Materials Chemistry and Physics 212 (2018) 298–307

Contents lists available at ScienceDirect

Materials Chemistry and Physics

journal homepage: www.elsevier.com/locate/matchemphys

Corrosion behavior assessment of tin-lead and lead free solders exposed to fire smoke generated by burning polyvinyl chloride

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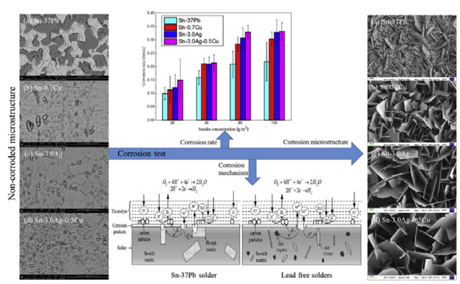
HIGHLIGHTS

- The corrosion characteristics of tin alloys exposed to polyvinyl chloride fire smoke atmosphere are investigated.
- Sn-37Pb solder shows better corrosion resistance than lead free solders (Sn-0.7Cu, Sn-3.0Ag and Sn-3.0Ag-0.5Cu).
- Sn-3.0Ag-0.5Cu solder exhibits the poorest corrosion resistance.
- The corrosion resistance of lead free solders is related to their microstructure.
- The mechanisms of both the corrosion and the corrosion resistance differences among different solders are analyzed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 4 October 2017
Received in revised form
26 December 2017
Accepted 20 March 2018
Available online 20 March 2018

Keywords:
Tin-lead solder
Lead free solders
Microstructure
Corrosion
Fire smoke

ABSTRACT

The corrosion characteristics of tin-lead and three lead free solders (Sn-0.7Cu, Sn-3.0Ag and Sn-3.0Ag-0.5Cu) exposed to fire smoke generated from polyvinyl chloride (PVC) were comparatively investigated through weight loss method and surface characterization techniques. Results show that the corrosion rates of each of four examined solders rise with the increase of smoke concentrations over the concentration range from 20 g/m^3 to 140 g/m^3. Sn-37Pb solder exhibits the optimal corrosion resistance, while lead free Sn-3.0Ag-0.5Cu solder has much poorer corrosion resistance in comparison with the former, even with the Sn-0.7Cu and Sn-3.0Ag alloys. As indicated by SEM and XRD, the corrosion resistance of these lead free solders may be related to their microstructure. When the alloys involve more intermetallic compounds, the more larger cathode areas are presented, the weaker the corrosion resistance seems to be. Further, XRD and Raman spectrum reveal that SnO and $PbCl_2$ are the main corrosion products of Sn-37Pb solder, while those of lead free solders primarily consist of $Sn_{21}Cl_{16}(OH)_{14}O_6$ and SnO. Accordingly, the corrosion mechanisms are further analyzed.

1. Introduction

The reliability of electronic components has attracted increasing attention with the ongoing application and miniaturization of electronic systems [1–3]. A higher system integration density such

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https://doi.org/10.1016/j.matchemphys.2018.03.057
0254-0584/

as smaller component size, closer spacing, and thinner metallic parts, is attributed to the demand for miniaturized systems, which makes the system more susceptible to corrosion [2]. Electronic components, such as integrated chip and connector, are the most essential part in the technology industry products and their corrosion in a harsh environment may cause the failure of technology industry products. For instance, a helicopter accident report indicates that the main cause of the failure of the helicopter from Mackay Aerodrome in Australian was the corrosion of electronic module due to particulate contamination and moisture as shown in Fig. 1 [4]. Furthermore, the failure of electronic components, to a great extent, is due to the corrosion failure of solder joints in harsh environments [5]. Tin-lead solders have been widely used in the electronic systems due to their low cost, low melting temperature, good solder ability, and satisfactory mechanical properties are considered [6,7]. Nevertheless, due to the intrinsic toxicity of lead, an increasing concern has been focused on finding more promising lead free solders with excellent physical and chemical properties [8].

Among various available lead free solders, Sn-0.7Cu, Sn-3.0Ag and Sn-3.0Ag-0.5Cu alloys have been generally researched on their reliability. There have been many contributions highlighting the corrosion characteristics, influence factors, corrosion products of tin alloys in corrosive condition such as neutral solution [6,9–13], acidic solution [14–16] and alkaline solution [17]. The corrosion behavior of Sn–Pb, Sn-0.7Cu, Sn-3.5Ag and Sn-3.8Ag-0.7Cu solders has previously been investigated in 3.5% NaCl solution [6]. It is observed that Sn–Pb solder has the poorest corrosion resistance and Sn-3.5Ag solder shows better corrosion resistance than that of two other lead free solders, and all the three lead free solders have the same corrosion products, $Sn_3O(OH)_2Cl_2$. Nevertheless, the corrosion behavior of tin alloys in fire smoke atmosphere has been rarely investigated yet. In a practical fire scenario, dense fire smoke could spread in a wide region far away from the burning areas and it could severely damage the electronic components through the corrosion effect of fire smoke rather than the thermal effect of fire. Smoke is a collection of gases, liquid inorganic compounds and solid particulates which consist of soot, semi-volatile organic compounds, volatile organic compounds and inorganic compounds [18]. The effect of fire smoke on the corrosion of metals is embodied in the following two aspects. For one thing, when directly exposed to smoke under humid conditions, metals would absorb vapor forming moist layer on their surface to dissolve corrosive gases. For another, when directly exposed to precipitation, metals would produce a uniform cover to absorb atmospheric particles [19]. In addition, cable fire is the most frequent and serious fire in the electronic system with electricity consumption surging around the world. As a sheath raw material for cable, PVC has been widely used due to its low price, flame resistance and electrical insulating. Particularly, fire smoke of burning PVC may induce greater corrosive damage to electronic devices due to the chlorine ions and the acid gases such as hydrogen chloride. Some researches have been carried out to study the effect of PVC fire smoke on the corrosion resistance of metals (carbon steel, stainless steel and copper) [19,20], while the microstructure of their corrosion products and the corrosion mechanisms have not been analyzed. In addition, the corrosion behavior of tin alloys under fire smoke atmosphere has not been analyzed yet. It is therefore essential to study the corrosion behavior of tin alloys exposed to fire smoke generated by burning PVC to provide adequate information for evaluating the reliability of the solder joints in high fire risk scenarios.

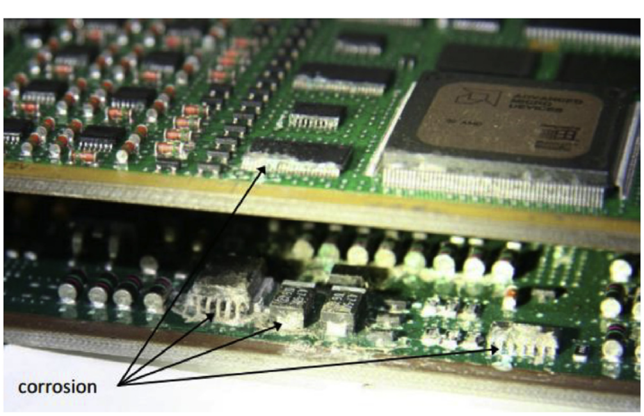

Fig. 1. Corroded electronic module in helicopter [4].

In this research, we aim to study the corrosion behavior of Sn-0.7Cu, Sn-3.0Ag, Sn-3.0Ag-0.5Cu and conventional Sn-37Pb solders exposed to different concentrations of PVC fire smoke for the first time. The microstructure of four non-corroded casting alloys and the surface morphology and chemical compositions of corrosion products on different solders are investigated. Furthermore, the influence mechanism of PVC fire smoke on corrosion resistance of different solder materials are also studied.

2. Experimental procedures

2.1. Materials and experimental setup

The samples were Sn-based commercially applied alloys, Sn-0.7Cu, Sn-3.0Ag and Sn-3.0Ag-0.5Cu alloys, the number of which denoted the weight percentage. For comparison, the Sn-37Pb alloy was also studied. The samples with the size of $75 \times 25 \times 1\ mm^3$ were prepared by melting the stoichiometric amounts of metallic elements with purity above 99.99%. For accuracy, two repeated corrosion tests for each solder material were conduct and triplicate samples were used for each test. Meanwhile, PVC powder was provided as the fuel to generate fire smoke. The value of fuel mass to affected air volume ratios is often used to represent the fire smoke concentration [21]. Four concentration levels ($20\ g/m^3$, $40\ g/m^3$, $80\ g/m^3$, $140\ g/m^3$) of PVC fire smoke were researched in this work.

The experimental device is composed of tube furnace and smoke exposure chamber (SEC). A schematic of the experimental setup is shown in Fig. 2. In tube furnace, PVC powder packed in quartz combustion boat was combusted to generate simulated fire smoke with the air flow rate of 5 L/min and the heating rate of 10 °C/min until the temperature ascended to 680 °C. The combustion products were directed into the smoke exposure chamber with dimensions of 1000 mm length × 1000 mm width × 900 mm height. Several stents were installed in SEC for hanging metal coupons to corrode. A quartz crystal microbalance (QCM) was positioned on the floor of the chamber to measure the mass deposition of the fire smoke over time.

2.2. Test procedure

The fire smoke corrosion environment could be rather complicated, which makes it difficult to quantify corrosion rate of metal with electrochemical method. Therefore, weight loss method was used for determining the corrosion rate. Besides, it was also recognized that the weight loss method could be more reliable for calculating the corrosion rate of material and provide effective reference for practical engineering application.

Prior to each test, the metal surface was ground to a smooth finish with silicon carbide paper. Subsequently, the surface was rinsed with deionized water, degreased with alcohol, dried with