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Corrosion development between liquid gallium and four typical metal substrates used in chip cooling device

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Abstract The limitation of the currently available thermal management method has put an ever serious challenge for computer chip designers. A liquid metal with low melting point around room temperature was recently identified as a powerful coolant of driving heat away because of its superior thermo-physical properties and the unique ability to be driven efficiently by a completely silent electromagnetic pump. However, the adoption of gallium, one of the best candidates as metal coolant so far, may cause serious corrosion to the structure materials and subsequently affect the performance or even dangerous running of the cooling system. To address this emerging critical issue, here the compatibility of gallium with four typical metal substrates (6063 Aluminum-Alloy, T2 Copper-Alloy, Anodic Coloring 6063 Aluminum-Alloy and 1Cr18Ni9 Stainless Steel) was comprehensively investigated in order to better understand the corrosion mechanisms and help find out the most suitable structure material for making a liquid metal cooling device. To grasp in detail the dynamic corrosion behavior, an image acquisition and contrasting method was developed. Moreover, corrosion morphology analyses were performed by means of scanning electron microscope (SEM). The chemical compositions of the corroded layers were evaluated using energy dispersive spectrometry (EDS). According to the experiments, it was found that, the corrosion of the 6063 Aluminum-Alloy was rather evident and serious under the temperature range for chip cooling. The loose corrosion product will not only have no protection for the inner substrate, but also accelerate the corrosion process. Compared to the 6063 Aluminum-Alloy, T2 Copper-Alloy showed a slow and general corrosion, but part of the corrosion product can shed from the substrate, which will accelerate corrosion action and may block the flowing channel. Anodic Coloring 6063 Aluminum-Alloy and 1Cr18Ni9 Stainless Steel were found to have excellent corrosion resistance among these four specimens. No evident corrosion phenomena were found under the examination of SEM and EDS when exposed for 30 days at the temperature of 60°C, which suggests their suitability as structure materials for the flow of liquid metal. However, as for the Anodic Coloring 6063 Aluminum-Alloy, surface treatment and protection are of vital importance. The present study is of significance for making a liquid metal chip cooling device which can actually be used in the future computer industry.

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1 Introduction

Thermal management for efficient heat dissipation is of crucial importance in developing highly compacted processors and MEMS devices. At present, individual micro–nano scale electronic devices can generate heat fluxes exceeding thousands of watts per centimeter squared in a very small area [1], which severely degrades the electronic chips' performance and reliability through, for example, thermal shock, electro migration or material failure [2]. Thus, removal of heat generated in the electronic component stays as one of the major concerns in designing computer systems for many years [3]. The application of conventional thermal management methods, such as fan-heat sink [4] and liquid

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cooling [3], may encounter trouble with the increasing demand for electronics cooling. And some novel and advanced methods, such as advanced heat pipe-heat sink [5, 6], novel thermoelectric microcooler [7], and carbon nanotube microfin structure [8], etc., which do have better performance in heat dissipation, were proposed. But these methods may involve complex design process, reliability and cost issues, which are the main obstacles for their commercialization and utilization.

Noticing that a liquid metal with low melting point around room temperature has a much higher thermal conductivity than that of common liquids, such as water, oil and lots of cooling fluid, Liu and Zhou [9] proposed for the first time to use liquid metal as an ideal coolant for the thermal management of computer chips, which was now proved as a powerful way in driving heat away, owing to its high efficiency, reliability, low energy consumption, relatively acceptable cost and easy to fabricate merits [10, 11]. The liquid metal owns superior thermo-physical properties and the ability to be driven efficiently by a silent, non-moving pump. So far, the best candidates of liquid metals are gallium and its alloys because of their unique property of low melting point, high thermal conductivity, non-flammable and non-toxic activity, low vapor pressure, high boiling point, etc. [12]. However, several crucial scientific problems were also raised at the same time, which may preclude liquid metal from being actually used in the computer industry if they are not well resolved. One of such typical issues lies in that gallium tends to cause serious corrosion to aluminum-alloy which was one of the most conventional cooling metals. Clearly, such adverse effect would greatly affect the commercialization and utilization of liquid metal chip cooling systems.

In fact, corrosion phenomenon between liquid gallium and some structure materials has been addressed before. Luebbers and Chopra [13] studied the corrosion behavior of liquid gallium to various structure materials used in the atomic reactor and pointed out that iron, nickel and chromium reacted quickly with gallium, while the Nb-5Mo-1Zr alloy had a better corrosion resistance to gallium. Narh et al. [14] tested the corrosion behavior between gallium and P–V–T system materials, and found that the 316 L stainless steel was slightly corroded while the other four thermoplastics were not affected. However, under the special working temperature range of a computer, which is much lower than that in an atomic reactor, and for the specific structure materials used in a liquid metal cooling system, few experimental data are available so far. This paper is dedicated to investigate the compatibility of gallium with four conventional and low-cost metal substrates that could be used in the chip cooling system. It will help clarify an ideal, economical and feasible structural material and thus promote further utilization of liquid metal chip cooling system in many related industries.

2 Experimental set up

2.1 Experimental materials

Generally speaking, aluminum-alloy and copper-alloy are usually adopted as cooling materials in the chip cooling system. In this experiment, the 6063 Aluminum-Alloy and the T2 Copper-Alloy that have been widely used were selected as research materials. Meanwhile, the Anodic Coloring 6063 Aluminum-Alloy, as the most economical and practical surface treatment material, and the 1Cr18Ni9 Stainless Steel with good heat dissipation performance and cost effective property were also studied in the experiment. The liquid gallium tested in this work was commercially available with a purity of 99.99 percent.

2.2 Experimental platform

According to Fig. 1, the entire experimental set up is composed of three parts: constant temperature-controlled circuit, corrosion platform and the image acquisition module.

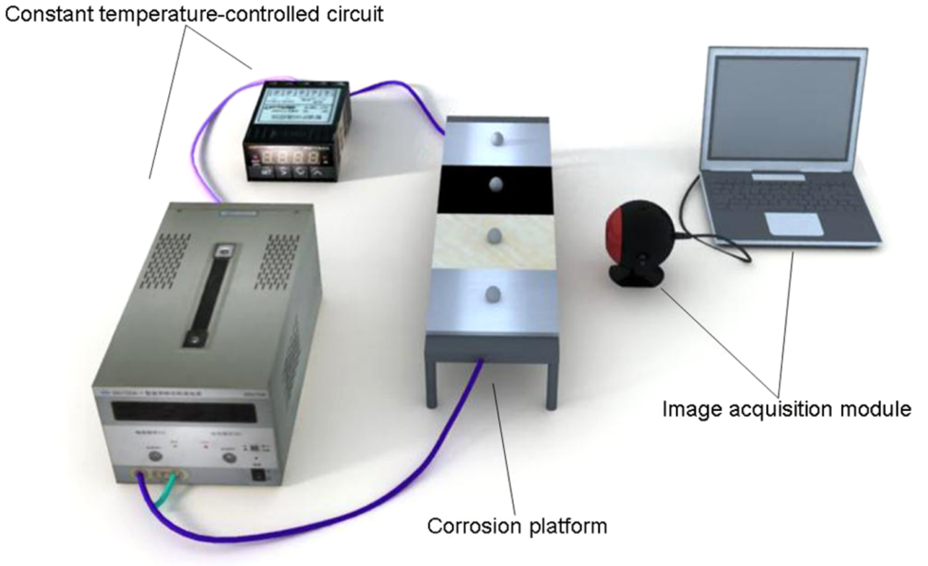
The constant temperature-controlled circuit uses PID Controller to take close-loop and negative feedback control of the temperature for corrosion platform, and the temperature control accuracy is within ±0.5°C. Its components include an XSC5 PID controller, DH1720A-1 regulated DC power supply, T-typed thermocouple, and a TEC1-12706 thermoelectric cooler. The corrosion platform can be of different sizes according to specific experiment demands as well as the refrigerating/heating capacity of the thermoelectric cooler. The image acquisition module includes a camera and a portable computer. Image acquisition software was developed to take pictures of the corrosion image via a specific frequency. The quantitative description of corrosion trends of four metal substrates was made by contrasting these images collected in a fixed location.

2.3 Experimental method

All these four kinds of metal substrates were cut to 45 mm × 25 mm × 1 mm in size, and were polished mechanically by waterproof abrasive paper to 300# except the Anodic Coloring 6063 Aluminum-Alloy, to reduce the roughness of the original surface of the specimens. After that, all were cleaned with cotton swab in soap water, and washed by clear water, then dried with filter paper.

During the experiment, the corrosion trends of the four metal substrates in the severe temperature of 120°C were studied through a novel and effective image contrast method at first. Subsequently, the corrosion experiments on the T2 Copper-Alloy, Anodic Coloring 6063 Aluminum-Alloy, and the 1Cr18Ni9 Stainless Steel were conducted for 30 days continuously with the temperature controlled at 60 ± 0.5°C.

Fig. 1 A scheme of the experimental platform



Then, the corroded samples were transversely cut, and the cross-sections were polished to 1500#, cleaned and dried. At last, morphology of the corroded layers was observed by means of scanning electron microscope (SEM) (S-4300, Hitachi, Ltd., Japan), and the element distribution in the corroded area was evaluated using energy dispersive spectrometry (EDS) (6853-H, HORIBA, Ltd., Japan), so as to verify which kind of the specimen had better corrosion resistance with gallium and could serve well as an ideal, economical and feasible structural material for the liquid metal chip cooling system.

3 Results

3.1 Corrosion trends of the four metal substrates with liquid gallium at 120°C

In order to grasp in detail the dynamic corrosion behavior and reduce material consumption, an image acquisition and contrast method was developed to record quantitatively the corrosion trends of four metal substrates. As shown is Fig. 1, a camera was placed in a fixed position to take pictures of the corrosion image via a specific frequency. With the continuous development of the corrosion, gallium ball would gradually immerge into the substrate. Therefore, the area of gallium ball in the captured images would gradually become smaller. By contrasting these images with different areas of the gallium ball, the corrosion trend could be quantitatively well described.

Figure 2 gives out the corrosion trends for four types of metal substrates under static contact with the liquid gallium at 120°C. In this picture, the longitudinal corrosion ratio $\eta(t)$ is defined as:

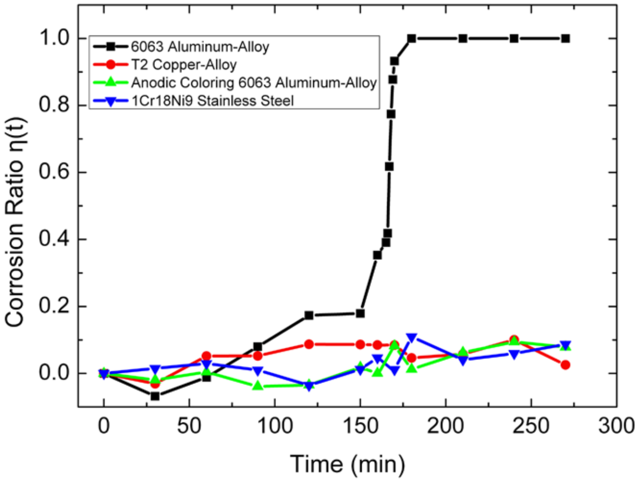


Fig. 2 Corrosion trends of four metal substrates with liquid gallium at 120°C

$$\eta(t) = \frac{S_0^{3/2} - S(t)^{3/2}}{S_0^{3/2}}, \tag{1}$$

where $S(t)$ is the area of liquid gallium ball when camera shoots at moment t; S_0 is the initial area of the gallium ball before corrosion, assuming that the scale relation between volume and area is 3:2. Furthermore, the area of gallium ball in the calculation is represented by the region pixels in the acquired image. From Fig. 2, it can be noticed that gallium has caused obvious corrosion to the 6063 Aluminum-Alloy. A severe corrosion happened after the first 150 min, and the corrosion ratio increased from 0.2 to 1.0 in about 30 min, which meant that nearly 80% of the gallium ball infiltrated into the substrate in the maximum-slope curve seg-

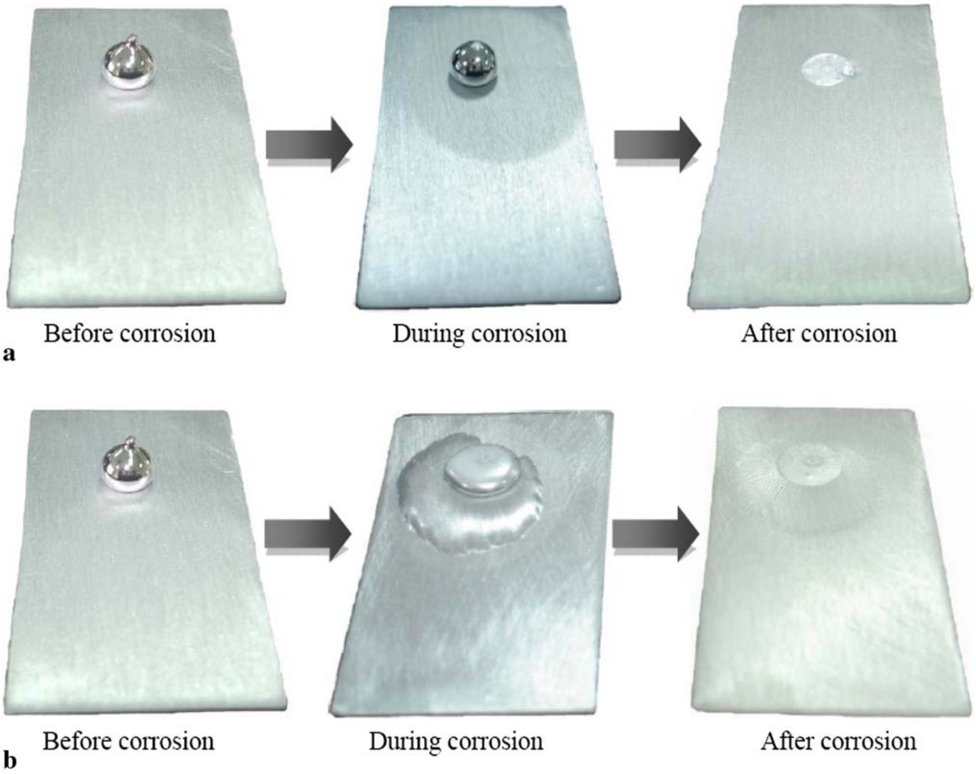


Fig. 3 Corrosion developments between the 6063 Aluminum-Alloy and liquid gallium: **a** no disturbance is exerted on gallium ball; **b** small disturbance is exerted on gallium ball

ment, and eventually liquid gallium fully immerged into the 6063 Aluminum-Alloy substrate. By contrasting to the severe corrosion of the 6063 Aluminum-Alloy, it was observed from the acquired image that the T2 Copper-Alloy, Anodic Coloring 6063 Aluminum-Alloy, and the 1Cr18Ni9 Stainless Steel had no such evident corrosion signs in nearly five hours at 120°C. Curve fluctuations of these three substrates in Fig. 2 were due to the limited resolution of the camera. If adopting a camera with higher resolution, curves would be even more precise and close to being horizontal.

Presented in Fig. 3 is the comparison of static and dynamic corrosion behavior for the 6063 Aluminum-Alloy at 120°C. It is clear that a suborbicular corrosion shadow emerged on the 6063 Aluminum-Alloy substrate during static corrosion, and spread around over time. During the dynamic corrosion process with small disturbance, which was performed by using a glass rod to gently shake the gallium ball on the 6063 Aluminum-Alloy substrate, liquid gallium would upswell from the flanking corrosion area, implying that infiltration action of liquid gallium on the 6063 Aluminum-Alloy was rather strong. Moreover, the flowing liquid gallium would cause severe scouring action and driving effect to corrosion product. Thus, due to the comprehensive actions of static and dynamic corrosion, the 6063 Aluminum-Alloy could not be used as structure material in the liquid metal based chip cooling device. However, as to the T2 Copper-Alloy, Anodic Coloring 6063 Aluminum-Alloy, and the 1Cr18Ni9 Stainless Steel, no similar corrosion signs were observed. Therefore, long-term corrosion tests of these three substrates were needed to confirm whether they could serve as suitable and economic structure materials in the liquid metal cooling.

3.2 SEM/EDS observation and analysis

3.2.1 SEM analysis of corroded surface

In the experiment, the 6063 Aluminum-Alloy experienced 5 hours of corrosion under 120°C, while the T2 Copper-Alloy, Anodic Coloring 6063 Aluminum-Alloy, and the 1Cr18Ni9 Stainless Steel were exposed for 30 days continuously at the controlled temperature of 60 ± 0.5°C. Figure 4 shows the corroded surface morphology of the 6063 Aluminum-Alloy and the T2 Copper-Alloy.

From Fig. 4(a), it is clear that gallium caused serious corrosion to the 6063 Aluminum-Alloy and a corrosion hole appeared in the corrosion area. The area which had no direct contact with gallium was named corrosion diffusion area with fewer processes, and was much smoother than the original corrosion-free surface; which means that corrosion product of the 6063 Aluminum-Alloy is relatively loose. On the one hand, it promotes gallium diffusion to form corrosion diffusion area; on the other hand, loose corrosion product is of low intensity, making the surface easy to be polished smoother with a cotton swab when washing.

Figure 4(b) indicates that the corrosion area of the T2 Copper-Alloy surface was evident, presenting rugged and

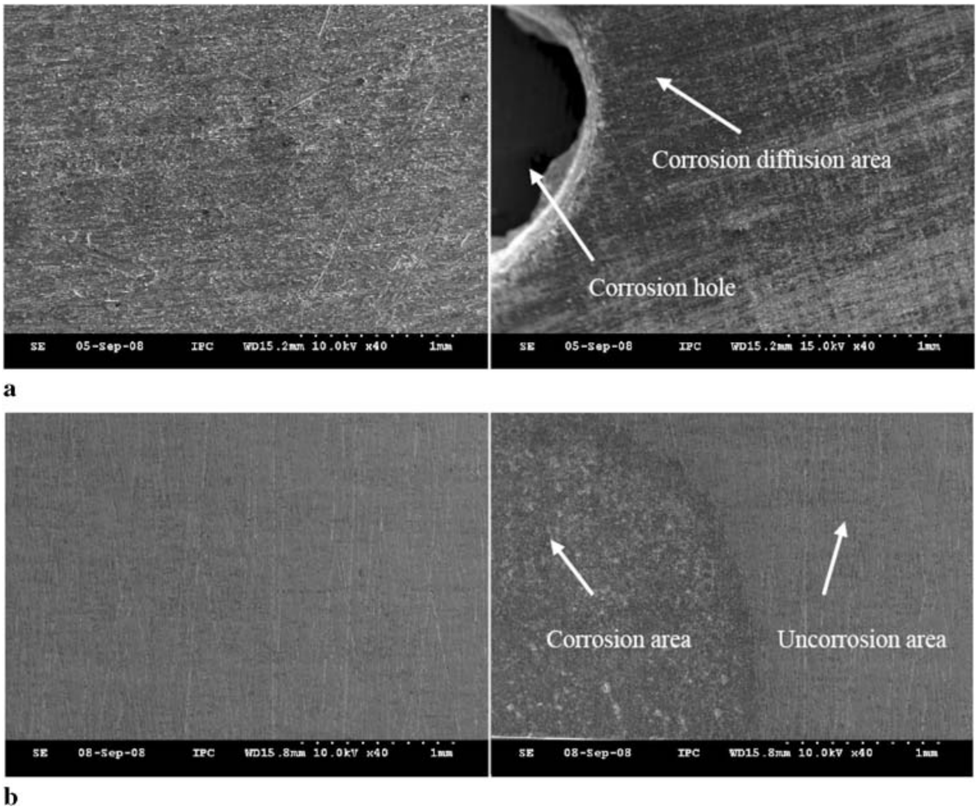


Fig. 4 Morphology comparison of corrosion-free/corroded surface of the 6063 Aluminum-Alloy (**a**) and of the T2 Copper-Alloy (**b**)

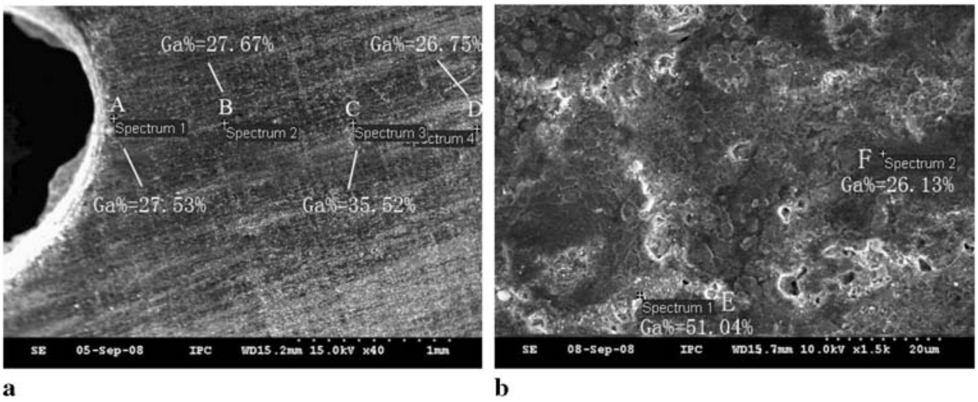


Fig. 5 EDS analysis of corroded surface for the 6063 Aluminum-Alloy: **a** near the gallium corrosion pits; **b** away from the gallium corrosion pits with collection points of different degrees of brightness

rough characters, but having no obvious cracks or defects. Meanwhile, the polished linear textures of the corrosion-free area no longer existed in the corrosion area, demonstrating that corrosion process first happened between gallium and the processes on the T2 Copper-Alloy surface, followed by the uniform corrosion. As to the Anodic Coloring 6063 Aluminum-Alloy and the 1Cr18Ni9 Stainless Steel, no evident corrosion was found under the examination of SEM after cleaning and drying.

3.3 EDS analysis of corroded surface

Figure 5 gives the EDS analysis results of corrosion surface for the 6063 Aluminum-Alloy. Zone (a) was near the gallium corrosion pit, and the layout of collecting points was from near the corrosion pit to points further away. Zone (b) was away from the gallium corrosion pit, and collection points took different degrees of brightness.

It is clear from Fig. 5(a) that the molar concentrations of gallium did not vary a lot at these four collecting points, and the concentrations were about 25–35%, showing no trend of declining as the distance from corrosion pit increased. In Fig. 5(b), points E and F were away from gallium corrosion pit. After amplifying the corrosion area 1,500 times under SEM and comparing EDS analysis results of areas with different brightness, it was found that brighter area (point E) demonstrated gallium enrichment phenomenon. By contrasting Figs. 5(a) and 5(b), the difference of molar

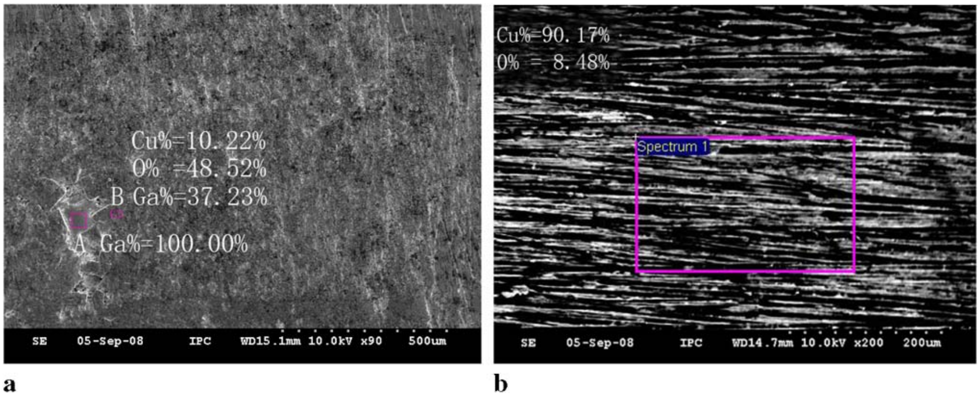


Fig. 6 EDS analysis of the T2 Copper-Alloy surface: **a** corrosion surface, **b** corrosion-free surface

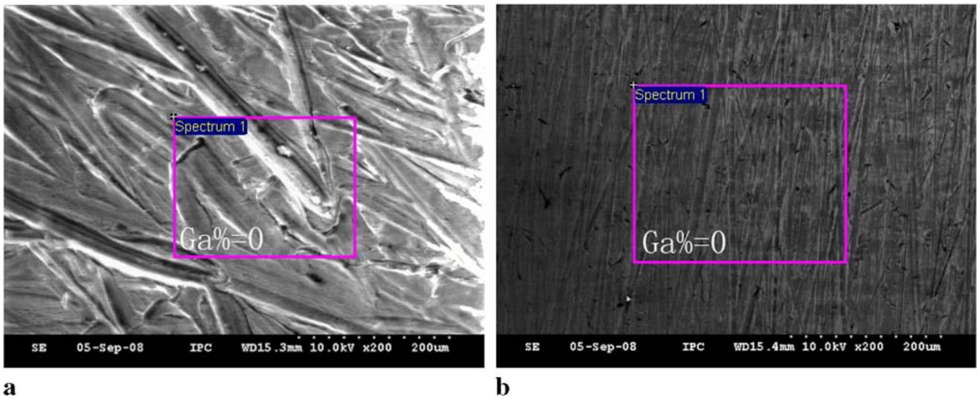


Fig. 7 EDS analysis of a corroded surface for the Anodic Coloring 6063 Aluminum-Alloy (**a**), and for the 1Cr18Ni9 Stainless Steel (**b**)

Table 1 Molar concentration contrast of key elements in corrosion-free/corrosion diffusion area of the 6063 Aluminum-Alloy

Molar concentration of key elements	Al%	Ga%	O%
Corrosion-free area	92.40%	0%	6.46%
Corrosion diffusion area	44.66%	27.53%	27.59%

concentration of gallium between areas near the corrosion pit (average of ABCD points) and away from it (average of EF points) was small. This suggests that gallium has strong infiltration capability in the 6063 Aluminum-Alloy. In the corrosion diffusion area, distribution of gallium is relatively uniform on a large scale and does not show the phenomenon that gallium content declines as the distance from corrosion pit increases. Nevertheless, it is possible that there would be uneven gallium distribution in a small-scale area.

Table 1 gives the molar concentration contrast of key elements between the 6063 Aluminum-Alloy's corrosion-free area and corrosion diffusion area. One could see that in the corrosion diffusion area, there was significant reduction in aluminum content, while gallium and oxygen content increased greatly despite limited accuracy of EDS, showing the fact that the corrosion between gallium and the 6063 Aluminum-Alloy mainly resulted from the dissolution or reaction between gallium and aluminum, and the increase of oxygen content was due to the reason that with loose corrosion product, oxygen got easier infiltration and would react with aluminum and gallium at a higher temperature.

Figure 6 is the EDS analysis of the corrosion surface for the T2 Copper-Alloy. We see from Fig. 6(a) that there was a gallium covered area (area A) and a corrosion product area (area B) on the corrosion surface. The EDS analysis showed that gallium molar concentration was 37.23% in corrosion product area (area B), while in gallium covered area (area A) the concentration was 100.00%. It indicated that liquid gallium had good compatibility with the corrosion layer, thus part of the liquid gallium could closely attach to the corrosion layer. After comparing Fig. 6(a) with 6(b), it was apparent that in the corrosion product area, there was significant reduction in copper content, while gallium and oxygen content increased a lot. This explained the fact that the corrosion behavior between gallium and the T2 Copper-Alloy mainly resulted from the dissolution or reaction between gallium and copper, and the increase of oxygen content in corrosion areas was due to the fact that the exposed copper and gallium were oxidized after corrosion.

Figure 7 shows the EDS analysis results of the corrosion areas for the Anodic Coloring 6063 Aluminum-Alloy and the 1Cr18Ni9 Stainless Steel. It can be seen from Fig. 7 that no gallium was detected on the corrosion surfaces of the Anodic Coloring 6063 Aluminum-Alloy and the 1Cr18Ni9 Stainless Steel, which showed that although there would

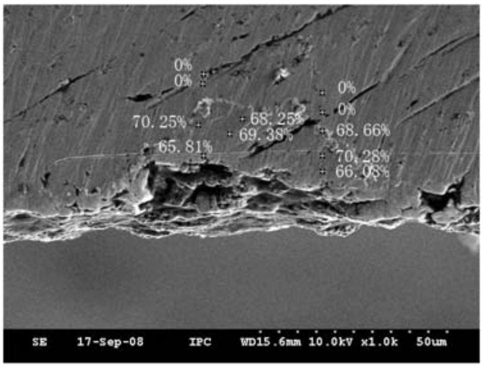


Fig. 8 Gallium concentration of a corrosion cross-section for the T2 Copper-Alloy by EDS analyses

be some adherence when removing gallium from these two specimens, the adhesive gallium would shed from the substrates after cleaning, washing and drying, making gallium undetectable on the corrosion surface.

3.3.1 EDS analysis of corroded cross-section

Figure 8 shows the gallium concentration of the corroded cross-section for the T2 Copper-Alloy by the EDS analysis. It indicates the corroded cross-section area and that gallium infiltrated into the substrate. Through the EDS analysis, it was found that gallium molar concentration in the corroded area was about 65–70%, and away from this area no gallium was detected. Furthermore, an evident notch was found in the corroded area, which meant that part of corrosion products would shed from the substrate. Considering the fluctuation of the corrosion surface, the corrosion rate was estimated to be 30–60 micrometer per month approximately, meaning a corrosion resistance of level 6–7 according to the Corrosion Resistance Classification of Materials [15], which belongs to a slightly high corrosion resistance grade. Nevertheless, in practical liquid metal cooling system, flowing gallium can take part of corrosion products away, which may not only accelerate corrosion action but also block the flowing channel. As a result, only by conducting a further dynamic test, we can judge whether the T2 Copper-Alloy could be used as a structural material for liquid metal cooling system.

Figure 9 is the EDS analysis of the corrosion cross-section for the Anodic Coloring 6063 Aluminum-Alloy and the 1Cr18Ni9 Stainless Steel. It can be found that there was no gallium detected in the corrosion cross-section of the Anodic Coloring 6063 Aluminum-Alloy and the 1Cr18Ni9 Stainless Steel, indicating that no liquid gallium infiltrated into the substrates, which accords well with the surface EDS analysis results discussed above.

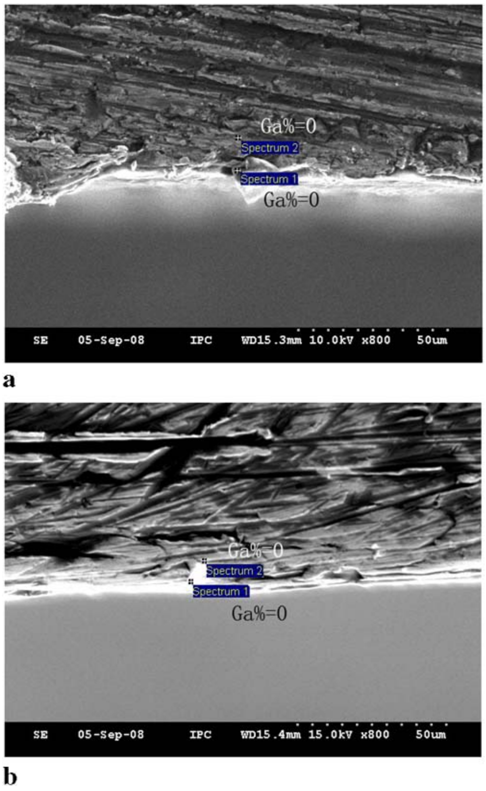


Fig. 9 EDS analysis of a corrosion cross-section for **a** the Anodic Coloring 6063 Aluminum-Alloy; **b** the 1Cr18Ni9 Stainless Steel

4 Discussion

Corrosion that liquid metal causes to pure metal is mainly represented by two forms: (1) pure metal dissolving in the liquid metal; (2) liquid metal and pure metal forming the intermetallic compound [16]. The 6063 Aluminum-Alloy shows serious corrosion with liquid gallium, which implies that aluminum has a high solubility in the liquid gallium, or it is easy to form an intermetallic compound. From Fig. 2, it can be seen that the typical corrosion curve of the 6063 Aluminum-Alloy with liquid gallium can be divided into three parts: pre-corrosion, in-corrosion and end-corrosion periods.

Because a thin oxide layer would form on the surface of the 6063 Aluminum-Alloy substrate even after completely polishing, cleaning and drying, in the pre-corrosion period the main actions are aluminum oxide dissolving in gallium and the two reacting with each other, which allows liquid gallium to access inner aluminum material. The time for this phase to occur is uncertain, depending on the surface treatment of the aluminum-alloy substrate. If the surface contacts with air for long after treatment, the time can be up to several days or even longer. In the in-corrosion period, liquid gallium begins to contact with inner aluminum, and corrosion happens as the surface oxide dissolves and reacts in gallium. But because oxide layer does not dissolve completely and gallium can only contact with surface processes of the substrate due to its large surface tension at the beginning, the contact area is limited and corrosion rate is low. As time goes by, since the surface oxides and processes are completely dissolved or reacted, the contact area is enlarged. Moreover, the corrosion product is loose, which greatly promotes the further contact and enhances the corrosion until the gallium ball completely immerges into the substrate. At last, in the end-corrosion period, gallium concentrations of different places in corrosion area tend to be indistinctive, and the surface corrosion shadow is becoming uniform.

Generally speaking, in order to guarantee that the structure material is not to be penetrated by corrosion, the following inequality must be satisfied:

$$t_{\mathrm{pre}} + t_{\mathrm{in}} > t_{\mathrm{InUse}}, \tag{2}$$

where $t_{\mathrm{pre}}, t_{\mathrm{in}}, t_{\mathrm{InUse}}$ are the pre-corrosion time, the in-corrosion time and the design life of structure material, respectively. It is easy to see that t_{pre} is related to surface treatment and can vary a lot; and t_{in} correlates with the element composition of aluminum-alloy and may not be easy to change. To meet inequality (2), the most cost-effective method is to prolong t_{pre}. Therefore, surface treatment should be the preferred method in dealing with aluminum-alloy materials.

According to the EDS analysis of the corrosion cross-section, the corrosion resistance level of the T2 Copper-Alloy is between grade 6 and 7, which belongs to a slightly high corrosion resistance grade. Therefore, the T2 Copper-Alloy can be used for containers of static gallium when the temperature is not high and when not considering the contamination that corrosion product causes to gallium. Nevertheless, in a practical liquid metal cooling system, flowing gallium can take part of corrosion products away, which not only accelerates corrosion action but may also block the flowing channel. As a result, to use the T2 Copper-Alloy as the structural material of liquid metal chip cooling system may not be appropriate.

As to the Anodic Coloring 6063 Aluminum-Alloy, although there would be some adherence when removing gallium from specimens, the adhesive gallium would shed from the substrates after cleaning, washing and drying. No evident corrosion signs were observed through SEM, and gallium was undetectable in both the corrosion surface and cross-section, showing that the Anodic Coloring 6063 Aluminum has very strong corrosion resistance. However, in a flowing liquid metal cooling system, the scouring effect that liquid metal of great density causes to the oxide layer on the surface must be considered. Meanwhile, the oxide layer should not be scratched so as to avoid gallium infiltration. What is more, the oxide layer has very low thermal conductivity, which will cause an increase of the system's thermal resistance though the oxide layer is generally very thin. Therefore, the Anodic Coloring 6063 Aluminum-Alloy could be used as structural material for a liquid metal cooling system only under conditions of good surface treatments and oxide layer protection, such as increasing the thickness and strength of oxide surface and preventing the oxide layer from being scratched, etc. Moreover, the increased thermal resistance should be correctly evaluated in practical design of a liquid metal cooling system.

The corrosion phenomenon of the 1Cr18Ni9 Stainless Steel was similar to that of the Anodic Coloring 6063 Aluminum-Alloy, and no signs of corrosion were detected. But the 1Cr18Ni9 Stainless Steel shows integral corrosion resistance, so surface destruction is out of concern. At the same time, its surface is of high strength, which weakens the scouring effect of liquid metal. The only shortcoming lies in the relatively low thermal conductivity. In general, after considering economy and practicality comprehensively, the 1Cr18Ni9 stainless steel is the best structural material among the tested specimens for a liquid metal cooling system.

5 Conclusions

In the presented experiment, a new method based on image acquisition and contrast was introduced to study in detail the corrosion trends of liquid gallium with four metal substrates, which significantly saved time and materials. But the precision depends on the resolution of the photographing equipment and the accuracy of image processing.

Liquid gallium has intense corrosion reaction with the 6063 Aluminum-Alloy, and the corrosion product is loose, promoting the infiltration of gallium into the corrosion product to form corrosion diffusion area with uniform gallium concentration. The corrosion product is also of low intensity. Thus, the 6063 Aluminum-Alloy cannot be used as the structure material for a liquid metal cooling system. Its typical corrosion curve can be divided into three parts: pre-corrosion, in-corrosion and end-corrosion periods.

Liquid gallium not only causes uniform corrosion process to the surface of the T2 copper, but also has good compatibility with the corrosion layer and can form gallium covered area on the corroded surface. The corrosion resistance level of the T2 Copper-Alloy is between grade 6 and 7, which belongs to a slightly high grade. But the T2 Copper-Alloy is inappropriate to be used as structural material of a liquid metal cooling system for the dynamic corrosion process will cause great damage to its surface.

The Anodic Coloring 6063 Aluminum has very strong corrosion resistance. However, in the flowing liquid metal cooling system, the scouring effect that liquid metal of large density causes to the oxide layer on the surface must be considered. Meanwhile, the oxide layer cannot be scratched so as to avoid gallium infiltration. What is more, the system thermal resistance will increase because of the thin oxide layer. Thus, the Anodic Coloring 6063 Aluminum-Alloy can be used as structural material of a liquid metal cooling system only after certain good surface treatments. And the increased thermal resistance should be correctly evaluated for practical design of a liquid metal cooling system.

The 1Cr18Ni9 Stainless Steel shows integral corrosion resistance, high surface strength and strong resistance to scouring. The only shortcoming lies in its relatively low thermal conductivity. Comprehensively considering the economy and practicality, the 1Cr18Ni9 stainless steel is the best structural material among the tested four specimens for a liquid metal cooling system.

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