PINCH EFFECT OBSERVATION IN MIG/MAG WELDING OF AWS ER 309L WIRE

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Abstract. *The aim of this work was to carry out an experimental register of the occurrence of the "pinch instability" phenomenon, through its high speed filming. The experimental rig is composed by an electronic welding power source, in constant voltage mode, AWS ER 309L electrode wire with 1.2 mm diameter and P410D stainless steel plate. Also, an appropriate commercial gas at 14 l/min was used for the arc and the weld pool protection. High-speed filming was used at 2000 frames per second for metal transfer visualization by using laser beam, optical scheme with lens and neutral density filter, in a technique known as shadowgraphy. The parameters, which allow the visualization of the pinch phenomenon, were reference voltage at 28 V, wire feed speed at 9.5 m/min and mean current of 265 A. The result showed that pinch effect leads to the electrode collapse if it occurs in the electrode extension, and therefore, it leads to the welding process instability.*

Keywords*: Welding, MIG/MAG, Metal transfer, Pinch instability, Shadowgraphy*

1. Introduction

In arc welding, the magnetic force may be generated in two ways: by the interaction of the welding current and an externally-applied field and by the interaction of the current with its own magnetic fields. Externally-applied fields have a limited application, for example, for deflecting the arc in order to improve weld profiles or avoid lack of fusion. The self-induced field, however, has effects which are noticeable in many aspects of arc welding. The most important are the local interactions in the liquid metal at a tip of the electrode, in the arc itself, and in the weld pool – functions upon which the success of certain weld process depend (Lancaster, 1986; Kin & Eagar, 1993 and 1993a).

The self-induced magnetic force is not very high; for example, a current of 100 A with a current density of 5×10^7 A/m^2 (a typical value for the cathode of an argon-shielded tungsten arc) will, under non flowing conditions, generate a maximum pressure of about 5×10^{-3} atm. The magnetic force is, however, of the same order of magnitude as the forces due to gravity and surface tension, and is therefore capable of generated flow. (Lancaster, 1986; Jones, 1996)

When current flowlines are straight and parallel and were there is no instability the $\vec{J} \times \vec{B}$ force is directed inward at right angles to the current flow and may therefore be counterbalanced by a static pressure gradient. In the vicinity of or within the welding arc, however, the current flowlines are often either divergent or convergent and the effect oh this geometry is the flux and, in part, the rotation of the plasma.

Consider a cylinder of fluid with current flowing axially along it. The fluid will be under a positive pressure due to containment within a confining vessel, or to gravity, or to surface tension forces, or to a combination of these effects. The $\vec{J} \times \vec{B}$ force however, acts inwards and, if the current density is increased sufficiently, it may overcome the stabilizing effect of the other forces, the cylinder will tend to collapse inwards and instability will occur. This phenomenon is know as the "pinch effect" (Lancaster, 1986; Kin & Eagar, 1993a; Jones, 1996)

For a cylinder, the magnetic field is purely azimuthal and acts everywhere at right angles to the current. Therefore, the magnetic force per unit volume at any radius r inside the conductor is:

$$\vec{J} \times \vec{B} = \frac{\mu_0 \cdot J^2 \cdot r}{2} \tag{1}$$

when J is the current density and μ_0 is the magnetic permeability in vacuum.

This force acts towards the central axis, and must be balanced by a radial pressure gradient in the fluid acting in the opposite direction. So:

$$\frac{\partial p}{\partial r} = \frac{\mu_0 \cdot J^2 \cdot r}{2} \tag{2}$$

Integrating:

$$p = -\frac{\mu_0 \cdot J^2 \cdot r^2}{4} + \mathrm{constant} \tag{3}$$

At the surface where R=r, the $\vec{J}x\vec{B}$ force disappears and the pressure is equal to the sum of the ambient and that due to the surface tension γ which, in the case of a cylinder, is equal to γ/R. Hence, the total pressure is:

$$p = p_0 + \frac{\gamma}{R} + \frac{\mu_0 \cdot J^2}{4}\left(R^2 - r^2\right) \tag{4}$$

To determinate the condition under which the magnetic force may generate a pinch instability, consider a cylindrical column of liquid surrounded by a gas, such as may be sustained, for example, by a jet of water in air. Initially we seek the criterion for instability in the absence of a electric current. The radius of the cylinder is R and its surface tension is γ. Suppose that the cylindrical surface is disturbed so that its profile (Fig. 1) is given by:

$$r = R + \varepsilon \cos\left(\frac{2\pi}{\lambda}\right) \cdot z \tag{5}$$

where ε is the amplitude of disturbance, λ is the wavelength, and z is the distance in longitudinal direction.

Ignoring the ambient pressure, which is constant, the pressure inside a liquid due to surface tension is equal to:

$$p = \gamma\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \tag{6}$$

were R_1 and R_2 are the principal radii of curvature of the surface.

For a cylinder, R_1 = R and $R_2 = \infty$ so that the pressure is uniform and is equal to γ/R. In the disturbed cylinder, however, the pressure is non-uniform. In the example given in Fig. 1, where the outward bulge have the maximum amplitude, the pressure is given for:

$$p_p = \gamma\left(\frac{1}{R + \varepsilon} + \frac{1}{R_\lambda}\right) \tag{7}$$

where R_λ is the longitudinal radius of curvature for r = R + ε.

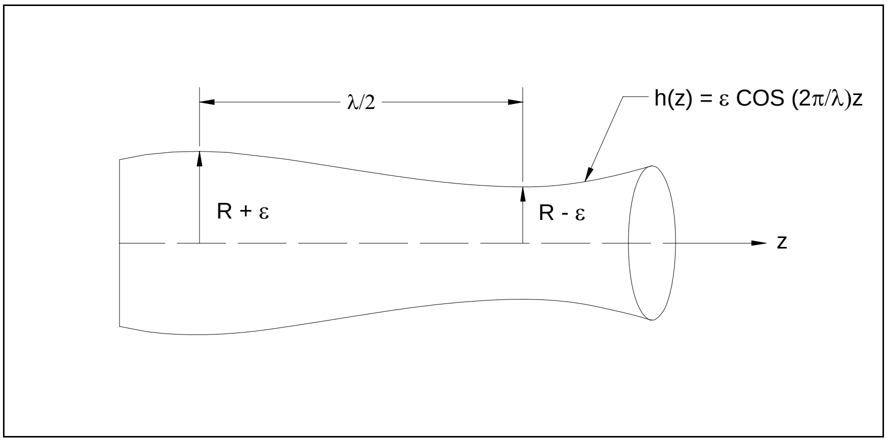

Figure 1. Perturbation of a cylindrical column of liquid.

In this case:

$$\frac{1}{R_\lambda}=\left(\frac{\partial^2 r}{\partial z^2}\right)_{z=\lambda}=\left(\frac{2\pi}{\lambda}\right)^2\cdot\varepsilon \tag{8}$$

In the bulged region, therefore, the pressure is:

$$P_p=\gamma\cdot\left[\frac{1}{R+\varepsilon}+\left(\frac{2\pi}{\lambda}\right)^2\cdot\varepsilon\right] \tag{9}$$

whilst, similarly, in the pinched region,

$$P_{pi}=\gamma\cdot\left[\frac{1}{R-\varepsilon}-\left(\frac{2\pi}{\lambda}\right)^2\cdot\varepsilon\right] \tag{10}$$

If the pressure in the bulged region is greater than that in the pinch, the liquid will flow into the pinch and tend to restore the cylindrical form, in other words, the system is stable. If the pressure difference is in the opposite sense, the system is unstable and the cylinder will break up into droplets. The requirements for stability may be expressed as:

$$\frac{d\left(P_p-P_{pi}\right)}{d\varepsilon}>0 \qquad (\varepsilon\to 0) \tag{11}$$

or from the Eq. (9) and (10):

$$\gamma\cdot\left\{\left[\frac{1}{R+\varepsilon}+\left(\frac{2\pi}{\lambda}\right)^2\cdot\varepsilon\right]-\left[\frac{1}{R-\varepsilon}-\left(\frac{2\pi}{\lambda}\right)^2\cdot\varepsilon\right]\right\}>0 \tag{12}$$

which leads to, for stability:

$$\lambda<2\pi R \tag{13}$$

a result that was first obtained by Plateau from energy considerations. The equilibrium situation may be expressed by:

$$\lambda_C=2\pi R \tag{14}$$

where λ_C is a critical wavelength. Disturbances having a longer wavelength that λ_C will tend to grow and cause the column to break up into droplets. Here, λ_C is independent of the surface tension γ.

In the presence of an electric current, we will give:

$$P_p-P_{pi}=\gamma\cdot\left[\frac{1}{R-\varepsilon}-\left(\frac{2\pi}{\lambda}\right)^2\cdot\varepsilon\right]+\frac{\mu_0 I^2}{4\pi(R-\varepsilon)^2}-\gamma\cdot\left[\frac{1}{R+\varepsilon}+\left(\frac{2\pi}{\lambda}\right)^2\cdot\varepsilon\right]-\frac{\mu_0 I^2}{4\pi(R+\varepsilon)^2} \tag{15}$$

and applying the condition for instability:

$$\frac{R^2+\varepsilon^2}{\left(R^2-\varepsilon^2\right)^2}+\frac{\mu_0 I^2 R\left(R^2+3\varepsilon^2\right)}{2\pi^2\gamma\left(R^2-\varepsilon^2\right)^3}>\left(\frac{2\mu}{\lambda}\right)^2 \tag{16}$$

and for a perfect cylinder:

$$\lambda_c = \frac{2\pi R}{\left(\sqrt{1+\frac{\mu_0 I^2}{2\pi^2 R\gamma}}\right)} \tag{17}$$

which implies that, in the presence of an electric current, the critical wavelength at which the column becomes unstable is reduced. Likewise, columns of small diameter will break up more easily than those of large diameter.

Another phenomenon known as “kink instability” can occur in cylindrical columns of liquids in presence of higher electrical current levels. This perturbation gives a helical flux form and an azimuthal component to the current. Due to attraction between parts of the helix where the current is in the same direction, if there is instability, the cylinder collapses into a spiral. The radial “pinch instability” and the “Kink instability” may both appear in welding, and have been demonstrated in the laboratory using a falling column of liquid mercury as show in Fig. (2).

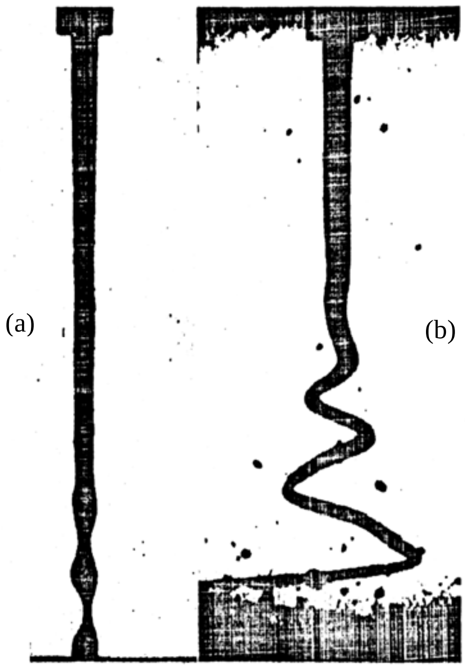

Figure 2. Instability in a falling cylindrical column of mercury carrying an electric current of 250-300 A a) radial Pinch Instability; b) Kink Instability (Dattner *et al*, 1958)

In welding, the “pinch instability theory” (PIT) composes, at side of the “static balance of the forces theory” (SBFT), and of the elements of physics of the arc, the basic base for the understanding of the metal transfer modes. However, numerical and analytical models that use these concepts have not gotten satisfactory answers in welding with spray and projected spray metal transfer modes. A large number of articles about this show only the effect of current in metal transfer, phenomenon that occurs in the extreme of the electrode and inward of arc, or its interaction with the weld pool. However, the objective of this paper is to show the occurrence of “pinch instability” in the extension of electrode, between the contact tip and the top of the arc, in a condition that it does not thwart the process stability, and in other condition that the pinch instability generates a magnetic cut-off of the electrode. This fact does not have bibliographical register, with its occurring in the extension of the electrode.

2. Materials and metodology

An electronic multi-process power source was employed for the welding, in constant-voltage mode and positive electrode. The electrode was the AWS ER309L with 1.2 mm diameter. For electrode, arc and weld pool protection, the commercial mixture STARGOLD SS at 14 l/min was employed. The contact-tip-to-work-piece-distance (CTWD) was maintained in 18 mm and the torch at 90º to work piece. The filming in high speed video camera was tacked at 2000 frames per second with laser back lighting, a optical lens group and an objective.

Two welding conditions were carried out. First, was applied a reference voltage of 28 V, feed rate of 9.5 m/min and travel speed of 52.3 cm/min. This parameters had offered a rms-current about 265 A. Later, was applied a reference voltage of 30 V, feed rate of 10.5 m/min and travel speed of 57.8 cm/min. This parameters given a rms-current around 281 A.

2.1. Shadowgraphy technique

In order to obtain a frame sequence with high in-time resolution, was used a laser cannon, an optic system and a high speed video camera. This system is showed in Fig. (2). The movies are recorded in a frames sequence with frequencies from 250 to 2000 frames per second, with mechanical shuttering, and electronic shuttering of 1/24000 in each frame (making possible to reduce distortions due to the movement of the filmed elements). This configuration allows frames with resolution of 252 x 188 pixels (h x v).

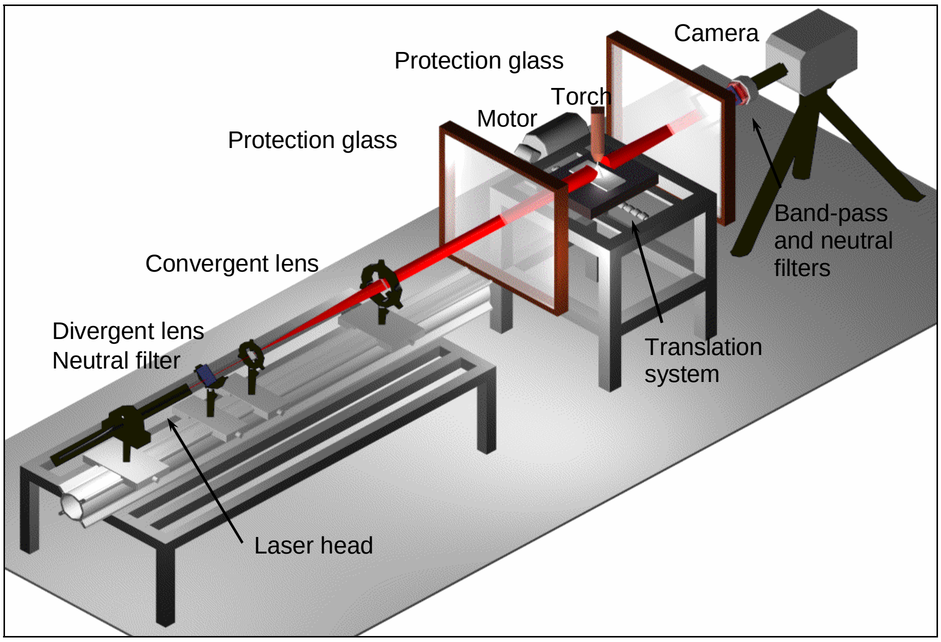

Figure 3. Shadowgraphy technique scheme (Vilarinho, 2000).

3. Results and discussion

In the Figure 4 the incidence of the pinch effect in the extension of electrode can be verified, which can have been generated for the current flux metal ally to the Joule effect. The incidence of this phenomenon can be verified, as in previous works (Dattner *et al*, 1958) using a liquid mercury column, but in the fused wire extension itself. Analyzing pictures 2, 3 and 4 of Fig. (4), one can be observed the incidence of a pinch effect, similarly to that it occurs with the liquid mercury column presented for Dattner *et al* (1958). In this figure, is observed that this phenomenon occurs for a small time interval, about 45 ms (interval of 2.5 ms between frames of Fig. (4)). Despite it has been observed, the collapse of the system does not occur.

In Figure 5, however, it is observed that the system entered in collapse. A "fluff up" happens as a result of the operating forces during the process. It was observed that the differentiation of parameters between the first welding (Fig. (4)) and second (Fig. (5)) is tenuous, but enough to generate an instability in the process and to disintegrate the electrode .This characteristic allows to assert that these two conditions are in the boundaries of the process operational envelope. A nip in the extremity of the wire observes itself continuously. Such effect also can be influenced by this phenomenon, beyond the phenomena generated for the draining of fluids in the casting part in the wire. Moreover, the electrode part that detaches from itself can be considered as spatter, and, therefore, it reduces the process quality.

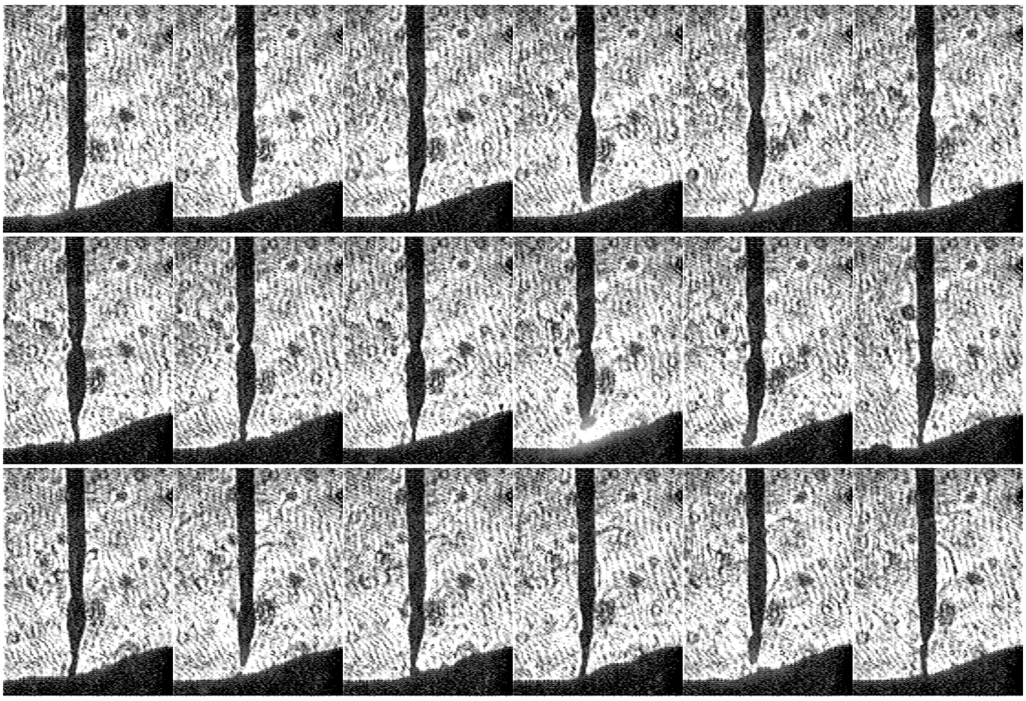

Figure 4. Pinch instability in ER 309L wire (28 V and 265 A)

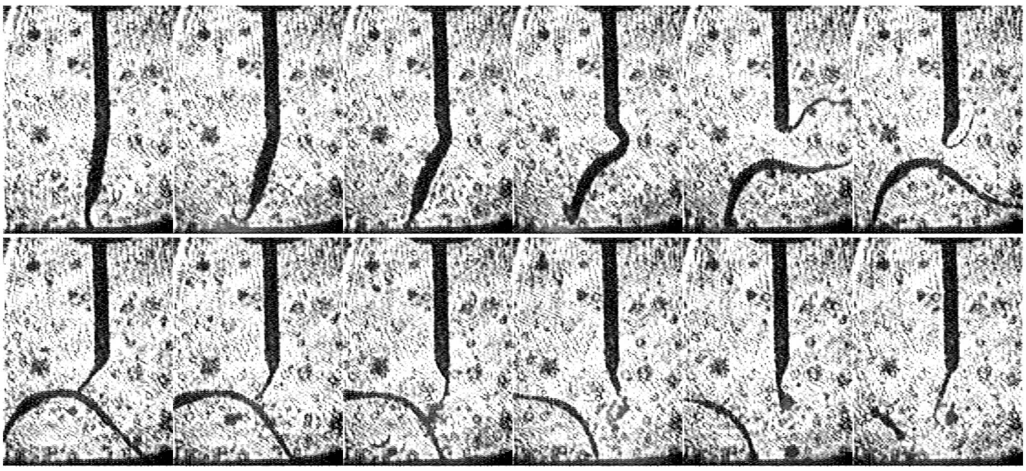

Figure 5. Collapse in weld process due to electro-magneto cut in electrode.

4. Conclusion and further work

Considering the objectives of this work and the applied methodology, it is possible to conclude that pinch instability can occur in the electrode extension, contributing to the instability of the welding process, depending on the selected parameters.

As a continuation of this research line, it is intended to model the experimentally-observed pinch effect according to the model presented in Section 1. In this case, it would be possible to predict when this phenomenon can occur or not.

5. Acknowledges

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