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Erosion behavior of Ti_3AlC_2 cathode under atmosphere air arc

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ABSTRACT

We report herein on the arc erosion behavior of Ti_3AlC_2 cathode under atmosphere at 7 kV d.c. voltage. The arc life and the breakdown strength for Ti_3AlC_2 are 28.468 ms and 1.239×10^6 V/m, respectively. The process of arc discharging can be divided into three stages: arc formation, steady burning and attenuation, which was observed by a high-speed camera. During steady burning, the arc column is the brightest and the largest. The eroded material was detected by X-ray diffraction, X-ray photoelectron spectroscopy, field emission scanning electron microscope and energy dispersive X-ray spectroscopy. Under the action of arc discharging, the arc erosion morphology characterized with cracks, pores, protrusions with holes displays on the surface of Ti_3AlC_2. Meanwhile, the material is dissociated and oxidized to TiO, TiO_2, Al_2O_3, arising from the high temperature and energy intensity of electric arc. The different composition and Marangoni effect are responsible for the multiple morphologies.

1. Introduction

The electrical contact materials are widely used in low-voltage circuit breakers, contactors and switches. Their performance, to a large extent, depends on the electric and thermal conductivity and the resistance of severe arc erosion. The stability and consumption of electrical contacts are affected by electrical arc, which is produced during application. It delivers the medium for heat transfer, light output and current conduction. Therefore, it is important to investigate the arc erosion behavior of cathode [1–3]. Recently, the layered ternary material MAX phase (M is early transition metal, A is a group IIIA or IVA element, and X is C or N) have become a major focus of the scientific community since they possess unique properties of both metals and ceramics [4–6]. One classic member of the MAX phase is Ti_3AlC_2, which crystallizes in a hexagonal structure with space group $P6_3/mmc$ with two formula units per unit cell. The Wyckoff positions are 2a and 4f for Ti atoms, 2b for Al atoms, and 4f for C atoms, as shown schematically in Fig. 1(a). Every Al layer is separated by three layers of Ti atoms, which presents the visible sequence of AC$\underline{A}$CAB$\underline{A}$B, as shown in Fig. 1(b). The underlined letters denote the layers of Al atoms and others are the Ti layers. The stacking sequence of Ti and Al atoms is accordance with the projection along $[11\bar{2}0]$ [7]. Ti_3AlC_2 is a kind of excellent material with low density, low thermal expansion coefficient, low friction coefficient, high modulus, high strength at high temperature, high temperature oxidation resistance, high thermal stability and so on. Most importantly, Ti_3AlC_2 has good electric and thermal conductivity [7–19]. Therefore, it is hopeful to use Ti_3AlC_2 as potential electrode and contact material. To date, previous reports investigated the erosion behavior of Ti_3SiC_2 under vacuum arc, which also belonged to MAX phase family. It was found that the dissociation of Ti_3SiC_2 took place at the cathode surface, resulting in the formation of solid TiC_x and gaseous Si [20,21]. Zhu et al. [22] confirmed that the phase decomposition of Ti_3SiC_2 contributed to the formation of a 5–50 μm thick converted layer. A melted and resolidified microstructure and a decomposed microstructure were formed at 1–20 μm top layer and 4–30 μm subsequent thick layer, respectively.

Our previous study concisely showed that under different breakdown voltages, the eroded performances for the Ti_3AlC_2 cathodes were different [23]. However, there was no theoretical model for understanding the formation of different surface morphologies under different experimental conditions. The concrete arc eroding processes are very important for the applications of Ti_3AlC_2 in the electrical contact materials, so we have tried to propose some theoretical models and discuss the mechanisms of arc discharging processes in detail. In which we have investigated the arc erosion behavior of Ti_3AlC_2 under atmosphere air at 7 kV d.c. voltage systematically.

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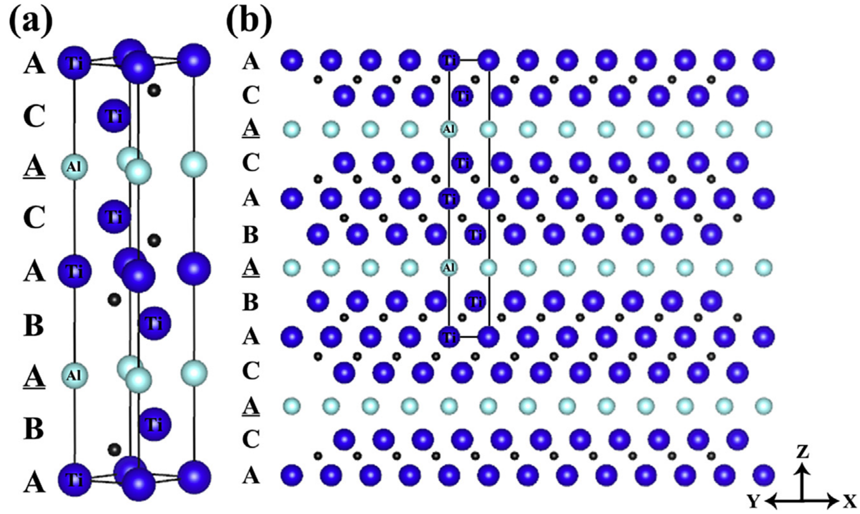

Fig. 1. (a) Crystal structure of Ti_3AlC_2; (b) Stacking sequence of T_3AlC_2 along [11$\bar{2}$0], the rectangle outlines the unit cell.

2. Material and methods

2.1. Preparation of Ti_3AlC_2 sample

The Ti_3AlC_2 sample used for cathode was synthesized by hot-pressed sintering technique. Chemicals including Ti (<45 μm, 99.9%), Al (<75 μm, 99.5%) and TiC (<50 μm, 99%) were produced by Institute of Non-ferrous, Beijing, China. In a typical synthesis, the mixed powders of Ti, Al, and TiC (the molar ration of Ti: Al: TiC = 1: 1.2: 2) with absolute alcohol were treated with ball milling at a rotation speed of 400 rpm for 5 h. The weight ratio of ball to powders was 15: 1. After being dried in vacuum, the mixtures were transferred into a graphite mold with a BN layer inside and subsequently sintered at 1300 °C under 30 MPa pressure in a flowing argon atmosphere for 30 min. Samples were cut into rectangular bars with a dimension of 10 × 10 × 3 mm^3 from the bulk material by electrical discharge machining method. The prepared specimens were grinding with abrasive papers from 200, 400, 600, 800, 1000 mesh and polished to a mirror finish. Finally, the specimens were cleaned by ultrasonic vibration in acetone for 30 min. The phase analysis of the sintered specimen was conducted by X-ray diffractometry (XRD, X'Pert PRO MPD) with Cu Kα radiation at 30 kV and 40 mA. The studies were performed over 2θ angle range of 30°–80°. Ti_3AlC_2 was the main phase. Very little Ti-Al compound and Al_2O_3 impurity were also detected (black line in Fig. 2).

2.2. Arc discharging test

Fig. 3 was the circuit diagram of arc erosion device. The polished Ti_3AlC_2 was fixed horizontally as a cathode, which can be operated upwards and downwards by a stepping motor controller (AKS-01Z). The anode was a pure tungsten rod, which was perpendicular to the cathode, with a tip radius of 2 mm. The experiment was carried out under atmosphere air (relative humidity 45–65%, 20–25 °C). A 7 kV d.c. voltage was applied to the gap between the electrodes. The cathode was driving towards the anode at a velocity of 0.2 mm min^{-1} until electrical breakdown occurred at a certain distance between them. Meanwhile, the discharged waveform and the parameters were recorded by a digital memory oscilloscope (ADS1102CAL). The arc behavior was observed and recorded by a high-speed camera (VW-9000, 12000 frames/s). The composition and oxidation state of the sample surfaces were scrutinized prior and after arc erosion with X-ray photoelectron spectroscopy (XPS). The XPS analysis was performed in an ESCALAB250 spectrometer using Mg K_α X-ray source (1253.6 eV). The eroded surface of the cathode was examined by field emission scanning electron microscope (FE-SEM, JEM-2100F), equipped with an energy dispersive X-ray spectroscopy (EDS).

3. Results

3.1. Chopping current

The chopping current of arc erosion is described in Fig. 4. When the electric arc is produced between the cathode and anode, the current is suddenly high to about 45 A from 0 A. The current decreases rapidly until it is smaller than a critical value, which is called "chopping current" (circles in Fig. 4) [24]. The arc life (τ_c) of the material is 28.468 ms (shown in Fig. 4).

3.2. Arc discharging behavior of Ti_3AlC_2 under air atmosphere

3.2.1. The stage of arc discharging between the electrodes

As shown in Fig. 5, images of arc discharging behavior of Ti_3AlC_2

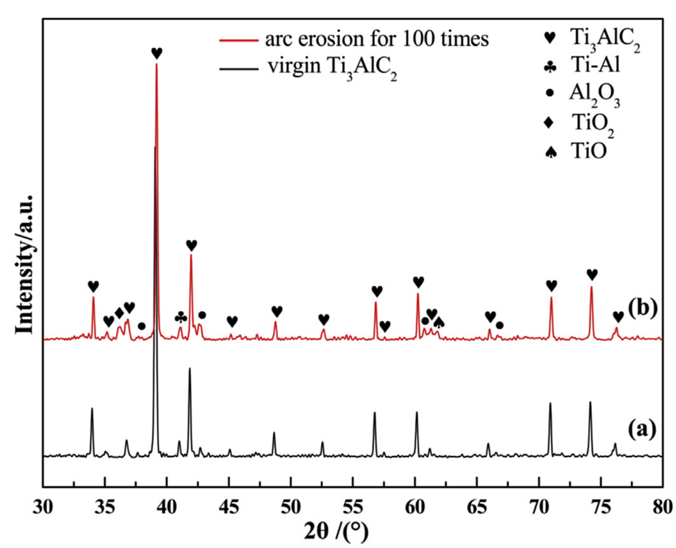

Fig. 2. X-ray diffraction pattern of (a) original material; (b) eroded material after 100 times discharge.