CONSIDERATIONS CONCERNING PLASMA ARC CUTTING MACHINING

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ABSTRACT
This paper presents an analysis of the plasma arc cutting (PAC) process, by using the systemic approach method. After a brief history of PAC is given, the operation principle is described and the PAC parameters (cutting speed, \(v_t\); current intensity, \(I_p\); plasma arc voltage, \(U_{ap}\); plasmogen gas) are analyzed. In this paper, the cutting speed parameter \((v_t)\) is analyzed as an evaluation factor of the cutting process machinability. The cutting speed \((v_t)\) represents one of the most important parameters in the case of plasma cutting process, due to the fact that this parameter has a direct influence on the productivity of the process and on the quality of the obtain surfaces also.

KEYWORDS: Plasma arc cutting, Metal cutting, Systemic approach

1. INTRODUCTION
Now, the industry has the possibilities to process some hard and very hard materials (alloys), with maximum of technical and economical efficiency, by using plasma machining methods. Thus, stainless steels, manganese steels, titanium alloys, copper, magnesium, aluminum and theirs alloys, cast iron and chemical industry toxic waste (by transforming into the marketable products) can be worked.

The machining technologies based on the thermal effect of plasma have an important place in the field of unconventional technologies. At present, the plasma arc machining (PAM) represents one of the most modern machining technologies used in the industry domains such as: machines manufacturing, electronics, aeronautics etc., due to its advantages, to the fact that it allows machining of the high-alloy refractory and stainless steels with maximum productivity, to the automation capacity, to the low expenses towards traditional techniques, and also due to the quality obtained of the surface material.

In the machine manufacturing industry, the plasma, as a “tool”, is used especially in cutting operations, coating, welding, melting, and assistance of the mechanical processing operations such as: turning, threading, drilling, grooving etc., in order to improve the machinability of various materials /6/.

The plasma/ion beam machining is based on the thermal or chemical effects generated in the contact zones between ions or plasma and the accessible surfaces of the workpiece /10/. The electric energy is used to form the jet of plasma in the presence of a plasmogen gas. The plasmogen gas (primary gas) must accomplish the following conditions: ensure protection to the incandescent electrode against the oxidation process; to be neutral toward the material of the workpiece. The mono-atomic inert gases, which are today the most used to produce thermal plasma (Argon, Helium, Azoth, air etc.), accomplish these conditions. Since in the process the thermal energy is delivered, the material in solid state is warm, melts and then boiled. The interatomic material bond-breaking is realized by thermal way.

We know that plasma is considered as the fourth state of matter, beside of the solid, liquid and gas states. Generally, we accept that plasma is similar to a gas, but it is characterized by a high level of dissociation and ionization, although on the whole, it behaves as a neutral medium.
Plasma includes a mix of: free electrons, cations, ionized molecules or atoms, neutral molecules and photons /3, 10/.
Plasma is characterized by: a high electric conductivity; a very good interaction capacity with the electric and magnetic fields; permanent source of electromagnetic radiations with large spectrum (infrared, visible, ultraviolet). The plasma state is given by the Saha’s formula: /3, 6, 7/

\[
\frac{p - x^2}{1 - x^2} = (2.4 \cdot 10^{-4} \cdot a^2 \cdot T^{2.5} \cdot e^{-e_0 U''} K)^T.
\]

Where: \(x\) – represent the ionization degree; \(p\) – pressure of the gas; \(T\) – absolute temperature of the gas; \(a\) – a constance, which depend on the static weights of the electron, ion and atom; \(e_0\) – electron charge; \(K\) – Boltzman constant; \(U''\) – ionization voltage.

2. BRIEF HISTORY OF PLASMA ARC CUTTING

The plasma process for cutting was developed approximately thirty years ago, for metals difficult to be cut by classic operations, and uses a high energy stream of dissociated, ionized gas, known as plasma, as the heat source. At present, the plasma cutting machine is directly linked to the computer aided design/computer aided manufacturing system which generates all the part shapes and the nesting plans. Plasma cutting offers productivity and cut quality benefits for some applications. It has the ability to cut thin materials with minimal distortions. Parts which are plasma cut do not require heat treatment.

The basic patent on plasma arc cutting (PAC) was applied for by Gage in 1955. His invention was the byproduct of his work to improve directional stability of the open arc used for TIG welding. Figure 1, taken from the early paper /9/, shows how even a slight arc constriction with a nozzle leads to a substantial plasma temperature rise, increases the arc voltage (and its power) and makes the arc more directional. In its original version, PAC was used primarily for cutting stainless steel and aluminium. Plasma gas was nitrogen or argon–hydrogen gas mixes. Since that first publication, PAC has come a long way. The major milestones were the following /9/.

(1) Introduction of air as plasma gas (1964). This allowed one to increase the cutting speed of steel and improve the cut quality dramatically. The cost was the faster erosion of the electrode: a tungsten cathode does not last long in an oxidizing environment. At that time it was replaced by zirconium when air was used.
(2) Introduction of N₂, water-injection plasma arc torches (1970), see figure 2. In this process 1- 2 L/min of water is injected into the arc with about half of it being either disassociated or evaporated by the arc. This type of PAC process produces extremely square cuts with almost no rounding of the top. Mechanized water-injection cutting became the gold standard of plasma cut quality on virtually all materials thinner than 75 mm for over 20 years.

(3) Oxygen water-injection plasma was introduced in the early 1980s with great in overall cut quality for mild steel plates 25mm and thinner.

(4) It was found that even a relatively low amplitude oscillation component of the arc current (current ripple) substantially increased the electrode erosion rate. Introduction of low ripple power supplies led to a further increase of the electrode life span. Eliminating current overshoot and sloping the current also improved electrode and nozzle life.

(5) Another important invention was the hafnium insert electrode, which lasts about 1.5 times as long as the earlier zirconium insert electrode. The vast majority of plasma cutting electrodes made today are hafnium insert electrodes. These serve up to 100A with forced air cooling and up to 400A with liquid cooling. Air cooled hafnium insert electrodes in simple user friendly air plasma torches mated with lightweight inverter power supplies revolutionized the plasma cutting marketplace during the 1980s. The use of hand held plasma in particular increased dramatically.

(6) Dual gas torches were introduced in the 1960s, see figure 3. The ‘secondary’ or ‘shielding’ gas improved cut quality and protected the torch during the process of piercing the plate. In the 1990s dual gas torches and their processes were improved to produce ‘precision’ plasma systems (very tight constricted arc jet) capable of competing with lasers in some applications.

As a result of these and other improvements, contemporary PAC has become a powerful industrial tool capable of cutting different metals with very high productivity. There is a whole spectrum of different PAC systems. On the one end of this spectrum there are the relatively simple, light manual systems designed to be used in small shops. They use relatively low current not exceeding 100 A. On the other side of the spectrum there are powerful systems for mechanized cutting designed to use high currents (~400A for oxygen cutting and ~1000A for argon–hydrogen mixture cutting). These systems, coupled with CNC cutting machines and controls, are very complicated and expensive.

3. OPERATING PRINCIPLES

According to the Welding Handbook, the plasma arc cutting process severs metal by using a constricted arc to melt a localized area of a workpiece, removing the molten material with a high-velocity jet of ionized gas issuing from the constricting nozzle. In today’s industry it is a
Metal plasma cutting devices are widely used in industry, and recent developments of torch design together with the use of oxygen as plasma producing gas allow improvement in cutting quality /4, 9/. Because of its oxidizing properties, oxygen leads to more regular surfaces inside the kerf with a better evacuation of the molten metal and less dross formation beneath the workpiece with increased cutting speeds /11/.

**Plasma arc cutting** is a very complex process that is used in order to cut steel and other metals (or sometimes other materials) using a plasma torch. In this process, an inert gas is blown at high speed out of a nozzle, see figure 4. At the same time an electrical arc is formed through that gas from the nozzle to the surface being cut, turning some of that gas to plasma. Due to the height concentration of the energy in a limited space, the material of the workpiece is wormed till the melting of a layer; afterwards, the melted material is removed from the cut by the plasma jet /5/.

![Plasma arc cutting principle](image)

**Figure 4:** Plasma arc cutting principle /2, 6, 12/.

**How it works.** The cutting procedure begins with arc ignition, which is a process consisting of several steps. It starts with igniting a pilot arc, an arc discharge between the electrode (cathode) and nozzle, see figure 5, a. Ignition of this pilot arc can be done in two different ways: one is with a short HF pulse applied to the electrode-nozzle gap, another is retract starting. The most common form of retract starting uses the pressure of the air supplied to the torch to drive back a piston to which the electrode is ultimately connected. The electrode and nozzle start out in con-

![Pilot arc ignition](image)

(a) Pilot arc ignition.

![The phase in which the arc attach to the workpiece (arc transfer)](image)

(b) The phase in which the arc attach to the workpiece (arc transfer).

**Figure 5:** Plasma arc cutting (PAC) phases /3, 6, 9/.
tact with an electric current running through them. When the electrode retracts a pilot arc is created /9/.

Once the pilot arc is created, the gas flow blows the pilot arc out of the nozzle thus creating an arc loop protruding out of the nozzle. If the work-piece is in position (typically within 5–15mm from the end of the nozzle), the arc will attach to the work-piece, the power supply will sense arc transfer and the nozzle will be removed from the circuit. The workpiece becomes the anode, and the main current establishes in the electrode-work gap /9/.

Generally, the main current gradually increases from some relatively low level to the nominal. Simultaneously, the type of plasma gas can be changed: often the arc starts in one gas (for example, in nitrogen), which is then switched to another (air or oxygen). Also, the gas flow may increase gradually. Note that during switching off the arc, the arc current and plasma gas may also decrease gradually. All these measures are taken in order to reduce cyclic erosion (erosion during arc-on arc-off switching).

There are two methods to begin the cutting process: piercing the plate or starting from the edge of the plate. The edge start is preferable to protect the torch. However, for some shapes, starting in the middle of the plate (piercing) cannot be avoided. After piercing is completed or when starting from the edge, the torch starts to move. To ensure cut quality, the stand-off should be kept constant. Optimum stand-off varies with current and material thickness, but 6 mm. is a typical value. In the modern PAC for automatic cutting, this is achieved by monitoring the arc voltage and automatically adjusting stand-off.

4. ANALYSIS OF THE PLASMA ARC CUTTING CONDITIONS. SYSTEMIC APPROACH OF THE PAC PROCESS

The machining technologies based on the thermal effect of plasma have an important place in the field of unconventional technologies. As in the case of other machining methods, at the plasma arc cutting (PAC), in order to obtain good results, it is very important to well know the process, this meaning to exactly know what are the parameters involved in the process and their influences.

The advantage of using the systemic approach method consist in the fact that we can obtain a general survey of the process which is analyzed, meaning that all the elements that composed the process are being taken into consideration and all the links between them are analyzed.

The first step on applying the systemic approach method is to establish the input parameters, the output parameters and the disturbing factors that can influence the process. The researches refers to this step as the "parametric description" of the process being analyzed, the initial level of any object investigation.

Input parameters – are depending on the workpiece material type and properties. We need to mentioned that plasma arc cutting machining requires electrically conductive materials. Thus, by using PAC process, high-alloy refractory and stainless steels, as well as other metals can be worked. It is important to underline the fact that the input parameters are those parameters that can be controlled, meaning that their values either are known from the start (ex. the type of material plate, thickness of the plate to be cut etc) or there are establish at the beginning of the PAC process by the human operator. The values of input parameters are established function of some factors that must be considered in the cutting process, in order to obtain the expected final result. The systemic approach method give us a general survey of the plasma arc cutting machining, allowing us to identify and analyzed the relationship between all the PAC system elements.

Output parameters – are referring to the quality of the obtained surfaces, to the productivity of the process and to the related costs, and also to the pollution of the environment.

Disturbing factors – are those parameters/factors that can not be controlled, that appear in the process without being planned.

The initiation of some researches regarding the plasma cutting process needed an analysis of the specific work conditions. By using the systemic approach method, the authors have identified the main input and output parameters involved in the PAC process, as well as the disturb-
ing factors which can influence the final result of the PAC process, see figure 6. The graphical representation from figure 6 aims to emphasize the interesting parameters/factors at the plasma cutting process and also the factors able to influence those parameters.

**Figure 6**: Plasma arc cutting as a system.

As input parameters, we consider: Plasma arc current, $I_p$; Plasma arc voltage, $U_p$; Properties of the material workpiece; Thickness of the workpiece, $g$; Plasmogen gas type and flow $D_{gp}$; Working speed, $v_t$; etc. Also, we have taking into consideration the disturbing factors (Current intensity variation; Inaccuracy of the equipment; Purity of the plasmogen) because they can also influence the final result of the cutting process (final quality of the cut, productivity, low cost etc)

In this paper, the PAC parameters (Plasma arc current, $I_p$; Plasma arc voltage, $U_p$; The cutting speed, $v_t$; The nature of the plasmogen gas; Plasma torch position to the plate) are analyzed.

- **Plasma arc current intensity, $I_p$.
  
  The value of plasma arc current, $I_p$, is depending on: 1. The geometrical parameters of the plate to be cut ($b$ - cutting width average, $s$ – thickness of the workpiece); 2. The cutting speed, $v_t$; 3. The gas flow, $D_{gp}$; 4. The plasmotron construction/1, 6, 8/. Usually, the cutting process uses plasma arc current intensity values till 800 – 1000 A. Between the plasma arc current intensity ($I_p$) and the factors enumerated above exist a relationship of direct proportionality /8/.

- **Plasma arc voltage, $U_p$.
  
  The value of plasma arc voltage, $U_p$, is establish function of the nature of the plasmogen gases, the ionization voltage of the gas and the gas flow, $D_{gp}$/1, 6, 8/. The values of plasma arc voltage ($U_p$) is beiger in the case of using the diatomic gases (H$_2$, N$_2$, O$_2$ etc); by using this types of gases, the maximum value for the $U_p$ could reach 300 V.

It is important to mention the fact that the plasma arc voltage grows proportionally with the gas ionization voltage and the gas flow, $D_{gp}$.
Also, we need to mention the fact that plasma arc current, \( I_p \), and plasma arc voltage, \( U_p \), together are establishing the type of the plasma generator that will be used in the process.

- **The cutting speed** \( (v_t) \) – represents one of the most important parameters in the case of plasma cutting process, due to the fact that this parameter has a direct influence on the productivity of the process and on the quality of the obtain surfaces also /8/.

Starting with the plasma arc cutting process energy balance equation, the cutting speed \( (v_t) \) can be calculated with the following formula /1, 6, 8/:

\[
v_t = \frac{\eta \cdot U_s \cdot I_p}{b \cdot s \cdot c \cdot \gamma \cdot t_{top}} \quad [\text{m/s}] \tag{2}
\]

Where:
- \( b \) – cutting width average;
- \( s \) – thickness of the workpiece;
- \( c \) – specific heat of the metal to be cut;
- \( \gamma \) – workpiece atomic mass;
- \( t_{top} \) – melting point of the metal to be cut;
- \( \eta \) – cutting process efficiency

Afterwards, the cutting speed which was determined above with the relation 2 must be experimental optimized. Thus, it can be determined the following values for the cutting speed, depending on the purpose followed /8/:

- \( v_E \) – represents the value of the cutting speed parameter to which the edges of the final cut are parallels;
- \( v_N \) – the value of the cutting speed parameter when we can obtain a very good quality of the cut without drops on the inferior side of the cut;
- \( v_L \) – the value of the cutting speed parameter to which the cutting is no longer possible (upper limit of the cutting speed).

Between those three values exist a corelation, as following:

\[
v_E < v_N < v_L \tag{3}
\]

According to some bibliographical references /1, 6, 8/, the values for the cutting speed parameter can be increase by:

- increasing the plasma arc current intensity \( (I_p) \), and thus, the plasma arc concentrations degree will also increase;
- increasing the plasma arc voltage \( (U_p) \) by using the diatomic gases, such as: H\(_2\), N\(_2\), O\(_2\) etc;
- increasing the cutting process efficiency \( (\eta) \) by reducing the heat losses inside the plasma installation and inside the heat affected zone ZIT as well, and also by ignition of some exothermal reactions that should lead to useful energy to grow.

But, the increase of the plasma arc current value is limited by the thermal resistance of the nozzle and also by the possibility to appear a secondary discharge, so called “double arcing phenomenon” (see **figure 7**), witch lead finally, to the plasmatron destruction.

One of the phenomena that put a limit to increasing capabilities of the PAC process is double arcing. In the normal mode of operation, the nozzle is electrically neutral: it is not electrically connected to any part of the circuit. During a double arcing event, the arc, which normally connects cathode and work, is split into two: one connecting the cathode and the nozzle, the other connecting the nozzle and work.

This event leads to catastrophic damage of the nozzle and electrode. In practice double arcing is seen to occur when the following conditions hold: the arc current is too high, and/or the nozzle orifice is too narrow, and/or the nozzle orifice is too long, and/or the gas flow is too low, and/or the gas flow does not have enough swirls.

Also, it has been noticed/demonstrated /9/ that used consumables (electrode and nozzle) are much more susceptible to double arcing than fresh ones.

- **The nature of the plasmodgen gas.** The plasmodgen gas (primary gas) must accomplish the following conditions /1, 8/: ensure protection to the incandescent electrode against the oxidation process; to be neutral toward the material of workpiece. The mono-atomic inert gases, witch are today the most used to produce thermal plasma (Argon, Helium, Azoth, air etc.), accomplish these conditions.
5. CONCLUSION

The plasma process for cutting was developed approximately thirty years ago, for metals difficult to be cut by classic operations, and uses a high energy stream of dissociated, ionized gas, known as plasma, as the heat source. The plasma arc cutting process was imposed due to the fact that it allows the cutting of high-alloy refractory and stainless steels with maximum productivity, through the automation capacity, through the low expenses towards traditional techniques, and also due to the quality of the cut and low thickness of the thermal influence zone (TIZ), within 1.50 mm. By using the systemic approach method, the authors have identified and analyzed the main input and output parameters involved in the PAC process, as well as the disturbing factors which can influence the final result of the PAC process.

7. REFERENCES