LOW OXIDATION POTENTIAL SHIELDING GAS INSTABILITY
IN GMA WELDING WITH CONSTANT CURRENT OPERATION

Maria Celeste M. de Souza Costa, mcelestemsc@deii.cefetmg.br
Federal Centre for Technological Education of Minas Gerais, Belo Horizonte
Cícero Murta Diniz Starling, starling@demc.ufmg.br
Federal University of Minas Gerais, Belo Horizonte
Paulo J. Modenesi, modenesi@demet.ufmg.br
Federal University of Minas Gerais, Belo Horizonte

Abstract. GMA welding is presently one of the most important joining processes of metals. However, this welding process presents a strong interrelationship between its operational parameters and a high sensitivity to changes in operational conditions that may hinder its use. Furthermore, a number of instability phenomena have been reported during GMA welding. Although some of these instability problems have been extensively studied, some of them, particularly those linked to the arc transition regions are still poorly known and studied. Strong arc instability that is characterized by repulsive metal transfer, strong variations in welding current and voltage, and high volume of spatter formation has been reported during the welding of low carbon steel with gas shielding of low oxidation potential. This problem was connected to alterations in electron emission mechanisms operating on the cathode surface. This paper analyses different characteristics of this instability phenomenon and relate them to the model that is presently available to explain it. All trials were performed with the process operationg in constant current to emphasize more fundamental characteristics of the instability. Welding voltage oscillograms, arc light intensity measurements, and high speed filming were used in this study. It was shown that changes in metal transfer characteristics, arc light intensity and welding voltage occur simultaneously during the instability. Changes in arc position and shape and its effects on the base metal (cathodic oxide removal) were also observed. The results agreed well with the model initially proposed. However, they also suggest that details concerning the onset of instability should be rethought.

Keywords: GMAW, Arc Instability, Arc Physics, Shielding Gases, Metal Transfer.

1. INTRODUCTION

Arc rooting phenomena have a profound influence on many aspects of arc welding, particularly in GMA welding. When welding steel with this process, oxygen additions to an otherwise inert shielding gas reduce arc root mobility and can significantly improve process stability (Hilton & Norrish, 1988). This effect is linked to the rebuilding of the oxide layer on the base metal and close to the arc root that is destroyed by electron emission to the arc (Patte *et al.,* 1968). Obviously, many other aspects including metal transfer conditions strongly influence process behavior during welding.

A great number of papers relating instability problems in GMA welding, including changes in metal transfer characteristics, can be found in the literature. In 1975, Lucas & Amin linked changes in metal transfer characteristics to the oxygen content of the steel wire. Gas bubble formation and explosion (probably of CO and CO_2) occurred at the wire tip when the content of oxygen in the steel was high. The problem could be avoided when manganese and silicon levels in the steel were high enough to prevent that reaction. In 1981, Agusa *et al*. studied the influence of cerium additions to the wire on arc stability during the welding of steel with pure argon shielding. They observed the sporadic occurrence of globular metal transfer in operational conditions typical of spray transfer. Rodwell, in 1985, observed, during GMA welding with carbon and stainless steel wires and spray transfer, the occurrence of process disturbances, including sudden changes of arc length, welding current, and bead shape. The author attributed these disturbances to contaminations of the wire surface and contact tip. GMA welding with short circuit metal transfer usually present a lower stability than with spray transfer. For the former condition, a number of studies have been presented that relate process stability to different parameters derived from the electrical signals of the process (Dutra, 1989; Modenesi & Avelar, 1999; Kang, *et al*, 2003).

In 1994, Modenesi & Nixon described, for the GMA welding of low carbon steels, an instability phenomenon that was linked to the oxidation potential of the shielding gas. Its manifestations included alterations in arc shape, welding current and voltage levels, and metal transfer type (which changed from stray to repulsive globular metal transfer). The authors claimed that the phenomenon was affected by several aspects of the welding process including the initial arc length, shielding gas composition, power supply characteristics, and the duration of welding. When using a constant voltage power supply and a sufficiently low welding voltage, the welding process would tend to initiate unstably, with repulsive globular transfer and high spatter generation. However, after a period of time that depended on the welding voltage and gas composition among other factors, the process would revert to stable operation. This transition was characterized by a sudden increase in arc length and current level that could be easily detected in the process oscillograms (Fig. 1).

When studying the phenomenon with constant current power supplies, the authors analyzed the influence of the arc length by changing the contact tip-to-work distance (CTWD). It was observed that unstable operation was more

frequent for small values of CTWD (shorter arc length). Under these conditions, strong variations of welding voltage occurred together with changes in transfer mode and arc shape. The periods of higher welding voltage occurs more frequently with the shortest arc operational conditions.

The duration of these periods tended to reduce when the arc length was increased (Fig. 2) what coincided with an improvement in process stability. Based on the evidences the authors linked the periods of higher welding voltage to the unstable operation. They also proposed that this instability was associated to changes in electron emission mechanisms from the base metal. Therefore, in the present work, this form of instability will be called *Cathodic Mechanism Instability*.
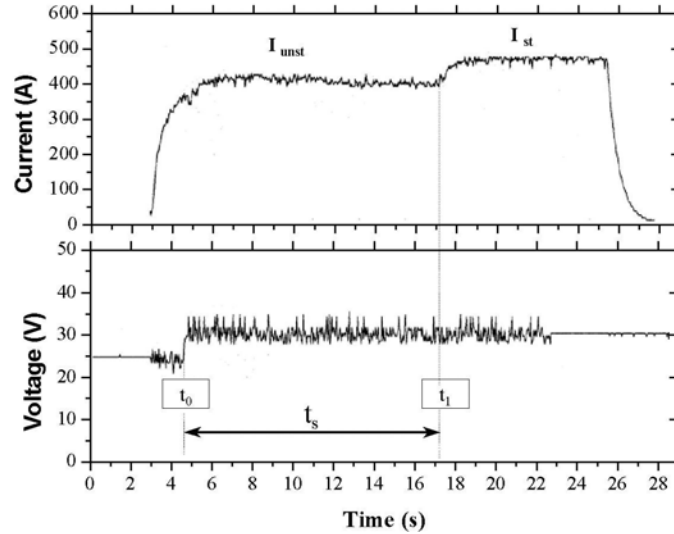

Figure 1. Current and voltage oscillograms of a welding trial with a constant voltage power supply that presented an initial unstable operation. t_0 – Arc start time, t_1 – transition from unstable to stable operation, t_s – unstable period, I_{unst} and I_{st} – current levels during unstable and stable operations.
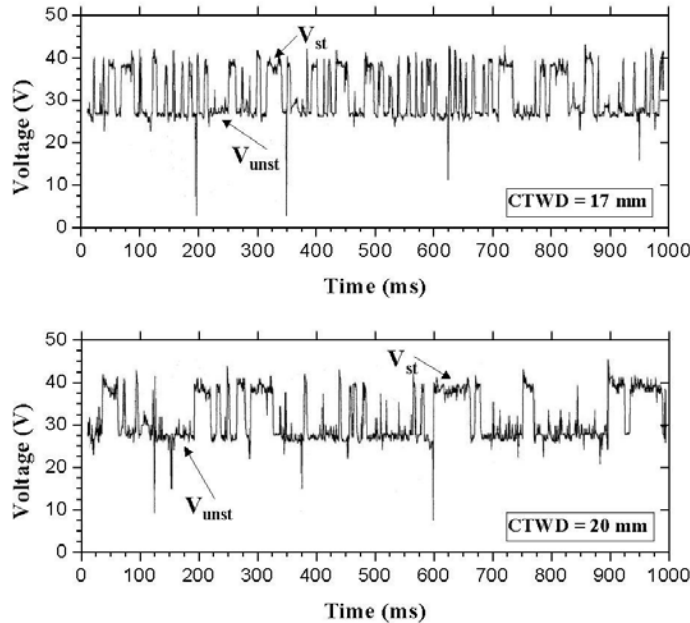

Figure 2. Voltage oscillograms of welding trials performed with a constant current power supply and different CTWD values. V_{unst} – Unstable operation voltage, V_{st} – Stable operation voltage.

Despite having a strong influence on operational condition of GMA welding, almost no systematic study of the instability of cathodic mechanism has been performed since its initial discovery. This can be understood by considering that shielding gases used for low carbon steel usually have a sufficiently high oxygen (or CO2) content to prevent the instability. However some recent studies (Tong, *et al*, 2005; Costa, 2006) have shown that this form of instability can occur for other forms of metal transfer, even with some shielding mixtures used for low carbon steels, and also for other

types of base metals, including aluminum and stainless steels. In this context, the present paper is part of a research work that intends to analyze aspects of this form of process instability. It aims to describe the main characteristics of this instability in carbon and stainless steels and in aluminum, and complement the previous works which high speed filming synchronized with voltage and current signals from the process. All the welding trials were performed with the power supply operating in constant current to emphasize more fundamental aspects of the instability.

2. MATERIALS AND METHODS

Welding trials were performed in workpieces of SAE 1020 steel (12.5 x 50 x 250 mm), AISI 304 austenitic stainless steel (6.35 x 70 x 300 mm) and AA1100 aluminum (6.35 x 50 x 200 mm). Surface scale of carbon steel specimens was removed by grinding, and, just before welding, the specimens were cleaned with a steel wire brush and washed with acetone. Stainless specimens were just washed with acetone before welding, and aluminum specimens were cleaned with chemical solutions indicated by an aluminum producer (Alcan, 1993) and the American Welding Society, 1991.

GMA bead-on-plates welds were deposited the specimen surfaces using a mechanized jig with an electronic power supply. AWS ER 70S6, ER 308 and E 4043 wires of 1.2 mm diameter were used with the carbon steel, stainless steel, and aluminum specimens respectively. Pure argon and Ar‑1%O2 were used as shielding gases for the trials with carbon and stainless steels. For aluminum, only pure argon was used.

The influence of the arc length was studied by changing the contact tip-to-work distance (CTWD). In all trials, welding current and voltage were monitored using a digital data logger. In some trials, the arc light intensity was also monitored. A photodiode was used as a light sensor and its signal was conditioned by an apparatus developed by Miranda & Ferraresi, 2002. All data files were processed by the SINAL program (Modenesi, 2005). The parameters used in the experimental trials are shown in Tab.1.

High speed video (2000 frames per second) with laser shadowgraphy was used in a few trials to observe metal transfer characteristics during unstable operation (Allemand *et al.*1985; Subramaniam *et al.*1998). The video was synchronized to the current and voltage signals from the welding process (Vilarinho, 2000).

Photographies were taken from the surface of some welding specimens to characterize to areas of cathodic cleaning on the base metal associated with the trial**.**

Table 1. Experimental conditions of the welding trials with constant tension operation.

Base Metal	Shielding	Wire feed rate (m/min)	Test voltage (V)
Carbon steel	Pure Ar	7	35 V
	Ar-1%O2	7	33 V
Stainless steel	Pure Ar	7	35 V
	Ar-1%O2	7	33 V
Aluminum	Pure Ar	6	23.5 V

OTHER OPERATIONAL PARAMETERS	
Gas flow: 16 L/min	Wire diameter: 1,2 mm
Welding speed: 25 cm/min	Data acquisition frequency: 100 – 4000 Hz
CTWD: 22 mm	Time of welding: 3,75 – 30 s
Nozzle diameter: 52 mm	Welding position: Downhand

3. RESULTS AND DISCUSSION

In the welding trials with constant current operation, voltage oscillograms displayed two clear voltage levels when the process presented some unstable characteristics (Figures 3 and 4). The voltage difference between these levels was around 10 V for both steels and around 5 V for aluminum. The high voltage periods tend to occur more frequently and to last longer when the CTWD (and, therefore, the arc length) was reduced what was followed by typical manifestations of the instability (repulsive globular metal transfer, and high spatter and fume levels). However, as the low and high voltage periods usually lasted less than 1 second, it was not possible to associate them by direct visual observation with the stable and unstable operations respectively. These results were quite similar to those reported by Modenesi & Nixon, 1994 for carbon steel.

Photographies of arc in welding conditions that lead to the two voltage level operation suggested that strong variations in arc shape could happen (Fig. 5). In order to establish the effect of these changes on arc luminosity levels, welding trials with constant current operation were performed monitoring the signal from a photodiode pointed to the arc together with the welding current and voltage signals (Fig. 6). A strong correlation between the voltage and light intensity signals could be observed in conditions of unstable operation. The results indicate that, during the high voltage periods that are associated to the unstable operation, the arc is brighter than during the low voltage periods. The

variations in the process (welding voltage and light intensity levels, arc shape, and fume emission) suggest that fundamental alterations should be happening in the arc during the occurrence of the instability of cathodic mechanisms. Changes in voltage for the same current level and shielding gas composition are generally associated to arc length variation, what is not happening in the present case, at least to explain a 10 V alteration. On the other hand, if the welding current and arc length are approximately fixed, changes in arc light intensity and fume level could be caused variations on the amount of metal vaporized to the arc.
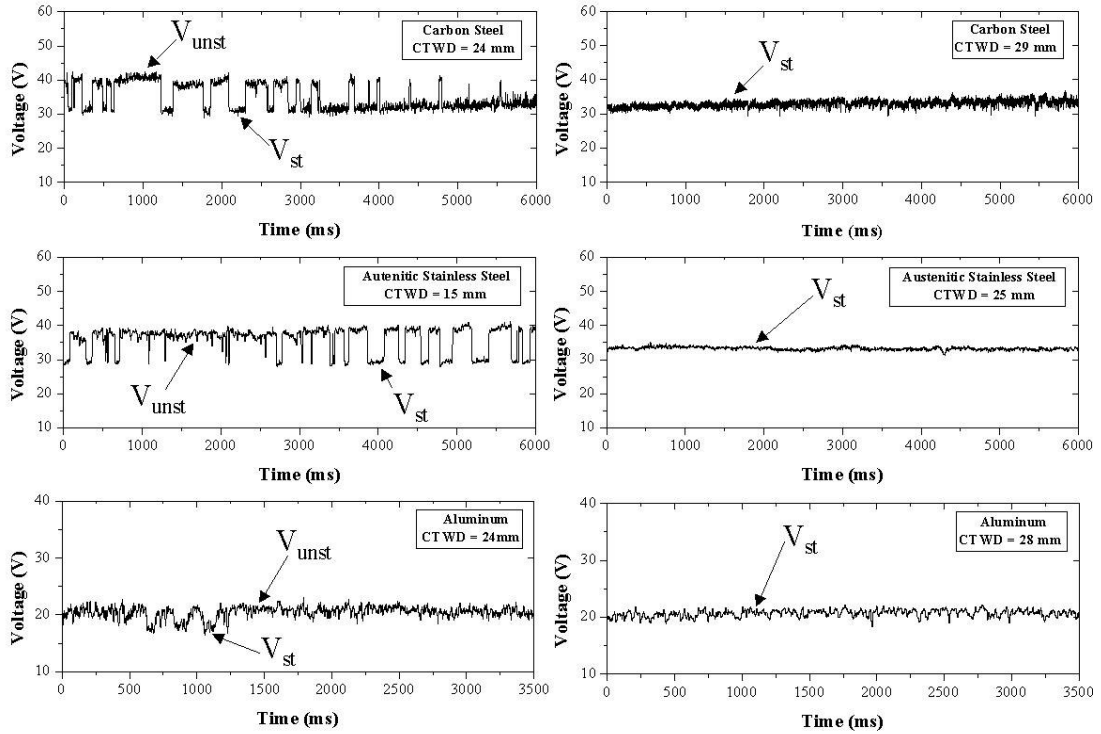
Figure 3 . Voltage oscillograms of welding trials with constant current operation for different materials and CTWD values. Welding current of 255 A for carbon and stainless steels and of 175 A for aluminum. Shielding gas: pure argon.
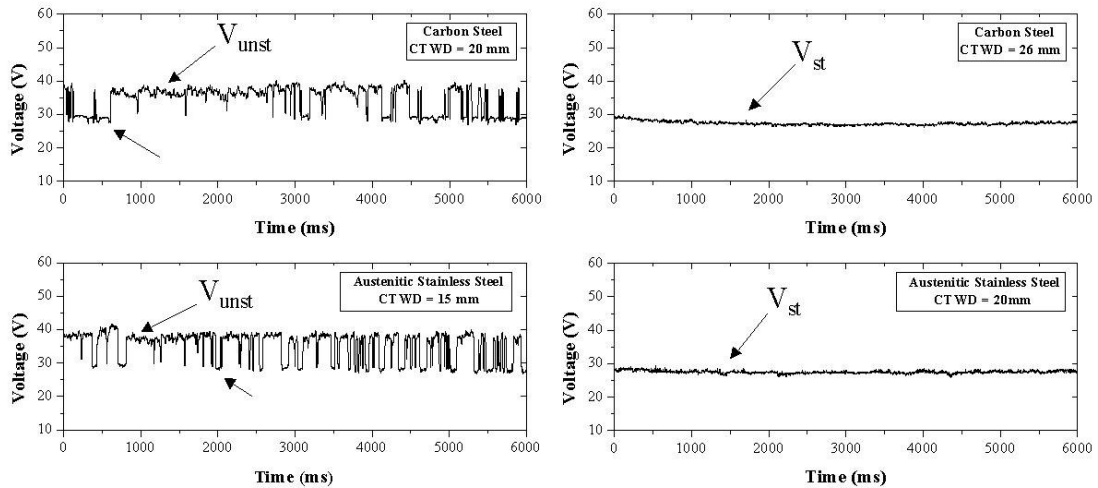

Figure 4 . Voltage oscillograms of welding trials with constant current operation for carbon and stainless steels and CTWD values. Welding current: 255 A. Shielding gas: Ar - 1%O2.
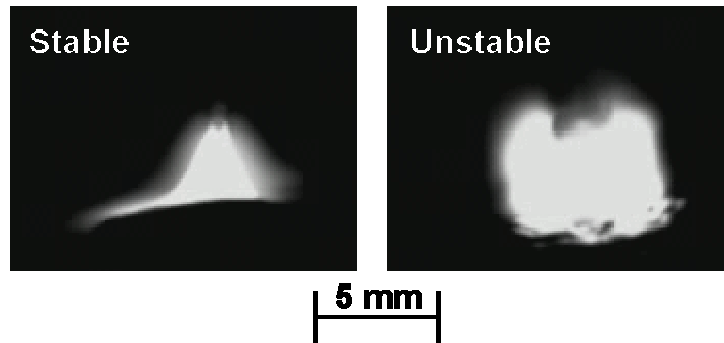
Figure 5 . Variations in arc shape observed during unstable constant current operation.

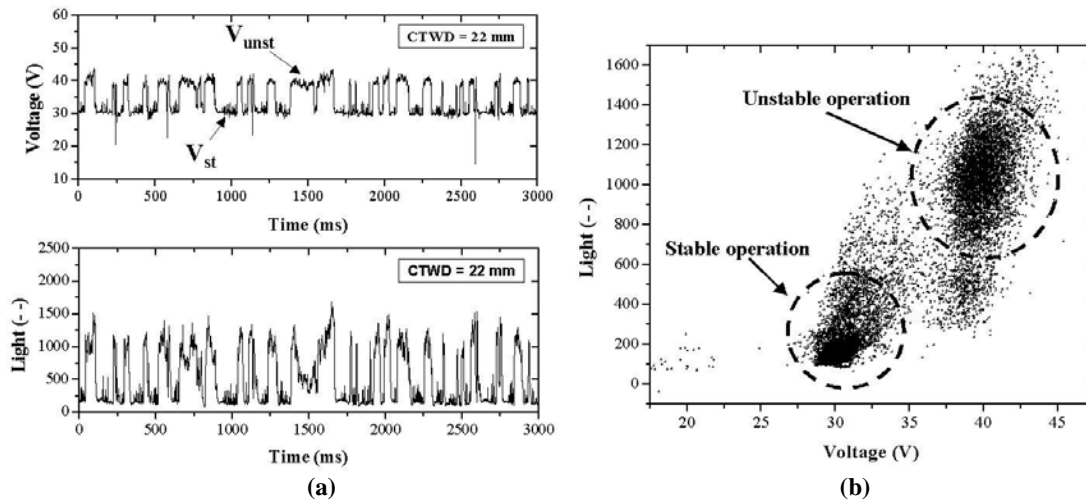(a)   (b)

Figure 6. (a) Variations of welding voltage and arc light intensity during a constant current operation trial with unstable behavior. (b) Voltage-light intensity relationship. Welding current: 255 A.

During the periods of high voltage level, the arc light intensity tends to present a stronger variability than the voltage. Particularly, a strong decrease in light intensity (Fig. 7) frequently occurs shortly after its initial increase after the beginning of a high voltage period. This effect may be related either to the increase of the liquid metal drop due to the repulsive globular metal transfer (resulting in a decrease in arc length) or to the higher level of fume generation that blocks the light being emitted by the arc. As the arc light intensity sometimes increases back during these periods, the first hypothesis seems to be more plausible. Indeed, in this case, a droplet detachment would increase back the arc length and, so, the luminosity of the arc. This also suggests that the variation in voltage that occurs between the periods of high and low voltage are not associated to changes in arc length but more probably to phenomena occurring outside the arc column. The changes in arc length due to the droplet formation and detachment that cause a strong variation in arc light intensity result in a much weaker variation in voltage.

Figure 8 presents, for a welding trial of carbon steel with pure argon and constant current operation, a small part of its high-speed video. A sequence of two unstable periods that lasts about 0.15 s is shown. At least the first unstable period seems to have being triggered by a rapid short circuit. Before this event the process operates with streaming spray metal transfer. After the short circuit (frame 2), there is a characteristic 10 V increase in welding voltage and most of the phenomena previously described for the unstable operation mode can be observed. A single drop with a diameter of around three times the wire diameter is formed during the first unstable period. However, differently from what was observed during welding with constant voltage operation (Costa, 2006), the arc length changes little up to the end of the first unstable period (frame 10). This droplet detaches from the electrode after a short interruption of the unstable operation (frames 11 to 14). The darkening of some frames suggests a higher fume generation. The images also indicate a stronger stirring of the weld pool during the unstable operation.
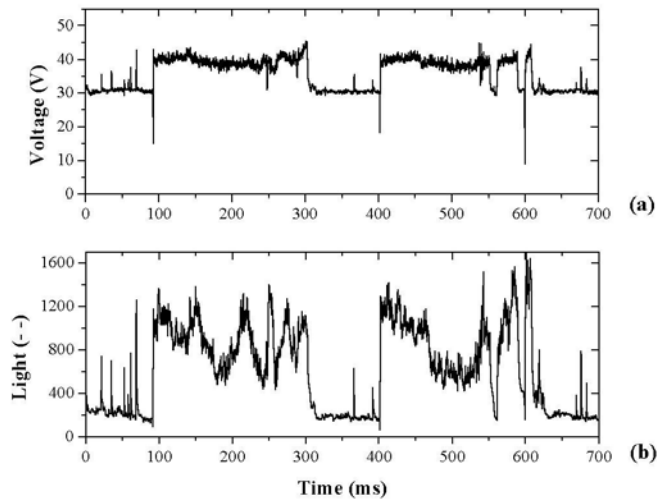
Figure 7. Detail of a welding voltage (a) and arc light intensity (b) oscillogram for unstable constant current operation.
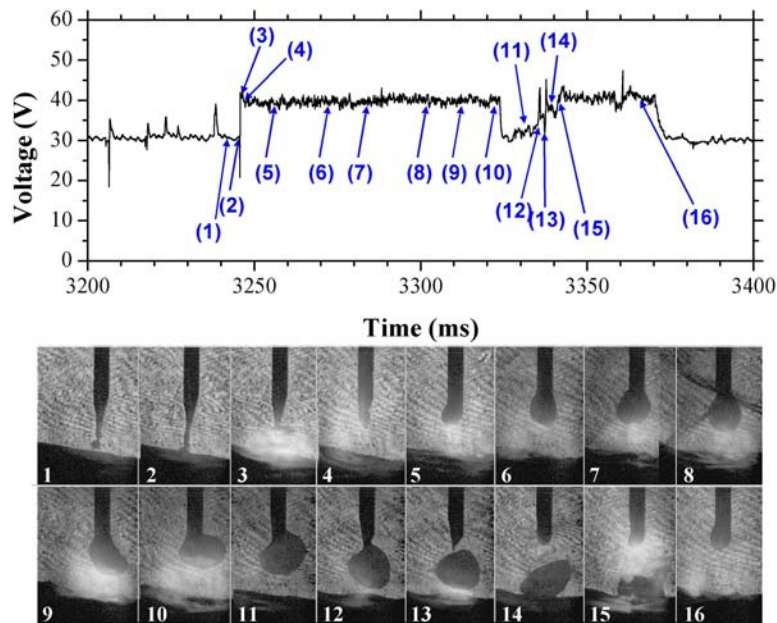

Figure 8. High-speed video of unstable operation periods synchronized with its voltage oscillogram. Welding of carbon steel with pure argon shielding and constant current operation.

The analysis of the high-speed videos of welding trials with unstable operation strongly suggests that the periods of unstable operation tend to start after a rapid short circuit of the wire on the weld pool (Fig. 9).

Modenesi & Nixon (1994) linked most of these phenomena to a change in electron emission mechanism in the arc. In GMA welding, electron emission from the cathode to the arc depends critically on the presence of oxide layers on the cathode surface (Guile, 1971). However, once the emission occurs in a given area, the oxide layer of this area is destroyed. Therefore, when welding with a shielding gas that has not enough oxygen to regenerate the oxide layer, its destruction forces the arc to deflect to reach new areas of the base metal still covered with the oxide layer. This effect increases the effective arc length and makes it more difficult to keep the arc operating. Under these circumstances, Modenesi & Nixon (1994) proposed that an alternative mechanism of electron emission could start to operate on the center of the weld pool. This alternative mechanism would be one based on the emission of vapor jets similar to those reported for low pressure arcs (Fu, 1989). The vapor generated by the cathode and forced into the arc would explain the increase in arc brightness and fume emission. The more punctual cathode would change the arc shape making it to contract near the weld pool. However, the electromagnetic force that generates the plasma jet in the arc depends on the inverse of the electrical conductor diameter. Therefore, the contraction of the arc near the weld pool could generate a

plasma jet directed from the weld pool to the electrode and this jet would prevent the metal drop from detaching from the electrode favoring a repulsive globular metal transfer (Modenesi & Nixon, 1994).
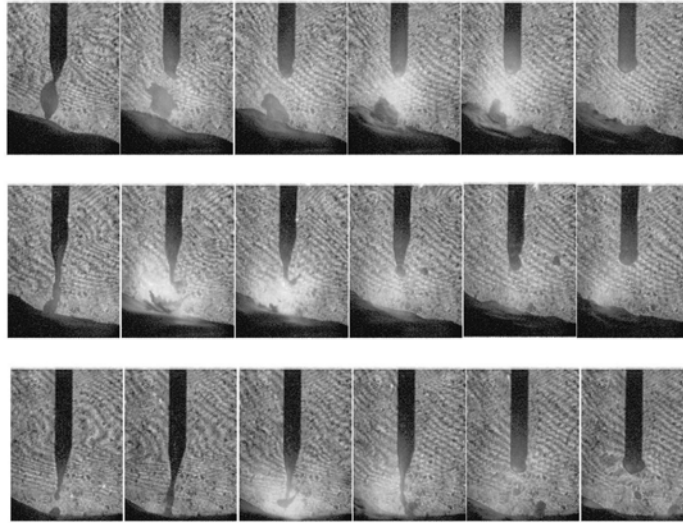

Figure 9. Three examples of the transition from stable to unstable operation triggered by rapid short circuiting of the wire on the welding pool. Welding of carbon steel with pure argon shielding. Time between frames: 1.5 ms.

The alternative electron emission mechanism could also explain the increase in arc voltage with no major change in arc length observed during the trials with constant current operation. For this type of operation, the welding voltage can be described as:

$$U = (U_C + U_A) + E \cdot l_a + k_e \cdot (h - AO) \tag{1}$$

where U_C and U_A are the voltage drops in the cathode and anode transitions, respectively, l_a is the arc length, E is the electric field in the arc column, h is the CTWD and A_O is defined in Fig. 10. The equation above does not consider voltages drops in the electrode and contact tip. A change in electron emission mechanism would move the ac root from point C to point A (Fig. 10) and cause a variation in the welding voltage:

$$\Delta U = U_{Instável} - U_{Estável} = (U_C)_{Instável} - (U_C)_{Estável} + (E \cdot l_a)_{Instável} - (E \cdot l_a)_{Estável} \tag{2}$$
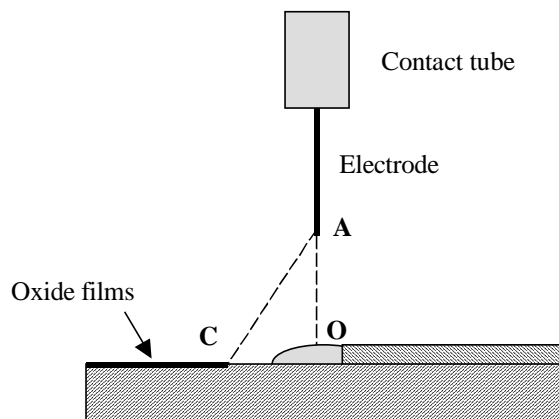

Figure 10. Schematics of the arc region in GMA welding.

As the effective arc length tends to become shorter during the unstable periods (Fig. 10), a first analysis of the term $[(E\ l_a)$Unstable $- (E\ l_a)$Stable] indicates that it contributes to reduce ΔU. However, alterations in the arc column during the transition from stable to unstable operation, may also affect the column electric field (E). The results of the present work suggest that a major alteration in the column is an increase of its metal vapor concentration. However, metallic

elements, like iron and manganese, and also silicon have lower ionization potentials than argon and, as the atomic weights of Fe and Mn are larger than that of argon, it is also expected that they do not increase the thermal conductivity of the arc. These results indicate that E may reduce during the unstable periods and, therefore, also favor a reduction of ΔU. Therefore, a positive value of ΔU of about 10 V should be related mainly to phenomena occurring in the cathodic drop region, for instance, changes in electron emission mechanisms as proposed for Modenesi & Nixon, 1994.

The results of the present work do not confirm that the instability is triggered by a competition between electron emission mechanisms caused by arc deflection as proposed by those authors. The major factor to start the unstable periods seems to be the occurrence of rapid short circuits between the electrode and the weld pool. A short circuit tends to momentarily extinguish the arc, and the explosion of the liquid metal bridge that follows generates a vapor cloud that could favor the emission of electrons by the weld pool. This also suggests that this form of instability should be more commonly observed in operational conditions that can present rapid short circuits. One example is the streaming spray metal transfer with short arc length that was used in most of the welding trials with steel of the present work. This also seems to happened in the paper of Tong *et al.*(2005) who observed abnormal voltage periods during pulsed and variable polarity GMA welding of aluminum.

During normal GMA welding operation, the arc consumes the oxide layers on the base metal close to the weld pool (Essers & Van, 1984). When using pure argon as shielding gas, this layer is not regenerated, and the arc tends to deflect away from the weld pool, leaving a surface area clean from oxide layers around the weld bead (Boughton & Amin, 1972). On the other hand, if an alternative electron emission mechanism that does not consume of oxide layers operates, this area should not be formed. Therefore, variations in the aspect of the area around the weld bead may be used as an indication of the operation of alternative electron emission mechanisms.

Figure 11 presents the surface of weld beads of carbon steel that were deposited with pure argon shielding and CTWD values of 20 and 26mm. Although in both cases the base metal is covered by a layer of welding fume, one can observe in the second photography (stable operation) the existence of a wide area with oxide removal on both sides of the weld bead. A similar area apparently does not exist in the first specimen which was welded with a large amount of instability. The second bead is also remarkably thinner than the first one. This possibly results from a lower wettability of the liquid metal in the stable operation due to the removal of oxide from the base metal surface.
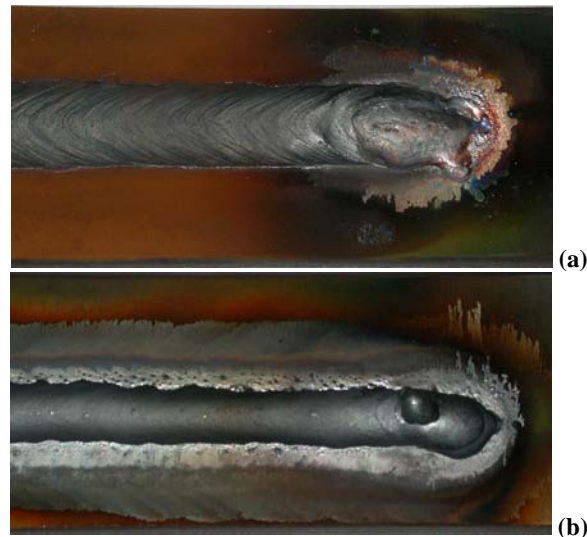

(a)

(b)

Figure 11. Weld bead surface for CTWD values of (a) 20 mm e (b) 26 mm. Carbon steel and pure argon shielding

4. CONCLUSIONS

Instability phenomena associated with the arc rooting characteristics in the base metal are described. These phenomena are associated with the use of shielding gases of low oxidation potential and a short arc length. It was shown that they can occur, with characteristics quite similar to those previously reported for carbon steel, in the welding of austenitic stainless steels and aluminum. In the welding of aluminum, in the condition used in the present work, the unstable periods tend to be shorter and less frequent that with both carbon and stainless steels.

The periods of stable operation, when using an inert shielding gas, are associated with areas of oxide removal around the weld bead. During unstable operation, these areas tend to disappear.

The periods of unstable operation are characterized by a brighter arc that is more constrict close to the weld pool, by a strong stirring of the liquid metal in the pool, by repulsive globular metal transfer, and by elevate fume generation. With a constant current power supply, these periods are associated with an elevation of around 10 V in the welding voltage.

The relationship between the variations of welding voltage and the unstable metal transfer and other phenomena was confirmed by high speed video with laser shadowgraphy. This technique also allowed to link the beginning of unstable periods to the breaking of rapid short circuits between the electrode and the weld pool.

The results of the present work agree with the previously proposed hypothesis that this instability is associated to changes in mechanisms of electron emission by the cathode to the arc.

5. ACKNOWLEDGMENTS

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