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RADIATION-INDUCED ALTERATIONS IN $SnAg_3Cu_{0.5}$ SOLDER JOINT

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This study aims to examine the effect of a broad dose range of gamma irradiation on the eutectic microstructure and micromechanical properties of solder joint. The mechanical properties including hardness, reduced modulus, and creep behaviour (soldered alloys) using nanoindentation. The $SnAg_3Cu_{0.5}$ (SAC305) solder paste for soldering was stencil-printed onto the surface of the printed circuit board to create the solder joint and reflow soldering, and was then exposed to a wide range of gamma radiation doses (from 5 to 50000 Gy). After the exposure, the samples undergo metallographic procedure prior to the indentation test. The hardness, intermetallic compound (IMC) thickness, also phase area before and after irradiation were observed via optical microscope and analysed via ImageJ. It was discovered that gamma exposure could alter SAC305 behaviour. During the 5000 Gy exposure, atomic displacement and transmutation products led to plastic deformation, resulting in increasing in hardness. Increased depth relative to length of stay correlates with an increase in radiation. Stress exponential outcomes produce a mixture of outcomes when the dose is increased. 500 Gy is the highest reduced modulus value. The increase in reduced modulus followed the increase in gamma radiation, according to the research. Gamma radiation altered the microstructure of SAC305 solder resulting a change in IMC thickness as the radiation increased. The phase area was analysed for SAC305 by using ImageJ. The eutectic phase area showed a parallel trend to the hardness value obtained. It was found that Cu_6Sn_5 and Ag_3Sn compounds dominated the intermetallic layer in the Sn matrix.

Keyword: lead free solder, eutectic, hardness, SAC, IMC thickness, ImageJ, radiation

INTRODUCTION

The bonding of electrical components to printed circuit boards is made possible by the soldering process, which is essential for the production of integrated circuits (ICs) [1]. Cell phones, personal computers, storage devices, and other everyday gadgets are all examples of electronic equipment widely used in technology and are everywhere in our daily lives. Between the components and the board in these devices, the solder joints serve as both mechanical and electrical connections [2]. Electronic packaging is becoming denser due to the rising demand for multifunctional electronic devices as technology develops. However, under extreme conditions, the solder joint's high heat density can force it to expand, which can result in cracking and jeopardise the joint's dependability [2]. The solder matrix's microstructure is also coarsened by the high heat, which weakens its hardness qualities and makes it softer. A material's resistance to persistent deformation is gauged by its hardness qualities. A crucial mechanical characteristic of solders is hardness, which has a direct bearing on the solder joint's capacity to sustain loads and deformations over the course of its service life. A typical technique for determining the hardness of small objects, including solders, is nanoindentation. A popular technique for interpreting nanoindentation data is the Oliver and Pharr approach [3], which gives the material's hardness as a function of the applied stress and the resulting indentation depth. The hardness of the solder samples can provide important information about their behaviour during thermal cycling, loading, and other environmental conditions.

In response to the toxic and hazardous effects of lead-based soldering, tin-silver-copper (Sn-Ag-Cu, SAC) solder alloys are being explored as a potential candidate to replace tin-lead (SnPb) solder in electronic assembly. Currently, several SAC solder alloys, such as SAC305, SAC0307, SAC387, and SAC396 are being produced and studied. The reliability of the solder joint is very important for the life of the electronic devices because the solder interconnection is exposed to failure under environmental conditions such as temperature, radiation, humidity, dust, shock and vibration [4-6]. Lehan et al. reported that exposure to gamma radiation changes the natural behaviour of SAC solder joints to become softer and more plastic [7]. Gamma radiation also caused the crystallite size of β-Sn grain in lead-free solder to become much smaller due to shorter interatomic distance, thus affecting the mechanical properties of the solder [8]. This raises serious concerns about the micromechanical alterations and functionality of solder material due to exposure to gamma radiation. The effect of gamma radiation on materials has sparked significant interest and prompted the creation of innovative materials with high gamma radiation resistance. The irradiated solder connection may have performed poorly due to gamma radiation-induced changes in its mechanical and microstructure properties. Eutectic phase area refers to the area occupied by the eutectic solid solution in a metallurgical microstructure. Eutectic refers to a specific type of solid-liquid mixture that has the lowest melting point compared to other solid-liquid mixtures with the same composition. Wang et al. [2] found that energetic electrons produced by gamma radiation altered the morphology of the IMC layer and caused microscopic flaws in SnPb solder. In solders joint, the eutectic phase area is important as it determines the strength of the solder joint. Lehan et al. reported that with exposure to gamma radiation (low dose 5-25 Gy), the distribution of eutectic phase area of SAC solder is parallel to the value of hardness obtained [9]. Thus, this open very important question on the microstructural change of solder interconnect materials after exposure to higher dose gamma radiation. Therefore, this paper aimed to explore the correlation between eutectic phase area and hardness under gamma radiation exposure to higher dose (50000 Gy).

MATERIALS AND METHODS

$SnAg_3Cu_{0.5}$ (SAC305) lead-free solder paste (supplied by Red Ring Solder (M) Sdn. Bhd.) was manually deposited onto a printed circuit board (PCB) using stencil printing to create a solder joint. The samples underwent reflow soldering at a maximum temperature of 260 °C prior to gamma radiation exposure.

The samples were then subjected to gamma radiation using an industrial Excel 220 Gamma Cell irradiator that utilized a Cobalt-60 source at 5, 50, 500, 5000, and 50000 Gy with an operating dose of 0.84 kGy/h. According to Yusoff et al. Cobalt-60 has the ability to provide sufficient energy to induce changes in the material's characteristics [10]. The samples were metallographically prepared to evaluate the mechanical properties through nanoindentation analysis, including mounting, grinding, polishing, and etching. The samples were then examined under an optical microscope (Inverted Metallurgical Microscope, Eclipse M200) for microstructural examination and evaluation of intermetallic compounds (IMC) growth on the soldered samples. The average IMC thickness was determined using ImageJ software and the eutectic phase area was calculated through thresholding in the same software. The center of the solder joint was subjected to nanoindentation using a Nanotest^{TM} Micro Materials indenter, with a constant loading rate of 0.5 mN/s, a maximum load of 10 mN, and a duration of 10 s until unloading. The obtained nanoindentation data was analysed using the Oliver and Pharr method [3], which corresponds to the hardness of the solder samples.

RESULTS AND DISCUSSION

The eutectic phase area, average size and hardness of SAC305 are tabulated in Table 1. Figure 1 shows the IMC layer thickness of the SAC305 solder. The micrograph demonstrated that throughout the soldering, Sn atoms from the solder alloy interacted with molten substrate elements to form the interfacial layer between the solder alloy and the substrate. The IMC thickness of the tested solders increased with increasing radiation exposure, suggesting that gamma radiation could influence the morphologies of SAC305 solder. This led to a change in IMC thickness. The heat produced by the gamma was expected to play a role in the development of IMC formation. The development of Cu_6Sn_5 IMC, which was stimulated by the aid of heat during irradiation, caused an increase in IMC layer thickness. The Cu_6Sn_5 IMC layer was created by facilitating the diffusion of Sn and Cu atoms from either the bulk solder or substrate using heat and high pressure [11]. The outshoots grew in size with the increment of radiation dose, causing changes in the IMC thickness. IMC growth was regarded as a common diffusion growth that should be restricted by the interdiffusion of substrate and solder components [12]. In the control sample, the IMC produced between the solder and the Cu substrate appeared thin and developed a scallop-like structure. Nevertheless, after irradiation, the interface became uneven, indicating the development of several outshoots inclining away from the substrate pad as shown in Figure 1. It is believed that the heat produced by gamma radiation changes the condition of IMC after being radiated.

Figure 2 shows the micrograph of SAC305 after the etching process, revealing the eutectic phase area of the solder. Using ImageJ, the eutectic phase area was analysed and tabulated in Table 1. A region or line on the phase diagram typically represents the eutectic phase area. Within this area, the alloy composition is such that it allows for the lowest melting point and a unique microstructure formation. The eutectic composition provides a balance between the solubilities of the two components, resulting in the formation of a eutectic mixture with desirable properties such as improved mechanical strength, reduced brittleness, or enhanced corrosion resistance. According to Table 1, the eutectic phase area and its size particle for the SAC solder showed a comparable trend to the hardness obtained based on a previous study done by Lehan et al. [7] and Kong et al. [13]. According to El-Daly et al. [14], the heat generated by gamma rays resulted in a coarsening behaviour of the β-Sn phase microstructure and IMC in the solder. The presence of the eutectic area was able to prevent the dislocation occurrence. Force is exerted on the solder surface during the indentation. The greater the eutectic area, the more likely the indenter will be unable to penetrate deeper into the solder, increasing the hardness of the samples. The continuous movement of dislocations facilitates deformation, which contributes to the reduced hardness properties [15]. Similarly, as the eutectic area shrinks, the solder's hardness decreases.

Table 1: Hardness and eutectic phase are of SAC305 solder

Sample (Gy)	IMC Thickness (μm)	Eutectic phase area (%)	Eutectic average size (μm)	Hardness (GPa)
Control	3.36	28.08	5.19	0.26
5	3.74	30.27	5.52	0.28
50	3.94	20.39	3.55	0.14
500	4.12	18.52	3.49	0.12
5000	4.68	21.33	4.96	0.18
50000	4.71	22.70	5.42	0.32

The change in hardness is due to the structural modifications within the alloy when exposed to gamma radiation. Gamma irradiation generated atomic vacancies, breaking bonds, and dangling bonds that can alter the mechanical properties of alloy [16]. In this study, the hardness value decreased following gamma radiation exposure up to 500 Gy, and then suddenly increased when the dose at 5000 Gy due to structural and atomic rearrangements of solder materials. Yusoff et al. reported that gamma radiation could alter the basic qualities of materials, such as its hardness and ductility [10]. The value decreased over time as the dose increased may be due to the defect in the alignment of the crystal structure, which then weaken the material structure and affected the hardness [10]. It can be concluded that the hardness of the solder decreased as it was subjected to gamma radiation up to 500 Gy before sudden increase when exposed to 5000 Gy due to structural and atomic rearrangement of solder material. The eutectic phase area of SAC305 solders is parallel to the hardness obtained.

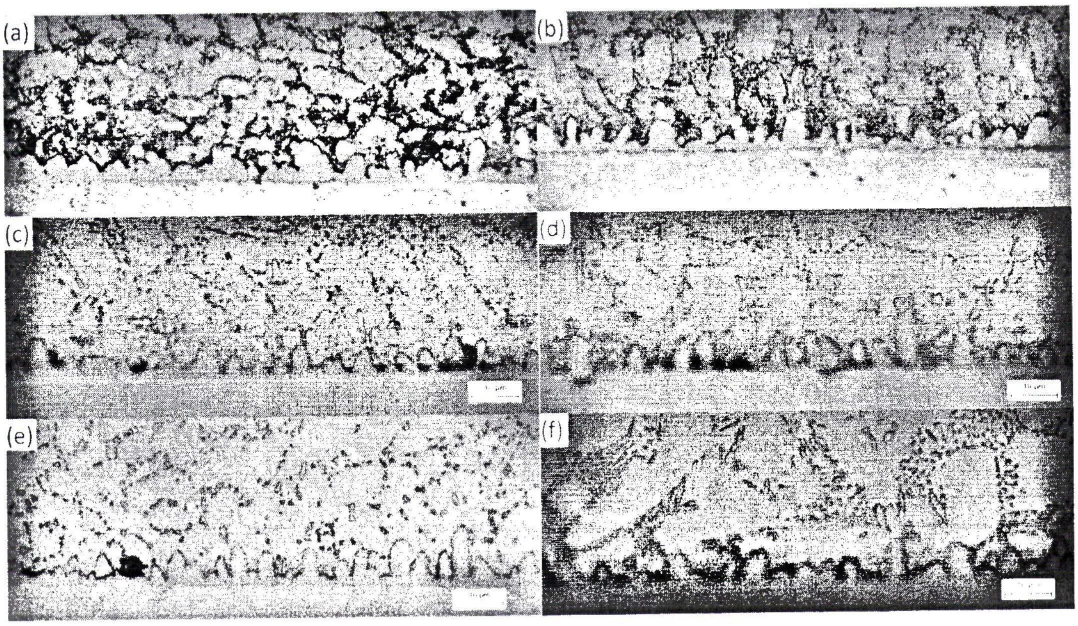

Figure 1: IMC of (a) control SAC305, (b) 5 Gy, (c) 50 Gy, (d) 500 Gy, (e) 5000 Gy and (f) 50000 Gy

After exposure to gamma radiation, the thickness of the examined solders increased with the dose. The heat generated by gamma rays induced the coarsening behaviour of SAC microstructure and IMC thickness increased. The microstructure evolution of the solder after exposure also showed a notable change. The eutectic phase area was parallel to the hardness values. The area shrank as the dose increased due to the coarsening of the Sn phase and the production of the Cu_6Sn_5 whiskers in the eutectic region. The eutectic area acts as a barrier that prevents dislocation in the atomic arrangement of the solder as the indenter penetrates the solder. The change of the Ag distribution was perceived substantially less in samples exposed to a greater dose of radiation. This was associated with a decrease in sample hardness due to the presence of Ag_3Sn intermetallic obstructs the occurrence of atom dislocation migration and increases in hardness due to structural and atomic rearrangement of solder material.

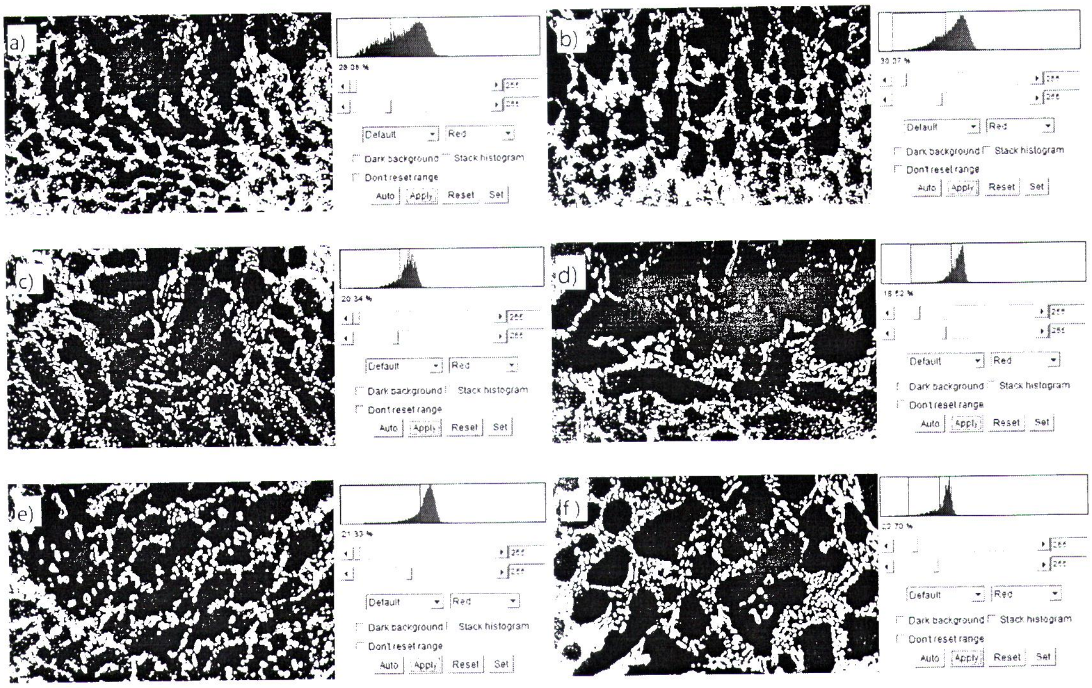

Figure 2: The micrograph of (a) control SAC305, (b) 5 Gy, (c) 50 Gy, (d) 500 Gy, (e) 5000 Gy, and (f) 50000 Gy after etching

CONCLUSIONS

This study investigated the effect of gamma radiation on the hardness and microstructural properties of SAC305 solder. Gamma radiation exposure influenced the hardness of the solder. The hardness initially decreased up to 500 Gy, indicating a disturbance in the atomic arrangements of the solder material. However, it suddenly increased at 5000 Gy, suggesting structural and atomic rearrangement. The IMC thickness of SAC305 solder increased with increasing radiation exposure, particularly the Cu_6Sn_5 IMC layer. The heat generated during gamma radiation exposure promoted the growth of the IMC layer. The eutectic phase area analysis showed a similar trend to the hardness values. A larger eutectic area contributed to higher hardness by preventing dislocation occurrence and restricting the penetration of the indenter. Further research is needed to investigate the long-term effects of wide range gamma radiation exposure on the mechanical and microstructural properties of solder materials and their implications for electronic devices' performance in radiation-intensive environments. Research and innovation in material science, simulation techniques, and mitigation strategies will play a pivotal role in advancing the field and enhancing the resilience of electronic devices to radiation-induced mechanical degradation.

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