Investigations on collective motion of cathode spots in the VAR process

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Abstract

The purpose of the present paper is to investigate numerically the movement of many cathode spots in interaction through their self-magnetic field. The movement of the spots is assumed to be controlled by a combination of stochastic random motion and a drift in the retrograde direction. It is shown that the cathode spots randomly nucleate near the center and then move towards the edge of the electrode. Many spots move collectively in the form of alignments of 3 to 7 spots. For large applied currents, the spots form a cloud that expands periodically in an anisotropic way.

Introduction

Vacuum Arc Remelting (VAR) is typically the final melting process in the production of a wide range of alloys[1]. During this process, a DC arc takes place under vacuum between an electrode and a water-cooled copper crucible. Due to the arc heating, a liquid metal film forms under the electrode. Large metallic droplets fall into a liquid pool which solidifies. During the process, the current emission is concentrated in small areas called cathode spots in which the current density reach very high values, thus creating strong Joule heating, enhancing the desired melting.

The temporal distribution of the arc controls the heat flux entering the molten pool. If the arcs does not distribute evenly over time there is a risk for spatial variations in the overheat, leading to undesired molten pool depth and shape. Obviously the ideal case is the presence of a diffuse arc that evenly distributes a heat flux into the melt pool, and off-centered arcs have been linked to the formation of defects in the ingot [2]. High-speed video observation showed that spots formed preferentially in the center, then moved with retrograde motion to the edge of the electrode[3].

However, in Refs. [4-5] it is reported the observation of a slow ensemble arc motion around the axis of the furnace with a time period of 20 to 40 seconds. More recently experiments showed that the cathodic spots seems to appear preferentially at the pinch-off neck of a droplet[6]. The arc movement, (i.e. the collective motion of the spots) could emerge from the interaction with the bulk plasma and or with the dripping process[7].

Modeling Approach

The problem

Let us consider N cathode spots on a disk electrode of radius R. Assuming that each cathode spot of radius *r* carries a current Ic. The sum of current flowing through the spots is the applied current: Ia=N*Ic. If the dynamic of a single cathode spot is known for any tangent magnetic field, how would collectively behave the ensemble of cathode spots ?

Assumption and simplications

The number of spot N and current Ic carried by a single spot are considered as constant. The spots disappear when they reach the edge of the disk, they are immediately replaced by a new spot randomly nucleating within a radius R/2 from the electrode centre. Within the spot, the electric current density is constant $I/(\pi r^2)$. Spot splitting is not considered. The only existing magnetic field is the magnetic field generated by the electric current flowing inside the spots.

Dynamic of a single cathode spot

We consider the case of cathode spots moving on a titanium disk. It is assumed that the cathode spot movement to be a superimposition of a random walk[8] and the retrograde drift motion.

The walk is isotropic, so that the walker is equally likely to move over a distance δx every time step τ in each possible directions along the x and y axis. The motion is assumed to be completely random, so the probabilities for each direction are 1/4. After a long time, the statistics of the walker should fit the experimentally observed diffusivity $D(=\frac{\delta x^2}{2\tau})$ of the spots [8,9].

The drift velocity *v* is extracted from the experimental measurement data provided in[9]. These data (in m/s) were fitted with:

$$\vec{v} = 24(1 - e^{-250 \cdot B})\vec{e}_r \quad (1)$$

Where *B* is the magnitude of the magnetic field(Tesla), and $\vec{e}_r$ is the unit vector in the retrograde direction.

Magnetic field

The magnetic field is generated by each electric current sources represented by the spots. The magnetic field is calculated with the magnetic potential method.

Numerical domain and parameters

The calculations domain is a disk of radius 0.1 m. The properties used in the simulations are presented in Table I.

Ia (A)	700-7000
R (m)	0.1
r (μm)	100 [6]
N	11 and 100
Ic(A)	100 [6,8,9]
D(m^2/s)	5.4 10^{-3}[8,9]
μ_0 (H)	$4\pi 10^{-7}$

TABLE I. DIMENSIONS AND PHYSICAL PARAMETERS

RESULTS

Simulations were performed for two numbers of spots, N=11 and N=100. Calculations from an initial random configuration were performed for a sufficiently long time to check if a pattern would emerge. Due to the retrograde motion all spots that randomly nucleate near the centre move towards the edge of the electrode. For N=11, no clear pattern could be seen in the results (Fig.1). However some alignment of 3 to 4 spots can be noticed. They spontaneously appear and survive long enough which indicates to not be from a random origin. It is remarkable that in these alignments, the distance between spot is relatively constant. This is clearly visible for alignments of 3 spots in Fig.1 b-d. This phenomenon is due to the cancelation of the magnetic field produced by two neighbouring spots along the perpendicular line passing through their midpoints. Ephemera shapes such as a pentagram can be formed (Fig.1c).

In contrast to N=11, the case with N=100 reached a kind of statistical “steady state”. This steady state consists in a continuous repetition of a cycle, separated in 3 steps:

- Nucleation within a short time of a cloud of cathode spots near the centre of the electrode (Fig. 2.a-c)
- Fast expansion of the cloud of cathode spots (Fig.2.b,c,d)
- Slow expansion of the cloud (Fig. 2 e-f).

It should be understood that these three steps are not clearly separated in time. For instance in Fig. 2f, the nucleation of a new cloud occurs during the slow expansion of the previous cycle. The same remark can be given to Fig. 2.a-b.

Long living alignment of several cathode spots can be seen during all the stage. The outside boundaries of the cloud are made of segments of 3 to 7 spots (see Fig. 2c-f), and not rounded as could be imagined.

Another interesting observation is the anisotropy of the cloud expansion. The privileged direction of the expansion is clearly seen with the spots distribution or with the strength of the induced magnetic field in Fig. 2c-f. The cloud expands more or less along an axis, which changes at each new cycle. On Fig. 2f based on the magnetic field strength, it can be foreseen that the new cloud will expand in a direction almost perpendicular to the previous axis

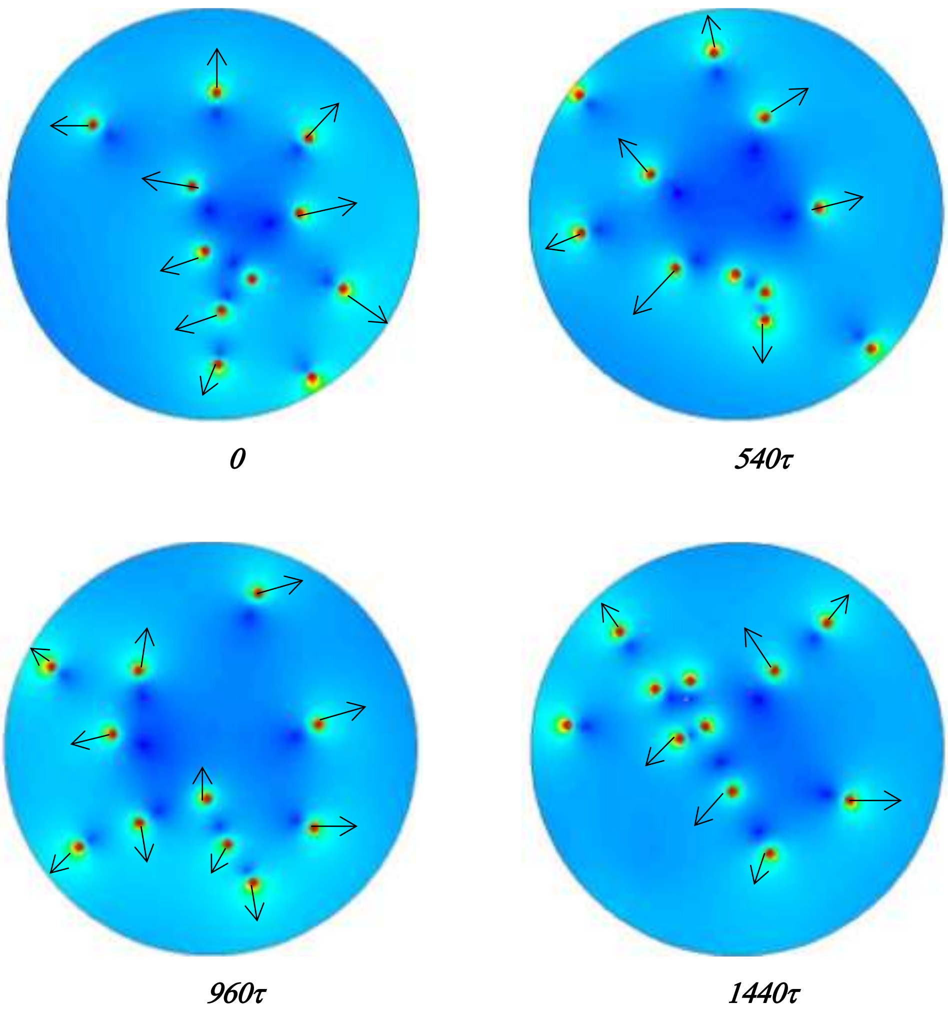

Fig. 1. Time evolution of spot distribution(red dot) and magnetic field(background color) for N=11.

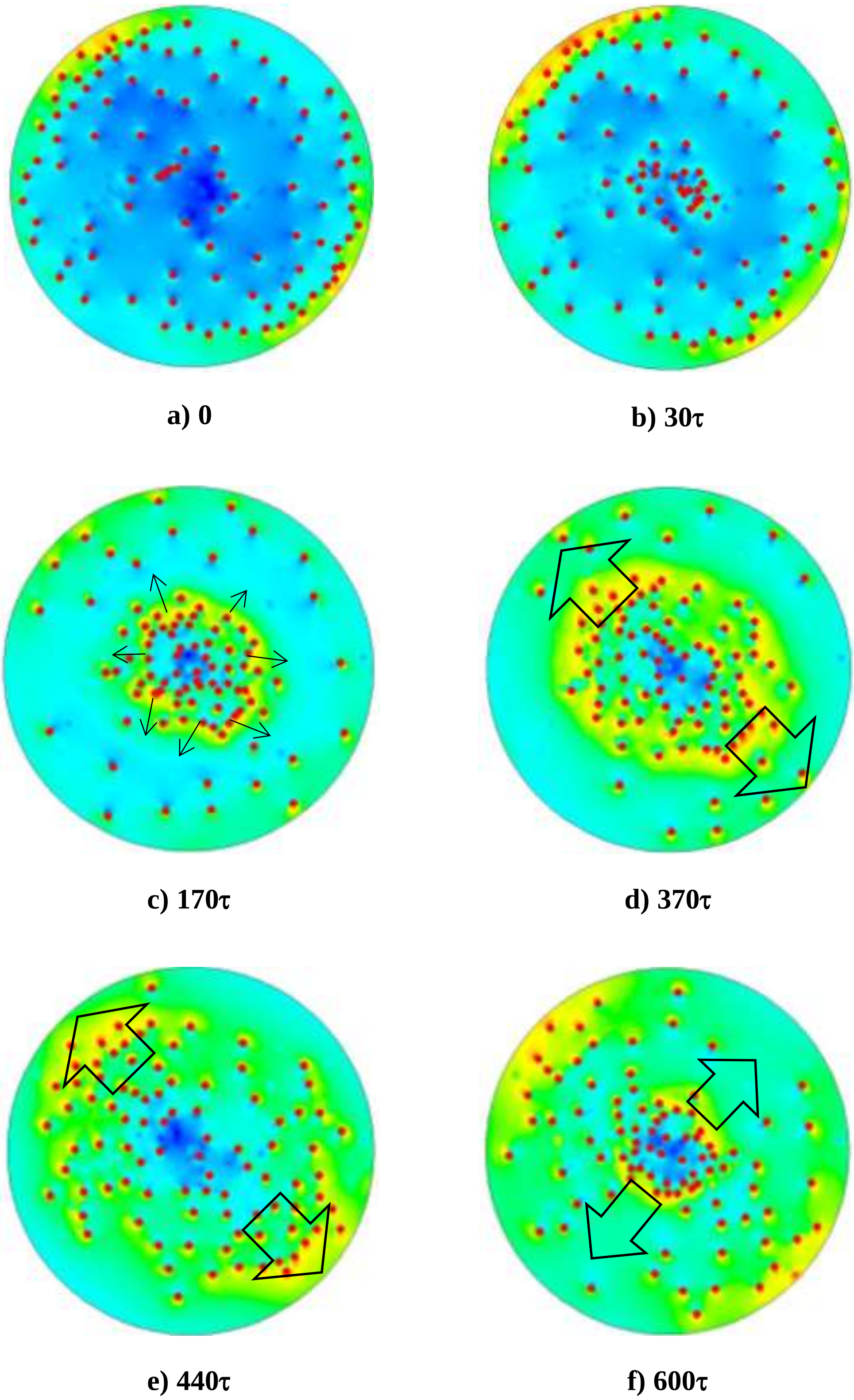

Fig. 2. Time evolution of spot distribution (red dot) and magnetic field(background color) for N=100

Conclusions and perspectives

Although very simple, the present model gives already interesting results on the difference in the behaviour between a single cathode spots and cloud of spots. Assuming that the dynamic of a single spot is known, the results of the model depend on number of spot, dimension of the electrode, and the nucleation law. Some important phenomena such as the Robson's angle and spot splitting could have considerable effects on the results. This constitutes our next goals. In longer-term, the modelling objectives are in the coupling with dripping during melting and with the bulk plasma. We hope that such model would explain the low frequency behaviour of the arc during the VAR process.

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