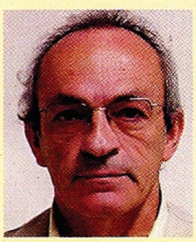
Electrical model for the plasma-MIG hybrid welding process

Moises Alves de Oliveira *is a mechanical engineer and manufacturing process specialist at Embraco/Brazil. Having obtained a M.Sc. degree in 2001, he received his doctorate in 2006 in a cooperative work between LABSOLDA/UFSC (Welding Institute at the Federal University of Santa Catarina, Brazil) and the Welding Training and Research Institute SLV München, Munich/Germany.*



Prof. Dr. Eng. Jair Carlos Dutra*, born 1949 in Palhoça/Santa Catarina, Brazil, studied mechanical engineering at the Federal University of Santa Catarina (UFSC), Florianópolis from 1968 to 1972 and received his M.Sc. degree in 1974. From 1983 to 1985 he developed activities at the Institute of Welding Automation (Prozesssteuerung in der Schweißtechnik APS) in a cooperative programme between UFSC and the Technical University Aachen. In this programme he received his doctorate in 1989. Since 1974, he has been director of the welding laboratory of UFSC.*

An electrical model is proposed for the plasma-MIG welding process, based on the association of a counter electromotive force with a resistive effect and based on the existence of a hybrid arc through which the plasma and MIG currents flow evenly distributed.

Moises Alves de Oliveira and Jair Carlos Dutra, Santa Catarina/Brazil

1 Introduction

The plasma-MIG hybrid welding process, the classical representation of which is shown in Fig. 1, combines the high productivity characteristics of processes which use consumable electrodes with the advantages offered by processes with permanent electrodes, such as arc stability and geometric control of the bead. Although this process was the object of a series of studies and developments in the 1970s and 1980s [1...3], it was not significantly absorbed by the industry. One of the reasons for the low use of this process may be the lack of arc stability under certain conditions which causes unstable metal transfer, irregular geometry of the weld bead and even the destruction of some internal parts of the welding torch.

This study aims to contribute to a better understanding of the physical and electrical phenomena involved in the coexistence of the electric arcs, with the objective of collaborating in improving the process stability. An electrical model is proposed to represent the plasma-MIG hybrid process, starting with an investigation and analysis of its static and dynamic behaviour. For the modeling of electric arcs, the association of a counter-electromotive force with a resistive effect is used – an arrangement proposed by Gohr Jr [4] and used successfully for the modeling of the electric arc of the

Communication from the Federal University of Santa Catarina, Brazil

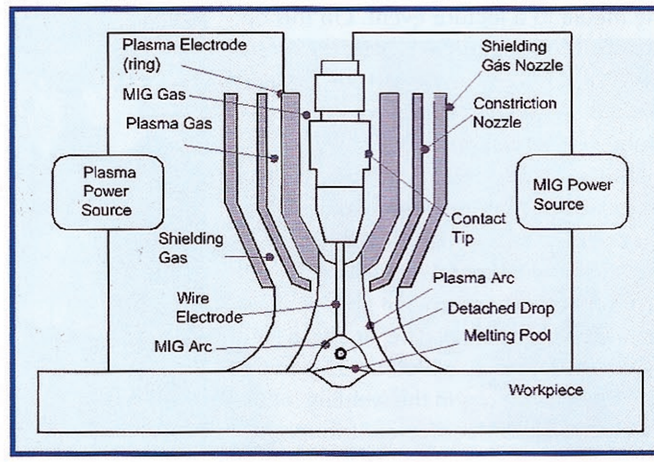


Fig. 1. *Classical diagrammatic representation of the plasma-MIG welding process [1].*

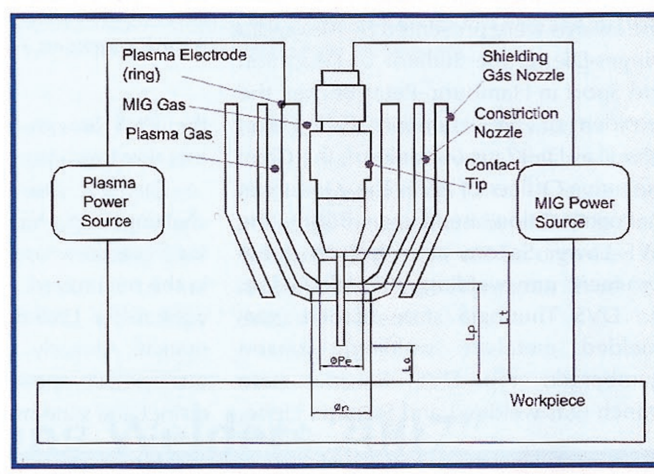


Fig. 2. *Experiment set up.*

MIG/MAG process. Also, the existence of a plasma arc, through which the plasma current flows, and of a hybrid arc, through which the plasma (I_{CP}) and MIG (I_{CM}) currents flow evenly distributed and without separation, is proposed.

2 Experimental procedure

For the investigation of the curves of the static characteristics of the process, simple deposition welding tests on 10 mm × 200 mm × 250 mm aluminium specimens were carried out, using AlSi5 wire with 1.2 mm of diameter as the filler metal. During the experiments a distance between the MIG contact tip and the workpiece (L_t) of 22 mm and a distance between the solid point of the wire and the specimen surface (L_a) of 4 mm, were maintained. Also, a distance of 14 mm between the plasma electrode face and the specimen surface (L_p) was maintained. The welding gun used is equipped with a copper ring electrode with 7 mm diameter ($ØP_e$), as the anode of the plasma arc, and a constrictor nozzle with a diameter ($Øn$) of 11 mm, Fig. 2. The gun displacement was carried out automatically by a six-axis welding robot. The experimental bench has two electronic

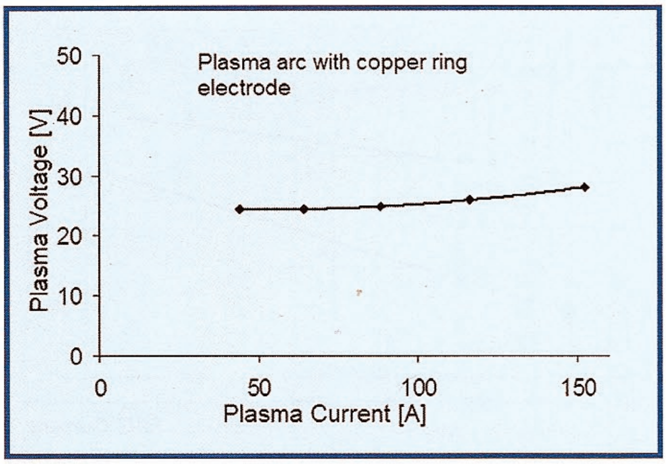


Fig. 3. *Constant characteristic curve for the plasma arc with copper ring electrode 7 mm diameter, on an aluminium surface. Pure argon as the internal, external and shielding gas, with flow rates of 5.5 and 10 l/min, respectively.*

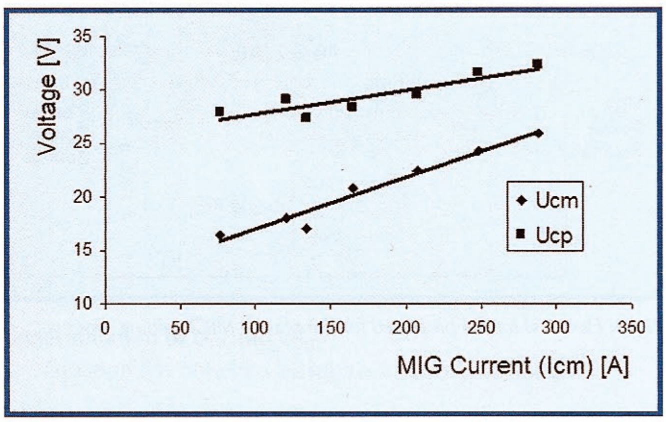


Fig. 4. *Voltage of the plasma and MIG circuits as a function of the current which flows through the wire electrode – constant plasma current (I_{CP} = 64).*

power supplies, controlled by a PC with a software specifically developed for the plasma-MIG welding. During the experiments, the currents and voltages of the plasma and MIG electrical circuits were measured with an acquisition rate of 5 kHz per channel, using a computerised data acquisition system. These data were analysed and treated statistically and, later, the average currents and voltages of the plasma and MIG arcs were calculated for each welding condition. For each MIG current value selected, the wire speed was adjusted until the distance between the solid point of the wire and the workpiece surface reached 4 mm. After the adjustment of the wire speed, the voltage measurement was carried out. With the use of lower currents, the metal transfer was globular, becoming a spray with the use of higher currents.

3 Static and dynamic characteristics of the plasma-MIG process

Initially, an experiment was carried out to observe the behaviour of the static characteristics of the plasma arc, when this is formed between a copper ring electrode and an aluminium surface, with reverse polarity, without the presence of the MIG arc.

In the graph of Fig. 3, it can be observed that the voltage versus current curve has a form typical of electric arcs generated by permanent electrodes, and that for an arc length of 14 mm, the average voltage has values between 25 and 30 V.

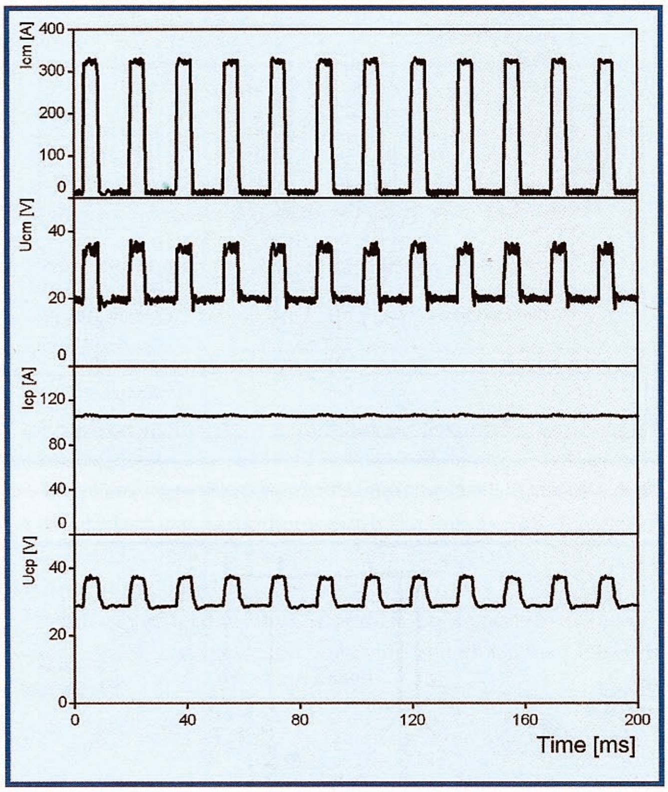


Fig. 5. *Oscillogram of currents and voltages for a weld carried out with pulsed MIG current.*

The graph of Fig. 4 shows the results for the measurement of the MIG circuit voltage (U_{CM}) and the plasma circuit voltage (U_{CP}) as a function of the current which flows through the wire – in this study called the MIG circuit current and represented by I_{CM} – maintaining the plasma circuit current (I_{CP}) constant. It can be seen that U_{CM} has a linear relation with I_{CM} and, even keeping I_{CP} constant, the voltage U_{CP} also shows an increasing linear dependence on the MIG current (I_{CM}). With this result it is assumed that the voltages U_{CP} and U_{CM} can be described by linear equations singularly dependent on I_{CM}, if the plasma current (I_{CM}) is kept constant. The same behaviour was observed for the plasma-MIG using steel (ER 70 S-6) and bronze (CuSi3) wires and with different levels of plasma current. However, for this paper, only the results obtained with aluminium wire will be presented.

This behaviour can also be observed for welding with pulsed current, Fig. 5. It can be noted that the pulsation of I_{CM} results in a pulsed nature of U_{CM} and U_{CP} voltages, even though I_{CP} remains constant.

One explanation for the influence of the I_{CM} on the U_{CP} is to assume that below the solid end of the wire electrode, a separation of the electric arc is not evident, which makes I_{CM} and I_{CP} flow through the same electrical path.

In a study in which the variation in the density of the electrical current of the arc in the plasma-MIG process was radially mea-

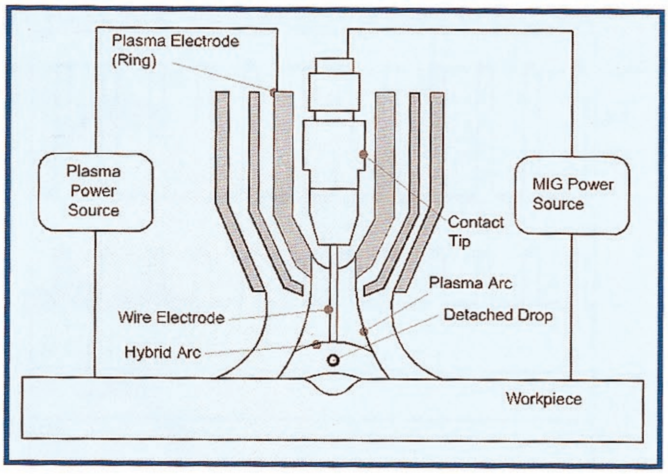


Fig. 6. Diagram of the plasma-MIG process with plasma arc and hybrid arc.

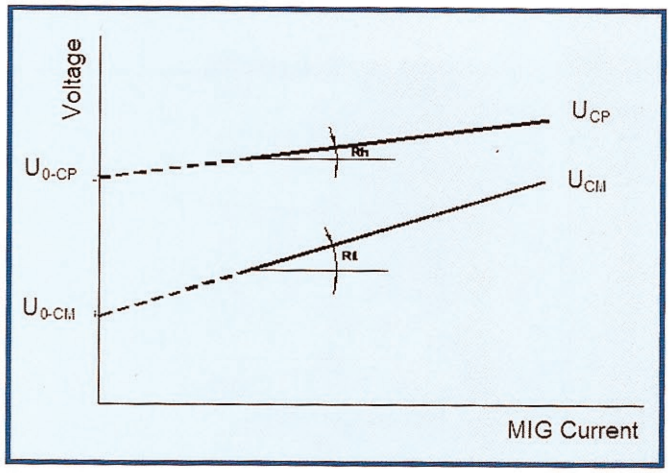


Fig. 8. Static characteristics of the plasma-MIG process.

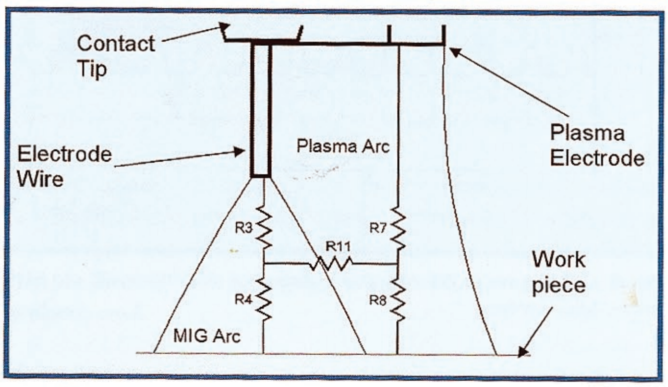


Fig. 7. Electrical modeling of the electric arcs for the plasma-MIG process, according to Matthes and Kohler [5].

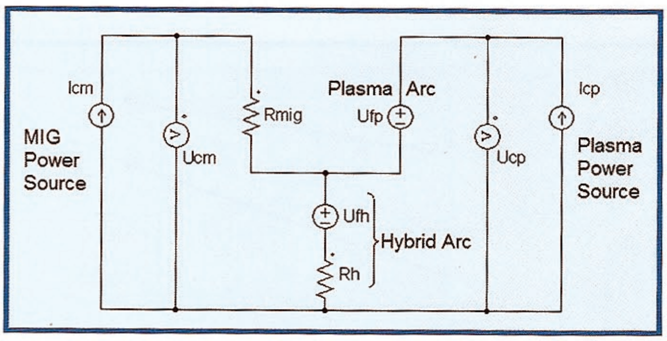


Fig. 9. Electrical model proposed for the plasma-MIG welding process.

sured, Ton [5] states that most of the total current of the process (I_{CM} + I_{CP}) flows through the periphery of the arc. According to this author, the greater luminosity in the center of the column, typically observed below the end of the wire electrode, is due to the existence of metal vapors concentrated in this region, and not because of a greater current density in the center of the arc column.

Given these considerations, it is assumed in this study that, below the solid end of the wire electrode, I_{CM} begins to circulate evenly distributed with I_{CP} after leaving the anodic region. Thus, it is proposed that the plasma arc is only denominated as such above the solid end of the wire electrode. Below this point, the existence of a hybrid arc is proposed, where the I_{CP} and I_{CM} currents circulate without physical separation, reaching the surface of the workpiece over the same cathodic region, Fig. 6.

4 Electrical model for the plasma-MIG process based on the association of a counter-electromotive force to describe the electric arcs

An electrical model to represent the hybrid plasma-MIG process was proposed by Matthes and Kohler [6]. In that study, the authors assumed the existence of two separate arcs (plasma and MIG), represented by electrical resistances (R3, R4, R7 and R8), along with the part of the MIG current which can pass to the plasma arc, through a transversal resistance (R11) which connects the two arcs, Fig. 7.

Gohr Jr. [4] developed an electrical model to simulate the GMAW process, which considered that the arc, besides being a resistive charge, had characteristics of a counter-electromotive force. With this model, Gohr Jr. obtained simulated oscillograms very close to those measured in real electric arcs. Baixo [7] carried out experiments where the GMAW voltage and current, during an open arc period, also showed a correlation with linear behaviour. The proposal to electrically model the electric arc associating its resistive effect with a counter-electromotive force is also appropriate for a plasma-MIG process, particularly when the curves of the static characteristics investigated in this study are analysed. U_{CM} and U_{CP} can be described according to Eqs. 1 and 2 as illustrated with the help of Fig. 8.

$$U_{PI} = U_{0PI} + R_h \cdot I_{MIG} \qquad (1)$$

$$U_{MIG} = U_{0MIG} + R_t \cdot I_{MIG} \qquad (2)$$

Based on these observations and assuming the existence of plasma and hybrid arcs, according to Fig. 5, an electrical model can be proposed based on the circuit diagram of Fig. 9. In this model, the

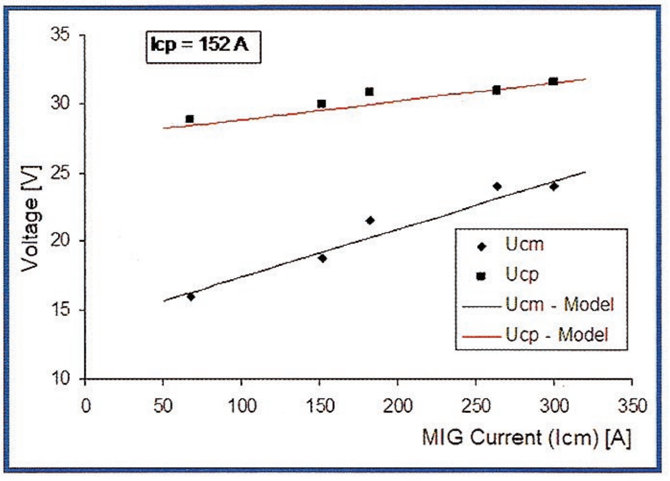


Fig. 10. Static characteristics of the plasma-MIG process – comparison of results calculated by the proposed model and measured results.

internal resistances of the power sources and the conductor cables have been neglected.

Considering the proposed electrical model, the U_{CP} and U_{CM} voltages can also be described by Eqs. 3 and 4, respectively:

$$U_{CP} = U_{fp} + U_{fh} + R_h \cdot (I_{CM} + I_{CP}) \tag{3}$$

$$U_{CM} = I_{CM} \cdot R_{mig} + U_{fh} + R_h \cdot (I_{CM} + I_{CP}) \tag{4}$$

Determination of U_{FP} and U_{FH}

Equation 5 is obtained by subtracting Eq. 3 from Eq. 4:

$$U_{CM} - U_{CP} = I_{CM} \cdot R_{mig} - U_{fp} \tag{5}$$

Substituting U_{CM} and U_{CP} with Eqs. 1 and 2, gives Eq. 6:

$$U_{0-CM} + R_t \cdot I_{CM} - U_{0-CP} - R_h \cdot I_{CM} = I_{CM} \cdot R_{mig} - U_{fp} \tag{6}$$

From the analysis of the proposed electrical circuit and the experimental results obtained in Fig. 4, it can be stated that:

$$R_t = R_{mig} + R_h \tag{7}$$

Substituting R_t in Eq. 6, the value of U_{FP} is determined with Eq. 8:

$$U_{FP} = U_{0-CP} - U_{0-CM} \tag{8}$$

Finally, substituting Eq. 8 in Eq. 3, the value of U_{FP} is determined with Eq. 9:

$$U_{FH} = U_{0-CM} - R_h \cdot I_{CP} \tag{9}$$

U_{0-CP}, U_{0-CM}, R_{MIG}, and R_h are determined by fitting the curves of the static characteristics of the plasma-MIG process, obtained experimentally, Fig. 4.

***Table 1.** Parameters for the validation of the model which simulates the plasma-MIG process statistically*

Wire		AlSi-5
Wire diameter	[mm]	1.2
Free electrode length	[mm]	18
Distance between the solid point of the wire electrode and the workpiece surface	[mm]	14
Plasma electrode/workpiece surface distance	[mm]	14
Plasma current	[A]	116
MIG current	[A]	70...330

Comparison of the data generated by the model with experimental results

In order to lest the workability of the above proposed model, an experiment was carried out, using aluminium wire, 1.2 mm diameter, and pure Ar as the MIG, plasma and shielding gases. The parameters used for this experiment are given in Table 1.

With the voltage values U_{CP} and U_{CM} obtained experimentally under these conditions, the following equations were fitted experimentally:

$$U_{CP} = 27 + 0.013 \cdot I_{CM}$$

$$U_{CM} = 13 + 0.035 \cdot I_{CM}$$

With this result, the values for the components of the electrical model can be calculated:

$$R_h = 0.013 \qquad [\Omega]$$

$$R_t = 0.035 \qquad [\Omega]$$

$$R_{MIG} = R_t - R_h = 0.022 \qquad [\Omega]$$

$$U_{fh} = U_{0MIG} - R_h \cdot I_{CP} = 13 - 0.013 * 116 = 11.9 \qquad [V]$$

$$U_{fp} = U_{0PI} - U_{0MIG} = 13.6 \qquad [V]$$

With the values calculated above, the terms of Eqs. 3 and 4 are determined and, thus, the voltages U_{CP} and U_{CM} are calculated as a function of the current I_{CM} and for any plasma current I_{CM} used.

$$U_{CP} = 25.6 + 0.013 \cdot (I_{CP} + I_{CM}) \text{ [V]} \tag{10}$$

$$U_{CM} = 11.9 + 0.013 \cdot I_{CP} + 0.035 \cdot I_{CM} \text{ [V]} \tag{11}$$

Fig. 9 shows the data simulated by Eqs. 10 and 11 and the measured data for the welding under the conditions described in Table 1 using, however, an average plasma current of 152 A.

5 Discussion

It was not the objective of this study to relate the components of the electrical model with the physical characteristics of the electric arc. However, some considerations can be made in relation to the behaviour of the components of the proposed electrical model.

The value of the counter-electromotive force of the plasma arc U_{FP} should show a directly proportional relationship with the plasma arc length – the distance between the ring electrode and the end of the wire. Another factor which must influence the magnitude of U_{FP} is the wire electrode setback, defined as the distance between the ring electrode and the constriction nozzle. The diameter of the plasma electrode, flow rate and the nature of the gas through which the plasma current circulates also, probably, influence the U_{FP}.

R_{MIG} represents the resistive effect which causes the voltage drop during the passage of the current through the MIG circuit. The effect of the conductor cables and internal resistance of the power source can be neglected, when the voltage measurement is carried out at a point as close as possible to the MIG contact tip. In the results shown, the R_{MIG} value found is around 0.022 Ω, for the experiments carried out with a 1.2 mm aluminium wire in pure argon atmosphere. For this electrical resistance of the model to be associated with a resistive effect of the MIG circuit, it would be necessary to determine the resistive effects caused by the contact tip/wire (R_C), by the electrical resistance of the wire electrode (R_E) and by the resistive effect of the anodic region (R_A). R_C is dependent basically on the geometric and superficial factors of the wire and the contact tip. R_E is dependent on the free length of the electrode (L_E), its cross-sectional area (A) and the electrical resistivity of the electrode material (ρ). The electrical resistivity of the material is dependent on the temperature. For the MIG/MAG process, [8] presented a model for the temperature distribution in the solid electrode, as a function of the heat generated by the Joule effect and the heat transmitted in the anodic region to the solid electrode by the liquid metal. For the plasma-MIG process the boundary variables for the calculation of the temperature distribution and the "ρ" value are more numerous, since they are dependent on the heat transfer to the wire electrode, from the plasma arc which surrounds it.

The hybrid arc proposed in this study concentrates the currents I_{CP} and I_{CM}, being modeled by the association of a counter-electromotive force (U_{FH}) and a resistive charge (R_h). The experiments reported here are also insufficient to reveal the origin of R_h. However, in an initial analysis, this resistive charge may be associated with the drop in voltage in the cathodic region, which clarifies the interaction existing between U_{CM} and U_{CP}, I_{CM} and I_{CP}.

6 Conclusions

According to the results obtained in this study, the following conclusions can be drawn:

- ☐ The static behaviour of the plasma-MIG process can be described by the linear dependence of the MIG (U_{CM}) and plasma (U_{CP}) voltages on the MIG current (I_{CM}), for a constant plasma current (I_{CP}).
- ☐ The results indicate that the process can be represented by the existence of two arcs: the plasma arc, located between the face of the plasma electrode and the solid end of the wire electrode through which the plasma current I_{CP} flows; and a hybrid arc, located between the solid end of the wire electrode and the surface of the workpiece, through which the currents I_{CP} and I_{CM} flow.
- ☐ The electrical model based on the association of a counter-electromotive force and a resistive effect to model the hybrid arc, and a counter-electromotive force to represent the plasma arc, gave good results in the representation of the static characteristics of the process.

The authors acknowledge the financial support from DAAD, CNPq, POSMEC and FAPESC and the technical support from TBi Industries and SLV München, in special Prof. Dr.-Ing. Prof. h. c. Dieter Böhme, Dr.-Ing. H. Cramer and Dipl.-Ing. W. Rosenfeld.

Literature

[1] Essers, W. G.: New process combines Plasma with GMA Welding. Wdg. J, Vol. 55 (1976), No. 5, pp. 394/400.
[2] Essers, W. G., et al.: Plasma-MIG welding – a new torch and arc starting method. Metal Construction (1981), No. 1, pp. 36/42.
[3] Essers, W. G., and R. Walter: Heat transfer and penetration mechanisms with GMA and Plasma-GMA welding. Wdg. J. (1981), No. 2, pp. 37-s/42-s.
[4] Gohr Jr, R.: Novos metodos de controle da soldagem MIG/MAG. Tesede Doutorado. UFSC – Florianópolis, 2002.
[5] Ton, H.: Physical properties of the plasma-MIG welding arc. J. of Physics D: Applied Physics. Vol. 8 (1975), pp. 922/33.
[6] Matthes, K.-J., and T. Kohler: Electrical effects and influencing quantities in the case of the hybrid plasma-MIG welding process. Welding and Cutting (2002), No. 2, pp. 87/90.
[7] Baixo, C. E. I.: Estudo da soldagem MIG/MAG pela técnica hiperbárica a seco. Tese de Doutorado. UFSC, Florianópolis, December 1999.
[8] Waszink, J. H., and L. H. J. Graat: Experimental investigation of the forces acting on a drop of weld metal. Wdg. research Supplement. April 1983, pp. 108-s/16-s.