Experimental investigation on the dynamics of cathode spots in arc plasma descaling

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Abstract. In the ferrous metallurgical industry, removal of the oxide layer on steel surface (i.e. descaling) with low pressure arc plasma is an environmentally friendly method. In this paper, high speed camera and oscilloscope were employed to diagnose the process of arc decaling. The evolution of cathode spots morphologies and the property of arc voltage fluctuations were investigated for different discharge conditions. The motion and lifetime of the cathode spots are affected obviously by discharge parameters such as pressure, electrode gap and arc current. The lifetime and velocity of the cathode spots are essentially depended on the properties of the substructure of the cathode spot. The fluctuations of arc voltage are directly associated with the dynamics of the cathode spots, and there are large voltage fluctuations for short spot lifetime, large velocity of the spots and poor conditions for spot ignition.

1. Introduction
The vacuum arc is widely used in many fields, such as vacuum circuit breaker and vacuum arc coatings, etc [1-4]. Cathode spots are the most predominant and most studied feature of the vacuum arc. The most common form of the cathode spots consists of an ensemble of luminous spots that move fast and randomly over the cathode surface. The materials under the spots are almost simultaneously evaporated and subsequently ionized. Each cathode spot consists of smaller substructures, called ectons or cells [5, 6]. The motion of the cathode spots on the surface is a direct consequence of the extinguishing and ignition of the ectons, which further results in the fluctuation of arc voltage and almost all other significant parameter fluctuations.

In recent years, low pressure arc have been employed to remove of the oxide layer on the steel surface [7-9]. In early work, researchers concentrated their studies on the treatment processes, e.g. surface roughness and arc voltage varied with the thickness of the oxide layer and the electrode gap, respectively [7-10]. Only limited attention was paid in the dynamics of the cathode spots. Shi et al. found retrograde motion of the cathode spots [11]. In our previous works, the role of the thickness of the oxide layers in affecting the spot dynamics was studied as well [12].

In this contribution, the dynamics of the cathode spots in low pressure arc descaling were further investigated, employing high speed camera and oscilloscope for diagnostic of the arc discharge. Experimental studies for the dynamics of the cathode spots were carried out via the evolution of the morphologies of the cathode spots and fluctuations of the arc voltage.
2. Experimental arrangement
The schematic arrangements of the experimental apparatus are shown in Fig. 1. The experiments were conducted in a glass vacuum chamber with a rotary pump. A copper cylinder with a diameter of 40 mm severed as the anode. A low carbon steel (99.672% of Fe, 0.04% of C, 0.25% of Mn, 0.038% of Al) of 30x30x3 mm³ was connected with the negative polarity of a dc power supply with a no-load voltage of 450 V and served as the cathode. The oxide layer with a thickness of 6.4 µm was formed in the process of hot roll in air atmosphere at a temperature of 1250 °C. A high-voltage pulse igniter with a voltage of 8 kV was used to ignite the arc discharge. Then, the arc discharge was maintained by the dc power supply. The plasma is produced through the discharge between anode and cathode. The arc current, electrode gap and work gas pressure were adjusted in the range of 100 to 1000 Pa, 10 to 50 mm and 10 to 60 A, respectively. After the chamber was evacuated to 5 Pa, the argon was introduced. The pictures of the cathode spots were captured by a high-speed camera (Phantom v 12.1) with an exposure time of 1 µs. The arc voltage was monitored with an oscilloscope (Tektronix TDS2014).

Fig. 1 Schematic illustration of the experimental setup for arc descaling

3. Results and discussion

Fig. 2 Morphologies of cathode spots for different pressure at an arc current of 30 A and an electrode distance of 15 mm.
Figure 2 shows the evolution of the morphologies of the cathode spots at 30 A, 15 mm while the pressure are 100 Pa and 1000 Pa. At the lower pressure, the cathode spots with large diameter and high brightness tend to agglomerate into several large spot groups. At 1000 Pa, the amount of the cathode spots becomes larger because of the splitting of the cathode spots. The current filaments formed by the ectons attract each other in the mutual self-magnetic fields due to the Lorentz force, while external work gas and the plasma pressure provide repelling forces. Therefore, the increase of the repelling forces between ectons with increasing the gas pressure makes the splitting of the spots more frequent [13].

The threshold current $i_{th}$ of an ecton is the same for a certain cathode material [6]. The ecton will extinguish when the current lower than $2i_{th}$, and split when current larger than $2i_{th}$. The ecton number is almost constant when the total arc current is unchanged. Consequently the amount of the ectons contained in one spot decrease at high pressure, and meanwhile, the spot number increase. The average lifetime of a spot

$$\theta = t_c / qL$$

Where $t_c$ is the cycle duration of the ecton, $q < 1$, $L$ is the total ecton number simultaneously operating during the spot operation [14, 15]. Hence, the average lifetime $\theta$ of the spot will shorten with the decrease of $L$.

Compared with other physical quantities of cathodic arcs, the arc voltage is intimately related to cathode processes, with very little distortion or superposition by secondary parameters of the system. The fluctuations of the arc voltage are essentially associated with the non-stationary process and are resulted from the extinguishing and ignition of the spots on the cathode surface. The fluctuations of the arc voltage also directly reflect the spot dynamics and the interaction between spots and cathode material. Tang et al. investigated the power spectrum of the arc voltage fluctuations and the evolution of the cathode spots, revealed the relationship between the spot dynamics and the nature of the cathode surface [12].

![Fig. 3 Fluctuations of arc voltage for different pressure at an arc current of 30 A and an electrode distance of 15 mm.](image)

The waveforms of the arc voltage were recorded at different pressure, as shown in Fig. 3. The arc voltage and its fluctuations increase significantly with gas pressure. From the view of the spot dynamics, the decrease in the spot lifetime and increase in the ignition frequency cause the rise of the voltage fluctuations, which corresponds with spot dynamics.
Electrode gap width plays an important role in controlling descaling rate in low pressure arc descaling. The descaling rate decreases with increasing the gap width at a constant current. Figure 4 represents the evolution of the cathode spots at 100 Pa and 30 A, while the gap width is 15 mm and 50 mm. When the arc operates with a large electrode gap width, the number of the cathode spots increases, but the brightness falls off. The length of the current filaments increase with electrode gap width, consequently the magnetic interaction between ectons is enhanced. The increase of the distance between the spots results in the decline of the plasma density. Meanwhile, the reduction of the electric field between the electrodes increases the velocity of the positive space charge. The local strong electric fields formed between the positive space charge and the cathode is beneficial to the ignition of the new ectons, and hence the spot velocity increases [16]. Spot motion is not motion of matter but a process associated with extinguishing and ignition of ecton sites, which is composed of a series of discrete processes.

Figure 5 shows the fluctuations of the arc voltage with a variable electrode gap width from 10 mm to 50 mm. When the electrode gap width increases, the voltage fluctuation grows. The reduction of the plasma density makes the ignition of the new ectons more difficult, which causes the increase of the voltage fluctuation. The higher spot velocity will lead to the increase of the voltage fluctuation as well.

Fig. 4 Morphologies of cathode spots for different electrode distance at a pressure of 100 Pa and an arc current of 30 A.

Fig. 5 Fluctuations of arc voltage for different electrode distance at a pressure of 100 Pa and an arc current of 30 A.
In the arc descaling, the descaling rate is approximately proportional to the arc current [9]. Figure 6 shows the spot morphologies with different arc current at 100 Pa and 15 mm. The spot number is found to increase linearly with arc current due to the splitting of the spots.

Figure 7 shows the change of the voltage fluctuation with arc current. It can be seen that the voltage fluctuation decrease with increasing the arc current. The ecton number and the plasma density both increase with arc current. The ignition of new ectons is facilitated by the existence of plasma generated from already active ectons [17, 18]. Additionally, there is long spot lifetime for high plasma density and thus the voltage fluctuation decreases.

![Morphologies of cathode spots for different current at a pressure of 100 Pa and an electrode distance of 15 mm.](image1)

![Fluctuations of arc voltage for different arc current at a pressure of 100 Pa and an electrode distance of 15 mm.](image2)

4. Conclusion
The experimental results show that the dynamics of the cathode spots is affected by the discharge conditions in the process of low pressure arc descaling. The motion and the lifetime of the cathode spots depend on the nature of the quasi-periodical mutual repulsion and attraction between the ectons within a spot. The increase of the pressure can enhance the repelling force between the ectons, which reduces the number of the ectons within a spot and consequently shortens the lifetime of the spots. The magnetic repelling force between ectons is enhanced due to the increase of the electrode gap width; therefore, the number of the cathode spots increases, but the brightness falls off. The spot number is found to increase
linearly with arc current as well. The fluctuation of the arc voltage is associated with the dynamics of the cathode spots, and there are large voltage fluctuations for short spot lifetime, large velocity of the spots and poor conditions for spot ignition.

Acknowledgments
This work was financially supported by the Natural Science Foundation of Anhui Province [No. 1708085ME96]

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