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EFFECT OF GAMMA RADIATION ON MICROMECHANICAL BEHAVIOR OF SNPB SOLDER ALLOY

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ABSTRACT

Tin-lead (SnPb) alloys are widely used in microelectronic packaging industry. It serves as a connector that provide the conductive path needed to achieve the connection from one circuit element to another circuit element. In this research, the effect of gamma irradiation on the micromechanical behaviour of tin-lead (SnPb) solder alloy has been investigated using the nano-indentation testing. Gamma radiation with a Cobalt-60 source were exposed to SnPb solders with different doses from 5 Gy to 500 Gy. In this study, the nano-indentation technique was used to understand the evolution of micromechanical properties (hardness and reduced modulus) of SnPb solder joints subjected to gamma irradiation. The results showed that the hardness of the SnPb alloys was enhanced with increasing of gamma radiation. The hardness was greatest at dose of 500 Gy of sample, 25.6 MPa and had the lowest value at un-irradiated sample. However, the reduced modulus was decreased by increasing the irradiation of gamma due to the intrinsic properties and the atomic bonding of the material.

Introduction

Nowadays with the technical advance, the world will see more satellites put into orbit around the earth. Tafazoli (2009) has found that the countries around the world are increasingly relying on space technology for telecommunications and military purposes. Public and private organizations have launched many satellites to discover the mysteries of the cosmos that have caught the attention of the entire world (Alhilal et al., 2019). It was quite different with the ground facilities, satellites moving in spaces that are far away from the earth. Marov (2020) stated that the harsh environment of space make each exploration is a big challenge due to the cosmic radiation which has always been the most serious risk to on-orbit satellite security.

Cosmic rays caused by the sun and other galaxies, are risk factor for satellites in the orbit for long duration deep space exploration missions (Badhwar & O'Neill, 1996). It is well known the space environment which is contribute to various levels of radiation-induced degradation that can cause significant effects in microelectronic devices, photonic devices, and integrated circuits. Radiation particles such as heavy ions, energetic electrons and gamma rays can degrade the device performance and cause the damage of module especially in the electrical systems (Li et al., 2017). To simulate approximately the space environment based on the equality of radiation effects, gamma ray source with 60 cobalt (Co-60) can be used in irradiating tests. Previous researchers reported that the test of the gamma ray irradiations were conducted on the electromechanical, electrical and electronics especially the interconnection part under the same radiation conditions that they will experience in the space environment (Schwank et al., 2013; Anderson et al., 2017). Wang et al. (2018) stated that Juno satellite took about five years to reach Jupiter but failed to go into orbit due to its mechanical damage. To ensure the microelectronic package in the satellites devices and equipment in a good condition, a detailed research of the gamma radiation effect to micromechanical behaviour of the solder joint is required.

Solder joint is considered as the weakest part in the aerospace microelectronic components where this device often failure in the space environments (Wen et al., 2019). The solder to connect the components in the microelectronic packages should have a good metallurgical bonding with the necessary mechanical strength and conduction properties (Cheng et al., 2017). The traditional tin-lead (SnPb) solder is broadly utilized in industry of aerospace which is not restricted by international law prohibiting the use of lead (Wang et al., 2018). SnPb solder also called soft solder and it was commercially available with tin concentrations weight between the range 5% and 70%. Therefore, SnPb solder alloy with an excellent reliability and wettability, low cost and low melting temperature (183°C) is relatively favourable in the field of microelectronic joining and manufacturing process of satellite (Zhang et al., 2019). Tu and Zeng (2001) reported that due to the toxicity of lead, it was banned to use in commercial electrical appliances for the aerospace industry. In this study, the SnPb solder alloy were exposed to Co-60 gamma ray with the variation of doses to evaluate gamma irradiation effect on the micromechanical behaviour of the joint.

The micromechanical properties were analysed through nano-indentation test on the cross section of the samples. Nano-indentation testing is special method for measuring the mechanical behaviours such as reduced modulus, E and hardness, H in a small size of materials. (Moharrami & Bull, 2014). The popularity of the nano-indentation technique has gained by the development of machines that capable to record the small displacements and loads at a high level of accuracy and precision. Due to the miniaturization of the device and the need smaller measurement of solder, conventional mechanical tests such as shear tests, tensile tests and macro hardness tests are not relevant for use. Oliver and Pharr (1992) was stated that the reduced modulus cannot be measured by using the conventional mechanical test because of the size of the contact impression which is not influence to the measurement. In nano-indentation test, the penetration depth below the sample surface is measured when a load is applied to the indenter. According to Oliver and Pharr method, the hardness is inversely proportional to the contact area and the Young's modulus is inversely proportional to the square root of the contact area. During the loading and unloading process, the load and displacement were continuously observed. The reduced modulus and hardness are then measured from the load–displacement curves (Li et al., 2016). The hardness was calculated as a maximum load divided by the expected area of the indentation. The hardness value can be calculated based on (1).

$$H = \frac{P_{max}}{A} \tag{1}$$

where P_{max} is the maximum load, and A is the indentation area of contact surface between the indenter and solder alloy. A reduce modulus, E_r can be described as in (2).

$$\frac{1}{E_r} = \frac{1-v^2}{E} + \frac{1-v_i^2}{E_i} \tag{2}$$

where E is the reduced modulus and v is the Poisson's ratio of the sample while E_i and v_i the reduced modulus and Poisson's ratio of the indenter, respectively (Oliver et al., 2004).

Materials and methods

In this research, SnPb solder paste and printed circuit board (PCB) with the surface finish of copper were supplied by RedRing Solder (M) Sdn. Bhd. The SnPb solder paste was printed manually onto the PCB by using the stencil printing. The soldered sample were reflowing in a reflow oven at 225 °C for eight seconds and cooled down at a room temperature. Then, the diamond cutter was used to cut the samples to the size of (5 mm × 7 mm × 1 mm). Co-60 gamma irradiation source exposed to the samples with variation of doses (5, 50, 500) Gy using Gamma Cell (Excell 220). One of the samples was left without irradiation (un-irradiated) as a control sample. After irradiation, powdered epoxy resin and liquid epoxy resin which are VersoCit-2 powder and liquid were mixed together and mould the sample with the ratio of 3: 2. These epoxy resins were slowly mixed in a plastic cup for 30 second. Then, the samples were ground using silicon carbide (SiC) paper with a measuring grit from 600, 800, 1000 and 1200 grit with a rotational speed between 50-200 rpm. The flat surface of the sample is then polished using a branded polishing machine with 1 μm diamond particles. To observe the cross section and surface of the samples, an optical microscope was used to obtain minimal surface effects before nano- indentation test. As it completed, the samples were prepared for nano-indentation test. The nano-indentation experiments were performed by using nano-indenter machine with Berkovich indenter tips. A loading and unloading with a constant rate of 0.5 mN / s is exerted to the sample surface until it reached the maximum load at 10mN. A 30 s dwell time was applied at maximum loading until the unloading process. Three indents were made at each peak depth to obtain average results.

Result and discussion

This work is focused on the micromechanical behaviour of SnPb solder alloy using surface finish of copper for un-irradiated and radiated samples. The penetration depth, *h* and the indentation load, *P* are recorded from the loading process during the nano-indentation test. Fig. 1 presents the typical load-displacement depth (*P*-*h*) curve for four samples of SnPb solder alloy. It shows the comparison between the radiated samples and un-irradiated sample of SnPb solder alloy. In nano-indentation technique, the penetration depth, *h* and the indentation load, *P* were recorded simultaneously when the tip of the indenter penetrated to the solder surface. The loading and unloading curves represent the elastic-plastic properties of solder. At the initial condition, the deformation during indentation was purely elastic. Plastic deformation begins to occur as the depth of penetration increased. During the indenter withdrawn, only elastic deformation occurs (Yusoff et al., 2014). It can be seen that the un-irradiated sample of SnPb solder alloy is the softest phase which was penetrated to an instantaneous depth of over 1400 nm.

For the irradiated sample, the maximum penetration depth was increased with reducing dose of gamma irradiation. In this case, when the penetration depth shifted to a smaller value, it shows the greater resistance of the layer (Chiu et al., 2018). As seen in Fig. 1, there was a visible staircase shape at the dose of 5 Gy gamma radiation from the loading part in the *P*-*h* curve of indentation which is called a pop-in event. This yield point has been found to occur at a discontinuity in the *P*-*h* curve. The initial pop-in typically occurs at a load, *P* that corresponds to the maximum shear stress under the indenter tip (Choi et al., 2012). During indentation, the resultant strain can cause some avalanche of atomic activity for activation nucleation and propagation of dislocations (Schuh et al., 2006). It stated that the pop-in event is also observed at a higher load which is associated with the evolution of a complex defect structure. Based on our observation, we assumed that this pop-in event might be due to the creation of the induced defects as gamma radiation effect. The electrons produced by gamma rays have caused the lattice atoms are shifted through the photoelectric and Compton effects (Yusoff et al., 2014; Saad et al., 2014).

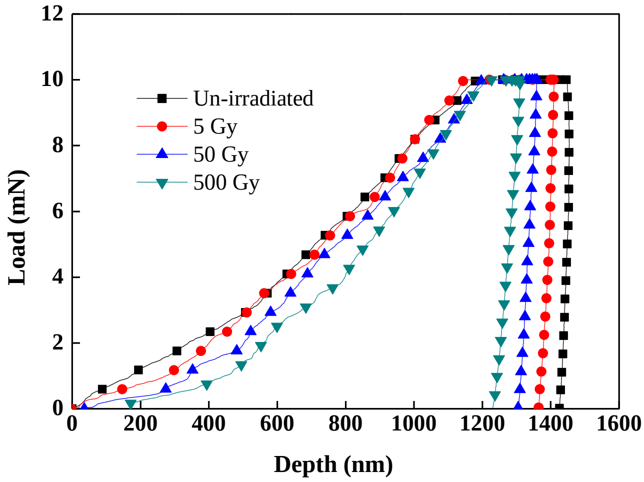

Fig. 1: Graph load versus depth for SnPb solder alloy.

Fig. 2 shows the variation values of hardness obtained at different dose of gamma radiation and un-irradiated sample. We obtained that the increasing differences in hardness results with decreasing the depth of penetration. The sample without irradiation has reached 186.7 MPa of hardness. After being irradiated by gamma radiation, the hardness was increased continuously with the increasing of the irradiation doses. The highest hardness of about 245.6 MPa was obtained for samples which was irradiated at 500 Gy. The result shows that the hardness was increased with the increasing the dose of gamma irradiation and it also strongly dependent on the penetration depth of the plastic deformation (Chen et al., 2009). Dwivedi et al. (2011) expressed that the hardness was depends on the defect in the atom thereby increasing force required to plastically deform the material. These defects are around the indentation and it becomes the specimen's resistance to plastic deformation. It is may be occurred during the irradiation and will influence the atomic structure of the samples. The influence of the radiation damage may lead to more strengthening of the samples.

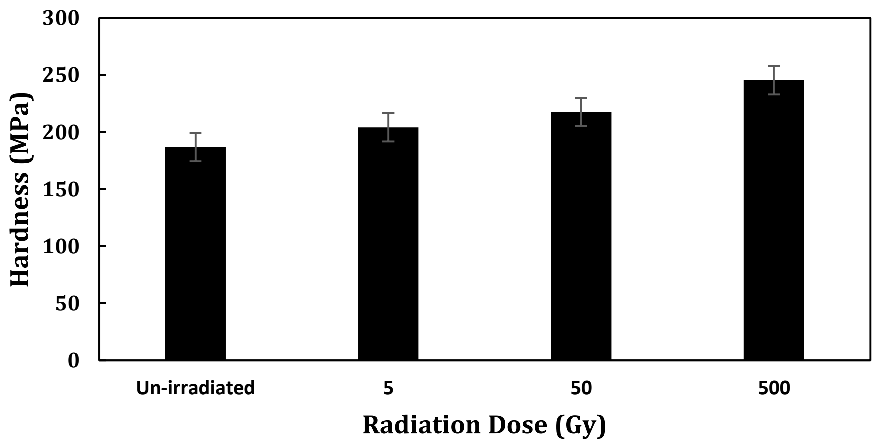

Fig. 2: Variation of hardness at different dose of gamma irradiation and un-irradiated samples.

Fig. 3 shows the reduced modulus of SnPb solder before and after exposed to gamma radiation which is obtained from unloading portion of *P-h* curves (Pharr et al., 2009). The values of reduced modulus were found randomly between 20-70 GPa. The reduced modulus of an un-irradiated sample is around 70 GPa which is the highest value among the radiated samples. The reduced modulus decreased when the dose of gamma irradiation was increased. It is also found that the reduced modulus of the 500 Gy of doses is lowest among the others. From physics perspective, reduced modulus is directly related to the atomic bond strength. The intrinsic properties of material are also related with the reduced modulus rather than the changes of microstructure (Shah et al., 2004). The irradiation damage will decrease the atomic bonds, hence reduces the elasticity of the material.

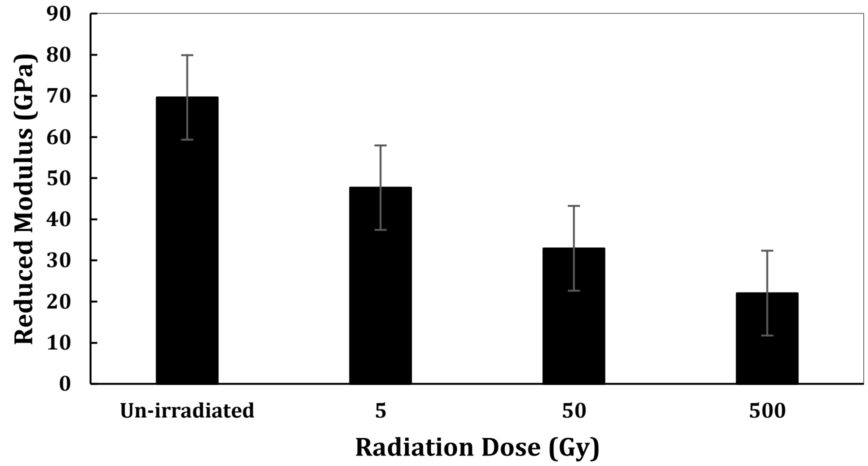

Fig. 3: Variation of reduced modulus at different dose of gamma irradiation and un-irradiated samples.

Conclusion

The gamma radiation effect on micromechanical behaviour of SnPb solder alloy was investigated by using nano-indentation technique. This technique is reliable for measuring the small size solders used in microelectronic industry and has been recognized to provide more detail than conventional methods. The measured of reduced modulus and hardness value extracted from the unloading part of load–displacement curve (*P-h* curve) by using Oliver and Pharr method. Based nano-indentation tests, the hardness has increased with the increasing dose of gamma radiation while the reduced modulus was decreased with the reducing irradiation dose. The sample with 500 Gy of gamma dose has the highest hardness of about 245.6 MPa. It shows that the gamma irradiation will influence the atomic structure of the samples and produced defects which is become the specimen's resistance to plastic deformation. Among four different types of samples, the SnPb solder which is un-irradiated with gamma ray has the highest reduced modulus, while the sample with 500 Gy of doses has the lowest reduced. It is due to intrinsic material properties such as atomic bonding of a substance.

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