Fundamentals and descriptions of plasma jet formation, arc trajectory and arc magnetic blow as a mean of facing correlated welding problems

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Introduction

Actual knowledge about the welding related phenomena is certainly the key for facing problems related to welding process operations. The field of study of these phenomena is known as physics of arc. Books and handouts about arc welding are written aiming to transfer new practices and theoretical knowledge to users. And they have to cite definition and characteristics of some fundamentals, such as plasma jet and arc blow formation. For instance, in the case of arc blow, classical pieces of literature such as AWS Welding Handbook (1991, p.48) do not further explain this phenomenon beyond "the result of magnetic disturbances surrounding the arc". The Lincoln's Procedure Handbook of Arc Welding (2000, p.3.2-1) limits to state that "the magnetic arc blow is caused by an unbalanced condition in the magnetic field surrounding the arc". According to Lancaster (1986, p.215), "arc blow may result from asymmetric current paths in the work-piece close to the arc or from the magnetization of the plate material". In the case of plasma jet, Houldcroft and John (1988, p.12) cite that "the flow of current in the arc results in a magnetic field, which involves the arc and tends to compress it, the so-called 'pinch effect'. Due to the way the arc expands from the electrode to the work-piece, an axial component of the pinch effect happens and it causes the hot ionised gas in the arc to be set in motion from the electrode to the work. This is sometimes called plasma jet and it is responsible for the depression, which is formed in the surface of molten pools at high welding currents". Lancaster (1986, p.128), in turn, declares that plasma jet is an "electromagnetically induced flow of gas in the arc column, which is directed away from the constriction at the electrode".

However, due to the complexity of the physics of arc related subjects, many concepts to explain welding phenomena, yet useful for teaching welding, are not so clear when one needs to go deeper in the subject. Some basic aspects of welding, apparently simple and broadly accepted, begin to fall in uncertainty when answers related to another phenomena need to be found. In our opinion, there is still a lack of full explanation on certain basic aspects on electromagnetic arc interactions. For instance, what really causes pressure into a compressive environment as an arc column? Or, how can a mass of plasma move away due to magnetic pressure? Is plasma jet the governing factor to direct the arc column? But, what (and for what) do the welding personnel need to study further this subject beyond what is given in the current literature?

One can say the knowledge is based on knowing the principles. There is a simple in-class exercise that a lecturer can use to demonstrate to the students how important learning principles is. Showing for 3 seconds a slide with different patterns of lines identified by numbers (Fig. 1(a)), a second slide is presented (Fig. 1(b)) with the same patterns, but in a randomised order. To the students is asked to fill in the blanks in 10 seconds. Following, it is shown in a third slide (Fig. 2(a)) the answer sheet and asked to the students how many of them were able to give right answers for more

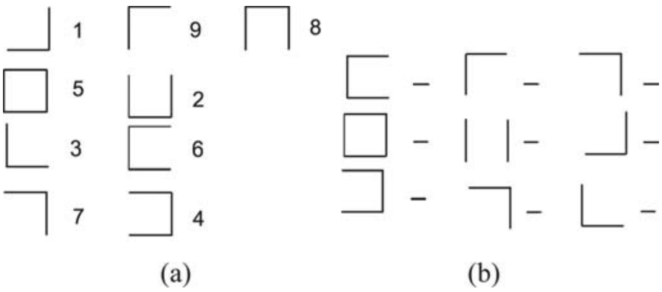

Figure 1. (a) step 1 - a sequence of patterns with numeric identification; (b) step 2 - a sequence of non-identified patterns, with blanks to be fill in.

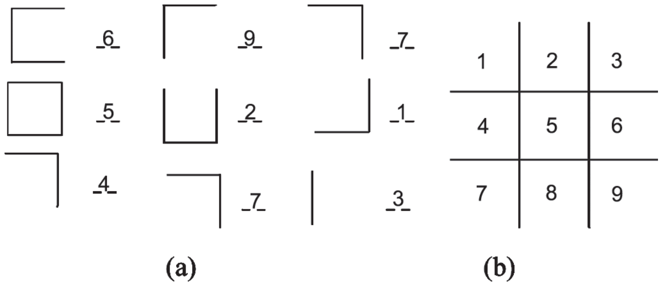

Figure 2. (a) step 3 - the answer sheet for Fig 2(b);
(b) step 2 - the principle of the pattern formation

than three or four patterns (it is not surprise if most of them say none). Finally, by presenting a forth slide (Fig. 2(b)) with the principle on how the patterns are built, there will be a general feeling that if I knew before the principals, I would not fail.

Thus, the objective of this presentation is, thought principles of electromagnetism, bring some descriptive models to explain plasma jet formation, arc trajectory and arc magnetic blow as a mean of help users to face correlated welding problems, taking as base for his/her actions further understanding of these topics.

The General Knowledge on

In a previous publication (Reis et al, 2009), it is described an e-mail survey was carried out to raise the degree of consensus on the understanding of welding specialists on plasma jet formation and arc blow phenomenon. Despite the fact that the authors do not claim any significance to the results, due to a non scientific sampling approach, the objective of finding out whether there were divergences or not was reached. But the survey showed some evidences about how people understand the subject.

There is some consensus that plasma jet in arc welding is formed due to a gradient of pressure between the electrode tip and the weld pool and the reason for the pressure at both regions is a resulting radial electromagnetic force that pushes the charged particles of plasma towards the centre line of the arc. Interestingly enough, the authors have not seen yet a clear reference to consensus answer in books. Nonetheless, 35% of the interviewees gave other answers.

Regarding the question on the reason for arc deviation in arc blow, the tendency was quite the same (the majority believes that the bulk of plasma mass changes place due to uneven forces created by a gradient of magnetic field, but a significant part - around 40% - has other opinion).

Thus, the outcome of this survey confirms that the subject is not so clear and it justifies the elaboration of a more comprehensive description for the phenomena. The text below was extracted of a presentation made during the IIW (International Welding Institute) 2009 Annual Assembly, entitled "Models to Describe Plasma Jet, Arc Trajectory and Arc Blow Formation in Arc Welding", reported in the IIW DOC. 212-1141-09 (Reis et al., 2009).

Magnetic Field Interactions in the Welding Arc

General Concepts

It is already known that the welding arc ionisation process takes place mainly due to energy transfer caused by inelastic collisions of particles (ions and electrons). It is also largely stated that the welding arc does not achieve a complete ionisation. Therefore, the arc is constituted by ionised and non ionised matter.

Before discussing arc trajectory and plasma jet formation in the welding arc, it is worth taking a brief look at the basic electromagnetic effect that governs the phenomenon. If an electrical charge travels inside a magnetic field, it will be subjected to a force with direction and magnitude described by Fig. 3. As there is an electrical current flowing through the arc, a magnetic field is induced (Fig. 4). Since the arc has a large number of charged particles (ions and electrons), this magnetic field creates a radial force field in the arc.

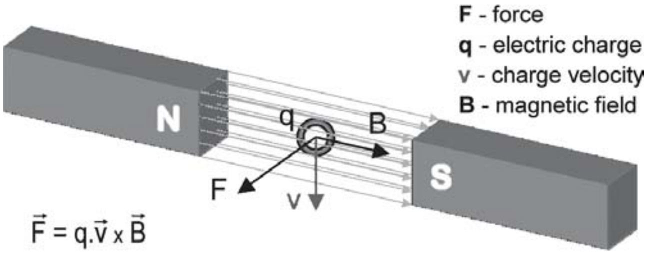

Figure 3. Force produced on a positive electrical charge moving through a magnetic field (if the electrical charge is negative, the force direction points to the opposite way)

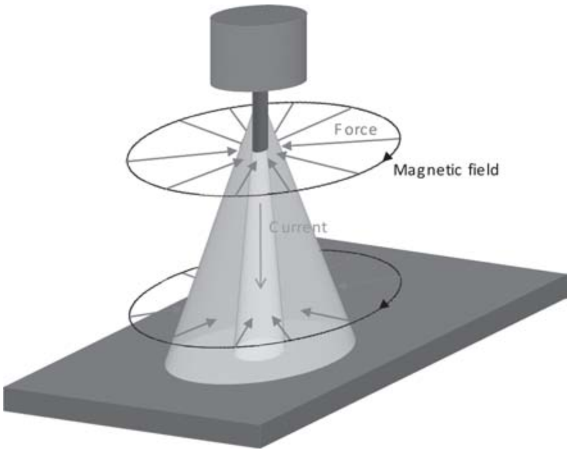

Figure 4. Magnetic field and consequent radial forces in a welding arc column

The Current Descriptive Model for Plasma Jet

The most accepted model to explain plasma jet formation was described by Lin and Eagar (1986) and through equations by Richardson (1989) in one of his class notes. In summary, as presented by Figure 5, this model considers that there is a distribution of pressure in the arc in radial and axial directions.

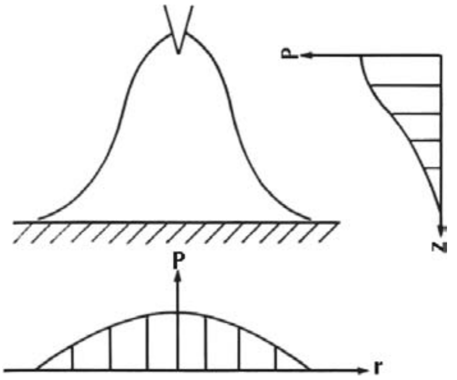

Figure 5. Pressure distribution along radial and axial directions according to Lin and Eagar (1986)

According to the model, this distribution is caused by the magnetic force field, which is different along the arc due to its shape (caused by the difference in size of the poles). As the pressure is higher in regions close to the electrode than the pressure close to the plate, there is a flow of plasma from the electrode to the plate, the so called plasma jet.

Even though the model explains the plasma jet phenomenon and it is widely accepted, two questions could emerge: a) if the pressure in the radial direction is higher in the centre than in the periphery of the arc, why does not plasma flow away from the arc towards this direction?; b) if plasma is a compressible matter, and the arc has no physical boundaries, how could electromagnetic forces push the bulk of the gas and plasma masses towards the centre line of the arc? A magnetic field would certainly not increase the pressure of a not confined amount of gas (not charged matter). Thus, at least a more comprehensive description of the phenomenon must be provided to prevent such questions.

The Proposed Descriptive Model for Plasma Jet

The authors of this work believe that the mentioned model for plasma jet formation is incomplete in terms of physical explanation and decided to suggest a model, aiming to improve the current understanding of the subject and looking for a point of common sense amongst welding users on the phenomenon (at least from the engineering point of view). In order to explain, in a more comprehensive approach, how the arc pressure distribution takes place, a model is proposed based in simple analogies as follows:

Consider a box filled with gas with a sliding wall connected to a shaft, as shown in the above part of Fig. 6(a). If the sliding wall is pushed by a mechanical force from position 1 to position 2, the gas in the box will be under a pressure P2, which is higher than P1. This gas compression is commonly stated as thermodynamic pressure. On the other hand, if the same experiment is conducted without the sliding wall, that is, the same force is applied to the shaft only (Fig. 6(b)), the pressure over the gas does not change (after reaching a statistic stead state), since there is no barrier to avoid the gas from exhausting. Thus, in the case of a gas (neutral particles), a volume of gas cannot be compressed if there are no barriers all around.

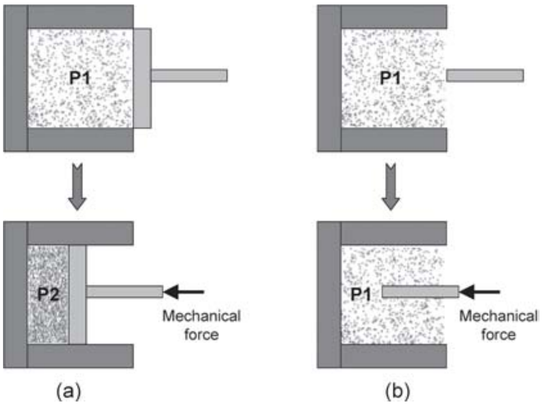

Figure 6. The thermodynamic pressure (P2 > P1) case

Now, let's replace the box by two horizontal walls charged (one positive and the other one negative), isolated from each other by a vertical neutral wall. If the gas is swapped by charged particles, these particles will tend to move from one pole to the other (Fig. 7(a)). If this assembly is now put under a perpendicular magnetic field, as showed by Fig. 7(b), a force will appear on each particle and they will be driven towards the vertical wall. Although there is not a physical barrier on the right side of the box (as in Fig. 6(a)), these particles are similarly compressed (Fig. 7(c)). The reason is that each single charged particle is driven towards the vertical wall by a force, preventing them from exhausting towards the right side, as happened in the case of Fig. 6(b). Thus, in contrast to a mechanical force, a magnetic force is able to compress charged particles, even without a physical barrier

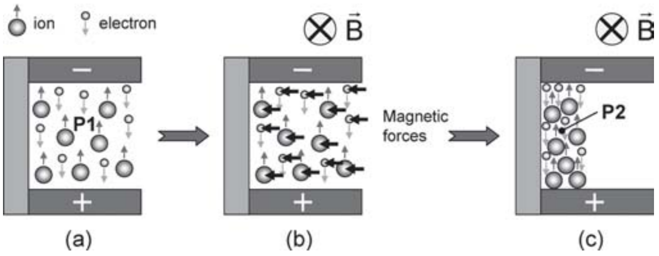

Figure 7. The case of the pressure due to magnetic forces (P2 > P1)

Figure 8(a), in turn, illustrates a situation in which two assemblies similar to the one in Fig. 7(a) are put together, inverse side to side (note that the magnetic field orientation is different in each assembly). If the vertical walls are removed (Fig. 8(b)), this new assembly is an analogy to a current-carrying conductor, which induces a circular magnetic field profile (entering from the right and exiting from the left). This, in fact, is a schematic model of a welding arc. Consequently, in a welding arc, charged particles would be compressed in a radial way towards the centre of the arc, increasing the density of charged particles, therefore, the pressure, from the arc periphery to the arc centre. Considering this fact as truth, the increase in the density of charged particles would also justify why the density of current is higher in the centre of the arc. As the magnetic forces on the charged particles, in totality, are similar to a barrier, there is no manner these particles can escape, even with a pressure higher in the centre than in the periphery of the arc. As the axial component of the magnetic force is low in the arc, there are no forces preventing the charges from moving in the arc column axis.

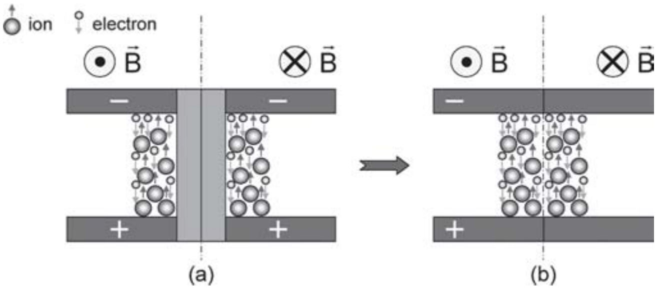

Figure 8. The schematic model of a welding arc showing compressed particles due to magnetic field, with no physical barrier

Now it is necessary to look for a reason for difference of pressure in the arc axial direction, which would justify the existence of matter movement (plasma jet). Considering that the electrical current is conducted through the entire arc (see Fig. 9), yet not homogeneously, there is more current flowing through a section with a radius "R" in the position "a" than through the same section in the position "b". Thus the magnetic field flux induced at point "A" would be more intense than the one induced at point "B". Thus, the magnetic force on a particle situated at the point "A" would be stronger than on a particle situated at the point "B". As arc radii are shorter close to the electrode, the pressure is higher in this region than in the regions approximating to the plate, as illustrated in Fig. 10. Thus, since the charged particles cannot escape in a radial way and there is a difference of pressure along the arc length (high close to the electrode and low close to the plate), a flow of plasma (mass movement) from the electrode to the plate is formed (plasma jet).

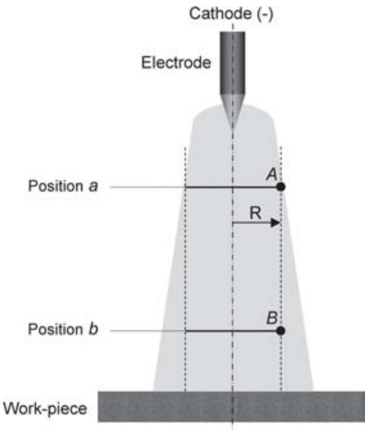

Figure 9. Two points at the same distance to the arc centre, but under uneven magnetic forces

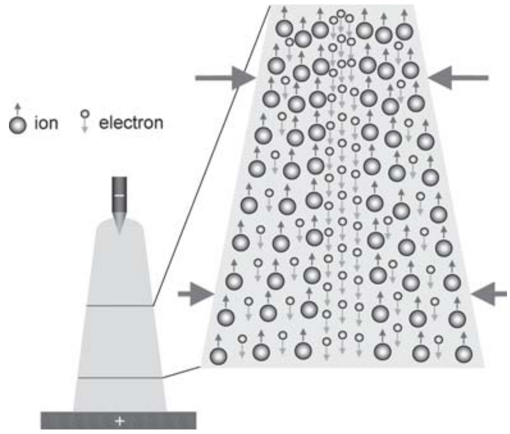

Figure 10. Charged particles compressed towards the arc centre line. The pressure is the highest closer to the electrode and progressively smaller on the way to the plate

Finally, it is mandatory to discuss the plasma jet composition. Electrons have no significant mass and cannot be responsible for the transportation of matter. Ions, on the contrary, could be. However, electrons and ions have a defined path, which is ruled according to the pole configuration. If the electrode is at the negative pole, ions must flow from the plate to the electrode, in the opposite direction of the plasma jet. This fact indicates the plasma jet is not formed exactly by movement of ions; otherwise plasma jet would occur only with the electrode at the positive polarity. The authors imply there might be two hypotheses for mass transportation, one not excluding the other. In the first one, the mass of ions can be transported from the electrode to the plate (plasma jet direction), whatever the electrode polarity, because the charge of the ions do not move with the mass. In a simplistic way of conceiving this phenomenon, it is like having the mass of ions moving to one direction, but the charges jumping, one after the other, to the next ion. Then, it is possible to have charges and masses travelling in opposite direction. In the second hypothesis, the mass of ions arrests or pulls (drags) non-ionized matter, since the ions themselves have volume (to compress atoms between them) and high speed (aerodynamic effect).

Summarizing, according to the proposed descriptive model, plasma jet (high speed movement of mass usually from the electrode to the plate surface) would be produced by a gradient of pressure along the arc axial direction. The pressure is caused by radial magnetic forces driven by a self-induced magnetic field around the arc column and perpendicular to the current flow. These forces push charged particles in the arc (mainly ions, which has significant mass) towards the arc centre. The gradient of pressure happens because of the arc shape, with stronger forces where the arc diameter is smaller.

The Plasma Jet Role in the Welding Arc Direction

The trajectory of the electrical arc may be ruled basically by two factors; the plasma jet and the electrical charge flow (current). As plasma jet is produced as a function of the magnetic forces, which, in turn, is generated by the current passing through the conductor (welding arc), it is difficult to define which one is the responsible for the arc trajectory. In order to identify the role played by both factors in welding arc formation, some experiments were carried out using the GTAW process. Figure 11 shows very low current arcs obtained through a high-frequency igniter and shielded by a low flow of Argon. In this case, the arc was driven by the shortest distance between the electrode and the plate. At the left side of Fig. 11, the electrode was closer to the horizontal plate, whilst at the right side the electrode was placed closer to the vertical plate. As soon as the distance to vertical plate becomes shorter than the distance to the horizontal plate, the arc changes its direction. This takes place due to the fact the electrons always look for the path with the lowest resistance, in this case, the shortest path. This indicates that in plasmas formed by low currents, the charge flow dictates the trajectory of the electrical arc, which could be called the electrons natural path effect.

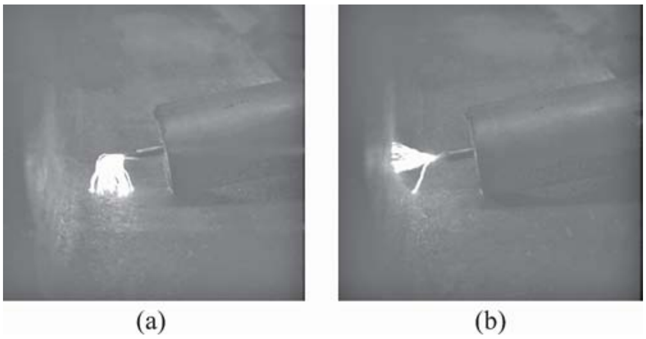
(a)
(b)

Figure 11. Very low current arcs obtained through a high-frequency igniter and low Argon flow in the inner corner of a steel angle bar: (a) electrode tip is closer to the horizontal side; (b) electrode tip is closer to the vertical side.

Figure 12 presents another arc formed by a low current produced by a high-frequency igniter and shielded by a low flow of Ar (electrode tip to plate distance was slightly longer than in Fig. 11). It is worth noting the plasma shape has two regions with distinct orientations. The first one, close to the electrode, has the same direction of the electrode and the second one is perpendicular to the plate. This behaviour indicates that there are two factors influencing simultaneously; the mechanical effect of the plasma jet and the effect due to the electrons natural path.

Figure 12. Very low current arc obtained through a high-frequency igniter and low Argon flow showing the change in plasma orientation

One could expect that higher currents increase the plasma jet strength. Fig. 13 shows now two actual GTAW arcs, with the same current level (100 A) and with vertical electrode to work-piece distances of 6 (a) and 12 mm (b). In Fig. 13(a), it can be seen that for higher currents the region defined by the electrons natural path practically does not exist. This is probably due to the increase of the plasma jet influence, oriented to the electrode centre line. A 100 A current was enough to keep a plasma jet high intensity throughout the arc. However, as the arc length is increased (Fig. 13(b)), it is possible to note a formation of a region in which the electrons natural path effect prevails. This probably takes place due to a loss of plasma jet intensity; plasma jet does not have enough intensity to keep the predominance through all the arc length.

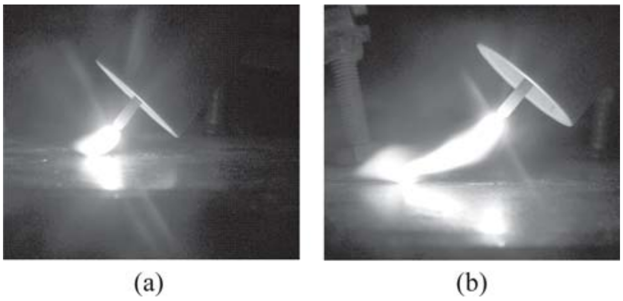

Figure 13. GTAW arcs with the same current level and different vertical electrode to work-piece distances: (a) the arc is short and plasma jet governs the arc trajectory; (b) the arc is longer and the electrons natural path effect overcome plasma jet effect at the end of the path

In order to improve visualization, both arcs showed in Fig. 13 are presented again in Figure 14. By the thin dashed line drawn over the shorter arc (6 mm), it is evident the arc has the orientation of the electrode most of the time, which means the plasma jet effect is predominant. Taking now the 12-mm-long arc image, it is possible to observe the thick dashed line does not match all way long the line that has the same orientation of the electrode. It is supposed that up to a certain point the arc is mainly under the plasma jet influence ("region under the plasma jet effect"). Just before the arc reaches the plate it is suddenly deviated, changing to a vertical orientation and staying mainly under the electrons natural path influence ("region under the electrons natural path effect"). However, it is important verifying a third region with a distinct orientation. Arc trajectory in this third region may be, by hypothesis, related to two effects (Fig. 15); the interaction between the plasma flow and the plate (fluid-dynamic effect) and the buoyant force effect, caused in the arc by the difference of density between arc and environs (thermal effect). This third region manifestation, which could be denominated "region under fluid-dynamic and/or thermal effect", can now justify the large deviation of the 12-mm-long arc from the electrode centre line when the arc approaches the plate.

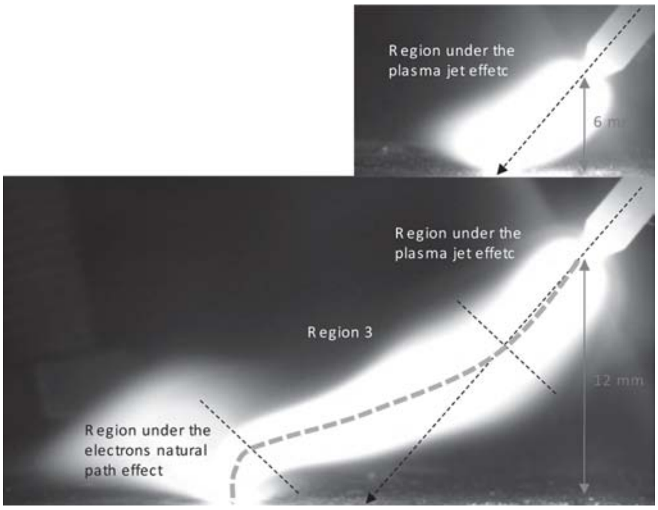

Figure 14. Regions under different effects in GTAW arcs with the same current level and different vertical electrode to work-piece distances

Figure 15. Fluid-dynamic effect (a) and thermal effect (b) on a welding arc trajectory

Figure 16 shows GTAW arcs with the same vertical electrode to work-piece distance, yet at different current levels. As the welding current is decreased from 100 to 50 A, keeping the same vertical electrode to work-piece distance (12 mm), it is possible to observe a variation in the extension

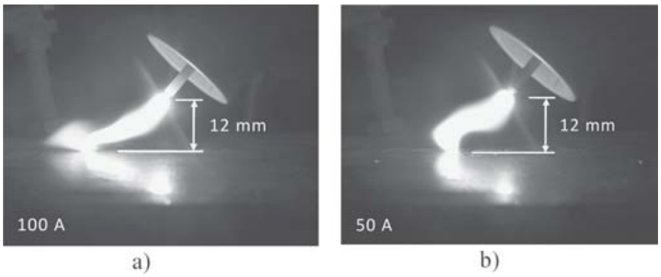

Figure 16. GTAW arcs with the same vertical electrode to work-piece distance and different current levels

of the regions; the region under the electrons natural path effect becomes more evident, while the regions under plasma jet and fluid-dynamic and/or thermal effects seem to weaken. This fact gives evidence of the fluid-dynamic effect, since a lower current level leads to a weaker plasma jet, consequently to a lower fluid speed.

Another indication of the balance of effects that takes place to define the arc trajectory can be seen in Fig. 17, which shows a GMAW in pulsed mode. When the current is at a low level (base current), plasma jet is not so strong and electrons natural path effect points the arc to the weld pool (shortest distance to achieve the plate). When the welding current is raised to a high level (peak current), the plasma jet effect gets stronger and points the arc straight down to the plate; the plasma jet effect prevails over the electrons natural path effect through all the arc length.

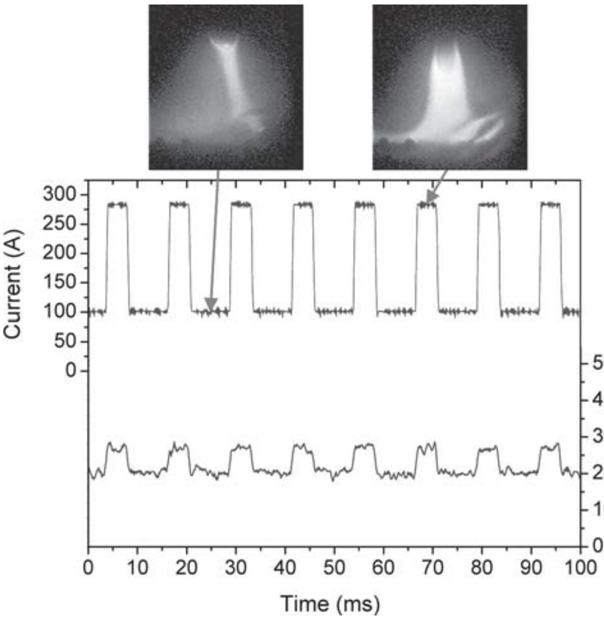

Figure 17. Welding current influence on the arc trajectory in pulsed GMA welding (After RESENDE, 2009)

The Arc Blow Phenomenon

General Concepts

In normal conditions, the magnetic field induced by the electrical current conducted by the welding arc tends to be uniform around the arc column (the resultant magnetic force around the arc is null). However, at some circumstances, there may be an unbalance in the symmetry of the self induced magnetic field around the electrode, which produces a resultant force. This resultant force 'blows' the arc in a direction opposite to the concentration of magnetic flux density. The unwanted deflection or the wandering of a welding arc from its intended path is termed as arc blow. Currently, arc blow is widely spread as a problem in welding and it is related to porosity, weld bead irregularities, etc. Among the possible causes are the collimated and unidirectional current flow path (earth cable position), gradient of magnetic permeability between the material and the environment (edge effect and mass concentration), residual magnetic field and even external magnetic fields, as the one produced by another arc (tandem GMAW).

Despite the worldwide acceptance of the above mentioned explanation for arc blow, one question could be raised: Is it possible to have a plasma volume pushed aside due to unbalanced magnetic forces in such a way the arc column would change position? A magnetic field would certainly not move a not confined amount of gas (not charged matter). Thus, at least a more comprehensive description of the phenomenon must be provided to avoid such questions.

The Proposed Descriptive Model for Arc Blow

Taking into account the resultant magnetic force interaction with the arc, two hypotheses can be considered:

1st - The arc (plasma column) moves and creates a new path for the electron flow;

2nd - The electron flow is displaced and forms a new path for the arc in another position.

The first hypothesis would be valid only if the resultant force responsible to the deflection of the plasma column had a thermodynamic nature. Only a thermodynamic pressure (like the atmospheric) would be able to push the arc (ionized and non-ionised matter) to another direction. In the precedent item, it was shown that magnetic field pushes charges, not non-ionized matter. On the other hand, the second hypothesis seems represent what happens, since it is in accordance to the model proposed for the plasma jet formation. As illustrated in Fig. 18, magnetic force acts on the charged particles only and these are the particles to be deviated. Once these charged particles (mainly electrons) go to another direction, they ionise a new path up to a point that the plasma column changes its direction.

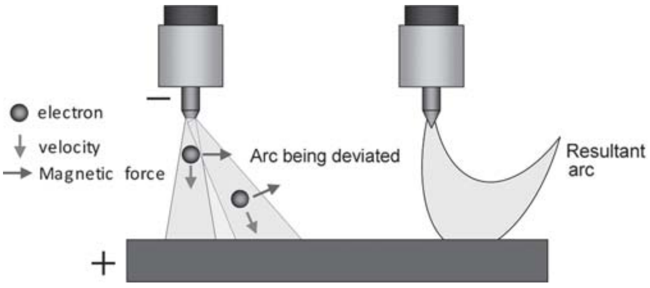

Figure 18. Welding arc being deviated as consequence of arc blow

Conclusions

Plasma jet formation would be better described as "the consequence of a gradient of pressure along the axial axis of an arc, pressure stronger close to the electrode (smaller area), which makes the plasmatic matter to move at high speed towards the plate (larger area). The pressure, in turn, is created by an increasing density of charged particles towards the arc centre line, due to magnetic forces that push the charged particles radially inward, regardless the electrode polarity. The higher the current flow density (the closer to the electrode), the stronger the pressure".

Plasma jet is not always the governing factor to define the arc trajectory. The influence of its effect becomes stronger as the current level is raised. However, there are two other factors playing concurrently, namely "fluid-dynamic and/or thermal effect" and "electrons natural path effect". The "electrons natural path effect" becomes evident when the current is low. Concerning the "fluid-dynamic and/or thermal effect", the dynamic part of the effect is proportional to the "plasma jet effect", that is, proportional to current level too.

Arc blow would be better described as "a deflection or a wandering of a welding arc from its intended path as a consequence of the displacement of its charged particles out of the way of the plasma column, in one direction, due to a force resulted from an unbalanced magnetic field around the arc (a new path for current flow is created away from the original one)".

Finally, these presented models, yet endorsed by electromagnetic theory and by flow mechanics, still lack a deeper theoretical analysis (by physics) and experimental validations. So far, the authors claim they may be satisfactory under engineering point of view.

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