Applied Thermal Engineering 107 (2016) 431–440

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

An alternative thermal approach to evaluate the wettability of solder alloys

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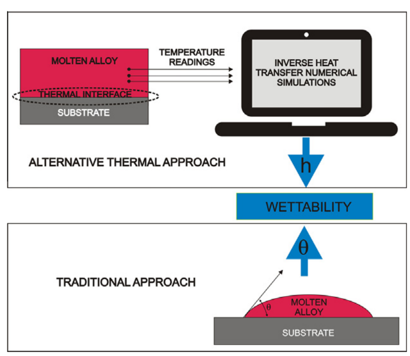
HIGHLIGHTS

- A thermal approach is proposed to qualitatively evaluate the wettability of solders.
- The approach is based on experimental results of solder/substrate thermal conductance.
- High temperature Zn-Sn solders are experimentally investigated.
- The approach is validated against experimental contact angles of wetting tests.
- The results indicate increase in wettability with decrease in alloy Sn content.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 19 May 2016
Revised 26 June 2016
Accepted 29 June 2016
Available online 29 June 2016

Keywords:
Zn-Sn solder alloys
Solidification
Wettability
Interfacial heat transfer coefficient

ABSTRACT

The aim of the work is to propose an alternative method to qualitatively evaluate the wettability of different alloys of a particular alloy system. The technique is based on a thermal approach supported by experimental/theoretical methodologies involving a directional solidification procedure and numerical simulations based on the solution of the inverse heat conduction problem (IHCP). The wettability strongly affects the heat ability to flow across the alloy/substrate interface during solidification, which is construed as a heat transfer coefficient (h_g). Particularly, for the alloys used in soldering processes, the wettability plays an important role in the integrity of solder junctions, being a fundamental parameter for selecting the most appropriate solder composition. The experiments were carried out with high temperature Zn-Sn solder alloys (10, 20, 30 and 40 wt%Sn) in a solidification device in which heat is extracted only through a water-cooled steel bottom. Experimental thermal profiles collected during solidification are used as input data to solve the IHCP and determine expressions h_g vs. time for each alloy examined, permitting a tendency of wettability to be established. In order to validate the wetting behavior indicated by the h_g values, alloy/substrate contact angles (θ) were measured on a steel substrate using a goniometer. It is shown that both h_g and θ indicate improvements in wettability with the decrease in the alloy Sn content.

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http://dx.doi.org/10.1016/j.applthermaleng.2016.06.177
1359-4311/

1. Introduction

According to Zeng et al. [1] even though Zn-Sn alloys revealed great potential as high temperature lead free solders for die-attachment applications, further development is required. As a matter of fact, Musa and coauthors [2] stated that characteristics of the Zn-Sn alloys such as mechanical properties, wettability and corrosion resistance still deserve attention in future studies. Zn-Sn lead-free solders are considered potential candidates to replace Pb-Sn alloys due to their low cost, relatively high melting temperatures, absence of intermetallic compounds, good thermal/electrical thermal conductivities and mechanical strength [2–5]. High temperature soldering operations (from 270 °C to 350 °C) may impact industries such as aerospace, telecommunications and energy, since efficiency and quality of joining materials for electronic components is a critical requirement [1,6].

The main disadvantages of Zn based alloys used as high temperature solders may be associated with characteristics of Zn, which is highly corrosive and also exhibits poor wetting behavior due to its high affinity with oxygen. However, as reported by Takahashi et al. [3], the addition of Sn to Zn leads to excellent oxidation resistance in high temperature/high-humidity conditions.

The microstructures of Zn-Sn alloys are formed by a primary α-Zn phase surrounded by the eutectic mixture, consisting of fine α-Zn platelets and a Sn-rich β-phase. As the alloy Zn content decreases, the fraction of the primary α-Zn phase decreases while the fraction of the eutectic Sn–Zn mixture increases. A partial morphological transition of plate-like Zn-rich cells into horizontal cylindrical-like cells has been recently reported to occur in microstructures of directionally solidified Zn-30 and 40 wt%Sn alloys castings [7]. As the eutectic temperature is too low, around 199 °C, certain instabilities during the soldering procedure may be expected, when a certain volume of liquid phase is formed [1,2]. In contrast, the presence of liquid in proportions up to 30% was not considered enough to provoke lack of stability, as reported by Kim et al. [8].

Although Zn-based solders can be inserted as part of electrical and electronic devices, the wettability of lead-free alternative solders and their consequences on the soldering process are tasks still to be accomplished. For instance, an adequate metallurgical bond between the solder joint and the substrate depends on the wetting conditions occurring on the metal/substrate interface [9]. The extent of wetting is measured by the contact angle that is formed at the juncture of a solid and liquid in a particular environment [9].

The effects of Sn content on the heat transfer efficiency at the interface between solder and substrate in Zn-Sn alloys remain undetermined. The capacity of heat to flow through the interface from the solder to the substrate directly contributes to the evolution of solidification and, consequently, controls the formed microstructure close to the interface between solder and substrate. As stated by Musa et al. [2] experimental investigations with a view to assessing solder wettability can be used to predict the performance of the new solder alloys. The transient interfacial heat transfer coefficient (h) is mainly dependent upon the thermophysical properties of the contacting materials, the roughness of substrate contacting surface, the melt superheat, the alloy freezing range and wetting behavior [10]. The heat transfer efficiency rendered by (h) is a key parameter in the control of the solidification kinetics, as it is in the microstructure evolution.

One of the mathematical methods available to determine h is the Inverse Heat Conduction Problem IHCP. It is also applied to determine the unknown cooling conditions of ingots solidified in chilled molds, given by the overall heat transfer coefficient (h_g), when surface temperatures during cooling are not available [10,11]. A recent study on Sn-0.7 wt%Cu-(xNi) solder alloys reported that a decrease in the initial wetting angle was shown to be associated with increase in the solder/substrate heat transfer coefficient, h_g [12].

The present study aims to develop an alternative thermal approach to evaluate the wettability of solder alloys. Firstly the wetting angles (θ) of Zn-10, 20, 30 and 40 wt%Sn solder alloys against AISI 1020 steel substrates will be experimentally determined using a goniometer; and secondly solidification thermal profiles and a IHCP method will be used to determine solder/substrate heat transfer coefficients (h_g) of directionally solidified (DS) Zn–X wt%Sn alloys. An interrelation between θ and h_g is envisaged with a view to permitting the wettability of solder alloys/substrates to be established from temperature readings during solidification.

2. Experimental procedure

Zn-10, 20, 30 and 40 wt%Sn hypoeutectic alloys were used in the solidification experiments as schematically shown in Fig. 1. These alloys were directionally solidified with heat being extracted only through a water-cooled carbon AISI 1020 steel bottom, polished to a 1200 grit surface finish. Heat losses in the radial direction have been avoided through an appropriate peripheral thermal insulation with a refractory material. The literature reports that the macrostructural response associated with unidirectionally oriented heat flux is typified by a morphology of columnar grains aligned along the growth direction, which is opposite to that of the heat flow direction [13]. Fig. 1 shows a representative macrostructural arrangement of the Zn-Sn system alloy consisting of columnar grains, assuring that the unidirectional heat extraction was dominant along the entire solidification process. Continuous temperature measurements in the castings were monitored during solidification via the output of a bank of fine type J thermocouples (0.2 mm diameter wire). Special care has been taken concerning the thermocouples tip position, which were placed along the vertical centerline of the cylindrical ingot, since this is the farthest location from the insulated wall, thus permitting possible effects of radial heat losses to be minimized. This region constitutes the best representative control volume of the microstructure growth upon unidirectional solidification. Further details about the solidification system used in this study can be found elsewhere [14].

In order to prepare the specimens for the wetting tests, cylinder bars (4.0 mm-height × 4.0 mm-diameter) were extracted from the central part of the directionally solidified Zn-Sn alloys castings. Before these tests, the Zn-Sn specimens were cleaned with a solution of 38% (vol.) H_3PO_4, 2% (vol.) HNO_3 and 60% (vol.) $C_2H_4O_2$ at 100 °C. Thereafter, the samples were dried properly and finally coated by adequate flux for testing.

The measurements of the contact angles (θ) were carried out in a Goniometer Krüss DSHAT HTM Reetz GmbH model from the average of θ_R and θ_L (R—right and L—left) values provided by a computational method (tangent-2) and three tests were carried out for each couple solder alloy/carbon steel substrate. Details on the experimental setup can be seen in Fig. 2. A desired purging gas atmosphere was maintained by passing argon through the furnace. Three specimens of each composition were available to be placed on the tester, heated and molten individually. The contact angles have been determined continuously as far as the form of the molten droplet changed. At the end, three evolutions of contact angle as a function of time have been acquired for each Zn-Sn composition, which allowed further average values with their standard deviations to be determined. A standard thermal cycle was imposed with melt superheats of 20% above the liquidus temperature of each alloy, considering a constant heating rate of 10 K/min and a natural cooling rate inside the furnace. The initial melting temperatures are consistent with those adopted for directional