

Experimental investigation of energy balance in plasma arc cutting process

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Abstract. The present paper describes the power balance of the arc cutting process provided by a plasma torch with steam working medium. The work was concentrated on definition of different power terms including power input as well as effective power utilization and losses as a function of plasma gas flow rate. The work was mostly experimental. The results have shown around 20% of total available power is utilized for material cutting and removing for the studied conditions.

1. Introduction

In the plasma arc cutting a source of heat is an electric arc generated by a plasma torch in the transfer regime. The torch is positioned above the material to be cut. The arc is established between the cathode inside the torch body and the material, which acts as an anode. A strong flow of the plasma gas, which is usually air or oxygen, blows out the nozzle through a narrow orifice, forming a plasma jet. Heat is transported first by convection to the plasma gas and then to material surface to melt it and to superheat the molten material inside a kerf followed by its removing [1].

Successful utilization of this technology requires advanced understanding of the processes, which take place on each step of cutting from plasma generation mechanisms, heat transfer between the flow and material, kerf formation and material removing. Both numerical and experimental investigations of different stages of the cut process have been done and reported in literature. These works report visualization of arc cutting [2], properties of the electric arc [3, 4], arc-material interaction and dross formation [5-7] during cutting with gas plasma. The present work represents experimental study of the cutting of mild steel carried out by the plasma torch working on steam. The main aim of the present work is to describe the energy balance of the steam cutting process and to estimate the process efficiency. The scope of this paper is limited to one type of the material and one process parameters. The only variable was the plasma gas flow rate. The results show distribution of the available electrical power of the torch among different energy terms such as power conduction and convection losses and energy required for cutting.

2. Theoretical description of the energy balance

The energy generated by the arc during cutting is transported to the plasma gas and then to material. A part of this energy is used for melting of the material and removing molten material from the cut and represents effective energy consumption. Some part of this energy represents losses. The main energy



terms are represented in Fig. 1. In fact, they can be divided on two different types – the energy sources (P_{tot} and P_{oxy}) and the energy consumption terms (Q_{cool} , Q_{lost_up} , Q_{HCL} , Q_{cut} , Q_{lost_down}).

The total energy balance of the arc cutting process can be described by the following equation:

$$P_{tot} + P_{oxy} = Q_{cool} + Q_{lost_up} + Q_{HCL} + Q_{cut} + Q_{lost_down}$$

P_{tot} is the total electric energy brought to the system $P_{tot} = UI$.

P_{oxy} takes into account the eventual exothermic reaction of iron oxidation occurring on the surface of the molten metal in the presence of oxygen. Indeed, liquid iron is very sensitive to oxygen and reacts with it very easily. Not only oxygen from air is brought towards the liquid iron but also reactive species present in the plasma.

Q_{cool} represents the power losses inside the torch body due to cooling of its components.

Q_{lost_up} is the energy lost by convection and radiation above the material.

Q_{HCL} are the heat conduction losses into material.

Q_{cut} is the energy required to heat material up to its melting point and to melt it. In principle, the material is not heated only to its melting point, but the molten material is being heated up further. The energy utilized for the molten material overheating is also taken into account in this term.

During cutting the plasma jet passes through the kerf taking away residual plasma gas enthalpy downwards the material. This energy term is considered to represent energy losses under the plate Q_{lost_down} .

All these power terms should be estimated to describe the entire power balance.

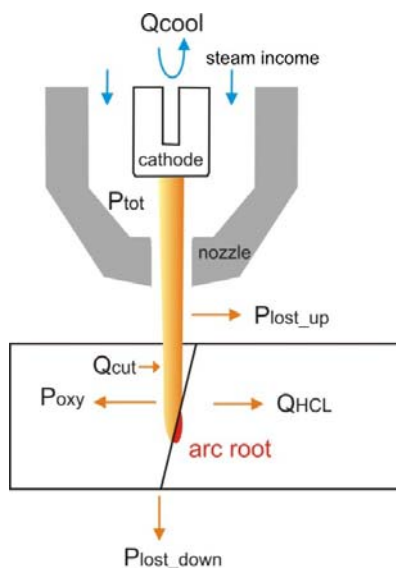


Fig. 1 Energy balance terms in plasma arc cutting

3. Experimental setup and operating conditions

The present study consisted of several steps. Each step required specific experimental conditions, which will be specified in the following sections.

A modified Fronius TransCut 300 system has been used in the present experiments. The principle diagram of the plasma torch is shown in Fig. 2. The main feature of the torch is the plasma medium. The torch is operated on steam originated from a water-ethanol mixture provided by the producer. The solution is supplied through the channels inside the torch body at definite pressure, where it is heated up to the temperature of vaporization. The formed vapor is heated and ionized utilizing the heat of arc. Thus, the plasma gas consists of products of dissociation and ionization of ethanol solution. The system has been slightly modified to enable higher arc currents up to 90 A. The negative terminal of the power supplies was connected to the cathode, while the positive one was fixed to the working piece. All measurements have been done at arc current $I = 60$ A. The arc is starting by a contact method between the cathode and torch nozzle in a low current regime ($I = 13$ A). The plasma gas blows the arc out the nozzle and the arc path is then reconnected to the work piece.

In the present experiments only an effect of pressure has been studied. Three series of experiments have been performed. The pressure of water was set to 4.5, 5.5 and 6.5 bar. The plasma medium flow rate has been measured during all cutting tests. The studied plasma torch parameters are summarized in Table 1. Increase of the water pressure resulted in corresponding increase of the torch chamber pressure and plasma gas flow rate. The plasma jet was always in the supersonic regime. The arc voltage and current has been recorded during cutting procedure using the oscilloscope LeCroy. The

average total electric power provided by the arc P_{tot} was then determined. Increase of the gas flow rate resulted in increase of the arc voltage and consequently of the total arc power. Detailed analyses of voltage drop between the cathode, torch nozzle and material have shown that voltage drop increases significantly on the nontransfer part of the arc inside the torch chamber. The voltage drop outside the torch stayed almost unchanged.

Table 1 – Plasma torch parameters for the performed cutting tests

	Pwater	gas flow rate	arc voltage, V	arc power
	bar	g/min	total	W
conditions 1	4.5	9	140	8400
conditions 2	5.5	11	148	8880
conditions 3	6.5	15	150	9000

The same material has been used in all experiments - 15 mm thick plates of mild steel S235JR. The surface of the plates was slightly rusty. The composition of the material was verified using EDX analyses. The result composition is shown in Table 2 together with corresponding values in norm EN 10025. Carbon content appeared to be slightly higher than the norm demands, but it may be caused by pollutions of the analyzer.

The torch was fixed at the same position, while the material was fasten to the moving system. The following cutting parameters have been applied: cutting speed – 30 cm/min, stand-off distance – 2 mm. Each cut was started from the edge of the plate. First, the torch was operated in a pilot arc regime and then the moving system was switched on to provide the cut. The cutting was carried out for around 150 mm always in the same direction to eliminate an effect of the flow rotation. After each cutting test the metal piece was cut some centimeters from the edge by a saw in such a way to enable analysis of the cut surface and kerf geometry and dimensions. An average kerf width was then evaluated to estimate amount of removed material for the energy balance evaluation.

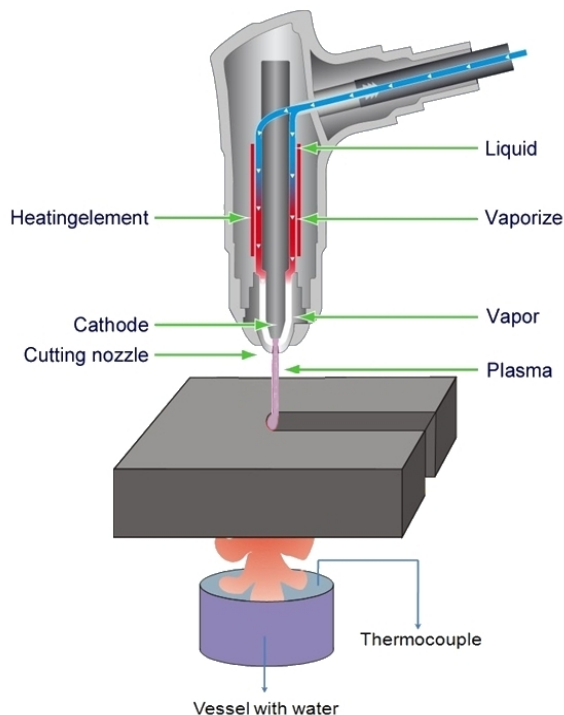


Fig. 2 Plasma torch TransCut and experimental arrangement for measurement of Q_{lost_down}

4. Experimental determination of energy terms

The present chapter describes experimental determination of the energy terms for evaluation of the energy balance of the cutting process. The parameters of the kerf after

Table 2 – Composition of the mild steel S235JR evaluated through EDX analyses and corresponding normalized values (EN 10025)

element	vol. %	
	measured	norm
C	0.635	<0,19
Mn	1.5	<1,5
Si	0.43	
S	0.01	<0,045
Ni	0.11	
Cr	0.09	
Cu	0.3	<0,6
Al	0.18	
Fe	97	

cutting tests are shown in Table 3 together with material melting rate. It is obvious that increase of the gas flow rate resulted in reduction of the amount of melted material. Indeed, both material melting rate as well as amount of swarf was smaller for higher plasma gas flow rate.

Table 3 - Kerf geometry and material melting rate for the studied conditions

	swarf	cut width	material melting rate	
	g/cm	mm	g/min	g/cm
conditions 1	1.695	2.45	86	2.87
conditions 2	1.58	2.175	76.3	2.54
conditions 3	1.4	2.025	71.1	2.37

Main energy terms have been evaluated for all three reported conditions and are shown in the following. It should be noted that the energy losses above the plate $Q_{lost\ up}$ are very difficult to estimate. They are considered to be small and were not taken into account. Energy losses inside the torch Q_{cool} is only the energy taken away by the cathode cooling water. Experiments have shown that they are insignificant in comparison to other terms (less than 2% of total power) and they were not taken into account.

4.1. Energy required for cutting

The following quantities have to be considered to evaluate this term: the volume of melted material, the melting point of material, and the temperature of the molten overheated material. Volume of the melted material was considered to be equal to volume of the removed material and was determined based on the kerf geometry. It is rather difficult to define material properties and melting point of the mild steel as they are strongly affected by the material composition even in the limits of the norm. The literature reports the following ranges for S235JR steel: melting point - 1450÷1500°C, specific heat - 450÷620 J/kgK, thermal conductivity – 40-70 W/mK. Moreover, material properties are changing with temperature. In the present calculations the following values were chosen (Table 4). The molten material keeps absorbing energy from the arc, which results in its overheating. A series of tests have been done to estimate temperature of the overheated molten material. It is rather difficult to provide measurement of the temperature inside the kerf during cutting. That is why so-called ‘edge-cutting’ experiments have been carried out. The plasma torch was moving along the edge of the material and plasma was melting and removing some part of it. Infrared pyrometer Minolta Land Cyclops 152A was focused onto the place of the leading edge continuously measuring its temperature. First, the pyrometer measured temperature on the cut surface when plasma torch was under operation. Then, the plasma torch and the material moving system were stopped simultaneously and the temperature reduction was measured as well. Such a procedure allowed estimation of temperature in the kerf during cutting and it was supposed to be around 1800°C. It appeared that the emission coming from the jet is negligible compared to the emission of material and the values measured during the torch run are valid and were used in the calculations. The estimated temperature values are rather rough as the field of view of the pyrometer was much higher than the size of the leading edge during the cutting.

Knowing the material melting rate and its temperature, it was possible to estimate amount of energy required for cutting Q_{cut} (Fig. 4).

Table 4 – Material properties of the used mild steel S235JR

Melting point	1475 °C
Specific heat	520 J/kgK
Heat of fusion	289 J/g
Density	7,86 g/cm3
Thermal conductivity	52,4 W/mK

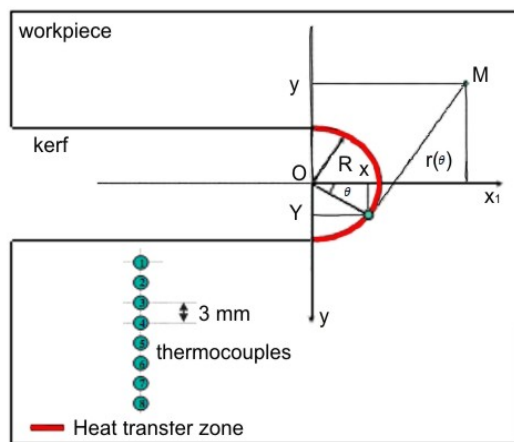


Fig. 3 Experimental setup and system of coordinate for the heat conduction model

(red line in Fig. 3). The solution of the heat propagation equation describes the temperature distribution inside the work-piece by the following equation:

$$T(M) = T_0 + \frac{Q_{HCL}}{2\pi\kappa_t h} * \frac{2}{\pi} * \int_0^{\pi/2} \exp\left(-\frac{\rho C v_t x_1(\theta)}{2\kappa_t}\right) * K_0\left(\frac{\rho C v_t r(\theta)}{2\kappa_t}\right) d\theta$$

where k_t – thermal conductivity of the material, ρ – density, C – heat capacity, V_t – cutting speed, $x_1 = x - V_t t$, R is the average half-width of the kerf measured after each cutting, K_0 is the zero order and the second kind of modified Bessel function and Q_{HCL} is a term of conduction losses inside the material. This model has been used to determine heat conduction losses to the work-piece. To do so a set of thermocouples was installed inside the work-piece perpendicular to the cutting direction at the distance 5 mm from the cut and 3 mm from each other (Fig. 3). Then the temperature inside the work-piece was measured during cutting. Data from the thermocouples were collected by the data logger Omega OM-DAQPRO-5300 and analyzed in the Matlab environment. The term Q_{HCL} was then determined by fitting the analytical data and experimental curves from thermocouple measurements. The results have shown that $Q_{HCL} = 3,2$ kW for the used material for conditions 2, which corresponded to 36% of the total energy available. The effect of the plasma gas flow rate on this term has not been studied yet and it was assumed to be 36% of the total power for all considered conditions.

4.3. Energy losses below material

Energy losses below material Q_{lost_down} have been determined from calorimetric measurement in the vessel filled with water and positioned below the plate at the place of cutting (Fig. 2). Water temperature increase has been measured while cutting. The result calculations took into account the following factors:

- Energy generated by the pilot arc before the cut was absorbed by the calorimeter as well and therefore had to be deduced from the energy balance;
- After each cut swarf was collected at the bottom of the vessel. These particles also bring additional heat, which is already taken into account in Q_{cut} term. The swarf was weighted and the heat bringing by them was also deduced.

These losses depend on the plasma gas flow rate and represent a big part of the total available energy (Fig. 4).

5. Energy balance of the cutting process

The result terms of the energy balance for studied conditions is shown in Table 5. The most important terms are also plotted in Fig. 4. It is evident, that energy utilized for cutting is decreasing with the plasma gas flow rate. However, the energy leaving the kerf is also decreasing. The reason for such behavior is not clear and more tests should be done to get better correspondence between power input and output terms. Moreover, effect of the plasma gas flow rate on losses to material Q_{HCL} should be done as well.

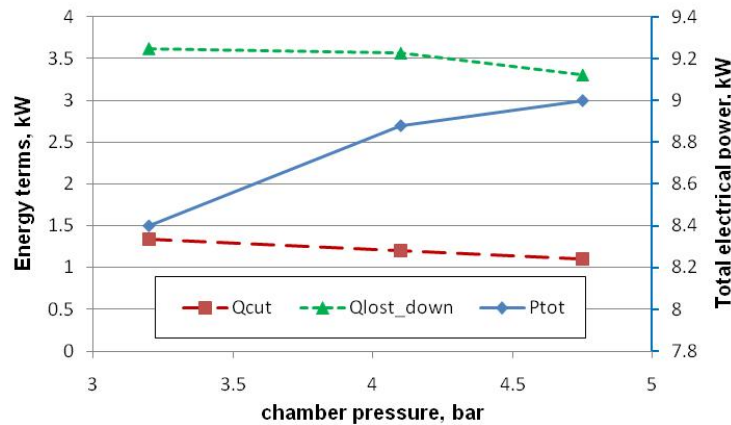


Fig. 4 Total available electric arc power and main energy terms as a function of chamber pressure

Moreover, one should not forget that steam can partially dissociate into hydrogen and oxygen atoms, which may also react with molten material. However, it is still not clear if oxidation is taking place during the steam cutting.

Table 5 – Energy balance of the steam arc cutting process as a function of the plasma gas flow rate

flow rate	Ptot	Qlost_down		QHCL		Qcut		Δenergy
g/min	kW	kW	%	kW	%	kW	%	kW
9	8.4	3.621	43.10714	3.02	36	1.337345	22	0.42
11	8.88	3.566	40.15766	3.20	36	1.202437	19	0.91
15	9	3.302	36.68889	3.24	36	1.105357	17	1.35

6. Conclusions

Energy balance of the arc cutting process by a plasma torch operated on steam was evaluated experimentally. It was shown that the biggest part of the available energy is either consumed by the material itself representing conductive losses or leaves material flowing through the kerf in the form of heated gas. About 20% of available energy is sufficiently utilized for the cutting itself. The efficiency of the energy utilization is reducing with plasma gas flow rate.

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