INVESTIGATION OF KINETICS OF ANODE SPOTS IN PLASMA CUTTING OF METALS

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The kinetics of interaction of the plasma column with a metal in the process of cutting stainless steel is investigated by high-speed photography techniques.

An increase in the productivity and improvement of the quality of plasma cutting of metals requires a detailed investigation of the process occurring during this operation. In [1-3] the energetics of interaction of the plasma column with metals has been investigated and a thermal model of plasma-arc cutting is proposed. A more rigorous investigation of the mechanism of cutting obviously requires consideration of electrodynamic forces accompanying the interaction of the plasma column with the metal [4, 5]. So far there is only one relatively complete investigation of the parameters of the plasma column as functions of the operating regime of cutting [7], from which one can get some information about the kinetics of the processes occurring during cutting. However, the use of a watercooled cylindrical nozzle instead of the cut metal for simplifying the experiment makes it difficult to estimate the reliability of the obtained results.

The present article is devoted to the investigation of the kinetics of interaction of the plasma column with the metal directly in the process of cutting Kh18N10T stainless steel by the methods of high-speed photography.

The investigations were carried out on OPR-10 plasma cutting equipment, which permits to obtain a current $I = 100-300$ A and voltage $U = 200$ V in the continuous regime. Commercial nitrogen was used as the plasma-forming gas. For the purpose of reliable photographic recording of the cutting process by a high-speed camera the construction for securing the plasma cutter in relation to the unit being cut was changed. A PMR-6 cutter was mounted on a rider and the unit (a metal strip) was placed on a carriage ensuring a uniform displacement of the unit with smooth regulation of the speed in the range 0.25-5 cm /sec. The distance between the cut of the cutter nozzle and the surface of the metal 1 was maintained with an accuracy of 0.2 mm.

The separate zones of the hollow of the cut and plasma column were photographed with SFR-2m and Krasnogorsk cameras in a wide range of operating regimes of the equipment. The recording of the radiation by the extra-high-speed SFR-2m camera was done mainly in the continuous regime from the end face of the cut (Fig. 1a). The slit of the camera was placed parallel to the axis of the plasma column, which made it possible to obtain continuous scan in the direction perpendicular to the motion of the plasma streams. The linear speed of scan was 375-1500 m/sec, which corresponded to the time resolution of the photographic recorder $\sim 10^{-6}$ sec. For eliminating the overlaying of images corresponding to different instants of time on the film a shutter was placed in front of the camera.

Photographs of individual segments of SFR-grams are shown in Fig. 2 for different operating regimes of the equipment; current intensity $I = 200-300$ A, thickness of the metal $\delta = 10-50$ mm, and the rate of cutting $v = 0.3-1.5$ cm/sec. The distance l was 6 mm, the diameter of the nozzle was $d = 2.5$ mm, and the consumption of the plasma-forming gas (nitrogen) was $R_{N_2} = 3400$ liters/h. These photographs indicate that the plasma column before the metal is not a stationary plasma formation. The discontinuous

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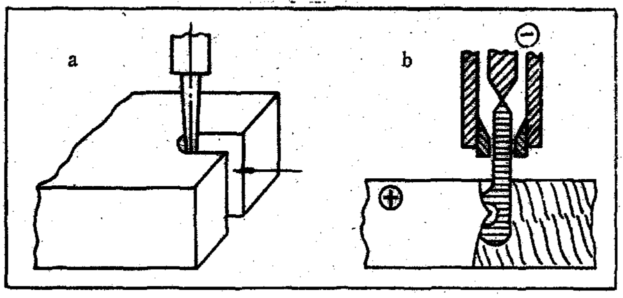

Fig. 1. Dividing cut (a) and sliding cut (b). Arrow shows the direction of observation.

structure of its photographic scan is a result of the existence of separate microplasmoids forming as a result of discrete processes at the electrodes [8]. The repetition frequency of these microplasmoids is 180 kHz. The discontinuous structure of the plasma jet made it possible to determine its velocity; for I = 200 and 300 A the velocity is practically constant along the plasma column and is equal to 1 and 1.3 km/sec respectively.

In the upper part of the hollow of the cut periodic enhancements of brightness are observed, which we identified as wakes of the anode spots. The width of the wake is 0.1 mm and may qualitatively characterize the dimension of the central zone of the anode spot. During the cutting of steel of thickness $\delta = 10$-50 mm with v = 0.3 cm/sec at currents I = 200-300 A the anode spot descends into the hollow of the cut not lower than 10 mm. An increase of the current intensity of the plasma cutter in the range I = 200-300 A for v = 0.3 cm/sec and $\delta = 10$ mm results in a decrease of the oscillation frequency of the anode spot f_a from 20 to 12 kHz. The rate of displacement of the spot remains almost constant at ~150 m/sec.

The frequency and the rate of displacement of the spot inside the hollow of the cut depend substantially on the thickness δ and the cutting speed v. On increasing δ from 10 to 50 mm the frequency f_a increases from 20 to 50 kHz and the speed v_a from 150 to 220 m/sec. An increase of v from 0.2 to 1 cm/sec at I = 300 A and $\delta = 10$ mm results in an increase of f_a from 12 to 25 kHz and of v_a from 150 to 300 m/sec. The depth of sinking of the anode spot decreases from 10 to 4 mm. In Fig. 2 this is illustrated by the photographs of three SFR-grams corresponding to different cutting speeds. For small v the traces of the vertical displacements of the anode spot are clearly recorded, while at the optimum cutting speed the anode spot does not move along the vertical.

The results of the analysis of SFR-grams agree well with the oscillograms of the voltage at the plasma equipment. The frequency characteristics of the used supply sources were investigated with the use of a constant active impedance of type RB-300-1. It was shown that the supply source of OPR-10 equipment has a variable component with frequencies of 100 and 300 Hz and the depth of current oscillations is not more than 5%. In the investigation of the temporal electrical characteristics of the discharge the method of oscillographing of the voltage was found to be most sensitive. An analysis of the obtained oscillograms for the operating regimes described above made it possible to establish that the frequency of voltage oscillations within the errors of measurements coincides with the frequency of displacement of the anode spot recorded on SFR-grams. The amplitude of the oscillations depends on the cutting speed and for v = 0.3 cm/sec it is ~12% of the supply voltage (I = 200 A, U = 185 V, $\Delta U = 20$ V; I = 300 A; U = 200 V, $\Delta U = 25$ V), while for v = 1.5 cm/sec it decreases by 7-8%.

These results can be obviously explained by the strong influence of the erosion plasma on the processes occurring within the hollow of the cut. In cutting metal with $\delta > 10$ mm the erosion plasma is blown downward incompletely and a part of it remains in the hollow producing favorable conditions for shunting the plasma column [6]. A decrease of the current intensity and also an increase of the thickness and the rate of cutting will lead to a deterioration of the ventilation of the hollow of the cut, i.e., to an increase of the fraction of the erosion plasma and thereby to an increase of the rate and frequency of displacement of the anode spot.

Below the region of existence of the anode spot intense radiating plasma streams are recorded; these are obviously formed by overheated metal drops. It is characteristic that the velocity of these streams is larger than the velocity of the plasma before the metal surface and for I = 200 A it reaches 1.5 km/sec, while for I = 300 A it reaches 2 km/sec.

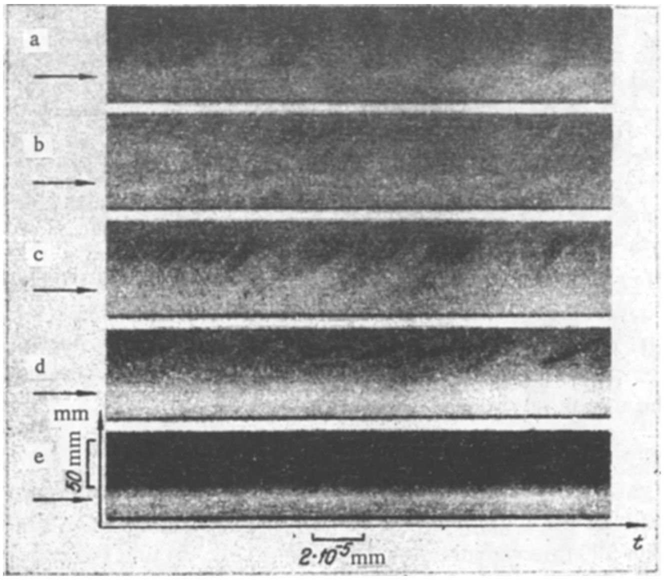

Fig. 2. SFR-grams of the hollow of the cut: a) I = 200 A, thickness of the metal δ = 10 mm, cutting rate v = 0.3 cm/sec; b) I = 300 A, v = 0.3 cm/sec, δ = 10 mm; c) I = 200 A, δ = 50 mm, v = 0.3 cm/sec; d) I = 300 A, δ = 10 mm, v = 0.7 cm/sec; e) I = 300 A, δ = 10 mm, v = 1.5 cm/sec. Scanning rate 375 m/sec. Reduction ×3. Arrow indicates position of the top surface of the metal.

The SFR-grams obtained by us make it possible to obtain information about the interaction of the plasma column in the hollow of the cut only to a depth of 10 mm. It was suggested that the disintegration of the metal occurs to a greater depth due to other slower processes accompanying the radiation of the plasma in the spectral region different from that recorded on SFR-grams. Therefore in the subsequent investigation of the process of cutting 16 mm motion pictures were taken with the Krasnogorsk camera using different light filters and were used for elucidating the nature of the lines forming from the melted metal on the lateral surfaces predominantly in the lower part of the hollow (Fig. 3). The distance between the lines is almost independent of the cutting speed and is ~2-3 mm. It was also shown that these lines are in no way connected with the nonuniformity of displacement of the unit [9]. A model, the so called "sliding cut" was used for the investigation of the line formation (Fig. 1b). Visual observations and motion picture scans showed that in this case there are two anode spots. The upper anode spot coincides with the position of the spot recorded earlier on SFR-grams. The lower spot undergoes a slow vertical displacement. It is characteristic to note that it starts its motion from the lower edge of the metal strip, ascends gradually to the zone of the upper anode spot, and then jumps back to the lower edge. The disintegration of the metal occurs due to the fact that an intense melting occurs along the path of the anode spot. This process is very ordered and occurs with a frequency ~1-0.5 Hz. A new line appears at the lateral surface for each displacement of the anode spot; therefore the zone between the lines is obviously the trace of the anode spot. This pattern is clearly observed visually, but on the motion pictures shows up less clearly without using special light filters because of different spectral composition of the radiation of separate zones of the hollow of the cut.

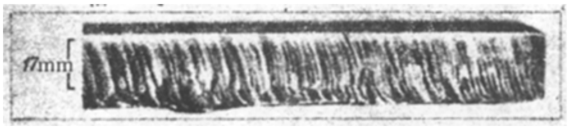

Fig. 3. Photograph of the lateral surface of the metal strip after plasma cutting.

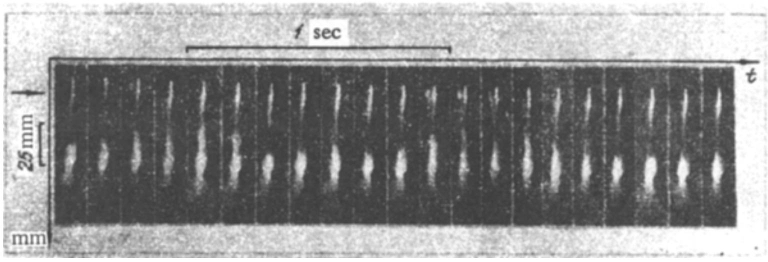

Fig. 4. Records of the hollow of the cut by the Krasnogorsk motion picture camera. $I = 300$ A, $U = 180$ V, $R_{N_2} = 3400$ liters/h, $\delta = 50$ mm, $v = 0.3$ cm/sec. Rate of pictures 8 frames per second. Reduction ×3. Arrow indicates the position of the upper surface of the metal.

In order to investigate the described process directly during metal cutting the hollow of the cut with the end face (see Fig. 1a) was photographed by the Krasnogorsk camera. A stack of light filters with spectral region of transmission 400-500 mm was used. It is evident (Fig. 4) that the recorded pattern is very similar to that obtained in "sliding cut." Low-frequency displacements of the anode spot also occur in the hollow of the cut.

The oscillograms of the discharge voltage were taken simultaneously with the photographs. It was found that at frequencies ~ 1 Hz the voltage fluctuations are random. Their amplitude is considerably smaller than the amplitude of the high-frequency oscillations of the upper anode spot and is about 1% of the discharge voltage.

An explanation of the recorded pattern may obviously be the following. The lower zone of the hollow of the cut is characterized by the fact that the dynamic thrust of the plasma jet has a very small effect on the displacement of the lower anode spot. Therefore the heating of the metal in the lower zone should be regarded as heating in the stationary anode spot. The lower edge of the metal strip is screened from the plasma stream and the anode spot starts its path from below. A large heat release in the anode spot results in a rapid melting and outflow of the metal downward; therefore the anode spot is forced to ascend in such a way that it is screened from the plasma stream. When the lower anode spot reaches the zone of the upper spot the melted connecting pieces are ejected from the hollow under the thrust of the plasma jet and the anode spot again jumps into the "shelter" at the lower edge of the cut. It should be noted that the melted connecting pieces are ejected not only downward but also upward. This is indicated by the lines of melted metal forming on the upper surface of the sample. The ejection of the metal against the high-speed jet may occur obviously only in the case when the disintegration is of a burst type, which happens in a strongly overheated metal. In the present case this is very probable, since the thermal energy is fed to the connecting pieces from both upper and lower anode spots.

The investigations carried out here indicate that two anode spots are formed in the hollow of the cut during plasma cutting of metals in the investigated range of the operating regimes. The upper spot undergoes vertical displacements with a frequency of 15-50 kHz, the lower with 0.5-1 Hz. The erosion of the metals has a significant effect on the frequency and rate of displacement of the upper anode spot. During cutting of metal of large thickness the main mechanism of disintegration of metal is the erosion in the zone of the stationary anode spot.

NOTATION

I	is the current intensity;
U	is the voltage;
l	is the distance between the cut of the cutter nozzle and the metal surface;
R_{N_2}	is the consumption of the plasma forming gas;
d	is the diameter of the nozzle;
v	is the cutting speed;
v_a	is the rate of displacement of the upper anode spot;
f_a	is the frequency of oscillations of the upper anode spot;
δ	is the metal thickness.

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