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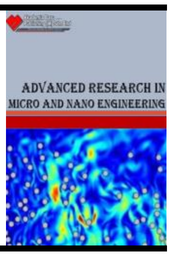

An Investigation of the Effect of Wide Range Gamma Radiation from Nanoindentation of the SAC305 Solder Alloy

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ABSTRACT

This study utilises nanoindentation testing to investigate the impact of varying gamma radiation doses on the micromechanical properties of Sn-Ag-Cu (SAC) alloy. Specifically, the focus is on evaluating changes in hardness, reduced modulus, and creep behaviour. The stencil-printed method and reflow soldering process were employed to apply the SAC solder paste and create solder joints on the surface of the printed circuit board. The soldered samples underwent exposure to gamma radiation at different doses, specifically 5, 50, 500, 5000, and 50000 Gy. The solder received in its original state was used as the control sample. Subsequently, the samples were subjected to a nanoindentation test in order to ascertain the correlation between load and depth, depth and dwell time, when exposed to radiation. The load-depth curve results indicate that there is a transition in the behaviour of solder joint materials from elastic to plastic deformation as the radiation dose increases. A finding has been made indicating that exposure to gamma radiation has the potential to induce a transition in the behaviour of SAC from an elastic state to a plastic state. The exposure to radiation doses has been found to induce changes in the atomic arrangement and structural properties of materials, leading to an increase in their hardness values. Nevertheless, it was observed that with increasing radiation doses up to 500 Gy, there was a noticeable decrease in the hardness value, which can be attributed to the occurrence of softening behaviour. Exposure to a high dose exceeding 5000 Gy leads to atomic displacement and transmutation products, subsequently resulting in plastic deformation. The stress exponent value signifies the occurrence of the deformation mechanism in solder material when exposed to gamma radiation. The study revealed that there was a shift in the deformation mechanism from grain boundary sliding to dislocation climb as the radiation dose increased from low to high levels.

Keywords:
Gamma radiation; Sn-Ag-Cu solder; leadfree solder; P-h curve; hardness; reduced modulus

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1. Introduction

Radiation can cause a variety of problems for electronic systems, including disruption of normal operation and component damage. Electronic systems can be designed with shielding or other protective measures to reduce or prevent exposure to radiation. The space station is exposed to a range of radiation types, including gamma radiation. Spacecraft electronic equipment may be exposed to high levels of radiation [1]. In determining the reliability of an electronic system, the most important component to consider is solder joint. Solder joint is used to create a conductive connection between the various circuit components, such as a microprocessor and a printed circuit board. This permits the controlled flow of electricity through the circuit, allowing the electronic device to function properly. The reliability of these interconnections and electronic packages is determined in part by the mechanical properties of solder joints, such as hardness, yield strength, shear strength, creep, and fatigue [2].

The tin-silver-copper (Sn-Ag-Cu, SAC) alloy has been widely used as an interconnect material due to low melting point and excellent wetting to replace for tin-lead (Sn-Pb) solder [3]. SAC305, also known as 96.5% tin (Sn), 3.0% silver (Ag), and 0.5% copper (Cu), has become the most widely used lead-free solder in industry due to its widespread recognition as an excellent lead-free solder with a melting point of 225 °C, which is ideal for electronic assembly stability. Even though innovations in lead-free soldering technologies have been acknowledged by the electronics industry, there are challenges associated with their applications [4]. The most susceptible part of an electrical component to damage is the solder joint [5]. Due to the failure of a single solder junction, electrical discontinuity occurred. The most prevalent solder joint failure was an open circuit caused by solder joint cracks, including complete fractures through the solder joint cross section [6]. It is of great interest to study the properties of solder alloys used in electronic devices because they contribute to a better understanding of long-term dependability [7].

The effects of radiation on solder are dependent on the type and duration of radiation exposure. In general, high radiation levels can harm electronic components, including solder, which detrimental their mechanical and electrical properties of the solder, such as its melting point and conductivity. In some instances, prolonged radiation exposure can cause the solder's atoms to become dispersed, resulting in a loss of structural integrity. This can result in the formation of voids or other defects in the solder, compromising its ability to form a reliable and durable bond between the components it is joining [8]. Several studies [2,9,10] have provided evidence that the mechanical properties of solder joints are negatively affected by harsh environments. In the study conducted by Guan *et al.,* [11], it was observed through differential scanning calorimetry (DSC) analysis that the melting temperature of the SAC305 solder alloy decreased with prolonged irradiation time. Various industries, such as nondestructive testing, medical science, health services, and radiography, frequently subject electronic devices to radiation [1]. Furthermore, the preservation of the equipment's structural integrity will guarantee its continued proper functioning, even under conditions of heightened radiation exposure.

While with reasons of safety, the study of the effects of ionising radiation on solder materials is a perennial topic of study. Particularly in the electrical system, radiation particles such as gamma rays, heavy ions, and powerful electrons can impair device procedures and cause module failure [12]. Earlier study reported that the dislocation activity occurred as gold wire bonding exposed to gamma rays which resulted in microstructural changes [13]. Consequently, this raises a significant concern regarding the behaviour of solder materials when exposed to gamma radiation. Several earlier studies have examined the effect of gamma irradiation on the mechanical, electrical, optical, and damage mechanisms of different types of solder joints [14]. Nevertheless, there is a scarcity of research concerning the impact of radiation on the mechanical characteristics of solder when exposed to elevated levels of radiation. Yusoff *et al.,* [15] observed that the stress exponent value exhibited distinct deformation mechanisms under conditions of limited gamma radiation exposure. Hence, this raises a significant inquiry regarding the deformation mechanism of solder materials subsequent to their exposure to elevated doses of gamma radiation. Hence, the objective of this study was to investigate the impact of varying levels of gamma radiation dosage on the micromechanical properties, specifically hardness, reduced modulus, and creep characteristics. Therefore, further investigation is necessary to examine the impact of gamma irradiation on SAC305 solder junctions, potentially prompting subsequent inquiries into the dependability of these solder connections affected by radiation. Additionally, it functions as a point of reference for the development of solder connections that are resistant to radiation.

2. Methodology

2.1 Research Process

The SAC305 solder joint was prepared using stencil printing of Sn3.0Ag0.5Cu solder paste. The PCB was then subjected to a 225°C reflow soldering process to form the solder joint. The sample of solder was cut to a small size at the designated location. Once the samples were soldered, they were prepared for irradiation. In this study, soldered samples were exposed to five exponentially increasing doses of gamma radiation: 5 Gy, 50 Gy, 500 Gy, 5000 Gy, and 50000 Gy at a dose rate of 930 Gy/h. The sample were irradiated using gamma cells (Excel 220 Gamma Cell irradiator). A non-irradiated SAC305 joint with a gamma dose of 0 Gy was used for the control sample. The following Eq. (1) was used to determine dose rates (A) and exposure time

$$A = A_o e^{-\lambda t} \quad (1)$$

where A is the current activity dose rate, A_o is the original activity dose rate, λ is the decay constant that is equal to $[\ln 2]/t_{1/2}$, t is the time and $t_{1/2}$ is the half-life value of the cobalt source. Then the time of the exposure can be calculated with the Eq. (2)

$$Exposure\ Time = \frac{Dose\ of\ sample}{A} \quad (2)$$

At room temperature, a Nanotest^{TM} Micro Materials indenter was used to conduct a nanoindentation test. The samples were mounted with 15 g of powdered epoxy resin and 10 g of liquid epoxy resin prior to the nanoindentation procedure. In a plastic mould, the epoxy resin powder and epoxy resin fluid were carefully mixed for 30 s. After pouring it into the sample, it was allowed to cool to room temperature. As soon as the substance solidifies (within four hours), the sample is removed from the plastic mould.

The indentation test is capable of assessing various mechanical properties, such as creep, hardness, and reduced modulus. This is achieved by quantifying both the applied load and the depth of penetration, particularly in small-sized samples, as demonstrated in previous studies [16,17]. The measurement of penetration depth in nanoindentation testing involves the application of a load to the indenter, followed by the measurement of the resulting depth. This approach obviates the necessity for visual examination of the indentations. One element of the load-depth curve that encompasses both elastic and plastic deformations. During the initial loading phase, an elastic deformation was observed [18]. During the process of loading and unloading, there is a continuous monitoring of the displacement and load. The load-depth curves are subsequently employed to ascertain the hardness and reduced modulus of the material [19]. In this study, three indentations were made at the center of solder to obtain an average result. The indentation force was 10 mN, with loading and unloading rates of 0.5 mNs^{-1} and dwell times as long as 30 s gave a result of depth versus dwell time. The samples were then ground on a grinding machine with silicon carbide measuring paper (600, 800, and 1200 grit) until they displayed a flat surface. The sample was then polished using a machine that sprayed with 1 and 0.25 µm diamond particles. For optimal results, the inverted metallurgical microscope was used to examine the sample's fine surface and cross-section prior to creating indentations on the solder at controlled room temperature. The acquired nanoindentation results (load versus depth) were analysed according to Oliver and Pharr's method [20] to extract the hardness and reduced modulus value. Then, the graph of indentation depth versus time also plotted to study the creep behaviour by determine the stress exponent value.

3. Results

3.1 The Eutectic Phase Area

Figure 1 and Figure 2 illustrate the eutectic phase area of an as-received and the representative eutectic phase area of a gamma-irradiated SAC305 solder joint based on software ImageJ. It demonstrated the increase in the white area after irradiation of the sample. The obtained results revealed that the exposure to gamma radiation, the eutectic phase region of SAC305 solder was altered. The findings obtained is in line with study conducted by Lehan *et al.,* (2022) using 5 to 25 Gy dose of radiation on their solder joint which is stated that there was a change of eutectic area [21].

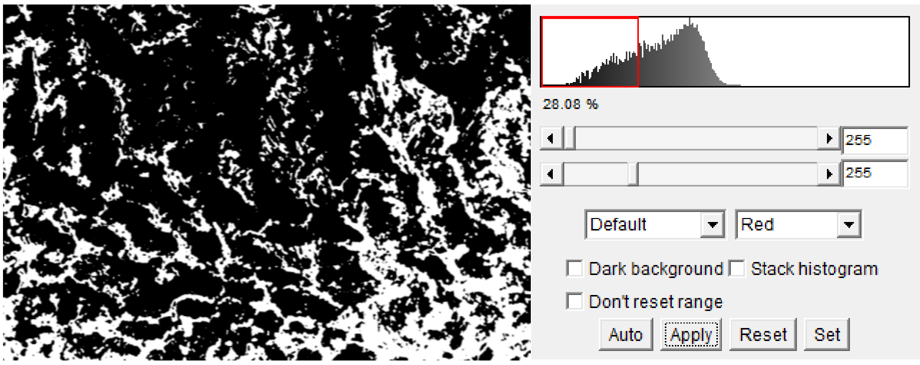

Fig. 1. Eutectic phase area images of as-received SAC305

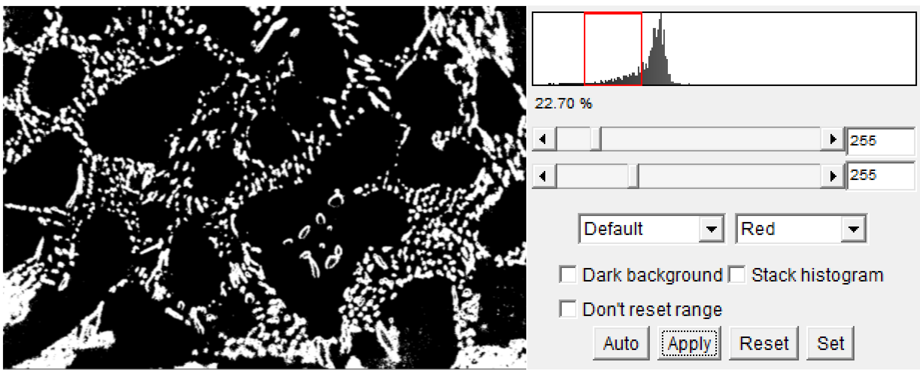

Fig. 2. Eutectic phase area images of representative radiated SAC305

3.2 Load Versus Depth

Figure 3 depicts the graph of load, *P* (mN) versus depth, *h* (nm) for as received and radiated samples. The *P-h* curve is the finger print of the materials. The trend of indentation depth is increasing up to 50 Gy and then beginning to decrease after exposure to 500 Gy. The depth for 5000 Gy was less than as received, whereas the depth for 50000 Gy increased. The greater the depth displacement, the lower the surface material's resistance to an applied force [22]. With the increase in penetration, plastic deformation will start to develop. Once the indenter has been entirely removed, only the elastic part of the deformation has taken place [13]. The forms of the indentation *P-h* curves revealed the structural changes that occurred in the indented sample during the test. As shown in Figure 3, the *P-h* curve for the 50 Gy soldered sample has a distinct staircase pattern when compared to those of other samples. Discontinuities and microstructure of the material during indentation were linked to displacement rupture in this staircase-shaped specimen [23]. The unloading segment of the *P-h* curve reveals the manifestation of altered intrinsic behaviour in the solder joint. The observed trend indicates that with an increase in radiation dose from 50 to 500 Gy, the *P-h* curve undergoes a rightward shift and assumes a linear downward trajectory, specifically in the unloading portion of the *P-h* curve. This phenomenon posits that the solder materials exhibit increased plasticity with an increase in radiation dose. Based on the findings obtained from the *P-h* curve analysis, it can be inferred that the SAC305 solder joint undergoes a transition in its mechanical response from elastic to plastic deformation as the radiation dose increases. The data pertaining to hardness values was obtained by extracting information from the load-depth profiles. This data was then graphically represented in Figure 4.

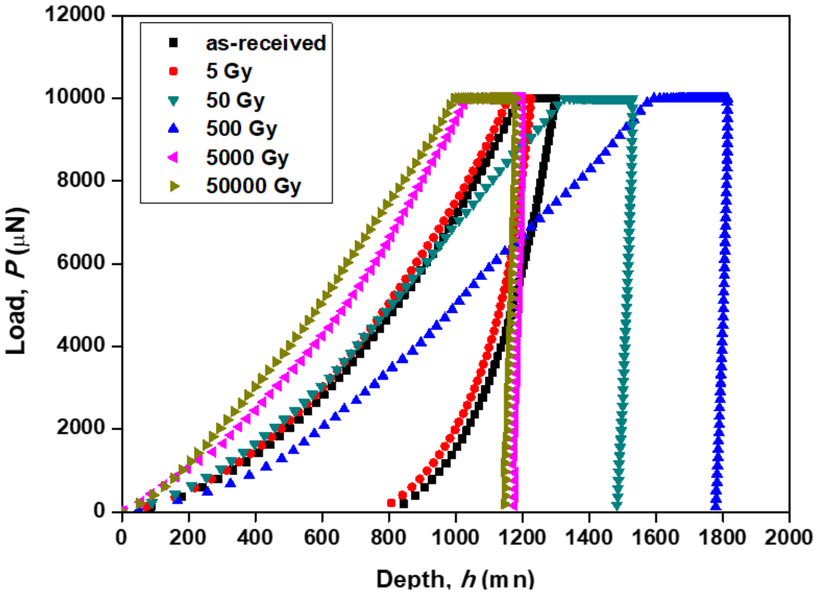

Fig. 3. Load versus depth for SAC305 solder joint

3.3 Hardness

Figure 4 shows the bar graph of hardness versus radiation dose for SAC305 solder with as received sample and gamma radiated samples. The yield strength of SAC305 solder is derived from the nanoindentation test hardness value [24]. The obtained graph demonstrates that after being exposure to 5 Gy, hardness value increased to 0.28 GPa. This is due to radiation induced atomic arrangement and structural of the materials [13]. Nevertheless, it was observed that when the exposure dose was elevated to 50 and 500 Gy, the hardness value exhibited a decline to 0.15 GPa. This decrease can be attributed to the occurrence of softening behaviour and the development of defects, including voids and cracks [6]. According to Nasir *et al.,* [25] the hardness values will be automatically decreased as the depth displacement increased. The hardness values, which were impacted by atomic defects, influenced the amount of force required for plastic deformation of the material [15]. According to Grossbeck [26], radiation damage can strengthen the sample by altering the solder alloy's atomic structure by adding impediments to dislocation motion. As a result of atomic displacement and transmutation products, this leads to plastic deformation, increasing hardness by more than 5000 Gy.

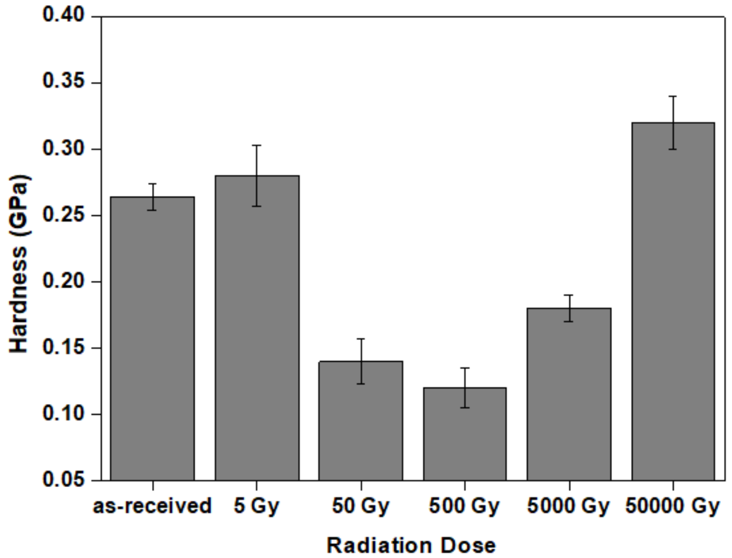

Fig. 4. Hardness versus radiation dose for SAC305 solder joint

3.4 Stress Exponent

In this study, the creep or constant load behaviour of a SAC305 solder joint is examined in details. Figure 5 depicts the creep versus time curve, also referred to as the indentation depth displacement curve for both as-received and irradiated SAC305 solder alloys. The indentation depth displacement reflects the change in depth after 30 seconds under a constant load of 10 mN. Gamma radiation exposure of 5 Gy has more indentation depth than those which exposed at 50 Gy. 50000 Gy has less indentation depth than those exposed at 500 Gy and 5000 Gy. This due to plastic deformation that some materials may exhibit time-dependent deformation mechanisms, such as creep, even under relatively low loads [15]. Creep refers to the gradual deformation of a material over time under a constant load. If creep is present during the indentation test, it can cause additional plastic deformation and result in a larger indentation depth displacement.

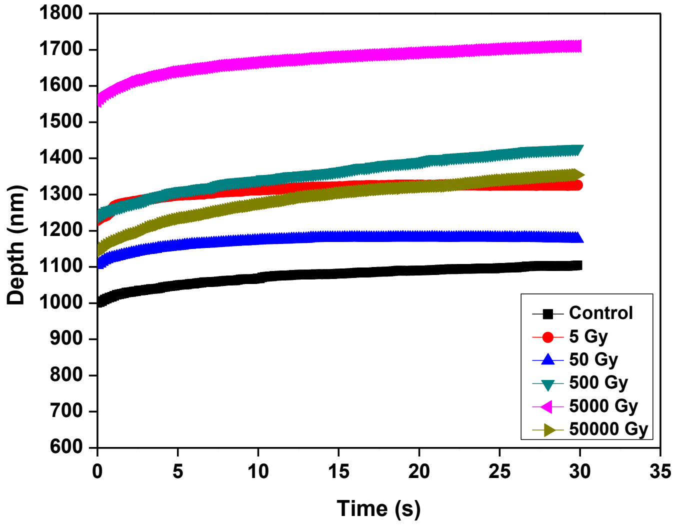

Fig. 5. Depth versus dwell time

The stress exponent can be used to describe how a material deforms when subjected to a load. The value of the stress exponent can be utilised to determine the deformation mechanism of solder alloys [27]. Figure 6 depicts the results of the stress exponent in relation to five distinct types of situations. The stress exponent is 1 indicated the presence of diffusion creep which caused by the lattice or grain boundary diffusion, stress exponent value between 2 and 3 are associated with grain boundary sliding, whereas the stress exponent value between 4 and 6 is associated with dislocation climb. The stress exponent value between 7 and 10 indicated dislocation movement, whereas values of 10 and above indicated dislocation glide according to the previous studies [28,29]. From the Figure 6 it showed that begin with as-received sample gave a value of 3 which mean there is grain boundary sliding which was normal when there was pressure given to a material. After exposure to 5 Gy, the value of 4 indicates a dislocation climb. At 50 Gy, it gave a value of 2 mean there is grain sliding boundary. For 500 Gy exposure, value of 1 which mean there was a diffusion creep and there is the dislocation climb during the exposure to 5000 Gy and 50000 Gy radiation dose.

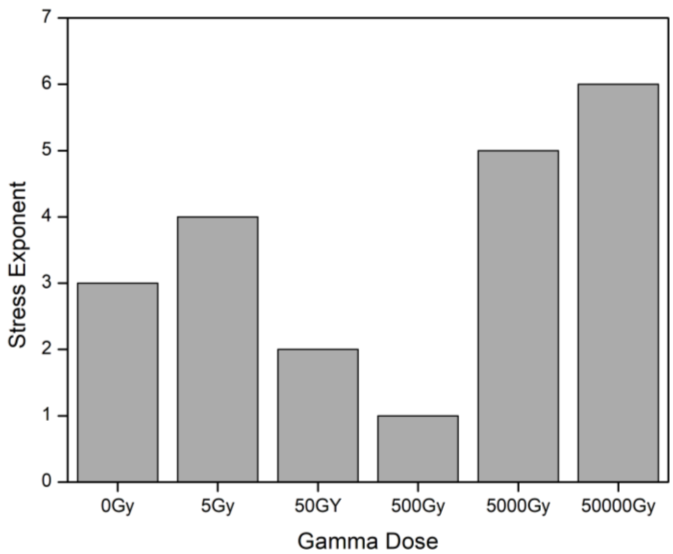

Fig. 6. As received and irradiated samples result for stress exponent

3.5 Reduced Modulus

The graphical representation in Figure 7 illustrates the correlation between the reduced modulus and the level of radiation exposure. The term "reduced modulus" typically pertains to the inherent characteristics of a material, such as its atomic bonding and stiffness [12]. According to the results obtained, as exposed to gamma radiation the value of reduced modulus increased to 83.5 GPa. Nevertheless, when the radiation dose was elevated to 50 Gy and 500 Gy, the reduced modulus value exhibited a decrease of over 50%, reaching 38.9 GPa and 30.8 GPa, respectively. The reduced modulus exhibited an increase subsequent to exposure to doses of 5000 Gy and 50000 Gy. Some materials undergo phase transitions at specific temperatures or under certain conditions. These transitions can lead to changes in the material's crystal structure, bonding, or arrangement, resulting in altered modulus values. This can be correlate with the transition of the solder materials from elastic properties to plastic properties as radiation dose increased.

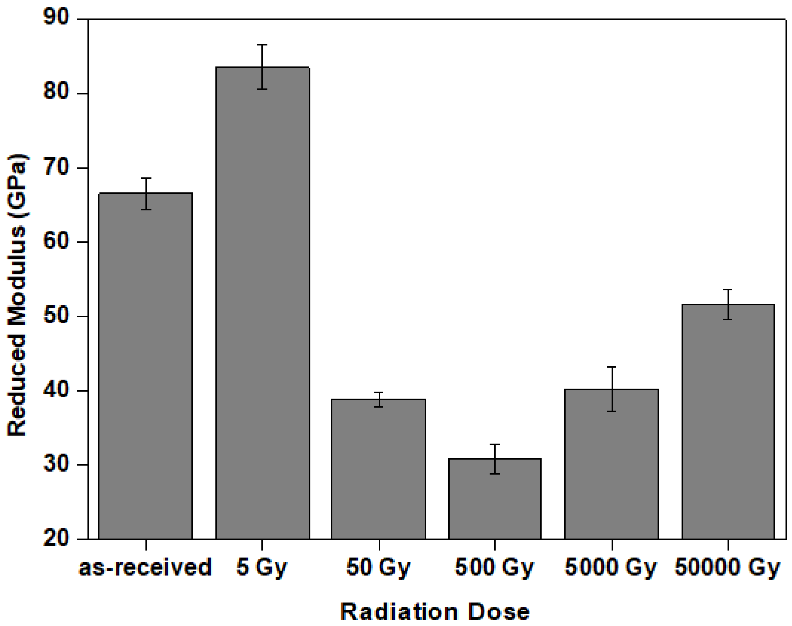

Fig. 7. Reduced modulus versus radiation dose of SAC305 solder joint

4. Conclusions

The present study aimed to obtain the load-depth curve, hardness, stress exponent, and reduced modulus of both as-received and irradiated SAC305 solder through the utilisation of nanoindentation testing. Based on the hardness measurements conducted, it was determined that the solder experienced a softening behaviour as a result of gamma radiation exposure. The hardness of solder can be altered through exposure to gamma radiation. The creep curve provides insight into the reduced modulus, indicating that gamma radiation has the potential to influence atomic bonding and stiffness. After experiencing an elevated radiation dose, the solder paste undergoes a transition from exhibiting elastic deformation to displaying plastic deformation. Consequently, this transition leads to alterations in the hardness and modulus values of the solder paste.

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