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INFLUENCE OF GAMMA RADIATION ON EUTECTIC PHASE AREA AND HARDNESS PROPERTIES OF SAC305 SOLDER

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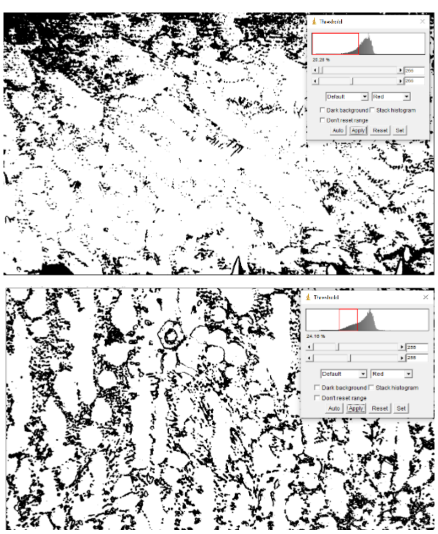
Graphical abstract



Abstract

Gamma radiation plays an important role in changing the properties and behavior of the materials. In this present work, the correlation between the intermetallic compound (IMC), eutectic phase area and hardness of the lead-free solder radiated with low dose gamma radiation were investigated. Using a technique known as stencil printing, the solder paste was manually applied to the printed circuit board (PCB). Subsequently, the solder PCB was reflow soldered at 260 ˚C and allowed to expose to a variation of low dose gamma radiation (5, 10, 15, 20 and 25 Gy). Prior to the indentation test, the samples were subjected to a metallographic process to examine the cross-section of the interface between the solder and the substrate. The microstructure, intermetallic compound (IMC) and hardness properties were captured and measured via optical microscope and nanoindentation test equipment respectively. The IMC thickness of the solders increased with increasing radiation exposure, suggesting that gamma radiation influenced the morphologies of the SAC305 solder, leading to a change in IMC thickness. The effect of the exposure of various doses of gamma on the phase distribution of the eutectic in the SAC305 solder was also investigated. The eutectic phase area showed a comparable trend in the value of hardness obtained. The eutectic area increased up to 29.65 % after being radiated by 15 Gy of gamma, then decreased to 17.66 % when exposed to 25 Gy. From the nanoindentation test, the load-displacement curves extracted the value of hardness of the SAC305 solder. It was found that, as the samples were exposed to 5 to 15 Gy of radiation, the hardness increased to 0.36 GPa. However, the hardness value of the sample decreased to 0.23 GPa as the dose increased. This phenomenon could be attributed to structural and atomic changes in the SAC305 solder alloy. The heat generated by gamma rays coarsen the microstructure and IMC hence influencing the hardness of the solder.

Keywords: Gamma radiation, Sn-Ag-Cu solder, microstructure, hardness, eutectic phase area

Abstrak

Sinaran gama memainkan peranan penting dalam mengubah sifat dan tingkah laku bahan. Dalam kerja ini, perkaitan antara sebatian antara logam (IMC), luas fasa eutektik dan kekerasan pateri bebas plumbum iaitu; SAC305 yang tersinar gama dos rendah telah diselidik. Menggunakan teknik yang dikenali sebagai cetakan stensil, pes pateri telah digunakan secara manual pada papan litar bercetak (PCB). Selepas itu, PCB telah dipaterikan secara aliran semula pada 260 ˚C dan dibenarkan untuk mendedahkan kepada variasi sinaran gama dos rendah (5, 10, 15, 20 dan 25 Gy). Sebelum ujian lekukan, sampel telah tertakluk kepada proses metalografik untuk memerhati keratan rentas antara muka antara pateri dan substrat. Struktur mikro, sebatian antara logam (IMC) dan sifat kekerasan masing-masing telah dicerap dan diukur melalui mikroskop optik dan peralatan ujian pelekukan nano. Ketebalan IMC pateri meningkat dengan peningkatan pendedahan sinaran, menunjukkan bahawa sinaran gama mempengaruhi morfologi pateri SAC305, membawa kepada perubahan dalam ketebalan IMC. Kesan pendedahan pelbagai dos gama pada taburan fasa eutektik dalam pateri SAC305 juga telah diselidiki. Luas fasa eutektik menunjukkan trend setanding nilai kekerasan yang diperolehi. Luas eutektik meningkat sehingga 29.65 % selepas tersinar oleh 15 Gy gama, kemudian menurun kepada 17.66 % apabila terdedah kepada 25 Gy. Daripada ujian pelekukan nano, lengkuk beban-kedalaman mengekstrak nilai kekerasan pateri SAC305. Didapati bahawa, apabila sampel terdedah kepada sinaran radiasi 5 hingga 15 Gy, kekerasan meningkat kepada 0.36 GPa. Walau bagaimanapun, nilai kekerasan sampel menurun kepada kepada 0.23 GPa dengan peningkatan dos. Fenomena ini boleh dikaitkan dengan perubahan struktur dan atom dalam aloi pateri SAC305. Haba yang terhasil sinar gama mengasarkan struktur mikro dan IMC seterusnya mempengaruhi kekerasan solder.

Kata kunci: Sinaran gama, pateri Sn-Ag-Cu, struktur mikro, kekerasan, luas fasa eutektik

1.0 INTRODUCTION

Soldering, which is an integral part of the integrated circuits (IC) manufacturing process, supports the bonding of electrical conduction in integrated circuits between electrical components and printed circuit boards [1]. Electronic devices are commonly used in all facets of technology in this modern day and are most usually found in domestic products such as cell phones, personal computers, storage devices, and other daily use devices. The solder joints that link electronic components provide the backbone of an electronic system, acting as both electrical connections and mechanical support between the components and the board [2].

Along with concurrent progress, the manufacture of electronic devices with multifunctional characteristics has driven electronic packing to increase its density throughout time. Due to technological advancement, solder junctions are continually reducing to a much smaller scale. In particular, the solder volume per junction of standard surface mount technology (SMT), which is approximately 0.01 to 1 mm^3, has been decreased to 10^{-4} ~ 10^{-5} mm^3 in modern fine-pitch assembly [3][4]. Solder joint size reduction has a substantial impact on the interfacial interaction of intermetallic compound (IMC) layer development and the progression of the solder matrix's microstructure [5]. According to Jeon *et al.*, (2020), the solder joint is subjected to a high heat density [6], which causes the IMC layer to expand, causing the joints to crack. As a result, the solder joint's reliability is jeopardized, especially in extreme settings. Furthermore, higher thermal coarsens the solder matrix's microstructure particle sizes and interfacial phase. Thus, the solder matrix might be softened, resulting in further deterioration in the hardness properties of the solder [7].

Traditional tin-based solder systems have been phased out of electronic manufacturing in order to lessen the toxicity and dangerous consequences caused by the use of lead as a soldering metal. Tin-silver-copper (Sn-Ag-Cu, SAC) solder alloys have been evaluated as a promising candidate for joining interconnections on Cu substrates in electronics assembly after significant investigation. Several SAC solder alloy series are currently being produced and explored, including SAC305, SAC0307, SAC387, and SAC396 [7].

Gamma radiation was employed as a technique in this research to investigate its effects on solder joint reliability. The influence of ionizing radiation, specifically gamma radiation, has generated curiosity, particularly in terms of the durability of electronic materials under extreme temperatures, as it can cause the atoms of one substance to become ionised or charged. According to Vaiserman *et al*., (2018) exposure to natural and man-made radiation sources can occur on a regular basis, particularly in research facilities and medical institutes. Radiation's major effects on the matter can be classified into three categories: atomic displacement, impurity generation, and ionization [8], [9]. Wang *et al.,* (2019) found that energetic electrons produced by gamma radiation altered the morphology of the IMC layer and caused microscopic flaws in the characteristics of SnPb solder connections [2]. Other than that, Lehan *et al.,* (2022) reported that exposure to gamma radiation changes the natural behavior of SAC solder joints to become softer and more plastic [10]. 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 [11]. This raises serious concerns about the micromechanical alterations and functionality of solder material as a result of being exposed 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 junction may have performed poorly due to gamma radiation-induced changes in its mechanical and microstructure properties. Thus, this paper aimed to explore the correlation between the hardness, IMC and eutectic phase area under low gamma radiation exposure.

2.0 METHODOLOGY

The lead-free solder pastes of $SnAg_3Cu_{0.5}$ (SAC305) is supplied by the Red Ring Solder (Malaysia) Sdn. Bhd. was prepared by manually deposited onto the printed circuit board (PCB) using stencil printing to form a solder joint. Prior to irradiation using gamma radiation, the samples went through reflow soldering at 260 °C of the maximum temperature. An industrial Excel 220 Gamma Cell irradiator with a Cobalt-60 source was used to irradiate the samples at 5, 10, 15, 20, and 25 Gy, with an operating dosage of 0.84 kGy/h. For evaluating mechanical behavior using nanoindentation analysis, the samples were metallographically prepared including mounting, grinding, polishing and etching. The samples were cold mounted with epoxy, then polished with DP Nap polishing cloth and 1 and 0.25 µm diamond spray. The samples were etched (5 % hydrochloric acid and 95 % methanol) and examined under an optical microscope (Inverted Metallurgical Microscope, Eclipse M200) for microstructural examination, including evaluation of IMC growth on soldered samples. Average IMC thickness was investigated using ImageJ software where the total thickness was divided by 100 [12]. In addition, the measurement of the eutectic phase area was calculated using ImageJ software by determining its thresholding. Afterwards the indentation was conducted at the center of the solder joint with three-sided pyramidal Berkovich tip using a Bruker-Hysitron TI950 Triboindenter. During the indentation, the loading rate was kept constant at 0.5 mN/s to the solder surface, achieving a maximum load of 10 mN and remaining for 10 s until unloading. The nanoindentation data attained was analyzed using the Oliver and Pharr method [13] which corresponded to the hardness of the solder samples.

3.0 RESULTS AND DISCUSSION

From the analysis conducted, the IMC thickness, eutectic phase area and average size and hardness of SAC305 were tabulated in Table 1. Figure 1 shows the traced of 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. As tabulated in Table 1, the IMC thickness of the tested solders increased with increasing radiation exposure, suggesting that gamma radiation could influence the morphologies of SAC305 solder, leading 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 the irradiation, caused the 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 and substrate using heat and high pressure [7]. 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 interdiffusion of substrate and solder components [14]. In the control sample, the IMC produced between 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 the gamma radiation promotes the growth of Cu_6Sn_5 IMC thus increasing the IMC thickness.

Table 1 Hardness, IMC thickness and eutectic phase are of SAC305 solder

Sample (Gy)	IMC Thickness (μm)	Eutectic phase area (%)	Eutectic average size (μm)	Hardness (GPa)
Control	4.97	20.28	2.55	0.26
5	5.24	24.16	4.87	0.28
10	6.53	27.30	5.12	0.36
15	6.56	29.65	5.62	0.37
20	6.80	25.34	2.73	0.30
25	6.83	23.74	0.65	0.23

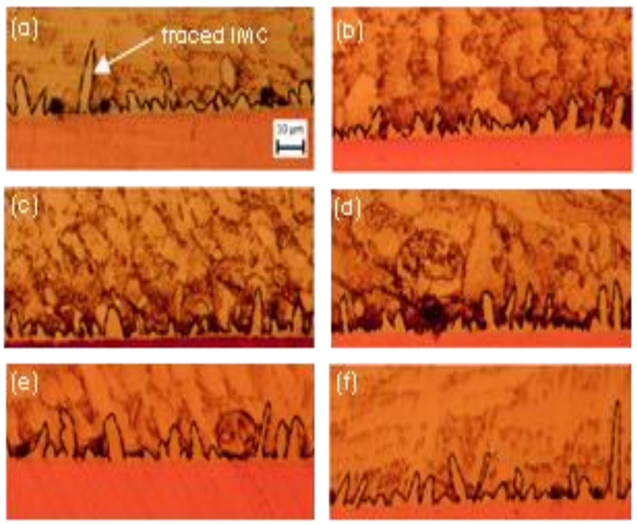


Figure 1 IMC trace of (a) control SAC305, (b) 5 Gy, (c) 10 Gy, (d) 15 Gy, (e) 20 Gy, and (f) 25 Gy

Figure 2 shows the microstructure of SAC lead-free solder consisting of primary β-Sn, platelet-type Ag_3Sn, and scallop-like Cu_6Sn_5. The element found is as reported in our previous study [10]. The phase distribution of the eutectic in the SAC305 solder was altered by different dosages of gamma radiation.

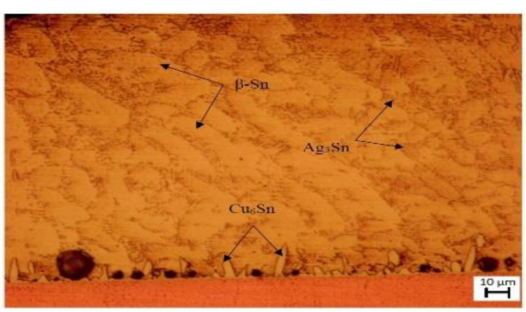


Figure 2 Microstructure of control SAC305 solder

Figure 3 shows the micrograph of SAC305 after etching process, revealing the eutectic phase area of the solder. By using ImageJ, the eutectic phase area was analysis and tabulated in Table 1. According to Table 1, the eutectic phase area and its size particle for the SAC solder showed comparable trend to the hardness obtained which based on our previous study [10] and Kong *et al*., (2017) [15]. According to El-Daly *et al.*, (2016) [16], the heat generated by gamma rays resulted in a coarsening behavior 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 [17]. Similarly, as the eutectic area shrinks, the solder's hardness decreases.

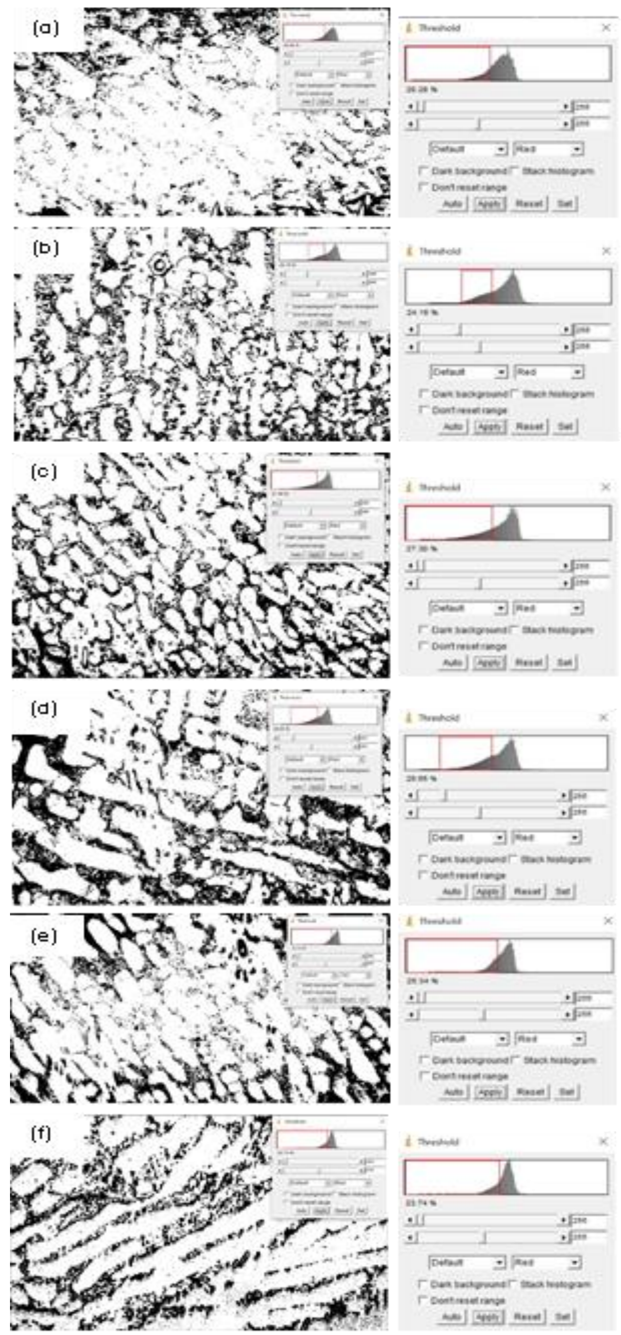


Figure 3 The micrograph of (a) control SAC305, (b) 5 Gy, (c) 10 Gy, (d) 15 Gy, (e) 20 Gy, and (f) 25 Gy after etching

The hardness values for SAC305 solder are obtained from nanoindentation test. The strength of the material is the rigidity of the material to the occurrence of plastic deformation owing to applied force and was abnormalities in the area where the indentation originated [18]. In this study, the hardness value increased following gamma radiation exposure up to 15 Gy, and then declined as the dose increased (25 Gy) due to structural and atomic rearrangements of solder materials. Yusoff *et al.,* (2014) [19] reported that gamma radiation able to alters basic qualities of materials such as its hardness and ductility. However, as radiation dose increases from 20 to 25 Gy, the IMC thickness continue to increase due to more heat generated. However, the value of the eutectic phase area and hardness decreased due to the changes in the morphology of the SAC305 solder. This result was similar in trend the findings of Wen *et al.,* (2019) [20], who discovered that exposure up to 1000 h of gamma radiation, resulted the reduction in the shear strength of gold-tin (AuSn) solder samples due to irregular IMC. 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 affecting the hardness.

It can be concluded that exposure to gamma radiation coarsen and increased the IMC thickness. The heat released during radiation promotes the development of Cu_6Sn_5 IMC thus enhancing the diffusion of Sn and Cu atoms. The hardness of the solder increased as it was subjected to gamma radiation up to 15 Gy before decreasing when exposed to greater doses of radiation due to structural and atomic rearrangement of solder material. The eutectic phase area of SAC305 solders is parallel to the hardness obtained. The area increased to 29.65 % when radiated with 15 Gy of gamma radiation and decreased to 23.74 % as the exposure dose increased to 25 Gy.

4.0 CONCLUSION

The correlation of IMC, eutectic phase area and hardness under low gamma radiation exposure on the SAC305 solder was successfully investigated via nanoindentation test and ImageJ software. As radiation dose increased up to 25 Gy, the IMC layer thickness of SAC305 solder joints increased to 6.83 µm as compared to the control sample. It is believed that the gamma radiation influenced and modified the microstructure of SAC305 solder, resulting in a change in IMC thickness. The eutectic phase area is parallel to the value of hardness obtained. The eutectic area increased up to 29.65% after radiated by 15 Gy of gamma, then decreased to 17.66 % when exposed to 25 Gy. As for the hardness, as exposed to 5 to 15 Gy of radiation, the hardness increased to 0.36 GPa and as it was further radiated, the value decreases to 0.23 GPa. These occurrences might be due to the changes in the structural and atomic arrangement of the solder. The heat released by gamma radiation coarsen the microstructure and increases the IMC thickness thus affecting the hardness of the solder.

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