Strange collective behaviors of cathode spots in low vacuum arc

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Abstract. Removal of an oxide layer from all surfaces of a metal plate using an arc in vacuum is conducted for this study. Results confirmed that cathode spots that appeared on the side faced to anode were able to exist on another side opposite from the anode as well. Although some features of the cathode spots are not unusual, some characteristics disagree with conventional explanations for low-vacuum arc behavior.

1. Introduction
Metal surface processing is playing an increasingly important role in metal manufacturing industries because life span extension of iron steel infrastructures or metal products is necessary to realize a self-sustaining society. As a preliminary treatment, surface cleaning such as descaling or decontamination is necessary to establish sufficient performance of surface processing. Although chemical and mechanical methods have been used conventionally for the metal surface cleaning, more efficient and eco-friendly methods are desired. The authors are studying and developing a method using arc in low vacuum as a metal surface cleaning innovation [1-2]. The method depends on characteristics of the “cathode spot”, which is a small, bright region that appears and moves on the cathode surface. Although the cathode spot is a well-known phenomenon, its behavior is mysterious. Many studies have been conducted both theoretically and experimentally for objects of various kinds and shapes, and not only objects of metal but of other electrically conductive materials such as carbon fiber [3-9]. Moreover, the improvement of energetic efficiency has been studied by changing the surface conditions [10-11].

One shortcoming of this method is that it requires a low pressure state such as several tens Pascals, even though it must not be high vacuum. The cathode spot activity is influenced by pressure [12-13]. The time necessary to produce the low-vacuum conditions occupies most part of one cycle of the processing. Therefore, reduction of this preparation duration is strongly desired for practical use. The authors attempt to satisfy that demand and to improve the efficiency by decreasing the number of times that waste gases are exhausted from the system. When this method was applied for descaling of both sides of a metal plate, for example, two exhaust operations were conducted because it was expected in general that the cathode spots exist only on the side facing the anode [14].

In the present research, the same treatment is attempted with a room that is opposite from the anode, which can enable the cathode spots to enter into that space. Using this system, the moving cathode spot behavior is investigated. Some strange features were found.
2. Experimental setup
Figure 1(a) presents a schematic diagram of the experimental arrangement used for this study. Descaling experiments in a low vacuum arc are conducted with an anode and test piece as a cathode set in a cylindrical stainless-steel vacuum chamber. The 300-mm-long vacuum chamber has 250 mm inner diameter. A cylindrical anode of 100 mm diameter is made of copper and is inserted through the upper side of the vacuum chamber. Facing this anode, a test piece support stage is inserted through the lower side of the vacuum chamber. Both the anode and the test piece support stage are water-cooled. Test pieces are a SS400 steel plate, which are 100 mm square and 3 mm thick. The test piece surface is covered with an approximately 5-μm-thick oxide layer, which makes the test piece dark, as presented in figure 1(b). Two stainless steel rods extend from the stage through two 7-mm-diameter holes in the test piece, which keeps the test piece about 60 mm separated from the stage surface. Actually, this room differs greatly from the previous experimental arrangement. The gap separating the anode and the test piece surface is 40-50 mm. In this test piece support device, a few ohms resistance is confirmed between the test piece and the negative electrode of the power supply. A 1-mm-diameter zinc wire is set in that electrode gap to short out the circuit and thereby initiate discharge. Before initiation of the discharge, the vacuum chamber gases are exhausted to about 10 Pa using a mechanical booster pump with a rotary pump. No gas is fed into the chamber. Therefore an arc is generated in residual air. The arc in low vacuum is started and sustained with a DC power supply (AR-SC120P; Osaka Electric Co. Ltd.) using constant current operation mode. Although the pressure in the vacuum chamber becomes higher than the initial value of 10 Pa, it does not exceed 100 Pa during the discharge. The arc current is controllable between about 50 A and 120 A. The current in the circuit and inter-electrode voltage of the DC power supply during the discharge are monitored respectively using a current probe and a data scanner. Photographs of the test sample during the discharge are taken using a camera (EOS X5; Cannon Inc.) and a high-speed digital camera (Fastcam MC2.1 10K-M2; Photron Ltd.).

3. Experimental results and discussion
After initiation of the discharge, some small bright spots resembling those presented in figure 2(a), which are called cathode spots, appear on the test piece. In the experiments, the arc is initiated in low vacuum using a large current flowing into a zinc wire that spans the electrodes gap. A part of the wire is melted in an extremely short time; an electric spark leads to arc discharge. Therefore, all cathode spots are on the upper side of the test piece at the beginning of the discharge. Each spot moves independently and in a random manner. There is apparently no regular pattern to their behavior, as shown also in our previous experiments [1-2]. High-density energy that is confined within the cathode spot causes rapid heating and vaporization of the oxide layer on the test piece surface, which results in
As descaling progresses and the residual oxide layer diminishes, the cathode spot motions gradually become quicker.

As arranged for this study, there is some room under the test piece. After most of the oxide layer on the upper side of the test piece has been removed, all cathode spots move into the lower side of the test piece, which is opposite from the anode. Figure 2(b) shows the lower side immediately after all spots have moved there. This feature agrees with previously described characteristics: the cathode spot preferably stays on the oxide layer [1, 8]. It is particularly interesting that their side change occurs in almost the same amount of time, going through the test piece periphery. The number of the cathode spots remains almost constant, although a slight change can be observed at every moment. Subsequently they continue removal of the oxide layer on the lower side toward the center. Their motions are slow as long as the oxide layer remains sufficient.

During oxide layer removal of the lower side, all cathode spots suddenly go back to the upper side and remain there for several seconds, as depicted in figure 3(a). Compared with the spots in figure 2(a), their sizes are apparently decreased. Their velocities are greatly increased. This phenomenon sometimes occurs. It is not appreciated because it prevents the oxide layer removal. However, figure 3(b) also shows the upper side of the test piece, where all cathode spots are on the lower side. In contrast to figure 3(a), the electrode gap is filled with an extremely bright cloud even though no cathode spot is confirmed on the upper side. These results seem strange because the cathode material vapor is believed to be ionized. Thereby, generated plasma is supplied by cathode spots [7, 15]. As the oxide layer remaining in the lower side decreases, and because it is restricted mainly around the center of the lower side, it becomes difficult for the spots to go to the central region. For that reason, the descaling efficiency is worse.

**Figure 2.** Cathode spots on (a) upper side and (b) lower side of test piece, respectively. Discharge current is 100 A.

**Figure 3.** Photographs of the inter-electrode gap when (a) cathode spots come back and (b) no cathode spots are on the upper side.
To investigate differences of the cathode spots between figures 2(a) and 3(a), their motion can be recorded using a high-speed digital camera. However, it is extremely difficult to catch the moving cathode spots in the field of view. Instead, the cathode spots images at the beginning of discharge are taken because the point of arc ignition can be decided easily by the zinc wire position. Figure 4 depicts a series of photographs, captured from motion images, in which the test piece upper side is covered with an oxide layer as well as figure 2(a). The time interval between the pictures is 12.5 ms. A picture of crossed lines with every 10 mm gap is overlapped to ascertain the cathode spot velocities. The arc starts at the position shown by a cross mark. The cathode spots spread out immediately. One cathode spot indicated by an arrow in the pictures, for example, is traveling about 5 mm along the lateral line for 37.5 ms. Therefore its average velocity is estimated as about 0.13 m/s.

Figure 5 also displays a set of photographs of the cathode spot motion, in which the oxide layer on the upper side of the test piece is almost removed in advance, just as shown in figure 3(a). The number of observed spots decreases to fewer than half of those shown in figure 2(a), which means that electric power in a spot increases to more than twice as large. The time interval between the pictures is 0.125 ms.
ms, which is a hundredth of that of figure 2(a). Because the cathode spot indicated by an arrow in the pictures seems to move about 4 mm laterally and about 5 mm perpendicularly for 0.375 ms, the average velocity is about 17.1 m/s, which is about 130 times higher than that of the cathode spot in figure 2(a).

Although these results were obtained at the beginning of arc discharge, they suggest that the behaviors and characteristics of cathode spots depend strongly on the cathode surface state, which is similar to the results reported in some literatures [10, 16]. Therefore, a drastic and sudden change of cathode spot behavior is apparent when some small differences exist in a test piece, as they do in this research case.

4. Conclusions

Descaling experiments for all surfaces of a plate type test piece covered with an oxide layer were conducted. Cathode spot behavior was investigated in a low-vacuum arc. The cathode spots, which appear on the side facing the anode, remove the entire oxide layer on that side and move into the opposite side from the anode together, continuing the descaling. However, they sometimes go back to
the original side and remain there for a few seconds moving with extremely high velocity. The result obtained using high-speed digital camera observation reveals that the average velocity differs by two orders of magnitude with and without the oxide layer on the surface.

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