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Influence of rotating magnetic field on solidification microstructure and tensile properties of Sn-Bi lead-free solders

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ABSTRACT

The solidification microstructures and corresponding mechanical properties of Sn-20Bi and Sn-20Bi-0.4Cu alloys were studied with and without rotating magnetic field (RMF). Without RMF, the microstructures of both solders exhibit great numbers of undesirable columnar structure of dendrite primary β-Sn phase and large Cu_6Sn_5 phase. The RMF-driven flow has induced columnar-to-equiaxed transition (CET) of dendrite primary β-Sn phase, which simultaneously results in dendrite fragmentation, and provokes distinct grain and intermetallic compound (IMC) refinement effects due to Lorentz force acting on the melt. The individual contributions of RMF on the lattice strain, crystallite size, stress and energy density were evaluated from X-ray peak broadening using various Williamson-Hall models. RMF can also reduce effectively the lattice strain and crystallite size of both solders, which are likely vital prerequisite for property control on metallic materials. Tensile tests showed that the tensile strength of Sn-20Bi solder was enhanced and ductility of Sn-20Bi-0.4Cu alloy was improved. These effects could increase the elastic compliance and develop the drop impact reliability of bulk solders.

1. Introduction

Understanding the solidification behavior under robust melt flow is essential for controlling the microstructure and mechanical properties of alloys in industry. Whenever the melt flow is artificially applied during solidification of alloys, several modifications in microstructure can be distinguished. For instance, the dendrite structure may change their growth direction from columnar to equiaxed transition (CET) at the solid-liquid interface due to forced melt flow [1]. Both theoretical research and experimental investigations have shed light on the mechanisms associated with CET. The crystal growth by dendrite fragmentation is the possible mechanism for CET of grains in metallic alloys [2]. Recently, the most prominent techniques, such as the electric current pulse, ultrasonic vibration [3] and electromagnetic field have been applied to improve solidification microstructure of alloys and their mechanical properties [4]. Nevertheless, the application of electromagnetic field has three main advantages: i) its promising future as a completely contactless can influence the liquid-metal interface, ii) the flow intensity can easily be controlled by applying different processing parameters and iii) flexible dressmaking of the magnetic fields to design any flow pattern required [5]. Although the electromagnetic processing based on using permanent magnet stirring has been rarely reported, most of these studies have dealt only with the toxic Sn-Pb solder alloys. Zeng et al. [6] have studied the effect of rotating permanent magnet on solidification of Sn-Pb alloy, and the results indicated that the application of magnetic field significantly improved the flow intensity of liquid, surface pinholes, grain refinement and tensile properties. The magnetic field was optimized to capture the variations in melt convection during solidification of the alloy [7].

Because of the environmental and health issues of Sn-Pb alloy, a large scale lead-free solders such as, Sn-Ag-Cu, Sn-Zn, Sn-Sb and Sn-Bi alloys have been proposed and developed for microelectronic industry [8,9]. Due to their unique properties of low melting characteristics, high joint strength, good wettability and better reliability, eutectic Sn-Bi alloys have been widely used as possible lead-free alternatives [10]. However, the brittle nature of high volume fraction of Bi-rich phases could result in poor creep resistance as well as frangibility and poor ductility, which are generally the main problems restricting the application of Sn-Bi based solder in electronic industry. New kinds of low Bi-content Sn-Bi based solder with excellent mechanical properties and high reliability are expected. Most studies are focused on improving the microstructure, solidification behavior and mechanical performances of eutectic Sn-58wt%Bi solders through adding minor alloying elements [11], but there are seldom systematic data on the effect of small volume fraction of Bi-rich phase along with the RMF on solidification structure and tensile properties of lead free solder alloys. Recently, Nagira et al. [3] studied the effects of ultrasonic wave on dendritic growth of low Bi-content Sn-13at%Bi alloys using time-resolved in situ X-ray imaging.

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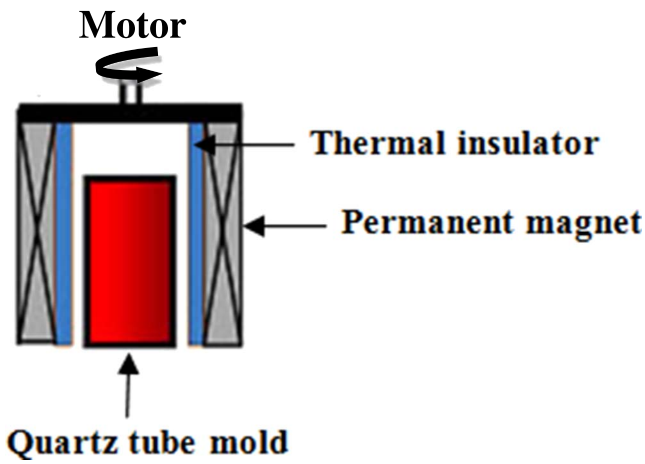

Fig. 1. Schematic view of the RMF process.

The ultrasonic wave caused a circulating convection, whose domain size was almost the same as the small specimen size (10 × 23 mm and thickness of 300 μm). It was established that dendrite fragmentations in the columnar zone were extensively enhanced by the secondary effects of ultrasonic wave. However, modification of the solidification process by RMF is a novel approach to improve the impact reliability of lead free solder alloys. This study aims to assess the influence of RMF on solidification structure and tensile properties of lead free Sn-20 wt%Bi and Sn-20Bi-0.4wt%Cu solder alloys, which show serious dendrite structure under common solidification conditions. The structure and morphology of the entire alloys are examined by field emission scanning electron microscopy (FE-SEM), energy dispersive X-ray spectroscopy (EDS). The particle size (D) and lattice strain (ε) are calculated in a systematic way by means of XRD analysis using Scherrer and Williamson-Hall models.

2. Experimental procedures

A schematic diagram of RMF experimental set-up is shown in Fig. 1. The magnetic field was constructed by a pair of disc-shaped NdFeB permanent magnets of 0.5 T with their N, S poles face to face. The interval between two faces was 40 mm. The rotating permanent magnets were controlled by an adjustable speed motor connected to power supply system, which permits precise rotation speed ω of 120 r/min. The rotation speed was selected being sufficiently small to neglect any influences arising from skin effect. Details are described in our previous work [12]. Experiments were performed with Sn-20wt%Bi and Sn-20Bi-0.4wt%Cu alloys. The two alloys were prepared from pure Sn (99.9%), Bi (99.9%), and Cu (99.99%) metals by melting in quartz tube at 600 °C for 60 min. The quartz tube has an internal diameter of 25 mm and height of 50 mm. The alloys were initially molten and then being stirred in the rotating permanent magnets during the whole solidification process. A cooling rate of 8–10 °C/s was achieved, so as to generate fine microstructures typically found in small solder joints in microelectronic packages. The solidification microstructure was examined near the bottom surfaces of the ingots to detect the gravity effect of phases (∼1.0 cm) by an optical microscopy (OM, KEYENCE VHX-500F) and field emission scanning electron microscopy (FE-SEM) JSM-5410, Japan after polishing and etching. A solution of 3%HCl, 2%HNO_3 and 95% (vol%) Ethyl alcohol was prepared and used to etch the samples. Phase identification was estimated based on Energy Dispersive X-ray Spectrometry (model Shimadzu EDS-720). The phase analysis of solder alloys was evaluated by X ray diffractometry (XRD, Phillips X'pert) at 40 kV and 100 mA using CuKα radiation (1.5406 Å) with diffraction angle from 20 to 90° and scanning speed of 1.2°/min. The homogenized cast ingots were then mechanically machined into wire sample with a gauge length marked 4×10^{-2} m and 1.2 mm diameter for each sample, as developed in the previous work [8]. Then, tensile properties were characterized using computerized tensile testing machine described elsewhere [13]. The tests were carried out at strain rate of $10^{-4}\,s^{-1}$ and constant temperature of 25 °C.

3. Results and discussion

3.1. Origins and effects of melt convection under RMF

The goal of rotating magnetic field on solidification of Sn-20Bi solder alloys is to generate an irregular rotating field and causing forced melt convection. Since the interaction of RMF with conducting melt flow is mainly depends on several non-dimension quantities, an adequate choice of magnetic induction value can lead to the required growing interface character that meets the requirements in industry. In current study, three important non-dimensional parameters are considered to control the liquid melt [14]: a) Hartmann number (H_a) which is the ratio between electromotive force and viscous force:

$$H_a = BR\sqrt{\frac{\sigma}{2\mu}} \tag{1}$$

H_a number plays an important role for evaluating the field velocity results from these two forces. b) Reynolds number (R_e) which quantifies the magnetic field skin depth with respect to cylinder radius:

$$R_e = \frac{\omega R^2}{\nu} \tag{2}$$

and c) Taylor number (T_a) which describes the magnetic force by rotating magnetic field, and can be driven by H_a and R_e as follows:

$$T_a = R_e \cdot H_a^2 = \frac{\sigma\omega B2R^4}{2\rho\nu 2} \tag{3}$$

where ω is the angular velocity, R is the cylinder radius with a value of 15 mm. The magnetic field is characterized by magnetic induction B, whereas ρ, ν and σ stand for the density, kinematic viscosity and electrical conductivity of Sn matrix with the values of 7600 kg/m^3, $2.1 \times 10^{-7}\,m^2\,s^{-1}$ and $3.5 \times 10^6\,\Omega^{-1}\,m^{-1}$, respectively. According to the physical fluid properties of Sn-20Bi solders, the calculated values of R_e and H_a are found to be 1.3×10^5 and 248.1, respectively, and thus the magnetic Taylor number in this study was about 7.9×10^9. In order to evaluate the effectiveness of these numerical results, Taylor number obtained during the present study is compared with the previously published results. Laminar flow is generally occurs at low T_a numbers, whereas turbulent flow occurs at high T_a numbers and is dominated by inertial forces, creating vortices and other flow fluctuations. Grants et al. [15] establish that the transition from laminar to turbulent flow can occur at T_a numbers larger than 10^5, and the flow intensity of melt become more pronounced with increasing the value of T_a. The present results with T_a value of 7.9×10^9 is considerably much greater than 10^5 obtained by [15] and larger than1.22×10^7 attained by Zeng et al. [6]. Hence, the melt flow can be considered as a turbulent flow. This indicates that as the rotational frequency of permanent magnet decreases, the melt convection increases, and under enhanced melt convection state, the volume fraction of undesirable dendrite structures could decrease. However, an additional important parameter during solidification is the thermal buoyancy, which influences the melt convection at lower T_a number. In order to verify the effectiveness of this type of convection mode, Nikrityuk et al. [16] estimated the critical T_a required for thermal buoyancy, and found that the buoyancy can be neglected for $T_a > 1.7 \times 10^6$. Thus, this type of convection mode is not generated inside the Sn-20Bi solder melts since the T_a value of 7.9×10^9 is much greater than 1.7×10^6 required for thermal buoyancy. As a result, the discussion in the following study is motivated by the magnetic driven-flow during induction melting, while the thermal buoyancy can be neglected.

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