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Wetting and pressureless infiltration in the CuTi/Al_2O_3 system under poor vacuum

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Abstract

Work is aimed at preparation of Cu/Al_2O_3 composite by pressureless metal infiltration of porous alumina with simple vacuum equipment. Improvement of wetting by addition of Ti to Cu is investigated in sessile drop tests with various geometrical configurations in vacuum of 1–10 Pa. The results showed that a pre-alloyed Cu did not wet alumina substrate while stacked Cu and Ti blocks did, even though the latter had the same nominal alloy content (Ti: 10 wt%). This result had been proved by a following pressureless infiltration test, i.e. a CuTi/Al_2O_3 composite was formed with stacked Cu and Ti blocks at 1300 °C. Wettability, interfacial chemistry and microstructure were discussed with the aid of SEM and EDAX analysis in the paper. It was suggested that the initial reactant, which benefits the wettability, could be evolved to the one with a higher O:Ti ratio due to poor vacuum condition, higher temperature and longer holding time.

Keywords: B. Composites; D. Al_2O_3; Wettability

1. Introduction

Metal-Matrix Composites (MMCs) containing a high volume fraction of reinforcement are paid more and more attention due to their advantageous properties as high stiffness and wear resistance up to high temperature. Amongst the many types of MMCs, some are reinforced with porous ceramic and ceramic foam [1–3]. The fine and interpenetrating ceramic/metal networks provide the composite with a high structural homogeneity and good ceramic to metal bonding. This type of composites offers a wild range of application and has been widely studied [4–7]. To obtain a composite with high strength, high electric conductivity, and high thermal conductivity and wear resistance, copper–alumina system is chosen. It is expected that copper will provide for good electric and thermal conductivity while alumina for good strength and wear resistance.

Fabrication of the MMCs with a high volume fraction of reinforcement or the interpenetrating composites can generally be achieved by infiltration of metal into reinforcement or porous ceramic [8–10]. A crucial problem of infiltration techniques concerns with the wetting behaviors in the system. In general, metal melts do not readily wet ceramics, especially covalently bonded ones. In this case, an external force is needed to achieve infiltration, e.g. mechanical pressure, as in the case of squeeze casting, or gas pressure. Application of external force can overcome the wetting difficulty but has serial drawbacks. On the one hand, residual porosity could persist in microstructure of the composites because pores below a limiting size cannot be penetrated by a nonwetting metal [11]. On the other hand, the process needs a relatively complex apparatus and possesses some intrinsic limitations, e.g. melting point of the metals or dimensions of the samples. Pressureless infiltration method is not limited by these items and has thus been widely used [2,8,11]. However, this method demands a more wettability of the melt metals on the ceramics in the system. To improve the wettability, active elements such as Ti and Cr have been added to the metal [12,13].

Adding active elements into the system leads to a reactive wetting and has been greatly studied [14–18]. For the Cu/Al_2O_3

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nonwetting system, Ti element is usually used to improve the wettability [19–22]. It is suggested that interfacial energy change predominantly contribute to the wetting improvement [19]. Kritsalis et al. [20] deemed that a metallic-like oxide TiO which benefits the wetting was formed at metal-ceramic interface. However another reactant $Ti_3(Cu,Al)_3O$, which attribute to improve wetting, was reported in a CuAg–Ti/alumina system by Voytovych et al. [22].

All of the reported results suggest that mechanism of the improvement on wettability of Cu-Ti/Al_2O_3 system is not totally clear at present. Meanwhile nearly all the studies reported were carried out in high vacuum condition (10^{-4}–10^{-5} Pa) except a few in pure inert gas atmosphere (using oxygen getters). So the results are hardly to be used directly in industry practice because high vacuum means high difficulty and high cost. The vacuum parameter is important just because Ti is greatly intimate with oxygen. Change of the vacuum parameter could lead a different kinetic behavior of wetting and a different result of pressureless infiltration. In present study, both sessile drop test and pressureless infiltration were carried out in poor vacuum condition (1–10 Pa). Cu–Ti alloy and that prepared in situ with different configurations were used to investigate the kinetic behavior of wetting. The nominal concentration of Ti is 10% in weight in all case. It is expected to get some technical suggestions about pressureless infiltration for CuTi/Al_2O_3 system in poor vacuum condition, and also the characteristics of the interface chemistry and microstructure in this condition.

2. Experiment

2.1. Sessile drop test

Sessile drop tests were performed in an alumina tube furnace (type LOBA/i 1400-45-400-1, HTM Reetz GmbH). Drop image was automatically recorded by a camera. Diameter or contact angle was measured from image of the drop with an error within ± 0.2 mm or ± 1°.

The alumina substrates were prepared by slip casting and being sintered at 1500 °C (heating rate 10 °C/min) for 1 h. The slurry used was a dispersion of 25% (vol) of alumina (Almatis CT 3000 SG) in a water base system (dispersant: Dolapic CE64, 0.7 mg/m^2). The density and open porosity of the alumina sintered was 3.86 g/cm^3 and 0.36% respectively measured by Archimedes' method. The upper surface of the substrate to contact with metal drop was abraded and polished to a roughness of R_a: 4–5 μm. (measured by Dektak II A). Copper (purity 99.95%) and titanium (purity 99.2%) were used in the tests. Copper alloy with 10 wt% titanium (CuTi10) was prepared by arc melting the copper and titanium in argon atmosphere.

The tests were performed in four different initial metal configurations. The first two configurations consisted of a small piece of copper or the pre-alloyed copper (CuTi10) placed on an alumina substrate. The third configuration denoted as Ti/Cu/S in the paper consisted of a titanium piece placed on a copper piece, which was placed on the substrate. In the fourth configuration denoted as Cu/Ti/S, a titanium piece was placed between a copper piece and the alumina substrate. The initial weight of the metal sample was around 100 mg expect that in the pure Cu configuration (180 mg). For the last two configurations, the titanium copper ratio was 1:9 being equal to the overall composition of the pre-alloyed CuTi10.

All the tests were carried out in a vacuum condition of ~2 Pa. Each test was performed first at 1100 °C (heating rate 20 K/min) for 10 min, then up to 1300 °C with a rate of 10 K/min and holding for 10 min (except the test with pure copper, which was hold at 1100 °C for 30 min and then stopped).

2.2. Pressureless infiltration

The alumina ceramic foam for infiltration was prepared by replicating polyurethane foam. The polyurethane foams with a pore size of 1.65–2.15 mm were uniaxially compressed to a final porosity of 85%. The slurry was the same as that used for slip casting and stated above. The polymeric foam was firstly immersed in the slurry in vacuum (8 kPa), and then slip casted. After drying, the polymer part was burned out and the ceramic part was sintered in a heating cycle up to 1315 °C (heating rate: 2 K/min for 800–1050 °C; 10 K/min for 1050–1315 °C) and 2 h dwell time at 1315 °C. After sintering, the density and open porosity of the alumina foam were 2.67 g/cm^3 and 32% respectively measured by Archimedes' method.

The ceramic foam with a size of $\Phi 14 \times 6$ mm and pieces of the respective alloy or metal were placed into an alumina crucible. The pre-alloyed copper (CuTi10) or stacked copper block with titanium block (the configuration was same as Cu/Ti/S stated above) used for infiltration was around 8 g in each test, and the titanium content was always nominally 10% in weight. The crucible was surrounded by loosely packed Ti chips (from pure titanium), as shown in Fig. 1. Infiltration process was carried out in the vacuum of ~10 Pa and at the temperature 1300 °C for 1 or 2 h.

2.3. Interfacial chemistry and microstructure analyses

The interfacial chemistry and microstructure were studied by SEM (Scanning Electron Microscope) and EDAX (Electron Dispersive X-ray Analysis). Prior to the investigation, the specimens were sectioned, embedded in resin, polished and gold coated. The triple line region on sessile drop specimen was

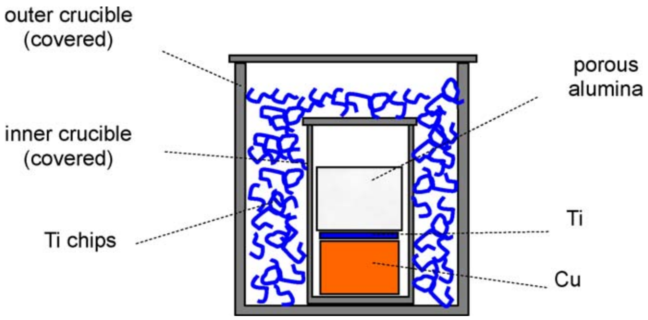

Fig. 1. Arrangement (schematic) of porous ceramic and metal for pressureless melt infiltration.

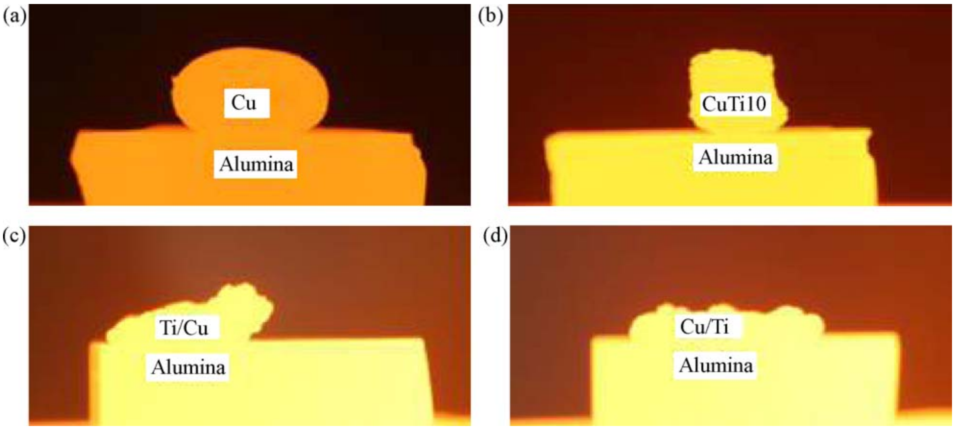

Fig. 2. Sessile drop tests under different conditions: (a) pure Cu on Al_2O_3 substrate at 1100 °C/30 min; (b) pre-alloyed CuTi10 on Al_2O_3 substrate at 1300 °C/10 min; (c) Ti and Cu on Al_2O_3 substrate, denoted as Ti/Cu/S at 1100 °C/9 min; (d) Cu and Ti on Al_2O_3 substrate, arranged as Cu/Ti/S at 1100 °C/3 min.

observed directly from the top of the substrate after removing the drop and subsequent coating with gold. The microstructure of the composites was also analyzed by XRD (X-ray diffraction).

3. Results

3.1. Wetting and spreading behaviors

The piece of the pure copper began to melt at about 1090 °C. After holding for 2.5 min at 1100 °C, a quasi-spherical drop was formed. The contact angle changed little at 1100 °C within 30 min and has a value about 138° (Fig. 2a). The piece of pre-alloy CuTi10 showed only a slight shape change due to melt in the interior part at 1010–1045 °C, and kept the shape with little change till 1300 °C (Fig. 2b). It is deemed that the surface of the alloy was oxidized and prevented the wetting between the CuTi10 and alumina. Fig. 2c and d show the situations of the configuration of Ti/Cu/S and Cu/Ti/S respectively. Even though having the same compositions (namely titanium has a content of 10% in the drop), the in-situ formed alloys in the Ti/Cu/S and Cu/Ti/S configurations showed a different behavior as that of the pre-alloy CuTi10. They began to spread even at 1100 °C instead of keeping a solid shape at 1300 °C.

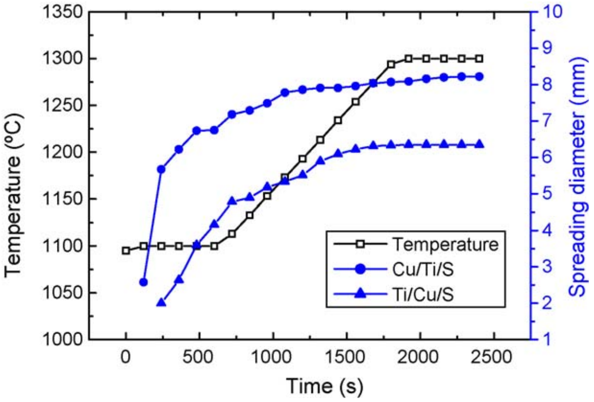

Fig. 3. Relationship between spreading diameter, temperature and time for Cu/Ti/S and Ti/Cu/S.

Fig. 3 shows evolutions of spreading with temperature and time for the Ti/Cu/S and Cu/Ti/S. For the Cu/Ti/S, it can be seen that the spreading speed was very fast within initial 4 min and a spreading diameter of 5.7 mm was obtained. In fact the primary diameter value of the liquid drop was lost due to the fast spreading (the primary diameter should be a little greater than 2 mm, as in the case of Ti/Cu/S). After the initial fast spreading, the spreading rate seemed kept at a constant and then gradually decreased. Finally the drop reached an equilibrium condition and the spreading stopped above the temperature 1270 °C. For the Ti/Cu/S, no very fast spreading existed at the initial stages. However the spreading evolution was very similar to that of the Cu/Ti/S, i.e. constant spreading and speed-reduced period.

It should be point out that the oxidized upper surface of the drop did not melt or dissolve in the drop during all the process (Fig. 2c and d). It is sure that the solid upper surfaces have influenced the spreading data obtained.

3.2. Pressureless infiltration

Metal infiltration into the alumina foam did not take place with the pre-alloyed copper CuTi10 at 1300 °C. But it did with stacked Cu block and Ti block in the arrangement Cu/Ti/Al_2O_3. This agreed with the results of the sessile drop test. Fig. 4a and b shows the microstructure of the samples with a holding time of 1 h and 2 h at 1300 °C respectively. There exist narrow channels (denoted by arrows in Fig. 4a) which were not infiltrated in the samples with a holding time of 1 h. And this situation can be greatly improved with a holding time of 2 h.

3.3. Interface chemistry and microstructure

SEM analysis showed that a two-layered structure existed at the interface of ceramic and alloy in samples from sessile drop tests and infiltrated composite, as shown in Fig. 5. Directly adjacent to the ceramic, a dark grey layer R existed. Between the R layer and the alloy matrix M, there existed a medium grey layer T.

Table 1 shows the typical results of the three kind of area in the microstructure of the sessile drop samples and the infiltrated

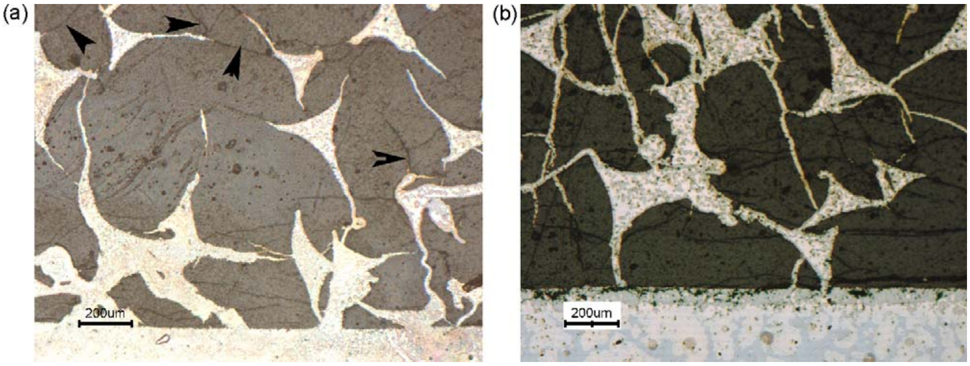

Fig. 4. Microstructure of the infiltrated samples at 1300 °C: (a) holding time 1 h (arrows show narrow pore channels); (b) holding time 2 h.

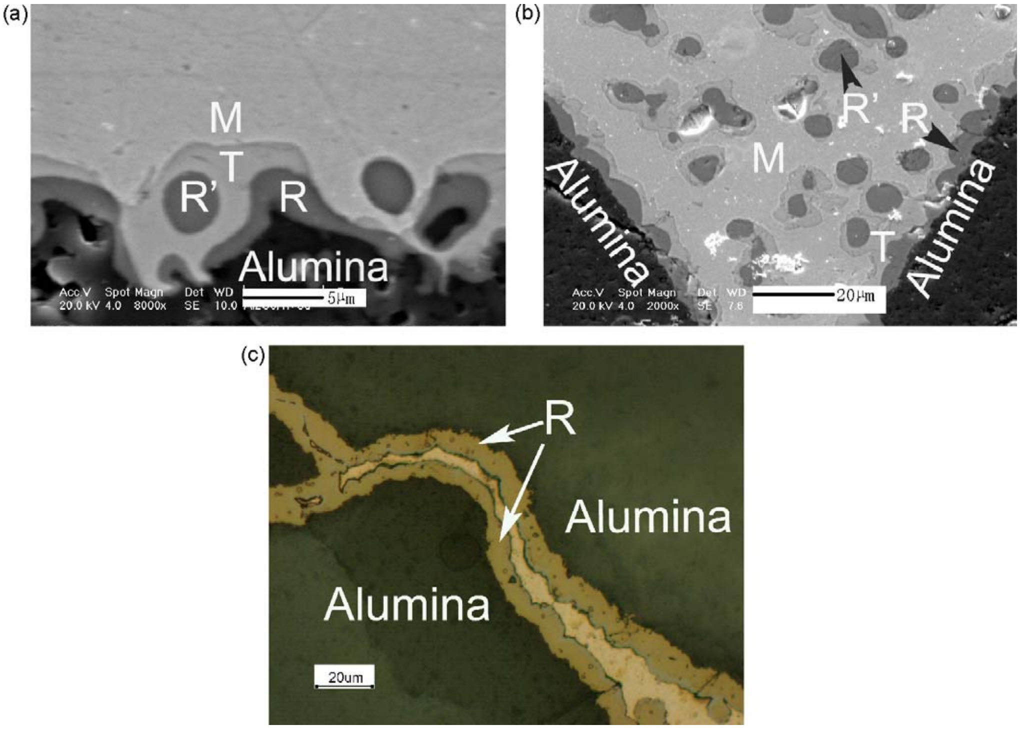

Fig. 5. Microstructure at ceramic-metal interface for samples after: (a) sessile drop test in the Cu/Ti/S configuration; (b) infiltration test; (c) infiltration test, showing an infiltrated small channel. R and R′ denote reaction layer, T transition layer and M metal/alloy matrix.

Table 1
EDAX results.

Samples	Area	Element (at%)				Element ratio		
		Ti	Cu	Al	O	O:(Ti + Cu + Al)	O:Ti	Ti:(Cu + Al):O
Ti/Cu/S	R	31.8	9.84	5.73	52.64	1.1	1.66	2:1:3.3
	T	30.13	28.61	2.16	39.1	–	–	1:1.02:1.3
	M	2.88	74.88	1.34	20.9	–	–	–
Cu/Ti/S	R	33.83	4.06	6.42	55.69	1.25	1.65	3.23:1:5.31
	T	27.42	47.87	2.74	21.97	–	–	1:1.85:0.8
	M	1.68	82.27	3.08	12.97	–	–	–
Composites	R	38.27	1.28	1.73	58.72	1.43	1.53	–
	T	32.24	29.78	6.7	31.28	–	–	1:1.13:0.97
	M	1.85	71.39	8.13	18.63	–	–	–

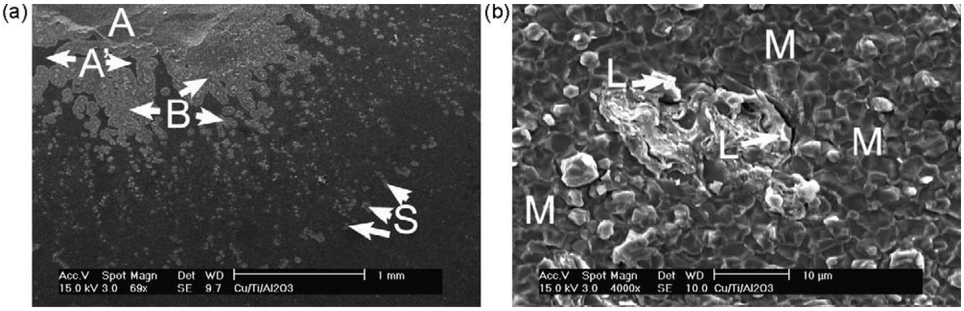

Fig. 6. SEM showing the triple line region on the alumina substrate (sessile drop test specimen in the configuration Cu/Ti/S), (a) low magnification; (b) high magnification for B area in (a).

composite by EDAX. Several points were tested for each kind of area in each sample and little difference was found. The results listed are individual ones but not the average value for each area in every test samples. Some calculation results for atoms ratio are also listed in Table 1 and will be discussed in the later part of the paper.

From Table 1, it can be seen that the distribution of the elements have a same tendency for all samples, namely Ti is mainly distributed in area R, Cu in area M and both of the Ti and Cu have the intergraded values in area T. However, the concentrations of the elements in a same kind of area are different for different samples which experienced different test (e.g. different configuration, different temperature and holding time).

It is noticed that the dark area existed not only at the border of the alumina but also in the center of the border region for the sessile drop test sample (R′ in Fig. 5a) or in the center part of the alloy for the composite sample (R ′in Fig. 5b). The EDAX results for the dark area R′ showed little difference with that in Table 1 for R area in the corresponding samples. Thus spots R′ are here considered to belong to the R layer but be isolated due to sectioning of the samples.

Table 2
EDAX results of the triple line region on sample Cu/Ti/S.

Area	Element (at%)				Element ratio
	Ti	Cu	Al	O	O:Ti
A	0.46	0	39.03	60.5	–
A′	0.62	0	46.67	52.71	–
S	30.76	0.57	2.79	65.88	2:1
M	48.30	2.69	0.40	48.61	1:1
L	36.78	6.73	0.23	56.25	

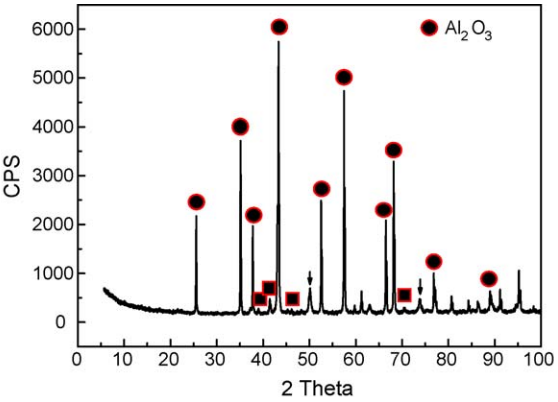

Fig. 7. XRD spectrum of the composite sample. The peaks denoted (■) may refer to Ti_3Cu_3O. Arrows are attributed to Cu despite of an unexpectedly big shift of 0.4° which might be due to dissolved oxygen.

The triple line region on the Cu/Ti/S sessile drop specimen was studied by SEM observing from top of the substrate, as shown in Fig. 6. The alloy drop was adhesive to alumina substrate strongly and a fracture took place in the substrate during the preparation process of the specimen. So a pit was formed on the surface, and denoted as ‘A’ in Fig. 6a. It can be seen that many ‘island area’ exist in the triple line region. The island areas show a radial characteristic. And the size of them decrease with the increase of the distance from the center (i.e. area B larger than area S in Fig. 6a). It is clear that the small island area was forming, growing and connecting each other in the spreading process. A higher magnification for area B is shown in Fig. 6b. It can be seen that this kind of area is mainly composed of small pits connected (denoted as M in Fig. 6b) and a little of light sticks (denoted as L in Fig. 6b) on the pits. The morphology of the area S in high magnification has shown a similar characteristic as M. The EDAX results for the area A, A′, S, M and L in Fig. 6 are listed in Table 2 (using the same test method as that for Table 1). It is obviously that the area A and A′ are alumina. The area S and M are titanium oxide but have different O:Ti ratio. Considering the L being thin, the EDAX result for them could be affected by M. It is thought that L is the alloy remained on M because of the Cu content.

XRD result for the composite is shown in Fig. 7. The diffraction of the Al_2O_3 is clearly but the others are too weak to be identified with certainty. The peaks denoted as‘■’ is probably referred to Ti_3Cu_3O. And that denoted by arrows should present the copper.

4. Discussion

4.1. Spreading kinetics for different configuration in poor vacuum condition

Ti is greatly intimate with oxygen. The tendency of Ti-containing alloy to oxidize is related to the concentration of Ti. The lower is the concentration of Ti in Cu–Ti alloy, the more tendency of the Ti to be oxidized [20]. To achieve the wetting or spreading in poor vacuum condition, it is the key that the reactive Ti has an opportunity to react with the alumina substrate before being oxidized. For the pre-alloyed CuTi10, the surface was quickly oxidized with temperature increasing. The melting in the interior part of the alloy led to a shape change because the oxidized surface layer was thin at 1010–1045 °C. The thickness and strength of the surface layer increased with the time and temperature increasing. As a result, wetting or spreading did not take place even at 1300 °C. However, the stacked Ti/Cu and Cu/Ti showed a great spreading on alumina at 1100 °C although having the same nominal composition with the pre-alloy CuTi10. It is thought that the stacked Cu and Ti block first melt at their interface. Second the Cu melted quickly with the temperature increase due to its relative low melting point. Then a mass of liquid Cu dissolved the Ti quickly. As soon as the Ti dissolved, localized Ti-containing alloys were formed. Because of being concentrated, only a part of the active Ti reacted with oxygen and to form oxidized surface layer that floated on the upper part of the liquid. The remains had the opportunities to act with alumina and led to the spontaneous spreading.

The spreading evolutions are similar for the two configurations and also similar to that obtained in high vacuum condition by Drevet et al. [23] and Nomura et al. [24]. The spreading process is composed of two stages. The first stage has a higher spreading rate than the second stage. It is deemed that transport of Ti from liquid to the triple line and, conversely, of Al from the triple line to the bulk liquid, was the rate limiting process in spreading. And the diffusion is continuously reduced during the spreading process [23].

However it is noticed that some differences exist in the spreading kinetics between the two configurations (Fig. 3). The differences are in (1) acting triggering time (T_t) between the drop and alumina substrate; (2) initial spreading rate; (3) the final spreading diameter (D_f). The differences can be related to the special Cu/Ti/S configuration and considered as follows:

In present study, as soon as the melting and dissolving process take place, the Ti will diffuse in the bulk liquid. Being at different position, the diffusion directions of the Ti in bulk liquid of Cu/Ti/S and Ti/Cu/S are different, namely to depart from the substrate for the former and to go to the substrate for the later. For the Cu/Ti/S configuration, the Ti piece contact with the substrate. When being dissolved, a part of them reacted with the substrate immediately. So this configuration had relative short T_t. For Ti/Cu/S configuration, the Cu piece existed between the Ti piece and the substrate. The dissolved Ti need time to diffuse to the substrate surface. So this configuration had a long T_t.

When the spreading was triggered, the concentrated Ti at the interface for the Cu/Ti/S gave a sufficient quantity to support to spreading. The Ti interacted with the substrate in suit, and even no diffusion was needed. This led to a very fast spreading in a short time. This initial stage was caused by special configuration (like a Ti coating on the substrate) and could not be considered as a normal spreading in traditional sense. As soon as the Ti that contact with the substrate was consumed, the spreading process was controlled by diffusion process as stated above.

During the diffusion process, a part of the active Ti reacted with oxygen and to form oxidized surface layer. The layer floated on the upper part of the liquid and limited the liquid to flow. The oxidation reduced the efficient quantity (Q_{eff}) of Ti to contribute to the spreading. It is easy to understand that the Q_{eff} for the Ti/Cu/S is smaller than that for the Cu/Ti/S. This is because more Ti was consumed during relative long distance to diffuse. This can explain the final spreading diameter in the Ti/Cu/S is smaller than that in the Cu/Ti/S although the drops in the two configurations have the same quantities and nominal compositions.

4.2. Interfacial chemistry and microstructure

Study on interfacial chemistry is important to understand the wetting of the alloy to the substrate. However different results have been reported [20–22,25,26]. Kritsalis et al. [20] firstly reported a metallic-like oxide TiO that benefits the wetting. Then Derby et al. [25] suggested that a Ti_4Cu_2O layer existed between the alumina and a Ti_3Cu_3O compound layer. Voytovych et al. [22] pointed out that the Ti_4Cu_2O did not modify the wetting, but the Ti_3Cu_3O did in a CuAg–Ti/Al_2O_3 system. Wan et al. [27] reported that the reactant was Ti_2O_3 in Ni–Ti/Al_2O_3 system, TiO_{1+x} in (Ni–Fe–Cr)–Ti/Al_2O_3 system and TiO_{1-x} in (Ni–Fe–Cr)–Si–Ti/Al_2O_3 system. The different results suggest that the interfacial chemistry is greatly correlated to the alloy system and test condition. The dependence of the reactant on the system and test condition is mainly because the interactions between Ti and O are complex and a range of compounds are possible, having a considerable range of stoichiometry with anion: cation ratios. Considering this situation, the assessment of interfacial chemistry and wettability in present study is addressed.

It is known that the composition analyzed by EDAX is half-quantities. But it can still have some degrees of certainty to compare the composition between a series of samples in the same condition (same tester and same gold coating) by the EDAX. However the EDAX results for the reactant layer between the alloy and alumina in present study showed distinctive differences in the different samples (Tables 1 and 2). It is considered here that the different samples correspond to different kinetic conditions and present different stages in the process of reaction and diffusion of the elements. It is clear that the composite sample is in a relative equilibrium condition being endured a higher temperature and a longer dwelling time. By contrast, the triple line region on the sample of sessile drop test is responsible to the initial stage of the interaction. For different interaction and diffusion stages, the evolution of the reactant should be considered. What the evolution of the reactant can take place in present study is because the possibility of the considerable range of stoichiometry with O:Ti ratio and the poor vacuum condition.

The evolution view can be supported by the elements distribution in each area for different samples. It was reported that the oxygen released from the dissolution of alumina is more likely to react with the titanium present at the interface than being dissolved in liquid copper, while aluminum can be

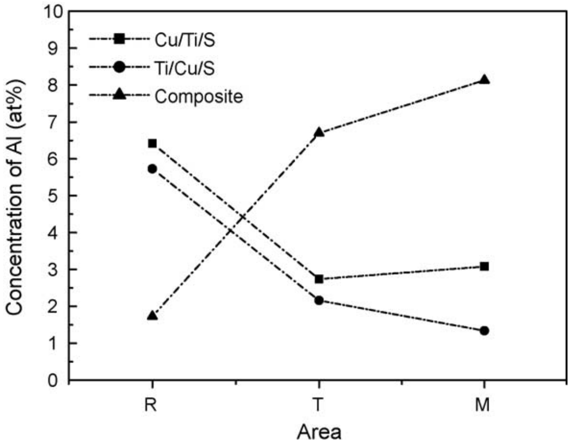

Fig. 8. Al concentration in different areas of the composite and sessile drop samples.

expected to go into solution in copper [26]. From Table 1, it can be seen that Ti and O is more concentrated in area R for the composite sample than that for the Ti/Cu/S and Cu/Ti/S sessile drop samples, while Cu and Al in area M. This can be more clearly seen from Fig. 8 which shows the concentration of Al in different areas in three samples.

The Ti oxides with a high degree of oxidation, such as Ti_3O_5 or Ti_5O_9 led to a wetting angle higher than 90° [28]. So it seems that the reactant, which can be formed in area R on the base of the composition listed in Table 1, might contradict good wetting in the samples. However the apparent contravention can be explained by considering the evolution of the composition of the reactant. It can be concluded with the EDAX results as follows: the initial reactant was probably TiO (M in Fig. 6b). This reactant should benefit to wettability of the alloy to the alumina substrate. This suggestion agrees with that obtained by Kritsalis et al. in high vacuum condition [20]. Then the reactant evolve to a oxide with a high O:Ti ratio in poor vacuum condition. It is also possible for the evolved oxide to absorb other cation (e.g. Cu cation) and form complex compound (e.g. Ti_xCu_yO). In fact the X-ray diffraction test has shown a possibility of the formation of a Ti_3Cu_3O compound (Fig. 7), but the formation is uncertain because of the reflection intensity being too small. With a longer time, the composition of the reactant layer R could show a more higher O:Ti ratio as the results listed in Table 1 for the composites.

It should be point out, the S areas in Fig. 6a has shown a higher O:Ti ratio (Table 2) than the B areas even though they present a more early stage of the reactions. It is thought that this result is because of the S areas being exposed to the atmosphere at high temperature and not protected by the alloy. So they can be easily further oxidized in poor vacuum condition.

The O:Ti ratio in area R for the composite sample suggests that an oxide Ti_2O_3 might have been formed. The purple color of the reactant is in agreement with this composition and also with Espie et al. [19]. However the formation could not be proved by XRD result in Fig. 7. The structure of the area T could not be proved by XRD because no information of the Ti–(Cu,Al)–O compounds which have an atoms ratio of 1:1:1 exist in database. Some diffraction peaks in Fig. 7 could not be identified while some expected phase, e.g. copper oxides did not appeared. The position of the reflection peaks of Cu (denoted by arrows in Fig. 7.) shifted a lot (about 0.4°). Usually peak-shift could be due to solute atoms and residual stress etc. It is no doubt that the Cu should dissolved the oxygen atoms in present test condition. However the 0.4° shift is unexpectedly greater.

5. Conclusions

1. In poor vacuum condition (1–10 Pa), Cu–10Ti alloy could not wet and pressureless infiltrate porous alumina due to formation of a surface oxide scale. A sufficient way is proved to solve the problem by using stacked pure copper and pure titanium. Using this method and using Ti chips as oxygen getter around the sample, a $CuTi10/Al_2O_3$ composite has been formed by pressureless infiltration at 1300 °C.
2. The initial reactant, which benefits the wettability, between the Ti-containing alloy and the alumina substrate could be evolved to the one with a higher O:Ti ratio due to poor vacuum condition, higher temperature and longer holding time.

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