Investigation of the Anode Attachment Process in Plasma Arc Cutting

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Abstract. The anode attachment process in plasma arc cutting is still not well understood in spite of decades of industrial use. Previously, several approaches were made to analyze the attachment mechanisms including imaging, discharge current and voltage measurements as well as the use of thermocouples. In this paper a different approach is described to evaluate the attachment position. Six electrically separated water-cooled copper plates arranged in layers are used as an anode emulating a workpiece. The current through each layer is measured individually using current Hall sensors. The thus obtained information about the current distribution across each plate is used to deduce the anode attachment position inside the workpiece. This diagnostics allows a quick determination of the influence of process parameter variations like the cutting current, gas flow rate, cutting speed or the torch distance on the current distribution inside the workpiece. Using this setup, it is observed that no single attachment appears; the current is divided to flow through all anode segments. The torch distance and cutting speed proved to have the biggest influence on the anode current distribution. Comparison between measurements conducted with the new setup and an experiment using steel plates instead of copper plates is provided.

1. Introduction

Plasma Arc Cutting (PAC) is a commercial process used to cut nearly every conducting material. The advantages of this process are the high cutting speed, the high quality of the cut and the low equipment cost. The process is competing with laser cutting and oxygen fuel cutting.

In plasma cutting a transferred arc is used where the material to be cut becomes the anode, while the cathode is located inside the so-called cutting torch. The anode energy is mainly transferred by electrons and convection as well as by chemical reactions when using oxygen containing gases. Their impact changes with the process parameters [1-6]. Moreover the position of the anode attachment is an important factor influencing the cutting quality as well as cutting speed. Some scientific publications [1, 4-11] describe investigations of the anode attachment of a cutting arc by various methods. Mostly video techniques (ultraviolet [8] and high speed imaging [1]) are used to identify the position of the attachment but also thermocouples [4] are employed to locate the hottest spot inside the workpiece and
also the cutting discharge voltage as a measure of the effective length of the arc is recorded [7]. All these publications are based on experiments done cutting mild or stainless steel.

In [4] Nemchinsky and Severance used thermocouples which are placed at various locations inside the workpiece (10 mm mild steel), thereby identifying the location which is the hottest. By measuring the temperature they found the hottest spot in the upper third of the workpiece and concluded that the arc must have its attachment there. The disadvantages of this technique are the low spatial resolution and slow response time as well as the fact that the temperature is influenced by the kerf geometry, which is irregular.

Osterhouse used in [7] the cutting voltage to determine the attachment position. By cutting mild steel sheets of different thickness he found out that the voltage did not change up to a certain thickness and that the arc attachment is essentially stationary. He came to the conclusion that the anode attachment is in the upper third of the workpiece. For a faster cutting speed he measured a lower cutting voltage and concluded that the arc is shorter and most likely has an attachment point closer to the workpiece surface. Moreover he found, that the nozzle-to-workpiece-distance has no strong influence on the arc anode attachment position. Furthermore he assumed that an increase in plasma and shielding gas pressure raise the downward force on the arc attachment. The fact that the arc voltage is also influenced by a change in vaporization is not considered.

Teulet et al. used in [1] a normal CCD camera observing the arc from behind. They used neutral density filters to be able to identify a bright spot and attributed that the arc attaches here. He determined, that the arc root position is not strongly affected by operating conditions and that the anode spot is always close to the middle of the plate thickness. Just for high cutting speeds the attachment point moves toward the top and a second spot or an oscillating spot close to the workpiece surface appears.

Bemis used in [8] a CCD camera in combination with an ultraviolet bandpass filter to determine the attachment point. The camera he used is placed below and on the side of the workpiece looking towards the cutting gap. He concludes that the brightest zone corresponds to the anode arc attachment and determines single/multiple spot attachments as well as a diffuse attachment of the arc.

Colombo et al. [9] as well as Kavka et al. [5] determined in contrast to [7] and [8] that the arc attachment is characterised by either a single or a multiple attachment moving from the top to the bottom. Davydenco [10] found that two anode attachments exist; the upper one moves with a high frequency between 15 – 50 kHz whereas the lower with 0.5 – 1 Hz. Kavka et al. [5] found an anode attachment mainly located in the upper part of the plate close to the top of the material.

In summary the attachment mode (spot, single / multiple or diffuse) of the arc as well as the movement frequency differ in the current studies. However detailed information about the exact position of the anode attachment are needed for modelling the process [11,12], where up to now only not-validated assumptions are made.

The use of the location of a bright spot as it is performed by [1,5, 8-10] to identify the attachment position might not show the actual current path. Investigations of the GMAW process by Schick [13] and Murphy [14] show that metal vapour which is produced may radiate brighter than the actual current conducting plasma. Therefore a method to determine the actual current path is needed.

2. New Experimental Setup - Segmented Anode
In this paper a new approach is made to determine the anode attachment position. Here it is assumed that the position of the arc attachment is synonymous with the position of the strongest current flow. This setup allows a quick and highly reproducible determination of the influence of various parameters.

2.1. Experimental Design
A state of the art, dual gas cutting torch (Victor Technologies XT 300) as shown in figure 1 is used. As displayed in the figure, the plasma gas is flowing around the electrode and the shielding gas around the plasma gas nozzle. Both plasma and shielding gas have a radial velocity component (vortex flow).
The ignition of the arc is achieved by a high-voltage-high-frequency source to establish the pilot arc which is established between the electrode and the plasma gas nozzle. The pilot arc ionizes the plasma gas allowing the ignition of the main arc between electrode and workpiece without using high voltage. The gases used are oxygen as plasma gas and air as shielding gas.

2.2. The Anode Attachment

In order to be able to find an alternative way to determine the location of the anode attachment a new approach with a segmented copper anode has been developed to reproducibly investigate different process parameters in a well-defined setting.

The new experimental anode consists of six 1.5 mm thick water-cooled copper plates, as shown in figure 2. The plates are held together by three non-conducting screws. Between the copper plates sheets of aluminium oxide are located in order to insulate the plates from each other. Each plate is connected individually by three 1.5 mm² copper cables to allow a current measurement through each plate via hall sensors (LEM LF 205 S/SP3 with a bandwidth of 100 kHz).

All individual plate cables are connected to the power supply (Victor Technologies Ultra Cut 300). Additionally the voltage drop across the arc is measured by a voltage transducer (LEM DLV 250 with a bandwidth of 16 kHz). The voltage is measured between torch and the connection point of all cables. All signals are recorded with a sampling frequency of 50 kHz by the National Instrument data acquisition board USB 6363 (16 bit) connected to a computer, as shown in figure 3. In the experiments the torch is fixed while the segmented anode is moved by a linear unit.
2.3. Verification Measurements

The conditions achieved with the water cooled copper plates described in section 2.2 differ from a real cutting process due to a reduction in evaporating as well as a different thermal conductivity of the anode material. Therefore verification measurements are performed to validate the results obtained with the segmented copper anode to draw conclusions about the influence of thermal conductivity and metal vapour. The general experimental setup and procedure for the verification measurement is the same as the one used with the segmented copper anode but the copper plates were replaced by 1.5 mm thick mild steel plates. Also the steel plates are electrically separated by 0.25 mm thick layers of aluminium oxide. The experimental setup is displayed in figure 4.

Each plate is connected by three 1.5 mm² copper cables that are welded to the sides of the mild steel plates.

3. Trials And Results

To characterize the anode attachment and to verify the measurements done, a total of three campaigns have been performed.

- Reproducibility trials (copper plates).
- Influence of different process parameters (copper plates).
- Verification trials (steel plates).

The first two are done with the water cooled copper anode described in section 2.2 and the verification trials are performed with mild steel plates as described in section 2.3.

3.1. Reproducibility

The reproducibility trials have been conducted with the standard parameter settings used in practice to cut 10 mm mild steel plates, listed in table 1.
Table 1. Standard parameter for 10 mm mild steel.

| Parameter                              | Value         |
|----------------------------------------|---------------|
| cutting current (A)                    | 100           |
| torch distance (mm)                    | 2.8           |
| cutting speed (mm s⁻¹)                 | 36.33         |
| plasma gas                            | oxygen        |
| plasma gas pressure (Pa)               | 760000        |
| shielding gas                          | air           |
| shielding gas pressure (Pa)            | 400000        |

To show the reproducibility of the diagnostic technique three tests are carried out for the same settings. The current flow through the six plates is displayed in figure 5. The colours for the current traces through the individual plates from top to bottom are red, green, dark blue, violet, light blue and grey. The basic shape does not change between the trials. Most of the current is running over the top three plates (blue, red and green). Also the amount of total current stays almost the same.

![Figure 5. Current flow over the six plates at the same set of parameters (plates from top to bottom: red, green, dark blue, violet, light blue and grey).](image)

In order to compare the three trials, the arithmetic mean value of the whole run is taken into consideration. The result is displayed in figure 6.

![Figure 6. Average cutting current over the six anode plates](image)
Trial two and three show almost the same behaviour regarding the current flow over the individual plates. Trial one is slightly different (value of the average current of plate 3 and 4 changes) but still shows the same tendency. The highest standard deviation in current is measured at plate number four with 1.51 A and the lowest at plate number one with 0.33 A. These fluctuations are still quite small and thus these results should allow for a reasonable allocation of the current distribution.

3.2. Different Process Parameters
In this section, the influence of process parameters on the anode attachment is observed. Only one parameter at a time is changed while the other ones are the standard parameters listed in table 1. The parameters changed are:
- Cutting speed.
- Torch distance.
- Plasma gas pressure.
- Shielding gas pressure.
- Total cutting current.

3.2.1. Influence of the cutting speed. Four cutting speeds were set in the range between 16.67 mm s\(^{-1}\) and 41.67 mm s\(^{-1}\). The average current running over each plate, depending on the cutting speed, is displayed in figure 7a.

![Figure 7a](image)

**Figure 7a.** Average cutting current over the six anode plates as a function of the cutting speed (a) and the torch distance (b).

The current flow across the top three plates shows a clear tendency; it increases with higher cutting speeds thus confirming the observations of [7]. The current flow ranges from 23.03 A at 100 cm min\(^{-1}\) to 28.96 A at 250 cm min\(^{-1}\). The tendency of current flow through plate number six (bottom plate) is different: it decreases with an increasing cutting current from 8.97 A to 2.38 A. The current flowing across plates four and five vary as shown in figure 7a; but the tendency is a decreasing current flow at an increasing cutting speed. Summing up a faster cutting speed pushes the current distribution closer to the top of the workpiece.

3.2.2. Influence of the torch distance. In this section, the influence of the torch distance (torch to plate standoff) on the anode attachment is observed. Four trials with distances of 2.0 mm, 2.4 mm, 2.8 mm and 3.2 mm were performed. The current flow across the top three plates rises until a distance of 2.8 mm is reached and drops slightly for a longer arc. The current across plate four displays an oscillating behaviour while plate five and six are showing a decrease in current with increasing torch distance, see figure 7b. For a small distance of 2.0 mm the amount of current flowing over each plate
is almost the same. With increasing cutting distance the current distribution is moved towards to the
top of the workpiece.

3.2.3. Influence of the plasma gas and shielding gas pressure. The influence of the plasma gas inlet
pressure on the current distribution is displayed in figure 8a. The current flowing over the top three
plates is again similar and makes up over two thirds of the total current. It has its maximum at a
pressure of 760 kPa. Plate four and five show an opposite behaviour while the current running over
plate six stays nearly constant.

Overall the changes of the current flow are much smaller compared to the parameters observed before.
The shielding gas pressure on the current distribution is observed at three different inlet pressures.
The current flows over all six plates are displayed in figure 8b. The current flow over the first three
plates does not change valuable. It slightly increases with a rising pressure. Plate four and five behave
the opposite way. Plate six has a maximum at about 400 kPa. The change in current distribution is
even smaller than the one depending on the plasma gas pressure.

3.2.4. Influence of the arc current. The influence of the total cutting current on the current distribution
over the six plates of the segmented anode is described in this section. For a total current of 50 A and
75 A the percentage of current flowing over the top three plates varies however, at 100 A they show a
similar distribution, see figure 9. The current distribution stays constant for 50 A and 75 A and
changes slightly for the 100 A.

Figure 8. Average cutting current over the six anode plates as a function of the plasma gas pressure
(a) and the shielding gas pressure (b).

Figure 9. Average cutting current over the six anode plates as a function of the total current
To sum it up, the change in the current distribution as a function of total current is not really significant.

### 3.3. Verification Trials

The verification trials have been done with standard settings used also for the reproducibility trials, see table 1.

The verification trials show a current flow over all six 1.5 mm mild steel plates just as it is the case for the copper anode setup (see figure 10a). Due to the fact, that the steel plates are connected by the molten metal after a short period of time only the first 0.2 s of the experimental run are taken into consideration. A second trial with this setup is due to the shortcut not possible. In contrast to the copper plate setup most of the current is flowing just through the top two plates (red and green in figure 10a). Comparing the mean values of the current flow over each plate for the reproducibility trials (copper) and the verification trial (mild steel) it is clear that there is a common tendency. In both cases the amount of current is decreasing with an increasing plate number as seen in figure 10b. Still there are major differences looking at the actual values, which are closer to the trials at a lower cutting speed or a lower torch distance.

![Figure 10](image1.png)

**Figure 10.** Current flow over the six plates of mild steel (a) and mean value of the current flow for different parameter settings (b).

Comparing the arc discharge voltage of the verification trial (mild steel) and one of the reproducibility trials (copper) shows that the voltage of reproducibility trial (copper) is slightly higher than the one of the verification trial (mild steel). The average voltage over a time period of 1.5 s shows an average voltage of 163.2 V for the verification trial (red plot of figure 11) and an average of 172.1 V for the reproducibility trial (green plot).

![Figure 11](image2.png)

**Figure 11.** Discharge voltage of the arc of a verification and a reproducibility trial
4. Discussion

In all trials described in this paper a current flow over all six plates was detectable. Therefore it appears that a single spot attachment of the arc does not exist. It seems as if the current is distributed across the thickness of the complete workpiece more or less concentrated in certain areas.

The measurements for the reproducibility trials differ depending on the time. Due to the high temperature gradient between the solid copper and the plasma jet of the cutting torch the presence of metal vapour cannot be ruled out. This metal vapour could cause the differences in the attachment behaviour and also the occasional fluctuations. Another effect could be the temperature of the copper anode which is not in a stationary condition due the short measurement time of a few seconds. An increasing cutting speed leads to an increase of the amount of current running over the top three plates. Therefore it can be concluded that the current conduction concentrates more in the upper region and confirms Osterhouse results [7]. The effect of the cutting speed was also discovered by Teulet in [1]. He discovered an attachment point moving towards the workpiece surface with an increasing cutting speed.

In the trials done also the torch distance was varied. The results show, that with a smaller distance between torch and workpiece, the arc divides more evenly across all six plates. The current flowing over each plate is almost the same for a distance of 2 mm. A possible explanation for this behaviour could be that due to the small distance no cold gas from the atmosphere is entrained into the cutting gap. The lack of cooling might allow the arc to attach over the whole workpiece thickness. Due to the sonic conditions of the arc, as described by Ramakrishnan et al. [15] or Freton et al. [11][12] it might also be possible that a shock layer of the under expanded flow forces the arc to attach over the hole thickness.

The deviations and tendencies of the change in the current flow distribution by varying the gas pressures and the total cutting current are not as significant as the two other parameters mentioned above. The low influences of the gas pressure also agree with the results of Teulet in [1].

The verification trials show the same tendencies as the trials with the copper anode. In both cases a current flow over all six plates can be detected, ruling out a single spot attachment of the arc. The high effort needed to perform a 0.2 s experiment with mild steel plates show that the copper setup is much more efficient.

In [5] Kavka presents the frequency spectrum of the cutting voltage of his cutting trials showing peaks at 50 kHz and at 200 kHz, those fluctuation cannot be detected by the presented experimental setup. The plasma cutting system Kavka is using operates with a vapour mixture of water and alcohol as plasma gas instead of oxygen as used in the trials presented here. It might be possible that this fact leads to the different attachment behaviour. It cannot be ruled out, that there might be fluctuations of the anode attachment that are beyond the capability of this setup. But the current recorded does not show significant fluctuations which may show a tendency towards diffuse attachment of the arc instead of a moving spot attachment.

5. Summary

In this paper, the anode attachment behaviour of the PAC arc was observed. This was done with a segmented copper anode consisting of six electrically separated water cooled copper plates emulating a workpiece. The parameters varied were:

- Cutting Speed.
- Torch distance.
- Plasma gas pressure.
- Shielding gas pressure.
- Total cutting current.

This method has been validated by observing the (1) reproducibility of the results, (2) actual cutting trials and (3) by comparing the discharge voltage of the arc. The following conclusions can be drawn based on this new method of anode attachment characterization:
The trials are reproducible.

The verification shows, that the adopted method is able to present tendencies of different cutting parameters.

Most of the current flows across the top three plates.

The biggest influence on the anode attachment is caused by a change of the torch distance and the cutting speed.

An increasing cutting speed, leads to a concentration of the anode attachment toward the top surface of the workpiece.

The smaller the torch distance the more equally the anode attachment distributes over the six plates.

The gas pressures of the plasma and shielding gas as well as the total cutting current have only a little influence on the anode attachment.

Similarities to the results given in the literature can be drawn, because most of the current flows through the top three plates of the segmented anode which can be compared well with the findings of [1,3]. Additionally, the influence of the cutting speed agrees well with the measurements done by [2,4].

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