Shock Wave Effect on Micromechanics Properties of Sn-Ag-Cu solder (SAC 387) via Nanoindentation

Nur Shafiqa Safee\textsuperscript{1}, Wan Yusmawati Wan Yusoff\textsuperscript{*}, Ariffin Ismail\textsuperscript{1}, Norliza Ismail\textsuperscript{2}, Emee Marina Salleh\textsuperscript{2}, Maria Abu Bakar\textsuperscript{3}, Azman Jalar\textsuperscript{2,3}

\textsuperscript{1}Center for Defence Foundation Studies, Universiti Pertahanan Nasional Malaysia, Kem Sg Besi, 57000 Kuala Lumpur, Malaysia
\textsuperscript{2}School of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia,
\textsuperscript{3}Institute of Microengineering and Nanoelectronics, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia,

E-mails: nshafiqasafee@gmail.com; yusmawati@upnm.edu.my*; ariffin@upnm.edu.my; iza_nza@yahoo.com; emme@ukm.edu.my; mabmarya@gmail.com; azmn@ukm.my

Abstract. A variety of Sn-Ag-Cu solder alloys have been proposed and recommended for use in industrial organizations for example Sn-95.5Ag3.8Cu-0.7 (SAC 387) by the European Consortium Brite-Euram in the European Union. In this study an effect of shock wave on micromechanics properties of SAC 387 solder was investigated via nanoindentation approach. Solder joint of SAC 387 on copper substrate was prepared by hand soldering techniques. Then soldered samples were exposed to shock wave at different distance of 1 m, 2 m and 3 m. The shock wave test was conducted using 500 g of trinitrotoluene (TNT). Hardness value of SAC 387 decreased from 300 MPa to 130 MPa after exposure. However the hardness and reduced modulus increased with increasing distance of the shock wave. The phenomenon revealed that shock wave deteriorated the micromechanics properties of soldered samples.

1. Introduction
Lead-free solder has been spread extensively in manufacturing many electronic applications due to the toxicity of lead for human health. A Sn-Ag-Cu ternary alloy is recommended to be a replacement of a Sn-Pb eutectic solder which has been used in electronic device. It’s due to Sn-Ag-Cu ternary solder has superb mechanical properties compared to Sn-Pb eutectic solder which are creep resistance, fatigue resistance, thermal resistance and tensile strength [1].

The mechanical stability of solder interconnects during dynamic conditions is crucial for high reliability electronic device especially in military in order to fulfill a vital role in the success of a mission [2]. The demand for complexity of electronic equipment such as low volume and highly sophisticated especially in military has resulted in an increase need to understand the failure mechanism dynamic load including drop, vibration and shock event.

A shock wave within a distance of about ten mean-free-path length was characterized by the very rapid increase, of all the physical properties, of the ambient gas, namely, the temperature, entropy density, particle velocity, and hydrostatic pressure. Based on previous research study by Wang et. al, there are many advantages of high pressure in reducing atom diffusion coefficient, to refine of grain and crystal structure, facilitate nucleus formation, and resulting in restrain in grain growth. Today,
high pressure has been appealing researchers’ huge attention because it can enhance microstructure of alloys [3-4]. The shock wave expands spherically and achieves pressure peaks for forming processes in the range of some mega Pascal [5]. Research conducted by Trdan et. al [6] revealed that shock wave refined the grain size of Al-Mg-Si alloy. Meanwhile Aydogan et. al [7], found shock loading increase the dislocation density and indirectly increase the hardness of HT-9 ferritic/martensitic steels.

The development of machine using nanoindentation method gained popularity that were capable by recording very small loads, displacements to a high level of accuracy and precision [8]. Nanoindentation employs an indirect measurement of the contact area between indenter and specimen in order to determine the material properties, namely, hardness and reduced modulus. Due to the miniaturization of device and needed smaller size of solder, conventional mechanical test such as tensile test, shear test and macro hardness test is not relevant to be used. One of the promising and power tools for determining the mechanical properties of solder is nanoindentation. This method gave an advantage of localized micromechanical properties in addition to other mechanical properties in conventional stress-strain data [9].

Therefore in this paper, effect of shock wave to micro mechanical properties of SAC 387 lead free solder were determined by using nanoindentation approach. There is only a little literature reported on lead free solder reliability due to the shock wave impact. This study becomes a great interest due to application of solder in military electronic devices and importance of their reliability properties.

2. Experimental Procedure

2.1. Sample Preparation

The lead-free solder wire Sn-95.5Ag-3.8Cu-0.7 (SAC 387) with diameter size of 0.6 mm supplied by Redring Solder (M) Sdn. Bhd and a copper substrate with 2 cm × 1 cm × 0.3 cm dimensions had been used in this experiment. The copper substrates were cleaned with acetone in ultrasonic bath for 5 min before starting the soldering process. The solder wire was soldered on a substrate at 100°C on electronic hot plate and cool down at room temperature [10]. Then the samples were place at distance 1 m, 2 m and 3 m from shock wave using 500 g of TNT equivalent and the non-exposure sample was used as control. The samples were cross sectioned and go through metallographic techniques. The samples were then cold mounted using epoxy resin followed by grinding using silicon carbide abrasive paper from 400 until 1200 grits and lastly polished with DP Nap polishing cloth, liquid lubricant and 1μm of diamond spray for nanoindentation test [11].

2.2. Nanoindentation

The nanoindenter machine (Micro Materials, NanoTest™) with Berkovich tip was used to perform the nanoindentation test at room temperature as shown in figure 1. Berkovich tip is preferred because a three-sided pyramid is more easily ground to a sharp point, and suitable for small scale indentation. Normally the face angle for Berkovich indenter is 65.27°. The indentation test was run at the centre of solder crossed section. The rate of 0.5 mN/s for a constant of loading and unloading was adapted to the sample surface until achieved at 10 mN (maximum load). At maximum load the dwell time is 30 second followed by the unloading process [11].

The graph from this experiment shows the hysteresis of load versus depth obtaining a means to determine hardness and modulus of the sample material, but also can identify the non linear events for example cracking, phase transformation and delamination of samples. This hysteresis consists of three segments, which are loading, dwell time at target load, and the unloading processes. These types of tests allow the measurement of viscoelastic properties of the specimen material. The thermal drift correction is 60 second hold time was applied at 90% unloading. The unloading curve is conceding as the elastic recovery of the material. The Poisson’s ratio value of indenter used in this experiment is 0.07 and Young’s modulus of 1140 GPa.
3. Results And Discussion

3.1. Depth, Displacement and Hardness Analysis

Semi-analytical procedures which is the experimental $P-h$ response has been proposed by various scientists to measure pseudo properties like characterizing resistance to deformation such as hardness $H$, plastic properties for example yield stress $\%$ and strain hardening exponent $n$ and elastic properties including elastic modulus $E$ [12]. Figure 2 shows the load versus depth of the SAC 387 alloy before (control) and after expose to shock wave with different distances. From this figure it shows that the sample at 2 m and 3 m distance consist of pop in and there is no superposition at 1 m sample indicating that the elastic deformation takes place inside the alloy. During the loading step in the indentation depth, these serrated jumps generally more pronounced Cu$_6$Sn$_5$ compare to Cu$_3$Sn. Pop in event have been discovered in epitaxial ZnSe on GaAs, single-crystal metals (Al, Ni, W), ionic crystals (BaF$_2$, CaF$_2$), semiconductors (Si, GaAs, InP), and attributed to the nucleation of dislocation [13].

Figure 3 (a) show the hardness values of SAC 387 after exposed to the shock wave at distance of 1 m, 2 m and 3 m. From the results, hardness of soldered samples obviously decreases from 300 MPa for control sample to 130 MPa, 170 MPa and 210 MPa for 1 m, 2 m and 3 m distance samples respectively. It’s revealed that shock wave degrade hardness of soldered samples. Besides, the distance of shock wave also influenced hardness by decreasing the values. Generally hardness ($H$) is a measure of a material’s resistance to deformation by surface indentation. The motion of dislocations in the atomic structure of a material will caused plastic deformation. By inhibiting dislocation motion through grain boundaries, imperfections or alloys, the yield strength of material may be changed. Material hardness can be increased by different means, including interstitial or substitution hardening, where atoms are
either added between or substituted in the atomic lattice. Ignatova et al [14] state that by increasing of shock wave intensity (pressure) lead to a decrease the dislocation density. The grain size also increase due to increasing intensity of shock wave and reduction of mechanism of fine grained copper to the level of coarse crystalline copper [14]. In Sn-Ag-Cu solder the primary phase formed is β-Sn phase followed by eutectic phase and intermetallic Ag₅Sn and Cu₆Sn. Therefore coarsening of grain size or sub grain of β-Sn tend to soft and resulted in low hardness value.

![Figure 3](image)

**Figure 3.** (a) Hardness and (b) Reduced Modulus of SAC 387 before and after shock wave.

3.2. **Reduced Modulus Analysis**

As reported by Suhling et al [15], the modulus of elasticity corresponds to the interatomic forces between adjacent atoms was illustrated by Hertzberg. Figure 3(b) shows the reduced modulus of SAC 387 for control sample which is 115 GPa higher than the samples of different distance from shock wave. On the other hand, the reduced modulus for different distance from shock wave increase rapidly which are 43 GPa for 1 m followed by 52 GPa, and 84 GPa, at 2 m and 3 m distance respectively. Under normal conditions, the atoms exhibit an equilibrium position to balance the attraction and repulsion forces. There is no broken in interatomic bond when an external force in shock wave is applied within the elastic region and only the balance of the attraction and repulsion forces changes [16]. The atoms will return to their original equilibrium positions after the external force is relieved.

3.3. **Plastic and Elastic Work Analysis**

Figure 4 the plastic work ($W_p$) and elastic work ($W_e$) data showed that, in all cases, the plastic work was more than the elastic recovery. All the plastic and elastic works were in the range of 0-10 nJ. The value of plastic work before shock wave is 5.28 nJ which is higher compare to the samples of different distance from shock wave which are 5.27 nJ, 4.48 nJ and 4.90 nJ for 1 m, 2 m and 3 m. However the value of elastic work for control sample is 0.09 nJ which is lower than the sample subjected to shock wave which are 0.21 nJ, 0.14 nJ and 0.11 nJ for 1 m, 2 m, and 3 m respectively. $W_p$ and $W_e$ can be correlated with the $H$ and $E$ values of the materials, respectively. Hence, low plastic work and low elastic recovery effectively translate to materials with high hardness and high Young’s modulus [17]. According to Khan et al [18], the results that obtained by Xu and Li showed that changes in plastic work/total work ($W_p/W_t$) are independent of the strain hardening of the material and directly dependent on the $E/\gamma Y$ ratio of the material.
Figure 4. Plastic and Elastic Work before and after shock wave.

4. Conclusion
The micromechanical properties of SAC 387 solder prepared by hand soldering with different distance from shock wave has successfully investigated using nanoindentation technique. The hardness and reduced modulus values increase with increasing distance of shock wave. After being exposed to shock wave the sample becomes softer. Shock wave resulted the microstructure changes of the solder material due to dislocation motion. Future work concerns deeper analysis on microstructure change such as grain boundary effect the failure analysis towards shock wave.

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