

## Effect Of 3% Molybdenum (Mo) Nanoparticles on The Melting, Microstructure and Hardness Properties of As-Reflowed Low Mass Sn-58Bi (SB) Solder Alloy

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### ABSTRACT

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The Sn-58Bi (SB) lead free solder alloy tested in this research with addition of 3% Molybdenum (Mo) nanoparticles equivalent to 0.6g mass to analyse the influences in the thermal, microstructure and microhardness. Elevation of 3.8°C was observed from the Differential Scanning Calorimetry (DSC) for the 3% Mo nanoparticles added SB solder alloy compared to the bare Sn-58Bi (SB) solder alloy that has a melting temperature of 142.25°C. The microstructures of the reinforced SB solder alloy were refined with closer lamellar structures of  $\beta$ -Sn and Bi phases compared to the unreinforced SB solder. The SEM/EDX and X-ray Diffraction (XRD) results validate the presence of the 3% Mo nanoparticles in the SB solder. Mechanical properties by means of Vickers microhardness of the Mo reinforced solder alloy showed an increment in hardness value by 2% compared to the bare SB solder alloy. The presence of 3% Mo as discrete particles (dispersion strengthening) contributes to the increase on the hardness value. The introduction of 3% Mo in to the SB solder alloy resulted in increase in the hardness due to the refinement of the microstructure and at the same time allows low temperature soldering in the electronic packaging industry.

#### Keywords:

SnBi solder alloy; low melting temperature; nanoparticles reinforcement; microstructure; mechanical properties

## 1. Introduction

In the soldering technology, the efficiency of a solder alloy is determined by the alloying process, such as Sn-Pb, Sn-Bi and Sn-Ag-Cu solders which are a mixture of one or more elements to the base materials Tin (Sn). The alloying elements will undergo diffusion process and forms intermetallic compounds or just present as a solid solution in the solder alloy depending on the solubility and

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reactivity of these elements [77]. This alloying process boosts the performance of a solder alloy by enhancing its properties by lowering the melting temperature (e.g. Sn-Pb, Sn-Bi), producing high shear strength (e.g. Sn-Zn-Bi) and enabling long-term reliability (e.g. Sn-Ag-Cu) due to better joint property. However, it could also contribute to some negative effect on the properties [67,74,80]. Lead free solder alloy are vastly investigated and the commonly claimed potential candidate is the Sn-Ag-Cu (SAC) solder alloys [19]. The noticeable properties of this solder alloy are its high melting temperatures (217°C) that can cause damage to other components in the PCB during soldering. In the same context, the high temperature could cause a high coefficient of thermal expansion (CTE) that may deteriorate the wettability and cause tearing of the solder alloy from the copper in the PCB board. Low temperature soldering is key to sustain to sustain other components from further damage due to high temperature exposure, and also contributes to further enhancement in the wetting and interfacial properties [2]. Nanoparticles reinforcement are debated to provide better mechanical integrity to a lead free solder in terms of shear strength and hardness and these context of the study is the most recent problem statement in this area of research [54]. Nanoparticles can act as separate or discrete particles (oxide and high temperature nanoparticles) or even involve in diffusion and affect the properties by an alloying manner (metals elements) [25,87]. Research by Yang *et al.*, [89] focused on the SnBi solder alloy with the additions of the Ni-coated carbon nanotubes (CNT) that shows an increase in the tensile strength up to 0.05%Ni-CNT content, but later reduced with added content of 0.1% and higher. The 0.05% additions produced the ultimate tensile strength of 63 MPa, which dropped to 61 MPa with 0.1% content. In the same study, the surface fracture trend of shifted from ductile to brittle mode observed. The drop in the tensile strength was attributed by the presence of many Ni-CNT, which forms cluster and leave gaps/pores that acts as the stress concentrator. Ani *et al.*, [11] also provided similar observation with the additions of TiO<sub>2</sub> in the SnAgCu solder alloy. In another study, SiO<sub>2</sub> nanoparticles were added to Sn<sub>0.7</sub>Cu solder alloy where there was an increment in tensile stress (43.4MPa) for 1.5wt% additions which was 25% higher than the bare Sn<sub>0.7</sub>Cu [26]. At the same time, a detrimental in tensile strength was observed with a higher concentration of SiO<sub>2</sub> of more than 1.5wt%. The initial boost in the tensile strength is because the SiO<sub>2</sub> resists plastic deformation and produces an Orowan strengthening effect. These findings were also discovered in the research of Ding *et al.*, [20] with additions of Al<sub>2</sub>O<sub>3</sub> nanoparticles in the Sn<sub>9</sub>Zn solder. The microstructure of the Sn<sub>3.0</sub>Ag<sub>0.5</sub>Cu solder added with TiC nanoparticles was refined with smaller grain size and presence of more IMC compounds. These findings were key factors to the increment of hardness as found in the studies by Billah *et al.*, [13] who incorporated Ni particles into Sn<sub>8</sub>Zn<sub>3</sub>Bi solder alloy. Investigations also show that the additions of nanoparticles could elevate the initial melting point of the mother solder alloy due to dissolution of the nanoparticles and the occurrence of melt undercooling before solidification. The proclamation was aligned to the research by Jung *et al.*, [46] with additions of TiO<sub>2</sub> and graphene nanoparticles to the Sn<sub>3.0</sub>Ag<sub>0.5</sub>Cu solder alloy and likewise reported by Zhu *et al.*, [95] (addition of carbon nanotube to SAC solder) and Chellvarajo *et al.*, [17] (additions of Fe<sub>2</sub>NiO<sub>4</sub> to SAC solder). In contrast, Xing *et al.*, [84] obtained a reverse trend of decrease in the melting temperature with additions of the Al<sub>2</sub>O<sub>3</sub> nanoparticles to the Sn<sub>9</sub>Zn solder alloy. Thus, the trend seems to focus on the SAC solder alloy system but few have argued on the reinforcement of the nanoparticles into a low melting solder alloy, such as the SnBi solder alloy. This paper investigates the additions of 3% Mo nanoparticles in the SnBi solder alloy and its effects on the melting, hardness and microstructure properties.

## 2. Preparation of Solder Alloy and Testing Setups

The Sn-58Bi (SB) solder alloy was prepared from Tin (Sn) (99.9% pure, Sigma Aldrich) and Bismuth (Bi) (99.9% pure, Sigma Aldrich) whereby both the elements were melted at 600°C for 1 hour (soaking time) in a furnace. The Mo (Sigma Aldrich) nanoparticles (Figure 1) was also weighed accordingly to 3% from the total weight of SB and inserted together at this point. The 3% Mo + SB nanoparticles solder alloy were further mechanically stirred at 350°C for 15 minutes to achieve homogeneity. The density of the SB solder alloy is 8.785 g/cm<sup>3</sup> and the density of Mo nanoparticles is 10.2 g/cm<sup>3</sup>. A simple weight calculation as in Eq. (1) was used to find the weight of the nanoparticle's additions [28].

$$C = \frac{m_1}{M} \times 100 \quad (1)$$

$C$  = weight concentrations of nanoparticles,

$m_1$  = weight of nanoparticles,

$M$  = total weight of solder alloy (20g)

This nanocomposite, SB + 3% Mo solder alloy was let to solidify under room temperature after the remelting process. The solder alloy was then cast into billets of 50 × 10mm as shown in Figure 2(b). The small dimension here will offer as replication of low amount of solder paste used in the electronic industry and at the same time preserve wastage of raw materials. A 16.6mg sample of unreinforced SB and 14mg of the SB + 3% Mo was placed into an aluminium pan and analyzed using the Differentials Scanning Calorimetry (DSC) to characterize the melting properties. The heat flow was kept at 20.00 °C/min with temperature from 100°C to 300°C under Nitrogen (N) atmosphere.

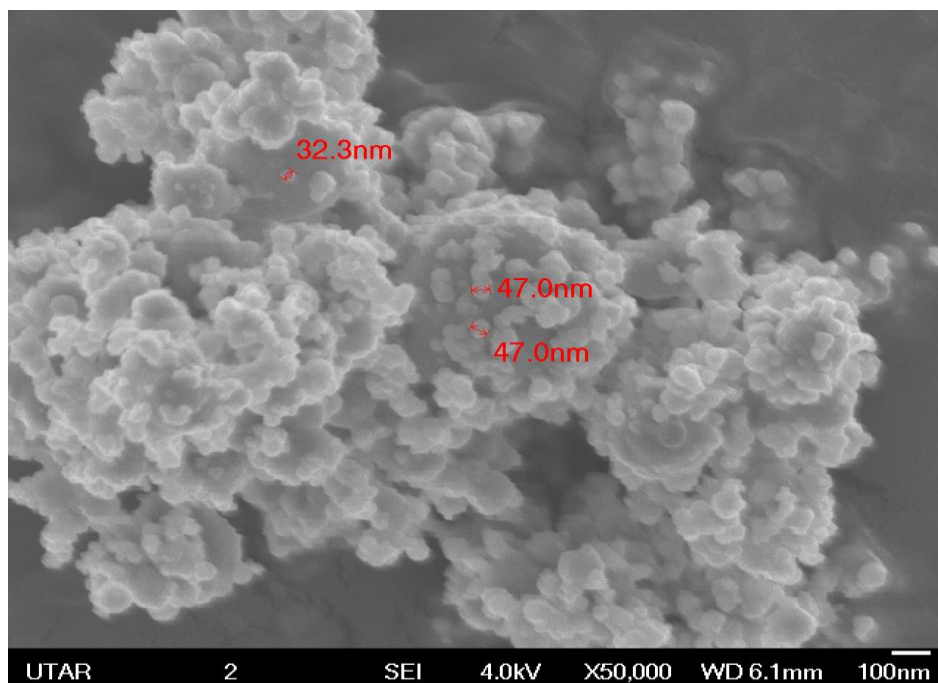
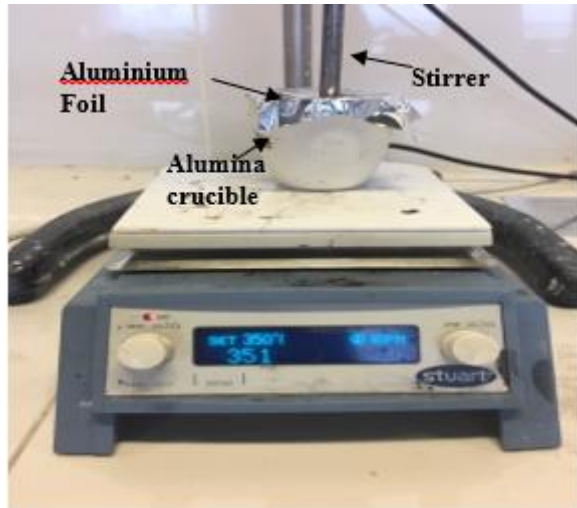
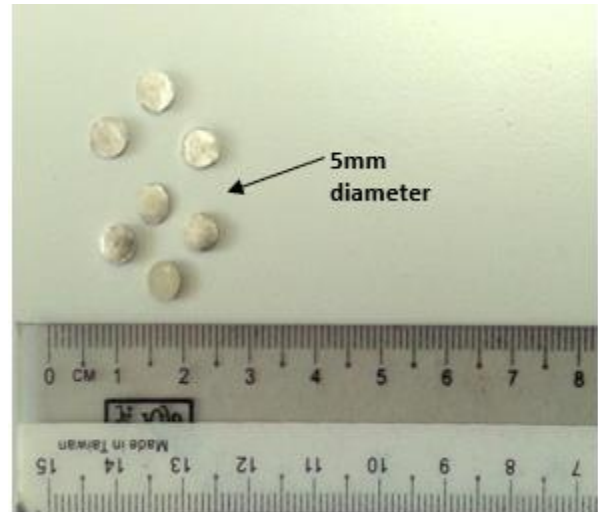


Fig. 1. SEM analysis of Mo nanoparticles size



(a) The alumina crucible containing SB added with nanoparticles enclosed with aluminium foil to avoid oxidation



(b) The solder billet of SB + 3% Mo nanoparticles with diameter of 5mm and thickness of 1mm

**Fig. 2.** (a) SB + 3% Mo under stirring process and (b) SB + 3% Mo nanoparticles billets

The T-Test was conducted on the SB and the SB + 3% Mo nanoparticles added solder based on the melting temperature to confirm the statistical difference and the statistics were shown in Table 1. The values of  $P = 0.000701226$  (SB + 3% Mo) and  $P = 0.027492247$  (SB) are less than ( $<0.05$ ), stating the rejection of null hypothesis and conclude that both samples are statistically different.

**Table 1**

F-Test for two samples variance using the onset and endset temperatures

t-Test: Two-Sample Assuming Unequal Variances	SB		SB + 3% Mo	
	Onset Temperature	Endset Temperature	Onset Temperature	Endset Temperature
Mean	141.782	148.138	141.79	150.844
Variance	1.61272	19.69027	0.5101	6.93883
Observations	5	5	5	5
Hypothesized Mean Difference	0		0	
df	5		5	
t Stat	-3.079275942		-7.417858519	
P(T<=t) one-tail	0.013746124		0.000350613	
t Critical one-tail	2.015048373		2.015048373	
P(T<=t) two-tail	0.027492247		0.000701226	
t Critical two-tail	2.570581836		2.570581836	

Microstructural observation of the SB and SB + 3% Mo was inspected and analysed using a high resolution scanning electron microscope (SEM) equipped with an energy dispersive X-ray spectroscopy analysis (EDX) system. The X-ray diffraction (XRD) was also conducted to examine and analyze the phase formation of the composite solder with the  $\text{CuK}\alpha$  radiation at an angle of diffraction of  $20\text{-}80^\circ$  with a scan range of  $2 \text{ min}/^\circ$ . The Vickers hardness test was conducted with 1kgf indentation load with a dwell time of 15 seconds. Five samples each with five indentations were tested to provide accuracy in the result. Eq. (2) was used to calculate the Vickers hardness value and to clarify the statistical difference of these samples, the raw data of the hardness value of  $D_1$  and  $D_2$  representing the average diagonal diameters was tested with the analyses of the Fisher Statistical-Test. The two variances (Variance 1: SB and Variance 2: SB + 3% Mo) was taken to validate the hypothesis. The calculated F value ( $F = 0.709652224$ ) was larger than the critical F value ( $F_{\text{Critical}} =$

0.314574906) stating that the null-hypothesis can be rejected. This statistic is shown in Table 2. This result validates the statistical difference between the SB and SB + 3% Mo solder alloy. All the properties were discussed in the upcoming sections.

$$HV = 1.854 \left( \frac{F}{D^2} \right) \quad (2)$$

$HV$  = Vickers Hardness Number,  
 $F$  = Indentation Force (1kgf:9.81N),  
 $D$  = Average diagonal diameter

**Table 2**  
 F-Test for two samples variance using diameter of indentations

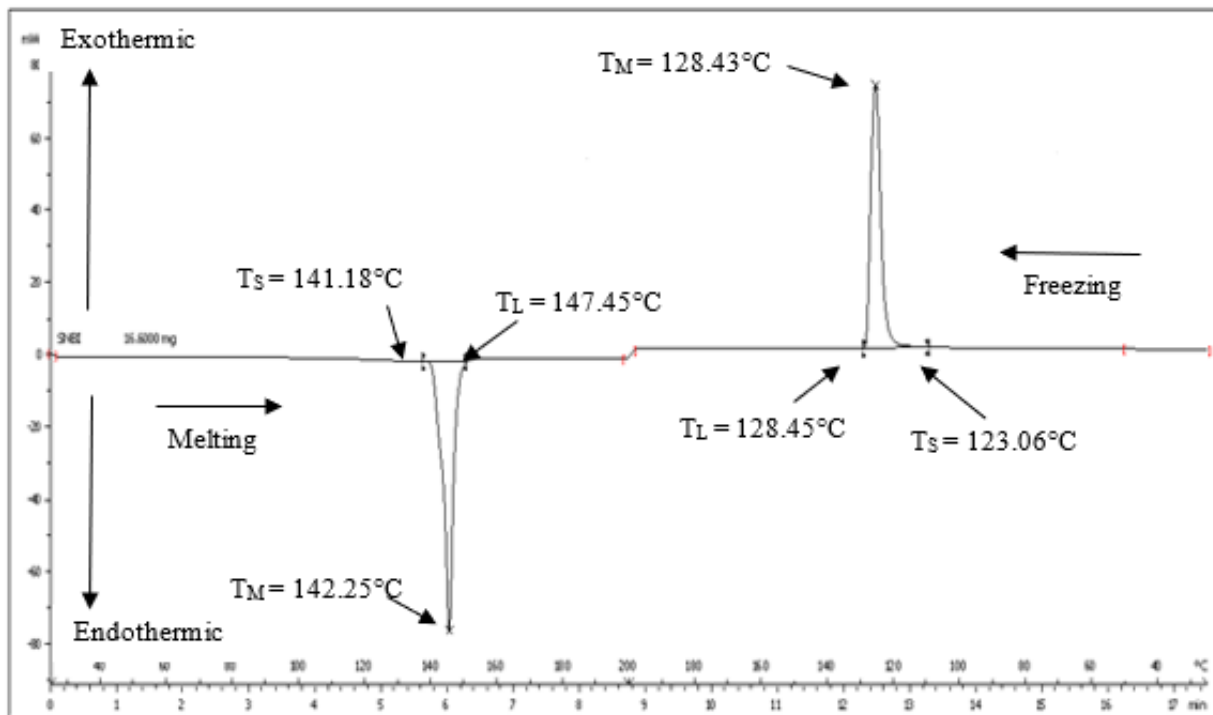
	D1	D2
Mean	80.122	79.505
Variance	5.869395556	8.270805556
Observations	10	10
df	9	9
F	0.709652224	
P(F<=f) one-tail	0.308811638	
F Critical one-tail	0.314574906	

### 3. Results and Discussions

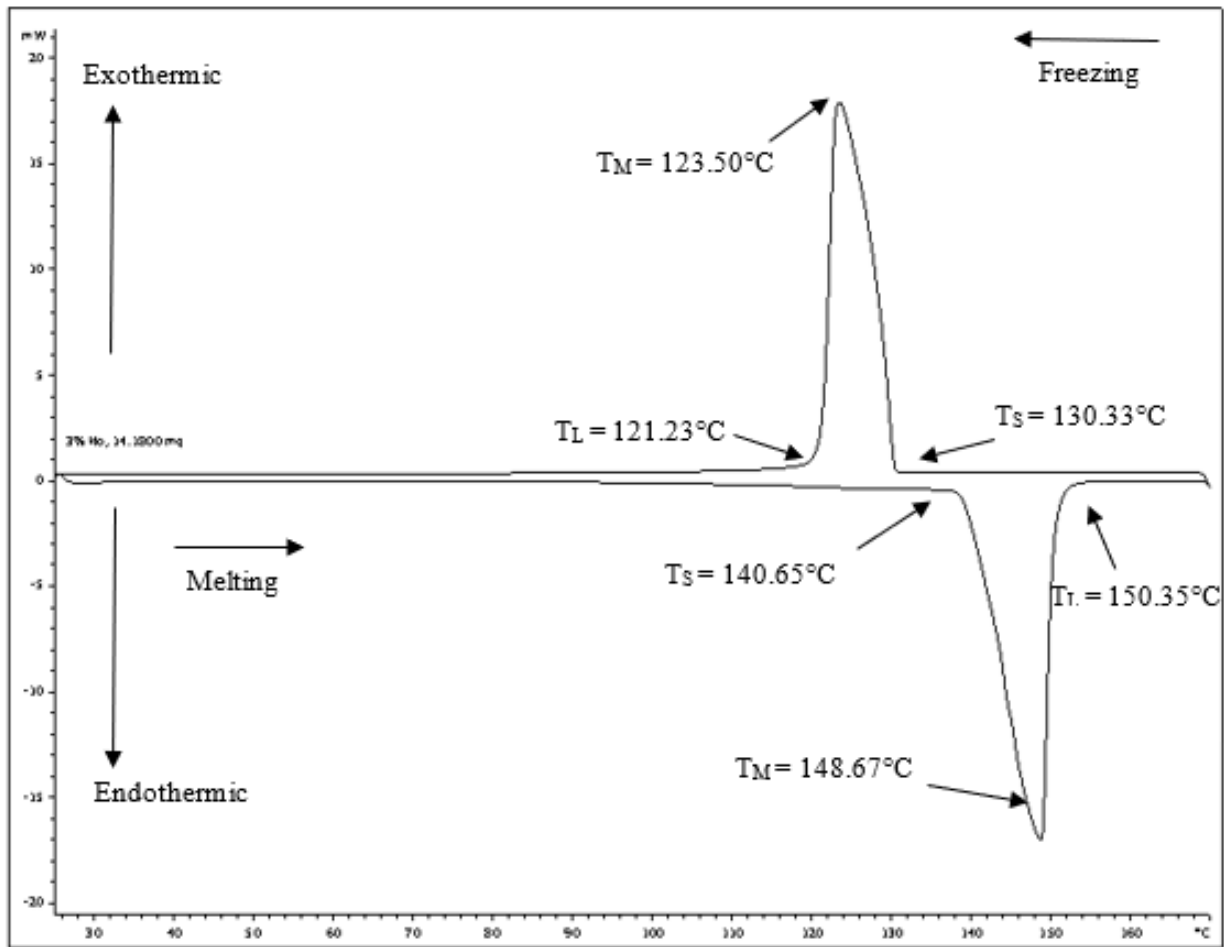
#### 3.1 Melting Temperature

Melting temperatures are crucial asset to a solder alloy because the temperature applied on the electronic board influences the energy consumptions and the thermal warpage that may deteriorate the solder interconnections [87]. The unreinforced SB and the SB 3% + Mo solder alloy's thermal properties was investigated using the DSC heating (endothermic) and cooling (exothermic) curves that is represented in Figure 3. The solidus  $T_S$ , melting  $T_M$ , liquidus  $T_L$  and pasty range  $T_R$ , ( $T_{\text{heating}} - T_{\text{cooling}}$ ) temperatures of the SB and SB + 3% Mo nanoparticles solder for the melting curve are shown in Table 3. The pasty range contributes to the prediction of the microstructure formation because at this range, the solidification occurs to form grains of the solder and range effects change of the heat capacity between solid and liquid and change in the heat fusion [14]. Both DSC readings for the heating curve show a sharp peak with the melting temperature  $T_M$  of 142.25°C for the SB solder alloy and 148.67°C for the 3% Mo nanoparticles added SB solder alloy. The specific heat capacity of the SnBi and SB + 3% Mo solder is 47.53 J/g and 7.78 J/g respectively, and demonstrates that the additions of the Mo nanoparticles reduces the specific heat capacity of the pristine solder. The Mo nanoparticles influenced an elevation of ~6°C in the melting point compared to the unreinforced SB solder. Increase of melting temperature with nanoparticles additions are collectively agreed in other research such as additions of 1% Ag-GNS nanoparticles increased ~2°C in the Sn3.0Ag0.5Cu [85]. Additions of 0.1% Al<sub>2</sub>O<sub>3</sub> nanoparticles increased ~4°C in the Sn3.5Ag0.7Cu [47]. Additions of 0.2% TiC nanoparticles increased ~5°C in the Sn3.0Ag0.5Cu [18]. Additions of 1% Al<sub>2</sub>O<sub>3</sub> nanoparticles increased ~2°C in the Sn3.5Ag0.7Cu [55]. And additions of 1.5% Ag nanoparticles increased ~1°C in the Sn9Zn [9]. The reason behind the slight increase in the melting point is because of the occurrence of melt undercooling before solidification endured by the Mo nanoparticles reinforced SB solder alloy. The degree of undercooling indicates the level of difficulty of a nucleation process during solidification. The degree of undercooling for the reinforced SB solder alloys was 2.45°C (12.7 °C vs 10.3°C) lower compared to the bare SB solder alloy as shown in Table 3. A smaller degree of undercooling is

necessary for better solder solidification. Another possible explanation on the increase in the melting temperature is the increase in surface instability of the molten SB solder as a reason of higher surface energy encountered upon presence of Mo nanoparticles. Unlike the unreinforced SB solder, the energy required to break free the atoms are higher in the Mo nanoparticles reinforced SB solder alloy. Ding *et al.*, [20] reported similar information after the additions of  $Al_2O_3$  nanoparticles in the Sn9Zn solder system. According to Zhu *et al.*, [95], the increase in the melting point is also due to the high melting point of the nanoparticle's material (e.g. Mo nanoparticles melting point =  $2623^\circ C$ ). Noor and Singh [23] also mentioned this explanation in a review study. As the remelting temperature was kept at  $350^\circ C$  in this research during mixing, there would be no chance for the supplied heat to melt the Mo nanoparticles, which possesses a melting point of  $2623^\circ C$ .



(a) SB



(b) SB + 3% Mo

**Fig. 3.** DSC curve of (a) SB solder alloy and (b) SB + 3% Mo nanoparticles

**Table 3**

Thermal properties of SB and SB + 3% Mo nanoparticles

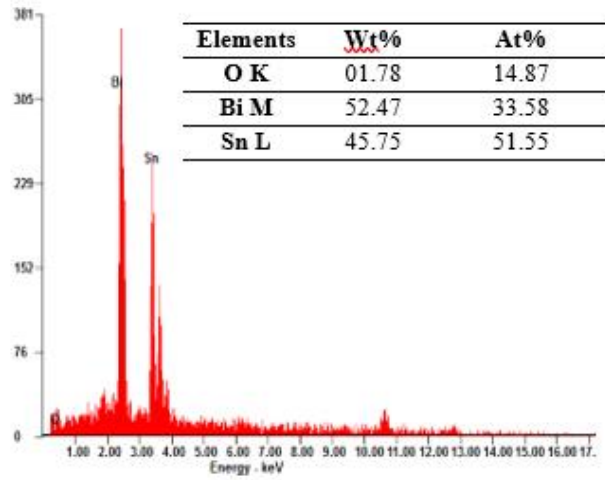
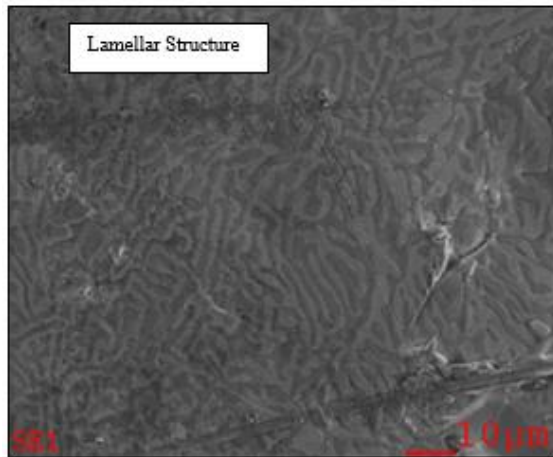
Solder	Solidus Temperature, $T_S$ (°C)	Melting Temperature, $T_M$ (°C)	Liquidus Temperature, $T_L$ (°C)	Pasty Range, TR (°C)	Undercooling ( $T_{S_{heating}} - T_{S_{cooling}}$ ) (°C)
SB	141.18	142.25	147.45	1.07	12.75
SB + 3% Mo nanoparticles	140.62	148.67	150.35	8.05	10.30

The solidus temperature of the Mo added SB solder reduces compared to the bare SB solder and contributed due to the melt undercooling affect as well. The change in the solidus temperature increases the pasty range of the 3% Mo nanoparticles added SB solder. However, the increase in the pasty range was not evidently large and did not affect the microstructure formation, which will be discussed in the next section. The range is still considered as the range closer to the eutectic range. Matching to the Lindemann's melting theory as well, a materials melting point is dependent on the energy required to overcome the interatomic interaction or in other words, it is an intrinsic property of the molecular in the SB solder alloy which is not affected by the presence of Mo nanoparticles [48].

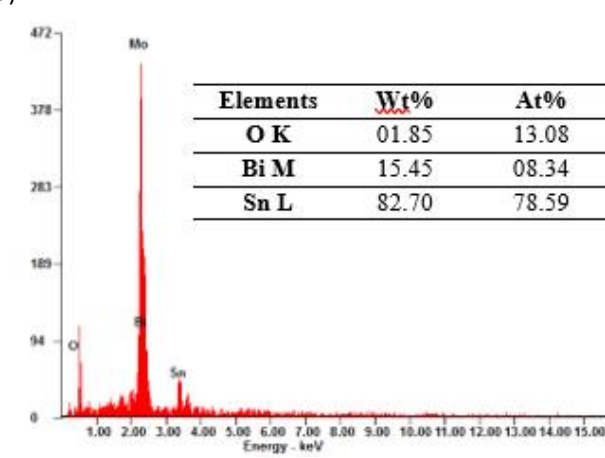
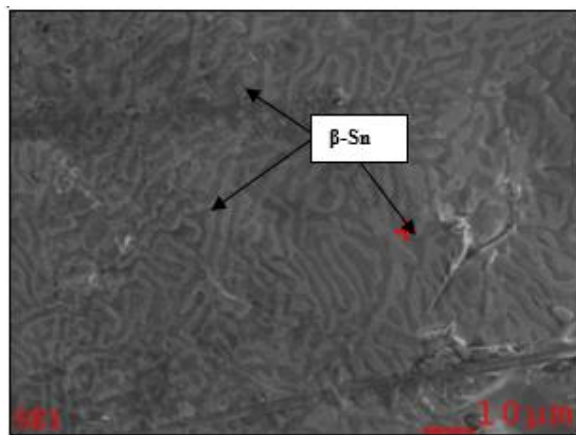
### 3.2 Microstructure of SB and SB + 3% Mo Nanoparticles Solder Alloy

The SEM images in Figure 4 shows the microstructure of the bare SB solder alloy with 1K magnification to demonstrate the (a) lamellar structure (b)  $\beta$ -Sn area and (c) Bi phases on the solder. The Figure 5(a), Figure 5(b) and Figure 5(c) depicts the microstructures of the SB + 3% Mo nanoparticles solder alloys at different places with the presence of Mo nanoparticles visible clearly. In both Figure 4 and Figure 5, there is a clear existence of lamellar solder alloy consists of the lamellar structure identified as  $\beta$ -Sn (dark phase) and Bi (light phases) confirmed by the EDX analysis with the points shown in Figure 4(b) and Figure 4(c). Shen *et al.*, [71] provided a similar observation of the lamellar structured formation in the SnBi solder matrix. The Bi element is known to not react with the Sn to form any IMC in the solder matrix because of its low solubility. In fact, the phases present matches with the SnBi phase diagram at a temperature of 140°C (melting temperature). The Mo nanoparticles have no solubility in the Sn matrix and Bi and do not react with these elements, which is evident from the SEM image of Figure 5. The Mo nanoparticles agglomerates and appear on top of the lamellar Sn and Bi phases as shown in Figure 5. The EDX analysis in Figure 5(a) and Figure 5(b) confirms the presence of Mo nanoparticles by taking the nominal weight percentage. Further confirmation of the Mo nanoparticles in the SB solder alloy is proven with the XRD test results in Figure 6(a). The peaks of Mo in the SB + 3% Mo in Figure 6(a) matches the strongest peak of  $2\theta = 40.5494^\circ$ ,  $58.668^\circ$  and  $73.7225^\circ$  in Figure 6(b). Comparing XRD results of the pure SB, the Mo peaks earlier did not appear as shown in Figure 6(c). The Mo nanoparticles can change the growth velocity of the SB solder alloy as it appears as discrete particles. Haseeb *et al.*, [38] also established similar incidence with the reinforcement of Mo nanoparticles in Sn-3.8Ag-0.7Cu solder alloy. As observed in Figure 5 (c), the yellow borders enclosing the lamellar structure of the SB + 3% Mo solder alloy were finer. The Bi phases were more elongated and narrower (closely packed) compared to the Bi phase in the pure SB solder alloy. The EDX analysis in Figure 5(c) confirms that this area was accommodated by the Sn and Bi while the Mo particles are not much existent. This observation explains that Mo nanoparticles affect the solidification and grain growth of the  $\beta$ -Sn and Bi. The Mo nanoparticles act as a separate site for nucleation during solidification that restricts the surface energy of the molten solder alloy. Hence, the high activation energy of the Sn would be limited, resulting in a smaller  $\beta$ -Sn matrix. This theory was agreed by Xing *et al.*, [84]. This statement was also linked to the research by Shin *et al.*, [72] explaining a similar reason with SiC nanoparticles additions in Sn58Bi solder alloy. Another study by Yang *et al.*, [90] with additions of 0.25% Mo in the Sn58Bi shared similar findings. Meanwhile, the agglomerations of Mo nanoparticles observed in Figure 5 did not to affect the refinement of the microstructure (does not act as a nucleation site) since the weight percentage is low. This proclamation was observed in the investigations of Zhang and Tu [94]. Moreover, during the molten state, the highly viscous molten SB rejects the agglomerated Mo nanoparticles. A comparable assertion was given with additions of NiO nanoparticles in the Sn3.0Ag0.5Cu solder alloy [15]. However, it is important to control the limit of the weight percentage additions of the nanoparticles since higher content will deteriorate the grain refining process which results in increased  $\beta$ -Sn grain sizes as reported by Jung *et al.*, [46].

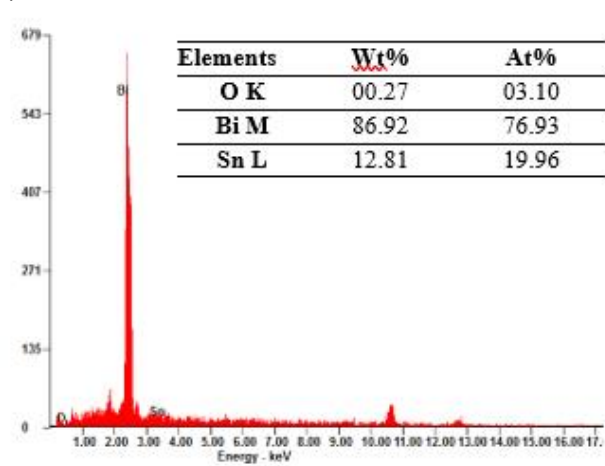
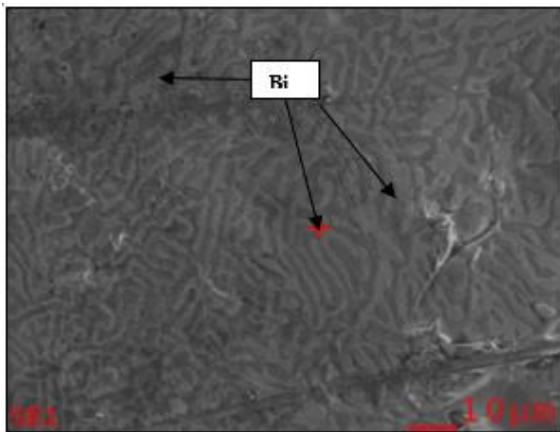




(a)



(b)



(c)

**Fig. 4.** (a), (b) and (c). Microstructure of pure SB

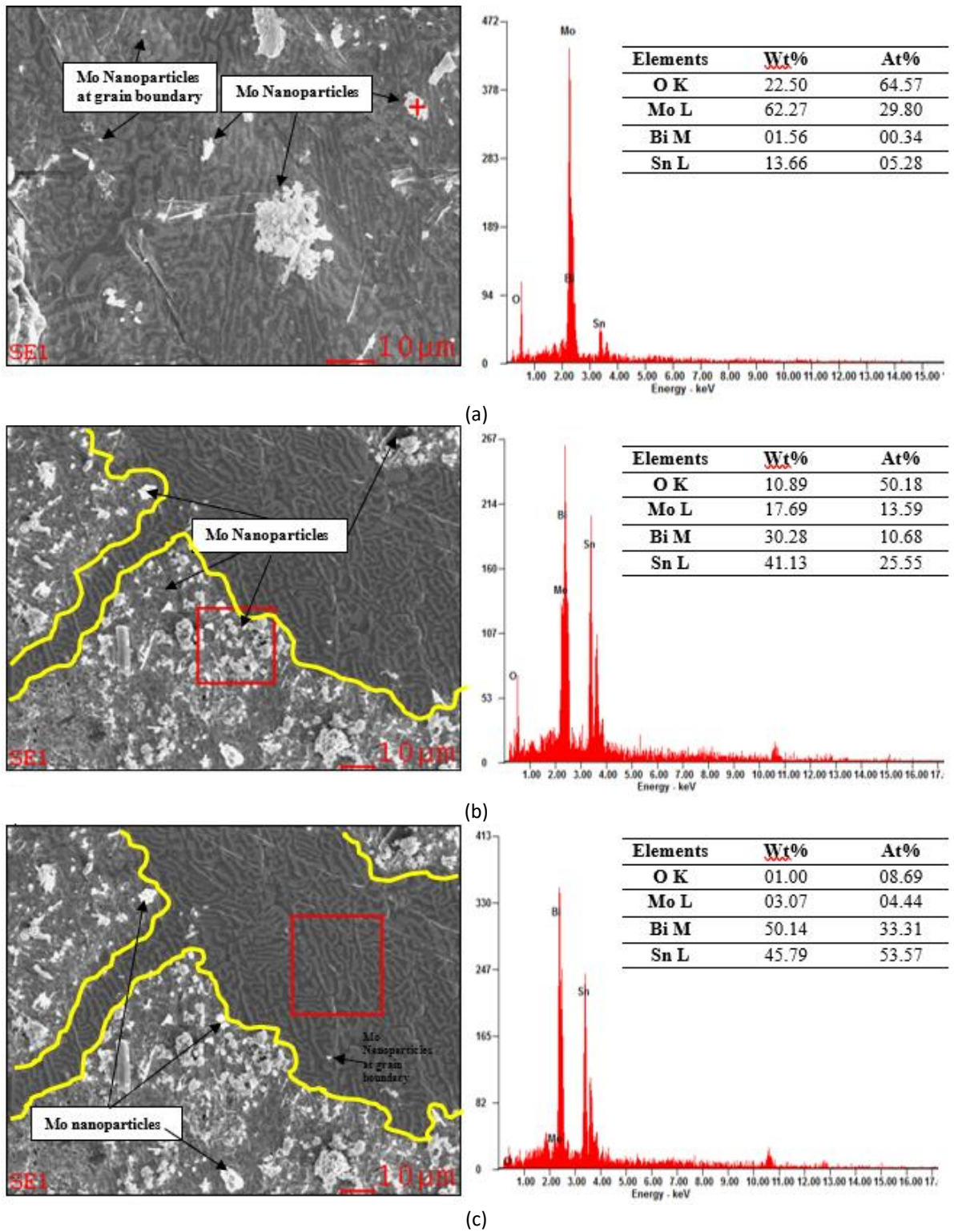
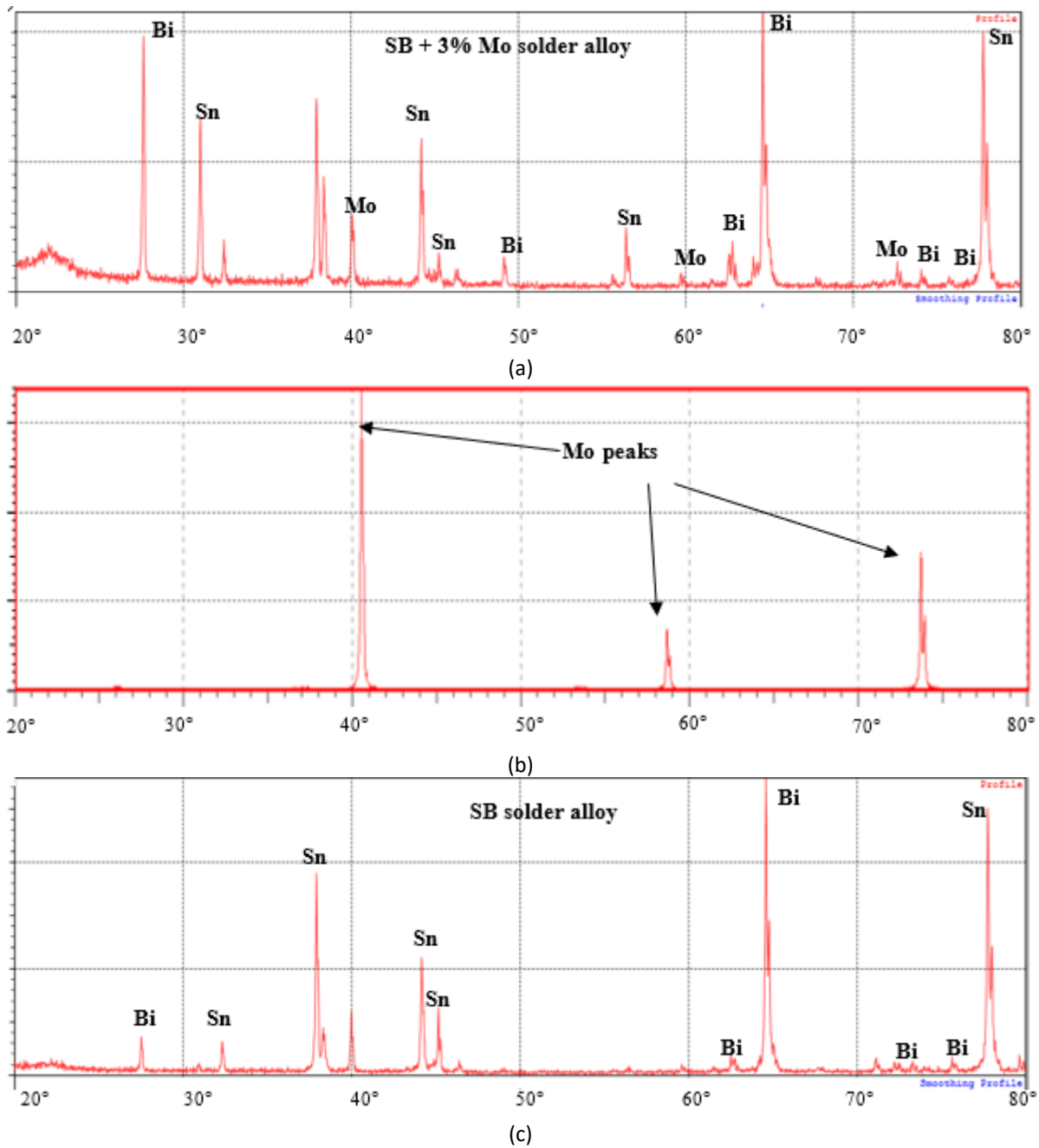


Fig. 5. (a), (b) and (c). Microstructure of SB + 3% Mo nanoparticles



**Fig. 6.** XRD result of (a) SB + 3% Mo, (b) Mo and (c) Pure SB solder alloy

### 3.3 Vickers Microhardness SB and SB + 3% Mo Nanoparticles Solder Alloy

Table 4 gathered the Vickers microhardness results of both the bare SB and the 3% Mo nanoparticles reinforced solder alloy from this research. The results show an increase of 2% for the hardness value for the 3% Mo reinforced SB solder alloy. The hardness value increment is clearly due to the presence of the Mo nanoparticles which harder than the Sn and Bi.

**Table 4**

Vickers hardness of SB+ 3% Mo and SB solder alloy

Solder	Vickers Hardness (Hv)					
	Indentation 1	Indentation 2	Indentation 3	Indentation 4	Indentation 5	Average
SB + 3% Mo	29.73 ± 6	28.02 ± 6	29.82 ± 6	29.73 ± 6	28.58 ± 6	29.2 ± 6
SB	27.84 ± 6	27.59 ± 6	29.39 ± 6	29.26 ± 6	29.82 ± 6	28.7 ± 6

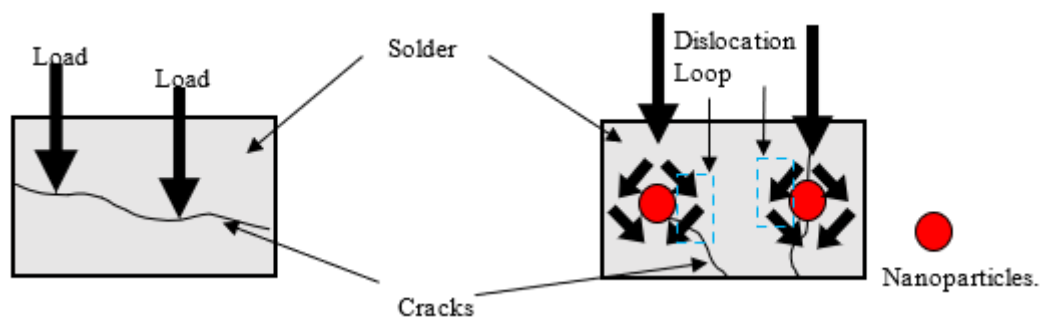
The physical property of these Mo nanoparticles which do not take part in any diffusion process enables the Mo particles to act as discrete particles. These Mo particles impede the dislocation motion and in mechanical terms, this phenomenon is known as the second phase hardening mechanism [10]. A second phase hardening mechanism occurs when small particles (resembled by the Mo nanoparticles) impede the dislocation motion upon stress induction [33]. Obeying to the theory of dispersion, these Mo nanoparticles pins along the grain boundary in the SB solder alloy. As more pinning of Mo nanoparticles at the grain boundary, the dislocation path needs to bend over or penetrate through these high dense dislocations, contributing to increasing in the stress/load [21]. Since the Mo particles could not be penetrated, dislocations path will need to loop over the Mo particles and with more piled dislocation loops being formed, an increase in the dislocation density occurs. This high dislocation density consequently increases the resistance of deformation of the solder. Figure 7 shows the schematic diagram of the explanation above. The Zener pinning theory could be also used to find the analytical result of the pinning stress but this was theory is not discussed in this research, but can be found elsewhere. On the other hand, the Mo nanoparticles can increase the stress/load needed to penetrate the solder alloy and as for that, the load is transferred to the Mo nanoparticles. This information stated alike by Kumar *et al.*, [51] with incorporation of the single-wall carbon nanotube (SWCNT) in the Sn-3.8Ag-0.7Cu solder alloy. This phenomenon is defined as the load-bearing effect [29]. The microstructure morphology of the SB + 3% Mo nanoparticles likewise contributes to the increase in the hardness. The uniform microstructure with finer  $\beta$ -Sn with the narrower lamellar structures is another factor that increases the hardness. Theoretically, a higher surface area of the nanoparticles per unit volume of the total solder alloy can increase the hardness of a material [48]. Yahaya *et al.*, [88] reported this clarification with TiO<sub>2</sub> nanoparticles additions in the Sn-3.0Ag-0.5Cu producing a similar increase in the grain size that reduces the hardness value. The Mo nanoparticles here provides another form of strengthening mechanism as solid particulates and increases the hardness of the solder. A study by Tsukamoto *et al.*, [37] in inspecting the influence of Ni particles in Sn-0.7Cu solder alloy correlates with this justification. Contrariwise, the stress/load easily penetrated deeper in the bare SB solder alloy because of less dislocation and absence of discrete Mo nanoparticles to act as second phase strengthening mechanism.

#### 4. Discussion on Mechanisms Influencing the Behaviour of Mo Nanoparticles in The SB Solder Alloy

In this research, the Mo nanoparticles were mechanically mixed into the SB solder alloy where the Mo nanoparticle's melting temperature is  $T_M = 2623^\circ\text{C}$ . There would not be any dissolution of these nanoparticles because of the lower temperature of  $600^\circ\text{C}$  used to melt the Sn and Bi together with the Mo nanoparticles. Therefore, as mentioned, the Mo nanoparticles will only exist as discrete particles. As spell out by Haseeb and Leng [39], nanoparticles additions should be ranging between 5-10nm in diameters to fully react with the molten solder alloy. In this research, the size of the nanoparticles was an average of 42nm and at this size, it is not possible for any reaction to take place. Furthermore, Wattanakornphaiboon *et al.*, [82] states that nanoparticles will not involve in any diffusion with the Sn due to nature of its low solubility. Consequently, the Mo nanoparticles will opt to accumulate along the grain boundaries (high-energy area) and the surface of the molten SB solder

alloy. This is because of the nature of the nanoparticles of being a surface-active element. It represents the distribution of nanoparticles in a molten solder alloy as per dispersed nanoparticles and as agglomerated nanoparticles [21]. It therefore confirms the presence of these Mo nanoparticles in this research affect the formation of grains ( $\beta$ -Sn and Bi) in the microstructure by changing the driving force and the growth velocity that resulted in the nearer lamellar gaps between the microstructure as noticed in Figure 5. In addition, during solidification, these Mo nanoparticles in the Sn matrix promotes heterogeneous nucleation site that makes the spacing between the lamellar structures smaller. Research by Billah *et al.*, [13] reported likewise with Ni particles additions.

This study also states that the hardness of the SB + 3% Mo nanoparticles and the strengthening effect can only be achieved with proper mixing of the Mo nanoparticles in the SB solder alloy. Therefore, any presence of high content of Mo nanoparticles are found to be less ductile and can degrade the strength of the SB solder alloy. The nanosized Mo particles act as load-bearing effect that resists the load by contributing as another strengthening insertion to the solder. This also could be related to the Orowan strengthening stating that the presence of the nanoparticles itself contributes as hardening mechanism that endures the loads upon induced stress. Moreover, Mo nanoparticles deeds as second phase particles in the solder matrix and will enhance the hardness of the solder alloy by not allowing slip plane to pass through it.



**Fig. 7.** Schematic diagram of stress/load penetration (a) bare solder and (b) nanoparticles added solder

## 5. Conclusions

This research examined the effects of 3% Mo nanoparticles addition on the thermal, microstructure and hardness properties of Sn58Bi solder alloy. Proper mixing of the Mo nanoparticles in the SB solder alloy appears to improve the microstructural and hardness properties in this study. The following conclusions are drawn from the results and discussion

- i. The 3% Mo nanoparticles were successfully mixed with the SB solder alloy supported with the EDX and XRD analysis. The presence of Mo nanoparticles was visible through the SEM images.
- ii. The addition of 3% Mo nanoparticles in the SB solder alloy increased the melting temperature in a minimal range ( $\sim 6^{\circ}\text{C}$ ) and is due to the melt undercooling before solidification. The melting properties are not to be affected by the nanoparticles addition according to the Lindemann theory.
- iii. The microstructure of 3% Mo added SB solder alloy had significant changes as the lamellar structure was observed to have closer gaps. This is explained by the surface adsorption theory where the Mo nanoparticles act as a site for nucleation and also reduces the growth velocity of  $\beta$ -Sn.
- iv. Vickers microhardness of the 3% Mo added solder was enhanced by a degree of 2% compared to the bare SB solder alloy. The Mo nanoparticle's influence in the microstructure produces a

more uniform microstructure (nearer lamellar structure) and contributes to this hardness enhancement. The Mo nanoparticles itself behaves as second phase insertion in the matrix that influences the higher hardness value.

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