Arc Erosion Behavior of Cu-Ti₃SiC₂ Cathode and Anode

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Abstract

Ti₃SiC₂ and Cu-Ti₃SiC₂ composite were prepared by means of powder metallurgy method and their arc erosion behaviors were investigated by SEM, XRD, EDS and micro-Raman spectroscopy. Erosion craters were formed after first vacuum breakdown; TiC_x was detected as a decomposition product of Ti₃SiC₂ electrodes and Cu-Ti₃SiC₂ cathodes and anodes. It is found that Ti₃SiC₂ particles are more vulnerable to vacuum arc erosion than Cu matrix in the Cu-Ti₃SiC₂ composite. Most of the arc erosion focused on the Ti₃SiC₂ particles during the breakdown. There are no erosion pits or craters formed on the Cu-Ti₃SiC₂ anode surface, but significant amount of Mo that transferred from the Mo cathode was detected. Reaction between Mo and Ti₃SiC₂ was also observed on the Cu-Ti₃SiC₂ anode surface.

Keywords: Cu-Ti₃SiC₂ composite; arc erosion behavior; cathode; anode

1. Introduction

With a space group of P6₃/mmc, the ternary compound Ti₃SiC₂, which comprises alternating layers of edge-shared Ti₆C octahedron and closed packed Si, is the most studied member of the MAX phase family (M_{n+1}AX_n, where n=1, 2, or 3, M is an early transition metal, A is an A-group element, and X is either C or N) [1,2]. This compound was first synthesized in the 1960s [3], and many studies were conducted in the recent years because of its excellent combination properties of both metals and ceramics [4]. For example, Ti₃SiC₂ has higher thermal and electrical conductivity than that of titanium metal at room-temperature [1,4]. It shows better high-temperature-oxidation resistance than that of graphite: the severe oxidation of Ti₃SiC₂ commences at about 1000~1100°C [5], while the oxidation rate of graphite begins to increase at 500°C (in air); meanwhile, the activation energy of Ti₃SiC₂ oxidation is much higher than that of graphite in the same temperature range [6]. The layered structure enables excellent self-lubricating property like graphite does [7]. The

investigation on the phase stability of Ti_3SiC_2 , however, gave quite contradictory results. For instance, El-Raghy [4] stated that Ti_3SiC_2 is thermally stable up to 1700°C . From Low's report [8], the dissociation of Ti_3SiC_2 under vacuum commences at 1200°C and becomes quite pronounced at 1500°C . Ti_3SiC_2 also possesses remarkable properties like good machinability, high temperature plasticity and strength, excellent thermal shock resistance, good chemical resistance etc [4,9,10]. Due to its excellent combination of properties, Ti_3SiC_2 particulate reinforced Cu-matrix composite could possibly be developed as a new kind of electrical contact materials. We have reported previously the erosion behavior of Ti_3SiC_2 ceramic and Ti_3SiC_2 particulate reinforced Cu-matrix composite in a vacuum arc discharge [11,12]. It is found that Ti_3SiC_2 will eventually decompose into TiC_x under both circumstances.

At present, Cu-graphite metal matrix composites are the most popular brush and sliding electrical contact materials due to the outstanding properties of the high electrical and thermal conductivity, the favorable arc erosion and welding resistance, and the excellent self-lubricating performance [13]; meanwhile, the most commonly used contact materials for vacuum interrupter are Cu-W [14,15] and Cu-Cr [16,17] alloys, which possess outstanding properties such as high electrical conductivity, high vacuum dielectric strength, high mechanical strength, and so on. However, all of them have some inevitable shortcomings which make them difficult to reconcile with the requirements in the practical applications. On account of the exclusive mechanical and physical properties of Ti_3SiC_2 and Cu, the preparation of Cu- Ti_3SiC_2 composite will possibly make a good combination of intrinsic properties of the two constituents and develop advanced materials with improved performance. In order to evaluate its performance in the vacuum breakdown process, the influence of vacuum arc on the phase stability of Ti_3SiC_2 and Cu- Ti_3SiC_2 composite needs to be examined.

In our previous publications [11,12], arc erosion behaviour and chemical stability of pure Ti_3SiC_2 and Cu- Ti_3SiC_2 under vacuum arc have been studied. The decomposition of Ti_3SiC_2 was detected on the surfaces of both anode and cathode. Dissociation of Ti_3SiC_2 took place and resulted in the formation of TiC_x as the major detectable product with small amounts of carbon as a by-product. As reported in Reference [12], Ti_3SiC_2 particles were more prone to be damaged by the vacuum arc than the Cu matrix and the erosion rate of Cu- Ti_3SiC_2 composites increased with increasing Ti_3SiC_2 content. In this paper, the vacuum arc behavior, arc-affected characteristic, zone morphology and phase evolution on the cathode and anode surfaces of a Cu- Ti_3SiC_2 composite are reported. The role of the TiC_x phase in the localization of the cathode spots on the surfaces of Ti_3SiC_2 and Cu- Ti_3SiC_2 cathodes is also investigated.

2. Experimental details

Copper powder with a purity of 99.5 wt% and particle size of $\leq 74\ \mu\text{m}$ and self-prepared Ti_3SiC_2 powder [18] with a particle size of $\leq 50\ \mu\text{m}$ were used to fabricate Cu- Ti_3SiC_2 composites. The mixture was prepared by mixing copper and Ti_3SiC_2 powders at designated weight ratios in a V-type mixer for 24 h. The mixed powders were placed into a 20 mm diameter graphite mold (20 mm in diameter)

separately and sintered at 750 °C under vacuum (1×10^{-2} Pa) by using a Dr. Sinter Type SPS-825 spark plasma sintering apparatus. The heating rate and soaking time were 100°C/min and 15 min, respectively. The applied uniaxial pressure was maintained constant at 50 MPa during sintering. High density pure Ti_3SiC_2 blocks were obtained by sintering Ti_3SiC_2 powders at 1500 °C under vacuum (1×10^{-2} Pa) by using spark plasma sintering.

Pure Ti_3SiC_2 and Cu-10mass% Ti_3SiC_2 composite was prepared for the vacuum breakdown experiments. The samples to be analyzed were cut from the prepared materials and machined to 5 mm rods with length of 8 mm. After polishing and cleaning with acetone, the samples were fixed into copper holders. The gap between anode and cathode was fixed at 0.3 mm. Vacuum breakdown experiments were carried out in a stainless steel vacuum chamber with a diameter of 30 cm and a height of 40 cm. The chamber was filled with argon and evacuated to 1×10^{-2} Pa by a mechanical pump and a sputter ion pump. The arcs were generated by a modified electric welding machine which applied a 10 kV DC voltage across the gap between cathode and anode. The peak arc current was about 20 A and the arcing time was set to 0.2 s. The arc current and arc voltage of the discharge were recorded by a Tektronix TDS-210 digital memory oscilloscope. Microstructures and composition of the tested samples were investigated by JEOL JXA-8100 scanning electron microscope (SEM) operating at 20 kV, equipped with a JEOL energy dispersive X-Ray spectroscopy (EDX). Raman spectra were recorded with a micro-optical spectrometer system (LabRam Aramis Raman Spectrometer) equipped with a CCD detector and three different laser sources (532.8, 633 and 785 nm). The as-prepared and the tested samples were characterized by a PANalytical X'Pert PRO X-ray diffractometer (XRD), with Cu K_α radiation, operating at 40 kV and 40 mA. The scanning step was 0.02° and step time was 0.1 s.

3. Result and discussion

3.1 XRD

The SPS sintered Ti_3SiC_2 and Cu-10mass% Ti_3SiC_2 samples are about 99% of the theoretical density. No impurity phase can be detected in the as-sintered sample by using XRD. Fig. 1(a) shows the XRD patterns of Ti_3SiC_2 cathode (with a needle shaped W anode) and Ti_3SiC_2 anode (with a needle-shaped W cathode) after 10 vacuum breakdowns. XRD pattern of pure Ti_3SiC_2 (TSC) is presented also for comparison, as shown in the figure. Only peaks of Ti_3SiC_2 can be seen in the TSC pattern. In the case of Ti_3SiC_2 cathode and anode, apart from the peaks of Ti_3SiC_2 , peaks of TiC_x also appeared after ten times of vacuum breakdown. From the XRD results, it can be concluded that some of the Ti_3SiC_2 particles decomposed after vacuum breakdowns while no other decomposition product can be detected other than TiC_x . Si may have evaporated during the electric arc discharge process, as a result of the high energy intensity of the vacuum arcs [11,12].

Due to the low Ti_3SiC_2 contents in the Cu-10mass% Ti_3SiC_2 composite, only weak Ti_3SiC_2 and TiC (a decomposition product of Ti_3SiC_2) peaks can be observed in XRD diffractogram. In order to reveal more clearly the composition change after the

vacuum arc erosion (100 vacuum breakdowns), a Cu-50vol.%Ti₃SiC₂ composite was prepared for XRD analysis. Fig. 1(b) shows the XRD patterns of Cu-50 vol.% Ti₃SiC₂ composite (CT50) before and after 100 vacuum breakdowns. XRD pattern of CT50 shows only Cu and Ti₃SiC₂ peaks. However, for CT50 cathode small peaks of TiC_x is presented in addition to Cu and Ti₃SiC₂ peaks. For the Mo anode, apart from the peaks of Cu and Mo, weak peaks of TiC_x were detected. It is believed that the anode acts only as a collector of the cathode injections (in low current) and the TiC_x deposits comes from the decomposed Ti₃SiC₂ of the CT50 cathode. However, no peaks of Si or Si-containing compound can be found. This result further confirms the decomposition of Ti₃SiC₂, which is affected by the high energy vacuum arc and TiC_x is the major decomposition product.

Fig. 1. XRD patterns of (a) pure Ti₃SiC₂ (TSC), arc-eroded Ti₃SiC₂ cathode and its counter Ti₃SiC₂ anode (10 breakdowns), (b) Cu-50 vol.% Ti₃SiC₂ composite (CT50), arc-eroded cathode and its counter Mo anode (100 breakdowns).

3.2 micro-Raman

Micro-Raman spectra of the Ti₃SiC₂ particles embedded in the Cu matrix of Cu-10mass%Ti₃SiC₂ (Cu-TSC10) cathode before and after the first breakdown are shown in Fig. 2. The Raman spectrum of Point A (Ti₃SiC₂ particle before arcing) shows three broad peaks at about 221, 625 and 658 cm⁻¹, which are in agreement with the Raman peaks of Ti₃SiC₂ single crystal, reported by Mercier [19] (224, 278, 625, and 673 cm⁻¹). Point B is located on the molten pool of an eroded Ti₃SiC₂ particle after the first breakdown. Raman peak at 221 cm⁻¹ vanished and the peaks at 625 and 658 cm⁻¹ are replaced by a broad peak at around 608 cm⁻¹. Lohse et al. reported three Raman peaks of TiC_x (the non-stoichiometry is due to carbon vacancies) at approximately 260, 420 and 605 cm⁻¹[20]. It is well known that TiC is a non-stoichiometric intermetallic compound with a broad range of compositions (due to carbon vacancies), the vacancy concentration of the compound affects its Raman spectrum. Combining the above results and information, it is likely that the broad peak at around 608 cm⁻¹ is caused by the presence of TiC_x. The absence of peaks at 260 and 420 cm⁻¹ may be ascribed to the different vacancy structure of the TiC_x.

(decomposition product) that found on the cathode after arcing. Besides, the amount of TiC_x formed after one arcing is very limited, since only one electrical breakdown was exerted on the cathode.

Fig. 2. Micro-Raman spectra of as prepared Ti_3SiC_2 particle (Point A) and **arc-eroded Ti_3SiC_2 particle (Point B) embedded** on the surface of Cu-10 mass% Ti_3SiC_2 (Cu-TSC10) cathode after first vacuum breakdown.

3.3 SEM

3.3.1 Cathode

Fig. 3 shows the surface morphology of the Cu-TSC10 cathode after the first breakdown. Fig. 3(a) is an overview of the arc-affected region (the white area). Fig. 3(b) shows the fringe zone of the arc-affected region. Other than fine erosion pits, no obvious change can be observed on the microstructure of the composite. As shown in the figure, most erosion pits are concentrated in the Cu matrix, while, a small amount of erosion pits occur on Ti_3SiC_2 particles. Fig. 3(c) shows the central zone of arc-affected region. It can be seen that arc discharges are concentrated on the Ti_3SiC_2 particles and large molten pools are formed on the particles. Fig. 3(d) is an enlarged image of a molten pool located in the eroded region. Holes and flaws could be observed at the interface of the Ti_3SiC_2 particles and the Cu matrix. In order to verify the new phases formed after the first breakdown, chemical composition of the selected regions in Fig. 3(b) - 3(d) was studied by EDX analysis and the results are shown in Table 1. The C contents obtained from this study are not used for quantitative analysis, since EDX results on light elements such as C are not accurate enough. From Fig. 3(b) and EDS result on Position *a*, it can be seen that other than a few pitting holes, the Ti_3SiC_2 particles remain almost unaffected. In the arc-eroded region, molten pools can be observed, as shown in Fig. 3(c) and 3(d). Both Position *b* and *d* demonstrate high Ti (more than 40 at.%) and C (more than 30 at.%) contents.

Chemical composition analysis shows that the Ti : Si : C atomic ratio on Position *b* is close to that of the Ti_3SiC_2 phase, while, the Ti : Si : C atomic ratio on Position *d* is far away from the composition of Ti_3SiC_2 phase, but Ti : C atomic ratio is close to that of the TiC_x phase. From the previous XRD results, it can be concluded that Position *b* is basically composed of Ti_3SiC_2 phase and Position *d* is TiC_x phase, which is a decomposition product of Ti_3SiC_2 . Both Positions *c* and *e* contain high Cu (more than 43 at.%) and high C (more than 25 at.%). Since there is no intermediate phase formed between the Cu-C binary and the mutual solubility of C and Cu are very limited, it can be concluded from the EDS results on Position *c* of Fig. 3(c) and Position *e* of Fig. 3(d) that Cu and C are the two dominant phases at those locations. Position *c* contains a higher Cu content of 71.0 at.% since it is located at the un-melted Cu matrix. Position *e* contains a higher C content of 47.8 at.%. It indicates that it may be transformed from a melted and decomposed Ti_3SiC_2 particle. No conclusion can be drawn from the EDS results on Position *f* of Fig. 3(d). The dark color of that location suggests that TiC_x and C are dominant. The melted areas contain high C concentration, which indicates that the Ti_3SiC_2 particles suffered more than that of the Cu matrix from the impact of the arc discharge. As seen from Fig. 3 and Table 1, the corroded areas have high C content, which indicates that these areas are originated from the Ti_3SiC_2 particles.

Fig. 3. Scanning electron micrographs of Cu-TSC10 cathode surface after first vacuum breakdown: (a) overview of arc-affected region, (b) fringe zone of

arc-affected region, (c) eroded region (central zone of arc-affected region), (d) molten pool (enlarged image of eroded region)

Table 1. EDX analysis on selected regions (shown in Fig. 3) on the Cu-TSC10 cathode surface

Position		<i>a</i>	<i>b</i>	<i>c</i>	<i>d</i>	<i>e</i>	<i>f</i>
Analyzed composition (at.%)	Cu	2.6	3.9	71.0	12.9	44.0	9.1
	Ti	42.1	45.0	2.3	46.6	5.7	23.8
	Si	13.5	13.1	1.4	9.3	2.5	9.0
	C	41.8	38.0	25.3	31.3	47.8	58.2
Major phase		Ti ₃ SiC ₂	Ti ₃ SiC ₂	Cu + C	TiC _x	Cu + C	--

From the above reported results, it can be concluded that the arc-affected region can be grouped into three characteristic zones according to their similarities in morphology and phase constituents.

- I. Fringe zone of the arc-affected region: The Cu matrix and the Ti₃SiC₂ particles in this zone basically remain intact. Many fine erosion pits formed quite evenly on the Cu matrix, but not all Ti₃SiC₂ particles were affected. Only a few erosion pits were formed on the largest Ti₃SiC₂ particle, as shown in Fig. 3(b).
- II. Eroded Ti₃SiC₂ particles zones (located at the central area of arc-affected region): Characteristics of these zones are the molten pool features. These zones reflect the decomposition of Ti₃SiC₂ under the influence of electrical arc. So basically they contain the decomposed products of Ti₃SiC₂ particles, as shown in Positions *b*, *d*, *e*, *f* of Fig. 3(c) and 3(d).
- III. Eroded Cu matrix zone (located at the central area of arc-affected region): As shown in Fig. 3(c), the eroded Cu matrix zone contains many erosion pits and majority of the matrix did not melt under the influence of electric arc. The Cu matrix in this zone contains high concentration of C and a small amount of Ti and Si, which are originated from the decomposition of Ti₃SiC₂ particles.

The arc erosion process begins with the striking of a high voltage on the surface of a cathode that gives rise to a small, highly energetic emitting area known as a cathode spot. The local temperature at the cathode spot is extremely high (capable of melting or vaporizing most materials) which results in a high velocity jet of vaporized cathode material which provides a medium for the breakdown [21-23], therefore leaves a crater behind on the cathode surface. The cathode spot is only active for a short period of time. Then it self-extinguishes and reignites in a new area close to the previous crater. This behavior causes the apparent motion of the arc. Therefore, field emission plays an important role in the initiation of vacuum breakdown. Neglecting the contribution of high temperature, under very high electric field, the field emission current density, J (A/m²) obeys the formula derived by Fowler and Nordheim [24]. The current depends on the electric field, E (V/m) near

the cathode surface, which is assumed to be constant. The work function, ϕ (eV), is defined as the minimum energy, which is required to bring one electron from the Fermi level to the vacuum level such that the electron can freely move. Fowler-Nordheim formula [24, 25] can be written as follow:

$$J = \frac{1.541 \times 10^{-6} E^2}{\phi t^2(y)} \exp \left[-6.831 \times 10^9 \frac{\phi^{3/2} v(y)}{E} \right] \quad (2)$$

where: $y = 3.79 \times 10^{-4} E^{1/2} \phi^{-1}$;

$t^2(y)$ and $v(y)$ can be taken as constants, $t^2(y) = 1.1$ and $v(y) = 0.95 - y^2$

As indicated from the above equation, work functions can be used to evaluate the breakdown strength of materials. Take CuCr and CuW as examples. Under electrical breakdown, the cathode spots prefer to occur on Cr particles for CuCr alloys [26] while on Cu particles for CuW alloys [13], since the work function of Cu is larger than that of Cr but smaller than that of W. After first vacuum breakdown, as shown in Fig. 3(b), both Cu matrix and Ti_3SiC_2 particles remain intact, sharp and distinct boundaries between the Cu matrix and Ti_3SiC_2 particles can be seen in the fringe zone of the arc-affected region. Erosion pits are mostly formed on Cu matrix while a small amount of pits formed on Ti_3SiC_2 particles. This result may ascribe to the fact that Ti_3SiC_2 has a higher work function value (5.07 eV) [27] than that of Cu (about 4.3~4.6 eV) [26]. In practical the work function of a material depends not only on its intrinsic property but also is affected by its morphology and surface condition. For instance, the surface roughness will lead to the reduction of work function. Although a cathode surface was chemically clean, i.e., free of adsorbate at the beginning, this cleanliness can only be maintained for minutes or hours even under ultrahigh vacuum. Actually real cathode surfaces are microscopically rough in nature and covered with adsorbates. These features affect the work function of the cathode material. The adsorbates, such as inert gas and insulating film, may reduce the work function of the material [25] and thus give a lower “effective work function”. After polishing, the Ti_3SiC_2 particles embedded in the Cu matrix should have a smoother surface compared to that of the Cu due to the much higher hardness of Ti_3SiC_2 . The rough Cu matrix surface together with the formation of insulating film on the Cu matrix surface (Cu can form oxides much easier than that of Ti_3SiC_2) will lead to the reduction of “effective work function” of the Cu matrix, when compared to that of the intrinsic work function of Cu. In the arc-eroded region, however, it can be seen from Fig. 3(c) that most large molten pools are formed on the Ti_3SiC_2 particles and only small pits are presented on the relatively smooth Cu matrix. A possible explanation for the severe damage of the Ti_3SiC_2 particles is that, Ti_3SiC_2 has lower thermal and electrical conductivity than those of the Cu. Under the influence of electric arcs, the heat accumulation at the particles leads to the decomposition of Ti_3SiC_2 (forming TiC_x as byproduct) and the formation of molten pools, as a result, the originally smooth Ti_3SiC_2 particle surfaces have been lost, as shown in Fig. 3(c). Since TiC has a smaller molar volume than that of Ti_3SiC_2 , voids were created at the decomposed Ti_3SiC_2 particles, as shown in Fig. 3(d), and thus the boundaries between Cu matrix and the original Ti_3SiC_2 particles became very rough, which further reduced the

“effective work function” of the molten pool areas originated from the Ti_3SiC_2 particles. Meanwhile, the work function of TiC (3.8 eV) [28] is lower than that of Cu, as a result, the subsequent arcing will be mostly focused on the newly-generated TiC_x phase.

Fig. 4 shows the surface morphologies of Cu-TSC10 cathodes after 100 vacuum breakdowns. As shown in Fig. 4(a), the cathode surface melted substantially (Mo rod with a radius of 2.5 mm as anode). Two characteristic features can be seen on the cathode surface: the large one has a conchoidal shape (as denoted by arrow W1) and the small irregular pits (as denoted by arrow W2) [17]. Fig. 4(b) shows a magnified image of Fig. 4(a). It can be seen that there are many conchoidal-shaped micro-craters with a diameter less than $10\ \mu\text{m}$. The craters are shallow and dispersive. Fig. 4(c) presents the surface morphology of a Cu-TSC10 cathode after 100 vacuum breakdowns (tungsten needle with a radius of 0.5 mm as anode). It can be seen that the eroded surface showed in Fig. 4(c) has many small pits and it is rougher than the eroded cathode surface that used a Mo rod as anode (Fig. 4(b)). The reason for these is due to the high energy concentration of the tungsten needle shaped anode tip.

Fig. 4. Surface morphologies of Cu-TSC10 cathode after 100 breakdowns: (a) Mo rod anode, (b) magnification of (a), (c) W needle anode

Fig. 5 shows the element distribution of a Cu-TSC10 cathode after 100 vacuum breakdowns using tungsten needle as anode (in conjunction with Fig. 4(c)). It can be seen that the cavities labeled as T1, T2, T3 and T4 in Fig. 4(c) are associated with Ti

and Si, but lack of Cu element. There is no doubt that the deep cavities labeled in Fig. 4(c) are the vestiges of decomposed Ti_3SiC_2 particles. Si element distributes more evenly than that of Ti element in the mapping. It indicates that Si is diffused (or transferred) to the adjacent region after the decomposition of Ti_3SiC_2 particles. The distribution of carbon could not be precisely determined by EDS due to the low atomic mass of the element. There are no deep cavities formed on the Cu matrix, therefore, conclusion may be drawn from the previous results that Ti_3SiC_2 particles are preferentially eroded to form deep cavities compared to Cu matrix under the influence of vacuum breakdown.

Fig. 5. EDS mapping of a Cu-TSC10 cathode after 100 vacuum breakdowns using tungsten needle as anode (in conjunction with Fig. 4(c))

3.3.2 Anode

Fig. 6 shows the backscattered electron images of the Cu-TSC10 anode surface after 50 vacuum breakdowns (Mo rod with a radius of 2.5 mm was used as cathode). It can be seen from Fig. 6 that there is no crater formed on the Cu-TSC10 anode surface. This is due to the low arc current used in this experiment (20 A), the anode acts only as a collector of the flux which is ejected from the cathode. As shown in the figures, because of the extreme temperature of the vacuum breakdown process, the Cu matrix, the Ti_3SiC_2 particles and the Mo droplets will react with each other to form different reaction phases. EDS results show that the dark area marked as *g* in Fig. 6(a) is made up of 20.0 at.% Mo, 6.6 at.% Cu, 48.8 at.% Ti, 13.9 at.% Si and 10.8 at.% C. The atomic ratio of Ti:Si is approximately 4:1, which is not too far away from 3:1, suggesting that the dark area is a partially decomposed Ti_3SiC_2 particles. The dark gray area marked as *h* in Fig. 6(a) demonstrates high Cu content, but only trace

amount of Ti and Si, which indicates that area is dominated by Cu phase. While, the light gray area *i* contains more 55.0 at.% Mo, 28.3 at.% Cu and 16.3 at.% C. Since no ternary CuMoC phase or binary CuMo phase has ever been reported, the light gray area *i* should be dominated by Mo-Cu-C [pseudo-alloy](#). Since the solubility of Cu in Mo is less than 12 at.% and the solubility of Mo in Cu is less than 12 at.%[29]. The composition of the *j* phase indicated in Fig. 6(b) consists 48.2 at.% Mo and 46.8 at.% C, with small amount of Cu and negligible amount of Ti and Si. The composition indicates that it may be MoC_{1-x} phase. Small droplets (as indicated by the arrow) can be seen in Fig. 6(b), which comprises mostly Mo. The droplets are believed to be related to the material ejected from Mo cathode, which results in the formation of the Mo layer on the anode surface. It can be concluded that, [the temperature in the spots at the anode surface](#) should be higher than the melting point of Mo (about 2610°C). The interaction between Mo and Ti₃SiC₂ may lead to the formation of MoC_{1-x} on the anode surface.

Fig. 6. Back scattered electron images of Cu-TSC10 anode after 50 vacuum breakdowns (Mo rod with a radius of 2.5 mm as cathode): (a) 500×; (b) 1500×

Table 2 EDX analysis on selected regions (shown in Fig. 6.) on the Cu-TSC10 anode surface

Position		<i>g</i>	<i>h</i>	<i>i</i>	<i>j</i>
Analyzed	Mo	20.0	23.7	55.0	48.2
	Cu	6.6	64.7	28.3	4.9

composition	Ti	48.8	0.2	0.2	0.0
(at.%)	Si	13.9	0.2	0.2	0.1
	C	10.8	11.2	16.3	46.8
Major phase	Partly decomposed Ti ₃ SiC ₂	Mo-Cu-C pseudo-alloy	Mo-Cu-C pseudo-alloy	MoC _{1-x}	

4. Conclusion

The phase evolution and vacuum arc behavior on the cathode and anode surfaces of a Cu-Ti₃SiC₂ composite were investigated by arc ignition under vacuum. The Ti₃SiC₂ on both Ti₃SiC₂ cathode and Cu-Ti₃SiC₂ cathode decomposed under the impact of vacuum arc and resulted in the formation of TiC_x phase as the main decomposition product. For Cu-Ti₃SiC₂ cathode, large cathode craters were mainly formed on Ti₃SiC₂ particles, indicating that Ti₃SiC₂ particles are more vulnerable to vacuum arc than that of the Cu matrix. Three characteristic zones of the arc-affected region were identified on the Cu-Ti₃SiC₂ cathode. In the fringe zone, many fine erosion pits were formed quite evenly on the Cu matrix, but only a few erosion pits were formed on the largest Ti₃SiC₂ particles, other than this, both Cu matrix and Ti₃SiC₂ particles basically remained intact. The characteristic of the eroded Ti₃SiC₂ particles zones are the molten pool features, which resulted from the decomposition of Ti₃SiC₂. The eroded Cu matrix zone contains many erosion pits and majority of the matrix did not melt under the influence of arc. The Cu matrix in this zone contains high concentration of C and a small amount of Ti and Si, which were originated from the decomposition of Ti₃SiC₂ particles. Distinct chemical reaction between Ti₃SiC₂ and Cu was not detected at the cathode. Though no craters were formed, the EDS results indicated that weak reactions between Cu, Ti₃SiC₂ and Mo took place on the surface of Cu-Ti₃SiC₂ anode.

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