Ar + 18%CO_2 shielding gas mixture. Where SC, short circuit transfer; G, globular transfer; R, repelled transfer; S, spray transfer; SC/G, transfer mode between short circuit and globular; and SC/S, transfer mode between short circuit and spray.

zone (Fig. 6). As a consequence, the magnetic field becomes stronger in the arc root (higher current density) than in the electrode, originating an electromagnetic retention force, which inhibits the droplet detachment. For mixtures with low quantities of CO_2 the opposite is verified and, consequently, the electromagnetic force changes from retention to detaching.

The reduction of the conduction zone with the increase of CO_2 content, also causes an expansion of the area where repelled transfer mode is observed, due to two reasons:

1. The reduction of the conduction zone creates a retention electromagnetic force, as explained previously.
2. Due to the small conduction zone, most of the heat is concentrated in that zone giving rise to a non-uniform heating of the droplet. In those small regions, the metal quickly reaches the boiling temperature with the consequent release of metal vapours, which will repulse the droplet.

The vaporisation force, mainly responsible for this type of transfer mode, is the result, not only of the reduction of the conduction zone, but also of the extremely active behaviour of CO_2. The carbon dioxide reacts either with the weld pool elements or with the electrode elements leading to the formation of extremely volatile oxides.

The difficulty in obtaining spray transfer mode with the increase of CO_2 is then due to the fact that the resultant force of surface tension and the gravitational force could not balance the electromagnetic and the vaporisation forces. It should be noted that the decrease of surface tension force promotes the detachment of a droplet and decreases with the increase of CO_2.

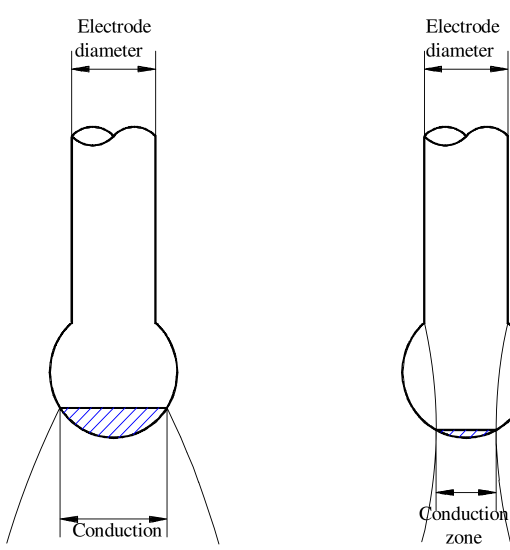

Fig. 6. Exemplifying scheme of the possible arc shape and conduction zone for mixtures with low (left) and high (right) content of CO_2 [1].

4.1.2. Binary argon/O_2 mixtures

No significant differences were observed in the transfer mode maps obtained with $Ar + 5\%O_2$ and $Ar + 8\%O_2$ gas mixtures, as it can be observed in Figs. 7 and 8. Both of them show a large region where spray transfer occurs when compared with CO_2 mixtures (Figs. 3 and 4).

However, it should be noted that with the $Ar + 8\%O_2$ mixture, the arc stabilises for lower voltages than with the $Ar + 5\%O_2$ gas mixture. Two hypotheses are proposed to explain this phenomenon. The first is related to the arc temperature, although no measurements were taken. It is likely that the arc temperature should be higher for mixtures with higher contents of O_2, especially in the vicinity of the electrodes due to exothermic reactions between O_2 and the electrode wire elements and the weld pool, especially iron and carbon.

The second is related to the formation of a more uniform and thicker oxide layer on the parent metal surface (cathode) which promotes electron emission and, consequently, increases arc stability.

For a certain current intensity it is necessary to impose higher voltages to obtain the same arc length, when using $Ar + 5\%O_2$ mixtures compared with $Ar + 8\%O_2$. The range of voltage and current intensity where spray transfer occurs is also narrower for the $Ar + 8\%O_2$ mixture, as a result of the slightly higher molten metal vaporisation.

The reasons why the spray transfer mode was observed in a wide range of current intensities, with mixtures with O_2, are related, not only with the decrease of the surface tension of the molten wire, but also with the arc shape that, in contrast to what happens with the mixtures with high content of CO_2, the arc envelopes the droplet, leading to a bigger conduction zone and, consequently, to a detaching electromagnetic force.

4.1.3. Ternary mixtures

Both ternary mixtures, $Ar + 3\%CO_2 + 1\%O_2$ and $Ar + 5\%CO_2 + 4\%O_2$ give rise to a large range of welding current and voltages where a stable spray transfer mode occur (Figs. 9 and 10.). However, this range is shorter than the one obtained with O_2 mixtures. In the case of repelled transfer mode, the $Ar + 4\%O_2 + 5\%CO_2$ shows a considerable zone with this type of transfer, particularly for lower welding currents. This phenomenon is related to the amount of active elements in the mixture, which promote reactions between the weld pool elements, with the subsequent vaporisation of the resultant elements, leading to a vaporisation force that repels the droplet.

As the current intensity increases, the repelled transfer disappears, despite of the increase of the vaporisation force (responsible for this transfer mode), because the electromagnetic detaching force becomes more important.

It should be noted that these mixtures provide more stable arcs, since the voltages required to stabilise the arc and the level of spatter are reduced.

The phenomenon described above can be analysed regarding the static force balance theory [5,8].

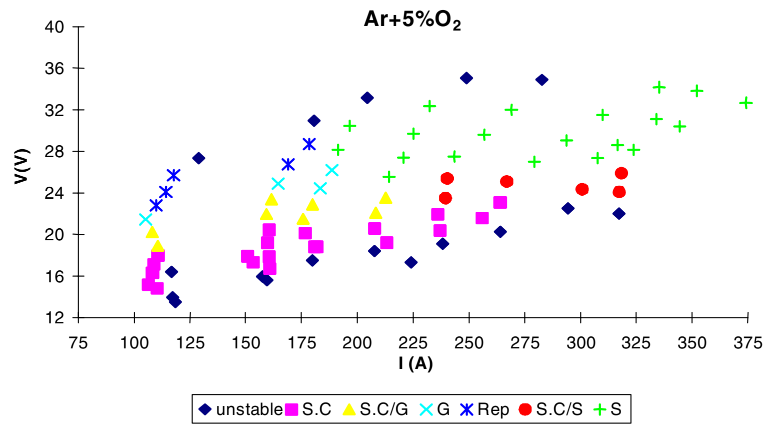

Fig. 7. Transfer mode map for Ar + 5%O_2 shielding gas mixture. Where SC, short circuit transfer; G, globular transfer; R, repelled transfer; S, spray transfer; SC/G, transfer mode between short circuit and globular; and SC/S, transfer mode between short circuit and spray.

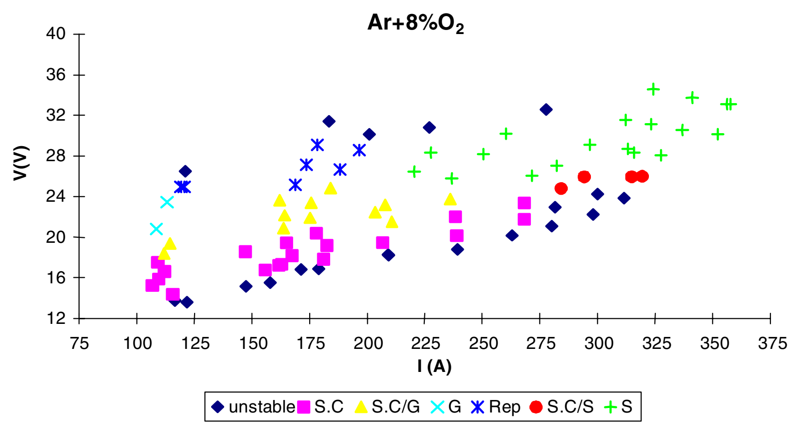

Fig. 8. Transfer mode map for an Ar + 8%O_2 shielding gas mixture. Where SC, short circuit transfer; G, globular transfer; R, repelled transfer; S, spray transfer; SC/G, transfer mode between short circuit and globular; and SC/S, transfer mode between short circuit and spray.

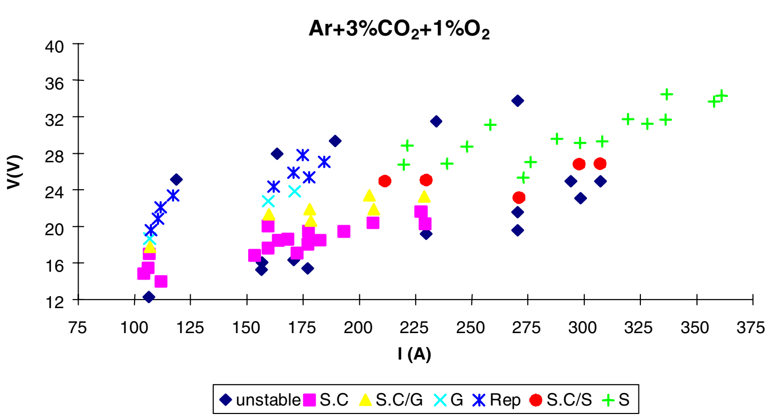

Fig. 9. Transfer mode map for Ar + 1%O_2 + 3%CO_2 shielding gas mixture. Where SC, short circuit transfer; G, globular transfer; R, repelled transfer; S, spray transfer; SC/G, transfer mode between short circuit and globular; and SC/S, transfer mode between short circuit and spray.

The analysis of the metal transfer mode shows that the static force balance theory is insufficient to explain the evolution of the different transfer modes, in particular because it does not take into account the arc voltage and the stick out.

Looking at the transfer mode maps, it is clear that for a certain current intensity the transfer modes progressed with the voltage variation and thus with arc temperature.

However, this theory does not take into consideration the heat developed at the anode (via electron condensation

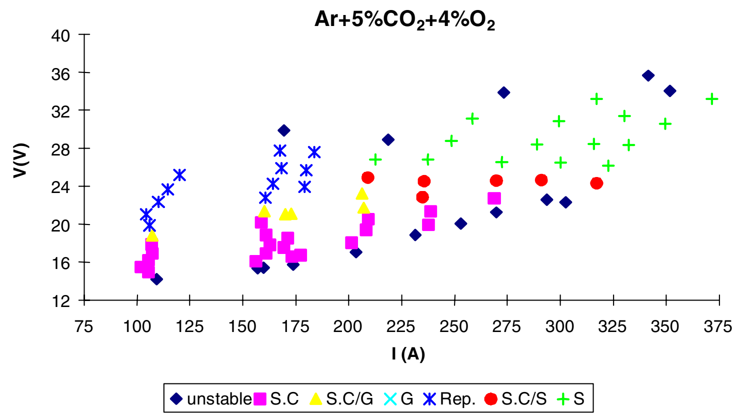

Fig. 10. Transfer mode map for $Ar + 4\%O_2 + 5\%CO_2$ shielding gas mixture. Where SC, short circuit transfer; G, globular transfer; R, repelled transfer; S, spray transfer; SC/G, transfer mode between short circuit and globular; and SC/S, transfer mode between short circuit and spray.

heat and joule heat), namely for lower current intensities, where droplet size is determinant for the transfer mode, as defined by:

$$\left(\frac{3KT}{2e} + V_a + \phi + \frac{\rho l I}{A}\right) I \qquad (6)$$

where K, is the Boltzman's constant, T, is the electron temperature entering the electrode, e, is the electron charge, V_a, is the anode drop voltage, ϕ is the work function of the electrode, ρ, is the average resistivity of the electrode, l, is the electrode extension, and A, is the cross-sectional area of the electrode.

4.2. Fume emissions

The reduction of welding fumes is necessary to improve the shop floor conditions for welders thus reducing the sick leave (both short term and long term) caused by welding fumes. This reduction is a technological, complex problem which involves the control of fume emissions at the source. The most frequently used welding processes are MIG/MAG (also named the GMAW = gas metal arc welding) and SMAW (shielded metal arc welding), used in about 70% of the welding jobs. Thus, work on reduction of fumes at the source should be concentrated on these processes. For GMAW and SMAW, reduction of the welding fumes can be achieved by proper selection of welding parameters.

EU as well as national maximum accepted concentrations (MAC values) of welding fumes have been legally described. These MAC values are decreasing in several countries to decrease the health risk for welders.

The effects of different shielding gas mixtures on fume emission rate and composition were studied with the aim of gaining a better understanding on how shielding gas composition and welding current influence fume generation. The results of this study are illustrated in Fig. 11, which represents the evolution of fume formation rate with the current intensity for the seven gas mixtures studied.

The pattern observed in the curves above is similar for all mixtures and can relate the FFR with metal transfer modes (see explanation on Table 3). Globally, the figure indicates that the fume formation rate increases with the increase of current intensity, as a result of the higher arc temperature. However, this increase is not linear, due to the different arc welding behaviours.

From Fig. 11, it can also be seen that as the carbon dioxide and oxygen content in the mixture increases, the fume formation rate also increases, both in ternary and in binary mixtures.

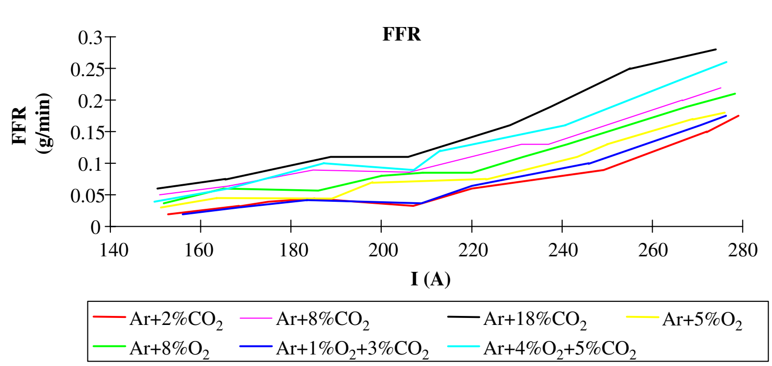

Fig. 11. Variation of fume formation rate (FFR) with the current intensity for the different gas shielding mixtures studied.

Table 3
Influence of the transfer modes on the fume formation rate (FFR)

Transfer modes	Increase I and V	FFR	Causes
Short circuit	↓	Increases	High SC frequency (see Fig. 12)
		Slightly decreases	Lower SC frequency – the amount of spatter corresponding to the SC break decreases (see Fig. 13)
Globular		Increases	Molten droplet size increases and so the time during which the droplet is exposed to a higher temperature
Spray		Slightly increases	Molten droplet size decreases
		Increases	The number of droplets that are transferred by time unit increases

It should be noted that from all the studied mixtures, the Ar + 2%CO_2 is the one that has exhibited the lower fume formation rate, followed by the Ar + 3%CO_2 + 1%O_2. On the contrary, the Ar + 18%CO_2 and the Ar + 5%CO_2 + 4%O_2 have presented the higher fume formation rate (Table 4). The majority of the particles has diameters lower than 0.25 μm and are in cluster shape. For that reason, it is the size of the clusters and not the size of the individual particles that controls the toxicity.

Table 4
Values of the limits of the fume formation rate for the different gas mixtures

Gas mixtures	Minimum FFR (g/min)	Maximum FFR (g/min)
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

5. Conclusions

This paper presents experimental data on the influence of the operating parameters (arc intensity and voltage) on the metal transfer modes of GMAW for each shielding gas mixture studied.

The data presented summarise the differences in GMAW metal transfer modes and their relation to fume generation rates for gas mixtures with different Argon, CO_2 and O_2 contents (Figs. 12 and 13).

From these results it can be concluded that:

1. The range of parameters for which the spray transfer occur decreases with the increase of thermal conductivity and the active component of the mixture.

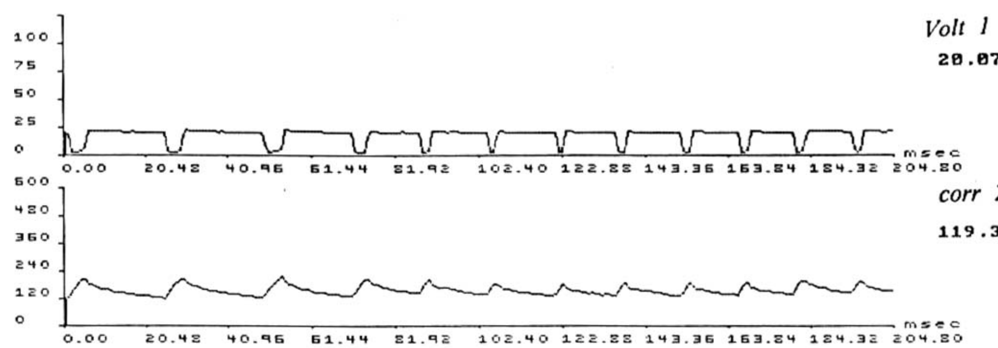

Fig. 12. Variation of current intensity and voltage for the high short circuit transfer mode. For each short circuit break, spatter is released, increasing the amount of fume.

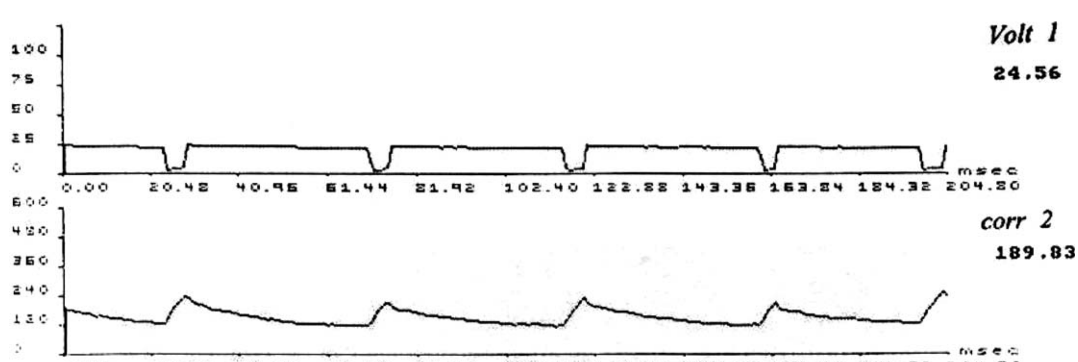

Fig. 13. Variation of current intensity and voltage for the low short circuit transfer mode.

2. Repelled transfer occurs due to the reactive behaviour of the mixture and the decrease of the conduction zone, caused by the increase of the thermal conductivity of the mixture.
3. The arc length increases with the oxidant potential of the mixture, in the absence of other factors.
4. The static balance force theory is not sufficient to explain the different transfer modes. It should include:
   - the electrode heating $\left(\frac{3KT}{2e} + V_{\mathrm{a}} + \phi\right)I$;
   - the stick out and electrode wire resistivity $\left(\frac{\rho \cdot l \cdot I^2}{A}\right)$.
5. The ternary mixtures are extremely flexible producing short circuit and spray transfer modes for a wide range of current intensities and voltages.
6. The fume formation rate increases with the increase of CO_2 and O_2 in the mixture.
7. The fume formation rate increases with the increase in arc temperature and instability, with the active component, thermal conductivity of the mixture and with the volume of the droplets.
8. The amount of fume released during welding is higher for mixtures with CO_2 relatively to the ones with O_2 having the same oxidising potential.

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