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Impact of thermal aging on the intermetallic compound particle size and mechanical properties of lead free solder for green electronics

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ABSTRACT

The $Sn\text{-}Ag_{3.0}\text{-}Cu_{0.5}$ lead free solder (*LFS*) alloy is mostly used as good alternative as compared to conventional Tin-Lead (*Sn-Pb*) due to its good mechanical properties and no harmful effect on environment but it stills has some problems to be solved regarding the growth formation of intermetallic compounds (*IMCs*). The *IMCs* present inside the bulk tin (*Sn*) matrix grow at high temperature and hence their impact on mechanical properties becomes more significant. In this work the effects of lanthanum (*La*) doping of $Sn\text{-}Ag_{3.0}\text{-}Cu_{0.5}$ is investigated as function of *IMCs* growth and mechanical properties including yield strength (*YS*) and ultimate tensile strength (*UTS*) under different thermal aging temperatures. The selected *La* concentration in this study is 0.4 wt%. The aging time is 50 h and thermal aging temperatures are 60 °C, 100 °C and 140 °C. The microstructure examination before and after thermal aging is observed using scanning electron microscopy (*SEM*) followed by image analysis to estimate the nature of *IMCs*. The chemical composition is confirmed with energy dispersive X-ray (*EDX*). The *YS* and *UTS* are also examined before and after thermal aging for the un-doped and doped samples from stress-strain curves using universal testing machine (*UTM*). It is investigated that inclusion of 0.4 wt% *La* into $Sn\text{-}Ag_{3.0}\text{-}Cu_{0.5}$ solder system results in increasing the *IMCs* growth rate and hence mechanical properties reduced. It is also observed that the microstructure becomes coarsen after thermal aging due to growth of average *IMCs* particle size with significant decrease in *YS* and *UTS*. Further, mathematical relations with minimum error are developed to predict mechanical properties (*YS* and *UTS*) at various levels of aging temperature, showing a reciprocal relationship between aging temperature and mechanical properties.

1. Introduction

Electronics has made life easier, as it has its wings in every field of science and is playing an important role in our daily life [1]. In electronic industries, solder joints are normally used to physically hold assemblies together, transmit electrical signals and make mechanical bond that connect the component to substrate [2]. The most commonly used solder joint alloy in electronics assembly is the $Sn_{63}\text{-}Pb_{37}$ due to its low melting temperature, good wettability and wide range availability with low cost and as good reliable solder alloy in electronic manufacturing for many years [3] but due to the negative impact of *Pb* on environment and low recycling rate of electronics, it got restriction in its utilization through legislation [4]. Therefore, several academic and industrial groups have developed different lead free solders (*LFSs*) to migrate towards green electronics. Among all, the most acceptable and popular is the *Sn-Ag-Cu* series [5] due to its good thermal fatigue properties, acceptable wetting properties and better joint strength than *Pb* bearing solders [6], in which $Sn\text{-}Ag_{3.0}\text{-}Cu_{0.5}$ is considered to be the best family member of the *Sn-Ag-Cu* series but it stills has some problems to be solved regarding the growth formation of *IMCs* [7].

The formation of thin layer of *IMCs* between solder and conductive metals is necessary for metallurgical bonding but the reliability of the solder joint is reduced when these *IMCs* become too thick due to their ability towards structural defects because of its brittle nature [1,8,9]. Therefore, excessive growth of *IMCs* is responsible for deterioration of solder joint, thermal fatigue life and fracture toughness of the solder joint [8]. The prolonged exposure to high thermal environment also results in increased thickness of *IMCs* because thermal aging is responsible for reduction in strength due to change in microstructure particularly the *IMCs* that can be considered as the life of any soldered joint after prolong exposure of the material at elevated temperature [10].

Solder connections also become under mechanical stresses and strains when an electronic device is in use due to the differences between the coefficient of thermal expansion (*CTE*) of the electronic components and the board to which the components are soldered [11]. The on and off switching of the system is also responsible for cyclic thermo-mechanical load [12]. In addition, when exposed to high temperature during services, solder assemblies are subjected to tensile

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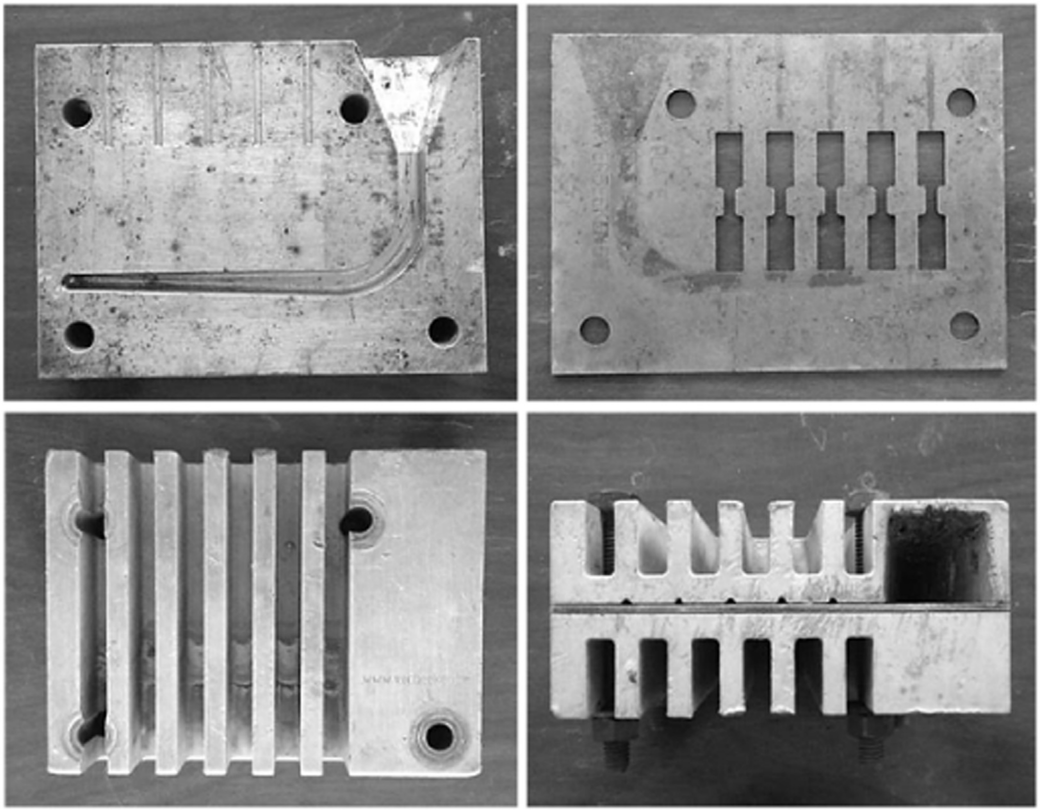

Fig. 1. Die for casting.

loading. Therefore, mechanical properties like yield strength (*YS*) and ultimate tensile strength (*UTS*) become very important in determining the maximum extend of tensile deformation which the solder joint can sustain before failure [13].

In order to overcome these shortcomings, and further enhance the properties of *Sn-Ag-Cu* solders, many researchers choose to add a series of alloying elements including indium [14], titanium [15,16], manganese [15], iron [14], zinc [17], bismuth [18], nickel [19,20], antimony [21,22], gallium [23], aluminum [24] and nanoparticles such as aluminum nanoparticles [25], cobalt nanoparticles [26], aluminum oxide nanoparticles [27], titanium oxide nanoparticles [28], cerium oxide nanoparticles [29], nickel coated carbon nanotubes [30], single-wall carbon nanotubes [31], grapheme nanosheets [32] and Ni-coated graphene nanosheets [33] to the *Sn-Ag-Cu* solders.

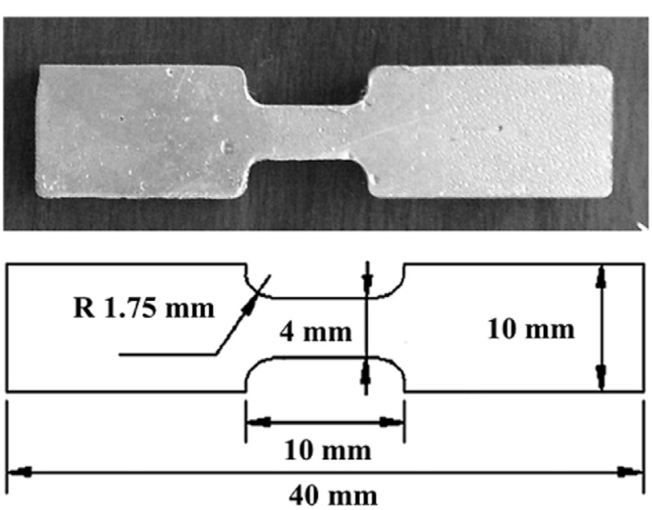

Fig. 2. Geometry of solder specimen.

However, rare earth (*RE*) elements have been regarded as the vitamin of metals and addition of small quantity of *RE* elements may bring down the rate of formation of the *IMCs* by changing the diffusion coefficient [34]. Several studies [35–42] have been conducted to find the effect of *RE* doping in solder alloys. These studies demonstrate that *RE* doping can significantly increase the improve properties of the solder, it can also reduce *IMCs* particle size and their growth on solder/pad interfaces, and thus greatly increase the solder joint reliability. Among all *RE* supplements, *La* has been considered to be the best additive due to their lower cost, wide availability and low melting point as compare to the other *RE* elements [34] but proper care is necessary in its concentration as greater concentration has adverse effect on the properties of the bulk solder [43].

Literature showed that Pei and Qu [44] conducted extensive testing to study the impact of *La* inclusion on creep and fatigue behavior of *Sn-Ag* alloy and concluded that *La* doping enhance the fatigue life by about five times. Furthermore, the optimized level of doping for better fatigue performance is around 0.1%. In another study of Pei and Qu [45], quantitative microstructure studies are performed to inspect the effect of *La* due to thermal aging for eutectic $Sn\text{-}Ag_{3.5}$ alloy. It is also articled that *La* addition (0.05, 0.1 and 0.25) wt% reduces the grain size remarkably and the new size remains stable during thermal aging. Another observation is that the interparticle spacing remains unaffected by the doping. Therefore, higher *La* doping level leads to higher volume fraction of the eutectic

Table 1
Selected *Sn-Ag-Cu* compositions.

Sn (wt%)	*Ag* (wt%)	*Cu* (wt%)	*La* (wt%)
96.5	3.0	0.5	0
96.1	3.0	0.5	0.4