

Article

Thermomigration Microstructure and Properties of Ni Nanoparticle-Reinforced Sn58Bi Composite Solder/Cu Solder Joint

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Abstract: A Sn58Bi composite solder reinforced by Ni nanoparticles was prepared using a mechanical mixing technique, and the thermomigration microstructure and properties of the solder joints were studied. The findings indicate that incorporating an appropriate quantity of Ni nanoparticles can enhance the microstructure of the composite solder and mitigate the coarsening of Bi-phase segregation. At 0.75 weight percent Ni nanoparticle content, the composite solder's tensile strength is 59.7 MPa and its elongation is 54.6%, both of which are noticeably greater than those of the base solder. When the thermal loading time is 576 h, the shear strength of the composite solder joint is 25.5 MPa, which is 30.1% higher than that of the base solder joint. This study reveals that the shear fracture path shifts from the boundary region between the solder seam and the IMC layer to the IMC layer itself. Concurrently, the fracture mode evolves from a mix of brittle–ductile fracture, characterized by quasi-cleavage, to a predominantly brittle fracture, marked by numerous “rock candy-like” cross-sectional features and secondary cracking. Adding Ni nanoparticles to the Sn58Bi composite solder/Cu solder junction can significantly extend its service life.



Citation: Fan, Y.; Zhang, K.; Chen, W.; Wu, J.; Wang, Y. Thermomigration Microstructure and Properties of Ni Nanoparticle-Reinforced Sn58Bi Composite Solder/Cu Solder Joint. *Metals* **2024**, *14*, 1420. <https://doi.org/10.3390/met14121420>

Academic Editor: Wislei Riuper Osório

Received: 13 October 2024
Revised: 20 November 2024
Accepted: 6 December 2024
Published: 11 December 2024



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Keywords: Ni nanoparticles; Sn58Bi composite solder; lead-free solder joint; thermomigration; microstructure; property

1. Introduction

In the realm of dense electronic assembly, lead-free solder joints play a pivotal role in establishing electrical connections, providing mechanical stability and facilitating heat transfer among semiconductor components [1]. As electronic packaging technology advances toward higher densities, the dimensions of lead-free solder joints are shrinking, currently ranging from 100 to 500 μm , and they may potentially decrease further in the future to between 20 and 100 μm [2–5]. The small temperature difference at both ends can form a maximum temperature gradient, resulting in the migration of metal atoms to form Kirkendall holes, micro-cracks, and other defects. It has become a prominent factor affecting the reliability of lead-free solder joints [6–9]. Sn58Bi is one of the most promising potential solders in the low-melting point solder system due to its low price, good conductivity ($11,000 \Omega^{-1}\text{cm}^{-1}$ at 190 °C), and good wettability (viscosity of 2.7 mPa·s and surface tension of 440 mN/m at 190 °C) [10]. However, its hard, brittle-rich Bi phase is easy to crystallize and forms a coarse microstructure, seriously affecting the solder joint's bonding strength and reliability of the solder joint [11–13]. It is urgent to develop a new high-strength and tough Sn-Bi solder to meet the higher requirements of thermomigration reliability of solder joints.

Particle-reinforced Sn58Bi composite solder has become an important research field [14–16]. Yang et al. [17] successfully synthesized Sn58Bi- x Ni composite solder. With the increase in Ni

within 1%, the microstructure of Sn58Bi solder was refined, and the elastic modulus and tensile strength were improved. Gain et al. [18] found that doping Ni nanoparticles in Sn58Bi composite solder could inhibit the generation of Cu_3Sn IMC during a brazing reaction. The formation of intermetallic compounds (IMCs) as a result of the interaction between composite solder and copper substrates plays a crucial role in determining the reliability of solder joints. Shen et al. [19] investigated the thermomigration effects on Cu/Sn58Bi/Cu solder joints subjected to a steep temperature gradient of $1309.5\text{ }^\circ\text{C}/\text{cm}$ and found that a large number of micro-voids and micro-cracks were formed in the hot end of the IMC after 300 h. Li et al. [20] experimentally determined that the IMC at the Sn58Bi/Cu interface tends to distribute symmetrically under a temperature gradient of $1300\text{ }^\circ\text{C}/\text{cm}$. Wei et al. [21] examined the thermomigration effects in Cu/Sn/Cu solder joints under $1046\text{ }^\circ\text{C}/\text{cm}$, noting an increase in joint hardness from the hot to the cold ends over extended periods. Chen et al. [22] delved into the thermomigration behavior of Sn-Bi57-Ag0.7/Cu joints under $625\text{ }^\circ\text{C}/\text{cm}$, discovering that Ag_3Sn can inhibit local grain reorientation and mitigate the development of IMC micro-voids and micro-cracks at the interface, and the solder joint's overall mechanical performance was improved.

In summary, although the research on thermomigration of low-temperature lead-free solder joints has made some progress, the research on thermomigration of particle-reinforced Sn58Bi lead-free solder joints still needs further exploration. This paper laid the groundwork for improving the reliability of lead-free solder joints by fabricating Ni nanoparticle-enhanced Sn58Bi composite solder via mechanical mixing and examining the microstructure and performance of both the composite solder and its joints.

2. Test Materials and Methods

2.1. Test Material

The raw materials used in this test are 50 nm Ni particles (Guangzhou Metal Metallurgy Co., Ltd., Guangzhou, China), 300 mesh Sn58Bi powder (Changsha Tianjiu Metal Materials Co., Ltd., Changsha, China); NC-559-V2-TF type washable flux (AMTECH, Tempe, AZ, USA); and the base material is made of purple copper plate with purity greater than 99.99%.

2.2. Preparation of Composite Solder

In this experiment, the mechanical mixing method was used to mix Ni nanoparticles with Sn58Bi powder using ultrasonic equipment [23]. The uniformly mixed solder powder was cold pressed and placed in a boiling furnace with a nitrogen atmosphere at $320\text{ }^\circ\text{C}$ for 30 min to prepare Sn58Bi- $x\text{Ni}$ ($x = 0, 0.25, 0.5, 0.75, 1\text{ wt.}\%$)-composite solder ingots for the experiment. The prepared composite solder ingots were then rolled into 0.2 mm thick sheets, as shown in Figure 1.

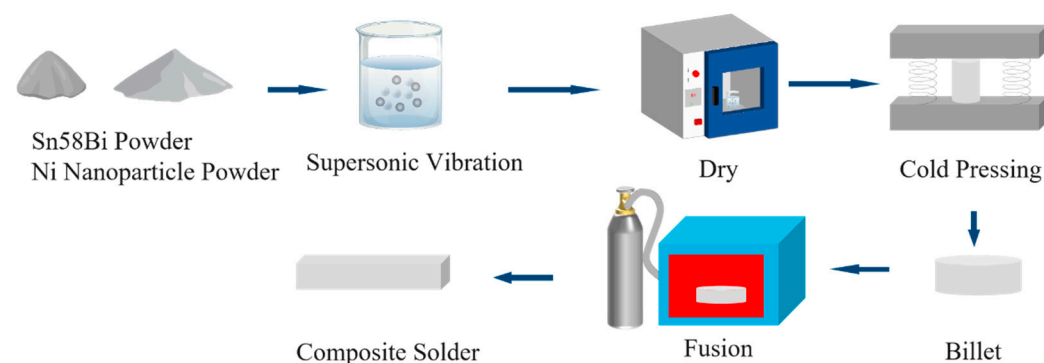


Figure 1. Schematic diagram of composite solder preparation process.

2.3. Soldering Test

The sample was brazed in the form of an integral lap joint and partial butt joint, as shown in Figure 2 [24]. After the surface intended for welding and the solder sheet had been meticulously ground and cleaned, 5% washable flux was added, and they were then

sent into a brazing furnace (Kaisi, Guangzhou, China). The brazing temperature was set to 190 °C, and the parts were held at this temperature for 180 s. After the brazing process, the sample was allowed to cool in the air, and subsequently, it was processed into the shape depicted in Figure 2b.

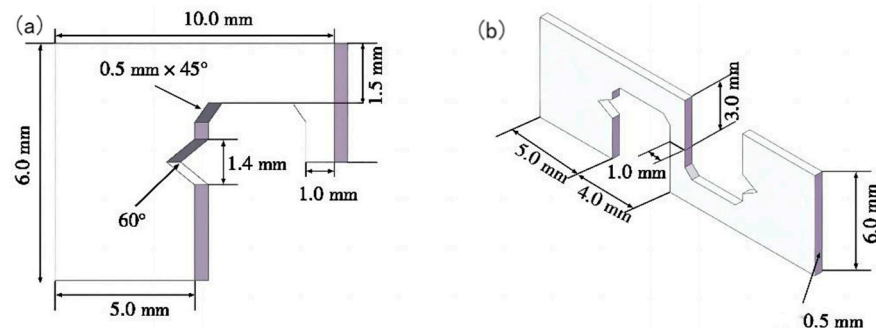


Figure 2. Size and shape of the samples (mm). (a) Base metal; (b) brazed sample.

2.4. Thermomigration Test

To establish the required temperature gradient for the thermomigration process in solder joints, a stable temperature difference is maintained between the two ends of the joint. This gradient is controlled by adjusting the heat dissipation rates at these ends. Figure 3 [25] illustrates the schematic of the thermomigration testing apparatus. The temperature field directly determines the temperature gradient during the thermomigration of joints. In this experiment, the finite element simulation software Abaqus2020 was used to analyze the temperature distribution of Sn58Bi- x Ni/Cu solder joints, and the temperature distribution at both the hot and cold ends of the solder joints could be accurately obtained. The average temperature was 85 °C, the solder joint height was 0.1 mm, and a temperature gradient of 1300 °C/cm was applied to the solder joint. Based on Fourier's law, the temperature distribution across solder joints is described by Formula (1):

$$T = T_{w1} - \frac{T_{w1} - T_{w2}}{\delta} \chi \quad (1)$$

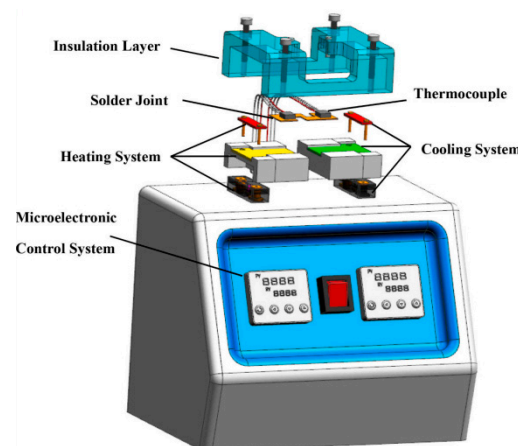


Figure 3. Thermomigration device and schematic diagram.

T_{w1} is the hot-end temperature, T_{w2} is the cold-end temperature, and δ is the welding height. It can be seen from the above equation that the temperature gradient $TG = (T_{w1} - T_{w2})/\delta$. From Figure 4, the cold-end temperature of the solder joint is 78.5 °C, the hot-end temperature is 91.5 °C, and the temperature difference is 13 °C. The thermomigration test was performed at 0 h, 72 h, 144 h, 288 h, and 576 h.

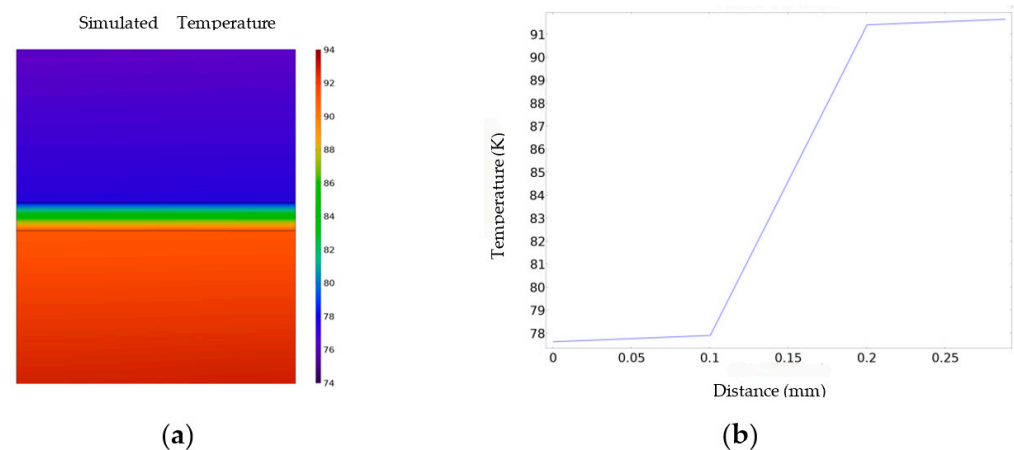


Figure 4. Simulation of the temperature field distribution of the solder joint heated to a steady-state at an average temperature of 85 °C. (a) Temperature field at 1300 °C/cm; (b) temperature distribution curves from the hot end to the cold end at 1300 °C/cm.

2.5. Test Plan and Detection Method

A scanning electron microscope (SEM) (JSM-5610LV, JEOL, Tokyo, Japan) was used to observe the microstructure of the composite solder and solder joints, and the composition of the composite solder and solder joints was analyzed by energy dispersive spectrometer (EDS). The spread area [26] was used to characterize the wettability of Sn58Bi-*x*Ni composite solder/Cu. The thickness of the IMC at the solder joint interface was measured using Image J. The tensile and shear assessments were conducted using the UTM2503 micro tensile (SUNS, Shenzhen, China) testing machine at a rate of 1 mm/min. The outcomes were determined based on the mean of five trials.

3. Results

3.1. Microstructure of Sn58Bi-*x*Ni Composite Solder

Figure 5 illustrates the microstructure of the Sn58Bi-*x*Ni composite solder. From Figure 5, one can see that the microstructure of Sn58Bi solder is composed of a β -Sn strip (dark region) + a massive Bi (bright region) binary layered eutectic structure, and the black spherical intermetallic compound Ni_3Sn_4 is formed after the addition of Ni nanoparticles. After adding Ni nanoparticles to Sn58Bi solder, the interlayer spacing of the alternating Sn-rich and Bi-rich phases in the microstructure of the composite solder decreases, the average grain size of the Sn and Bi phases decreases, and the microstructure is refined. When $\omega(\text{Ni}) \leq 0.75$ wt.%, the microstructure of Ni nanoparticles becomes finer, and the Bi-phase segregation is effectively inhibited with the increase in Ni nanoparticles. By incorporating a minor amount of Ni nanoparticles into the base solder, the Ni_3Sn_4 grains within the composite solder are evenly dispersed, leading to a significant refinement of the microstructure through heterogeneous nucleation [27]. However, the addition of Ni nanoparticles continues to increase, and when $\omega(\text{Ni}) = 1$ wt.%, Ni_3Sn_4 forms and aggregates in large quantities, and the spherical Sn-rich phase region expands, while the Bi-phase distributed around the Sn-rich phase begins to segregate to form coarse Bi blocks, the inhibition of Bi-phase segregation is weakened.

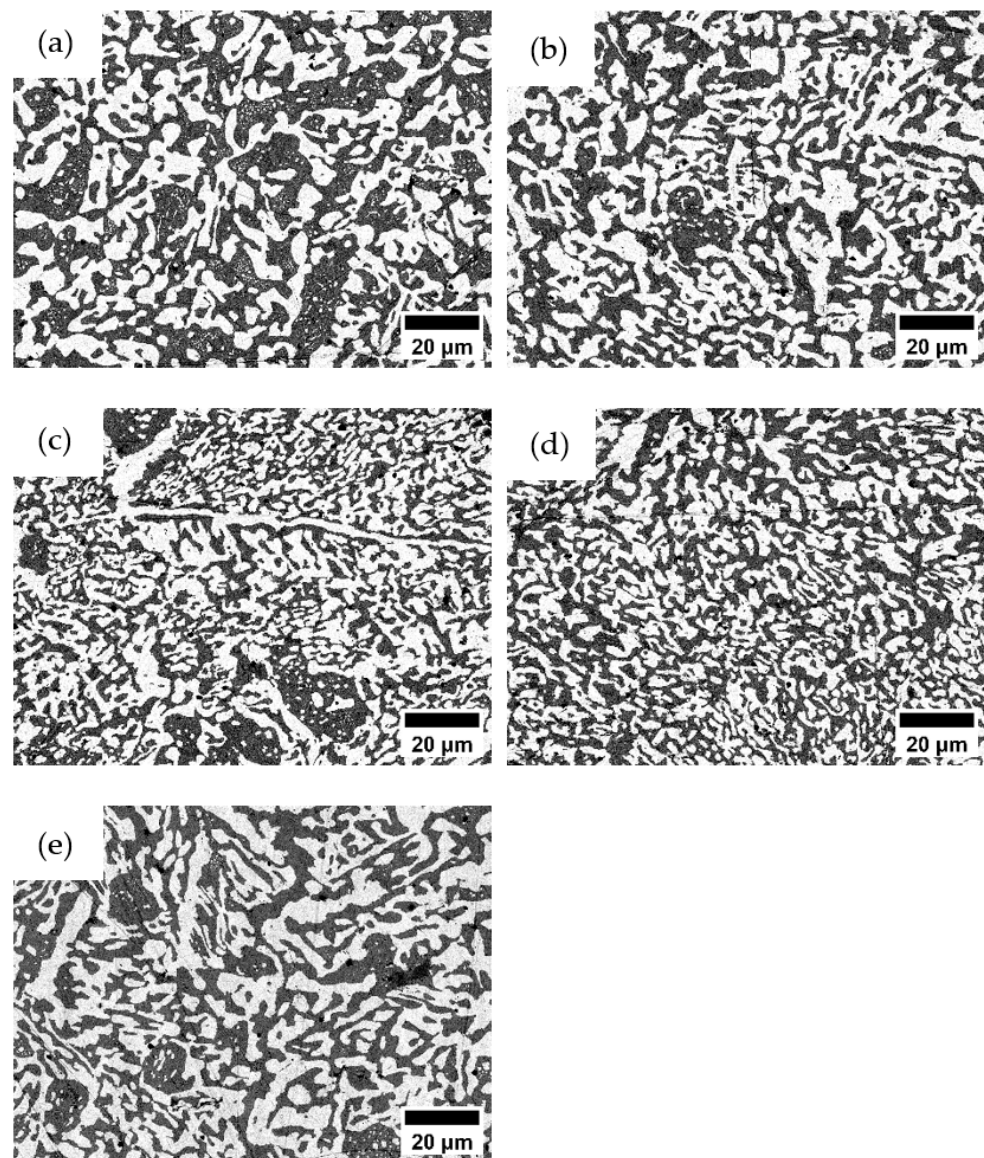


Figure 5. Microstructure of Sn58Bi- x Ni composite solder (a) 0.0 wt.%; (b) 0.25 wt.%; (c) 0.5 wt.%; (d) 0.75 wt.%; (e) 1 wt.%.

3.2. Properties of Sn58Bi- x Ni Composite Solder

Figure 6 illustrates the impact of varying quantities of Ni nanoparticles on the characteristics of Sn58Bi composite solder. It is evident from Figure 6 that the incorporation of Ni nanoparticles enhances the wettability of the composite solder, with a negligible effect on its electrical conductivity and melting temperature. Although Ni nanoparticles form a high melting point of Ni_3Sn_4 with Sn, the melting point and conductivity of composite solder are basically unchanged, which will not affect its application in low-temperature fields. When $\omega(\text{Ni}) = 0.5\text{wt}\%$, the spread area of the composite solder is 43.4 mm^2 , which is 37.8% more than that of the base solder. The surface tension between the Cu substrate and the composite solder may have decreased as a result of the addition of trace Ni nanoparticles. Composite solders' wettability is improved by increasing their spread area and diffusion rate. However, the addition of trace Ni nanoparticles can lower the solder's surface tension and prevent the interface interaction between the Sn and Cu substrate in the composite solder. Nevertheless, an excessive addition of Ni nanoparticles can lead to the agglomeration of Ni_3Sn_4 within the composite solder, which impedes the solder's flow and diminishes

its wettability. This is consistent with the study of Song et al. [28] that showed that Ni nanoparticles can improve the wettability of Sn20Bi composite solder.

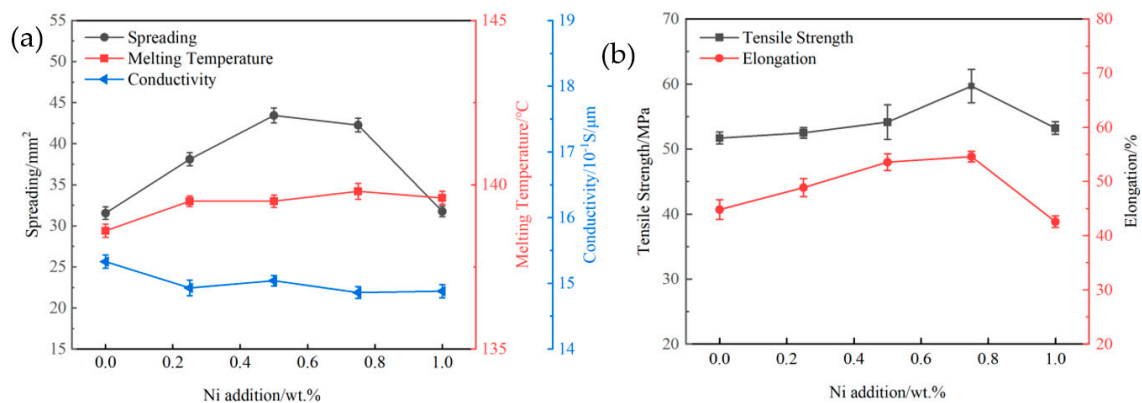


Figure 6. Properties of composite solder. (a) Physical properties and wettability; (b) mechanical properties.

The inclusion of Ni nanoparticles in the composite solder led to improvements in both its elongation and tensile strength. When $\omega(\text{Ni}) = 0.75$ wt.%, the tensile strength of the composite solder is 59.7 MPa, and the elongation is 54.6%. The tensile strength and elongation of the base solder were increased by 15.5% and 21.8%, respectively. This may be related to Ni_3Sn_4 second phase strengthening, which makes the microstructure of the composite solder finer and more uniform. When $\omega(\text{Ni}) > 1$ wt.%, the composite solder exhibits a tensile strength of 53.2 MPa, surpassing that of the base solder, while experiencing only a marginal reduction in elongation. This is because, with the increase in Ni content, the Ni_3Sn_4 in the structure will become coarse, and the coarse grain will reduce the strength and toughness of the solder and become the main source of crack growth [29].

Figure 7 illustrates the tensile fracture morphology of the Sn58Bi- x Ni composite solder. From the figure, the tensile fracture morphology of Sn58Bi solder is dominated by cleavage step + a few dimples, showing a mixed tough-brittle fracture mode dominated by brittle fracture. With the increase in Ni nanoparticles, the number of tensile fracture dimples of the composite solder increases, the size decreases, the fracture is rough, and the toughness is better. After adding an appropriate amount of Ni nanoparticles, the microstructure of the composite solder is finer, the grains are finer and more uniform, the crack propagation along the fracture direction is more hindered by grain boundaries, and the number and volume of grains involved in deformation increase, resulting in more plastic deformation before fracture, thus increasing the elongation of the Sn58Bi- x Ni composite solder. The Sn58Bi-1Ni tensile fracture shows a larger scale of quasi-cleavage and secondary cracks, which is an apparent brittle fracture mode.

In summary, Sn58Bi-0.75Ni composite solder has fine microstructure, relatively high tensile strength and elongation, and good comprehensive properties, and it can be used as lead-free solder for solder joints.

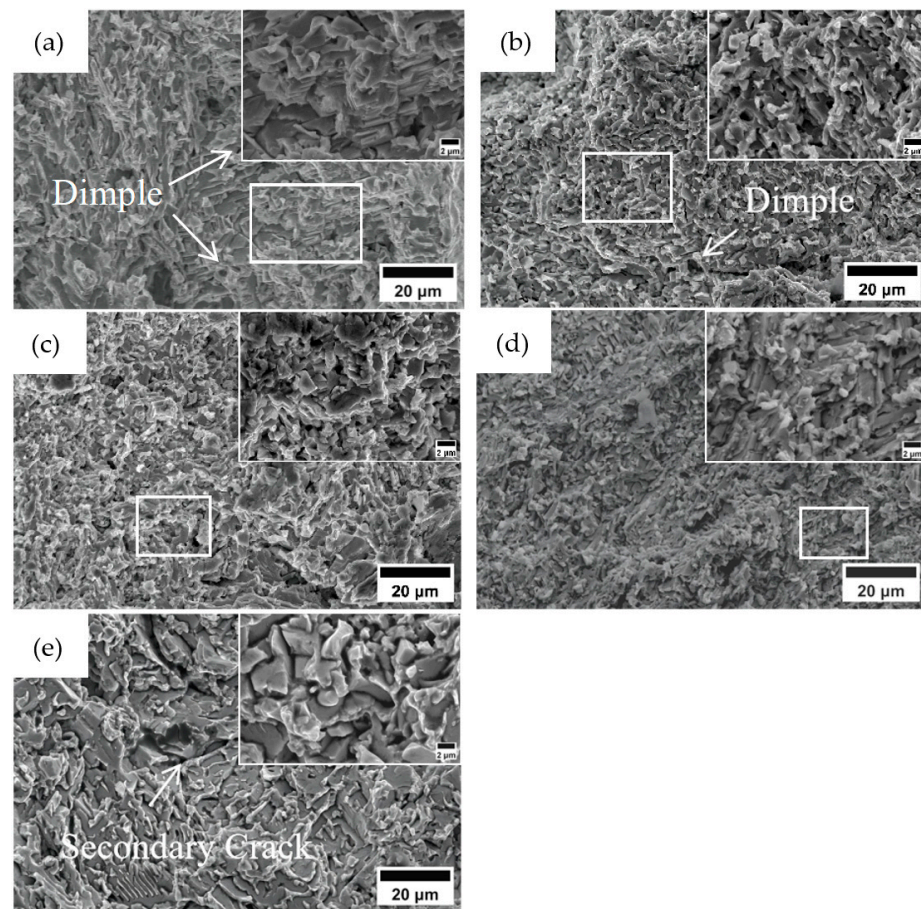


Figure 7. Tensile fracture morphology of composite solder. (a) 0.0 wt.%; (b) 0.25 wt.%; (c) 0.5 wt.%; (d) 0.75 wt.%; (e) 1 wt.%.

4. Thermomigration Microstructure and Properties of Sn58Bi-xNi/Cu Solder Joints

4.1. Microstructure of Solder Joint Without Thermal Loading

Figure 8 displays the microstructure of the Sn58Bi-xNi composite solder/Cu solder joints without thermal loading. The EDS analysis results of the micro-areas' compositions in Figure 8c are presented in Table 1. It can be observed from Figure 8 and Table 1 that the solder joint is composed of three parts from top to bottom, namely the solder seam, the interface IMC layer, and the Cu base material. The solder joint interface's IMC layer without Ni nanoparticles has a microstructure of Cu_6Sn_5 , while the solder joint IMC layer with Ni nanoparticles has a scalloped $(\text{Cu}, \text{Ni})_6\text{Sn}_5$ microstructure, as the ratio of the total number of Cu and Ni atoms to the number of Sn atoms is nearly 6:5. The reaction formula of the solder joint IMC layer phase is as follows [30,31]:

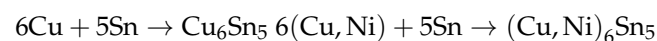


Table 1. EDS analysis results of micro-area components in Figure 8c (at%).

No.	Sn	Bi	Ni	Cu
A	100	-	-	-
B	88.9	7.9	1.0	2.2
C	51.9	-	0.5	47.6
D	-	-	-	100

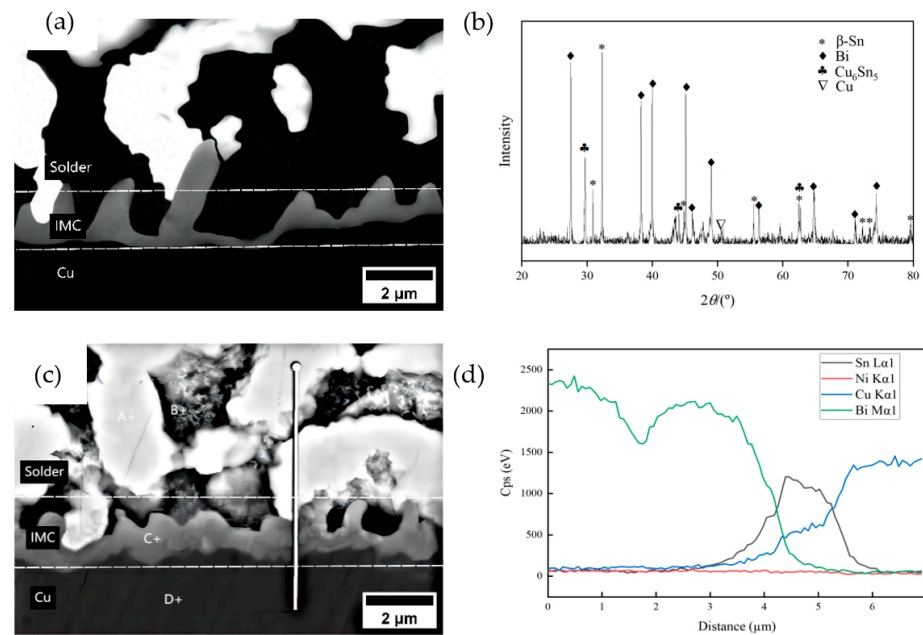


Figure 8. Microstructure of Sn58Bi- x Ni composite solder/Cu solder joints. (a) 0.0 wt.%; (b) Figure 8a XRD pattern; (c) 0.75 wt.%; (d) Figure 8c line scan EDS.

Compared with Cu_6Sn_5 , the $(\text{Cu}, \text{Ni})_6\text{Sn}_5$ at the solder joint interface IMC with Ni nanoparticles has improved Young's modulus, strength, hardness, and creep resistance [32,33]. The area of the solder joint where the solder is fused primarily consists of a tin and bismuth eutectic structure, along with Ni_3Sn_4 .

The Sn58Bi/Cu solder joint has an IMC thickness of $0.78 \mu\text{m}$ and a rod-shaped shape; after adding Ni nanoparticles, the IMC root of the solder joint interface thickens [34,35], reaching $1.07 \mu\text{m}$ in a scallop-like shape. This is because Cu_6Sn_5 is formed at the interface in the early stage of brazing. As the reaction proceeds, Ni atoms diffuse and grow into $(\text{Cu}, \text{Ni})_6\text{Sn}_5$. As a consequence of the lower activation energy of $(\text{Cu}, \text{Ni})_6\text{Sn}_5$ intermetallic compounds compared to Cu_6Sn_5 , it promotes the mutual diffusion of Cu and Sn atoms, promotes the growth of interface the IMC, and improves the bonding between the soldering seam and the interface IMC.

4.2. Microstructure of Solder Joint Under Thermal Loading

The microstructures at the hot and cold ends of the Sn58Bi-0.75Ni/Cu solder joint are depicted in Figure 9. The average thickness of the IMC layer at the hot and cold interfaces of the Sn58Bi- x Ni/Cu solder joint is illustrated in Figure 10. From Figure 9, with the increase in thermal loading time, Bi-phase courses in an obvious manner, the IMC growth trend is evident, and its shape changes from a scallop shape to a plane shape. At 0 h of thermal loading, the IMC at either end of the solder joint exhibits a scalloped pattern, with a mean thickness of $1.07 \mu\text{m}$. After 72 h of thermal loading (Figure 9a,e), the interface IMC at the hot end of the solder is a thick scallop shape with an average thickness of $1.62 \mu\text{m}$, and the interface is relatively flat. The IMC at the cold end is a thick scallop shape with an average thickness of $1.32 \mu\text{m}$, which is not much different from that at the hot end, indicating that there is no obvious material migration from the cold end to the hot end. After 144 h of thermal loading (Figure 9b,f), the interface IMC at the hot end of the solder joint is still a coarse scallop shape, with an average thickness of $2.49 \mu\text{m}$. The cold-end interface IMC is still a coarse scallop shape with an average thickness of $2.34 \mu\text{m}$. At this point, the interface is still relatively flat. After 288 h of thermal loading (Figure 9c,g), the interface IMC of the hot end of the solder joint is planar, with an average thickness of $2.91 \mu\text{m}$, and micro-voids and micro-cracks appear. The cold-end interface IMC is approximately banded with an average thickness of $2.87 \mu\text{m}$. After 576 h of thermal loading (Figure 9d,h), micro-voids

and micro-cracks on the interface IMC of the hot end of the solder joint expand, and the number increases, forming macro-cracks of large size with an average thickness of $3.72\text{ }\mu\text{m}$, which is easy to fracture at this position, which is consistent with the research results of Shen et al. [16]. The average thickness of the IMC layer at the cold end increases to $3.21\text{ }\mu\text{m}$, and the thickness is obviously different from that at the hot end.

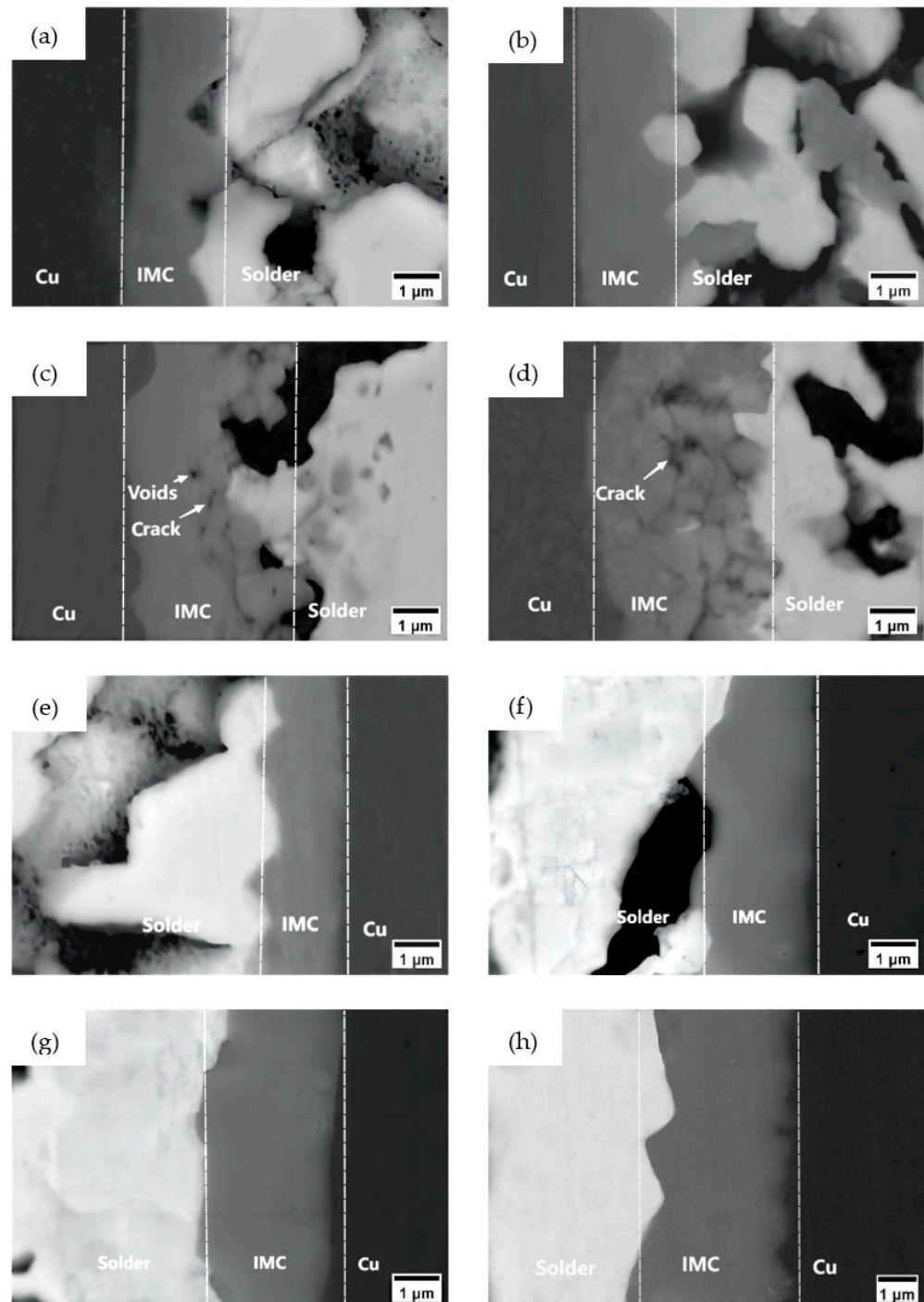


Figure 9. IMC microstructure of Sn58Bi-0.75Ni/Cu solder joint thermomigration interface: (a) hot end (72 h); (b) hot end (144 h); (c) hot end (288 h); (d) hot end (576 h); (e) cold end (72 h); (f) cold end (144 h); (g) cold end (288 h); (h) cold end (576 h).

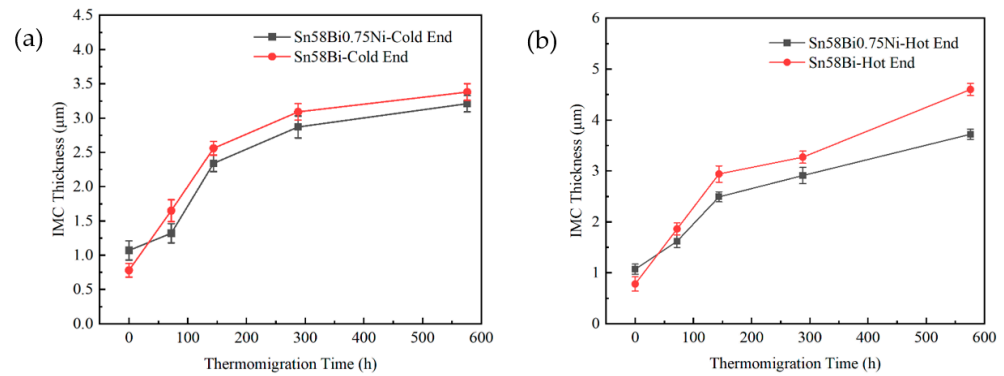


Figure 10. Average IMC thickness of solder joints under thermal loading. (a) cold end; (b) hot end.

The empirical power-law function and the Arrhenius relationship yield Equation (2) [36]:

$$\ln h = n \ln t + \ln k_0 - \frac{Q}{RT} \quad (2)$$

In this context, Q represents the activation energy for growth, h represents the thickness of the IMC, n represents the growth time exponent, t represents the thermal loading time, and k_0 represents the growth constant. Constructing a logarithmic plot with $\ln(t)$ on the x -axis and $\ln(h)$ on the y -axis yields a graph where the slope represents the value of n .

When $n < 1/3$, the growth rate is independent of the diffusion rate, and the interface IMC grows controlled by grain boundaries; when $n = 1/2$, the growth of the phase is controlled by the rate of atomic diffusion, and the interface IMC grows controlled by bulk diffusion; when $n = 1$, the interface IMC grows controlled by surface reactions.

The logarithmic relationship between the thickness of the IMC at the Sn58Bi-0.75Ni/Cu solder joints and the duration of thermal loading is depicted in Figure 11. As depicted by the straight lines in the figure, when TG equals 1300 °C/cm, the cold-end interface IMC exponent and the hot-end interface IMC exponent are 0.41 and 0.38, respectively, indicating that the growth of the IMC at this interface transitions from grain boundary-controlled to bulk diffusion-controlled.

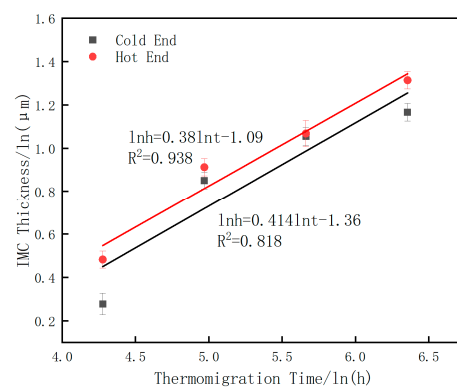


Figure 11. Logarithmic relationship between the thickness of IMC and time during the thermomigration process of Sn58Bi-0.75Ni/Cu solder joints at 1300 °C/cm.

The dynamic equation of IMC growth at the interface during the thermomigration process of Sn58Bi/Cu joints enhanced by Ni nanoparticles is Formula (3) [37]:

$$x_t = x_0 + \sqrt{kt} \quad (3)$$

where x_t is the interface IMC layer thickness at the time of thermal loading t , x_0 is the interface IMC layer thickness before thermal loading begins, t is the thermal loading time,

and k is the growth coefficient of the interface IMC layer. The larger the k value is, the faster the IMC layer grows. Otherwise, the slower it is.

The IMC thickness at the solder connection interface and the square root of the thermal loading duration are used as coordinates to build the graph, as seen in Figure 12. The growth coefficient k of the IMC layer is shown by the figure's linear slope. Figures 10 and 12 show that the IMC layer thickness grows at a somewhat faster rate at the hot end than at the cold end. The IMC thickness at the cold end continues to increase as time passes, and the growth rate slows down as time passes. The thickness of the IMC at the hot end is more significant than that at the cold end for the following reasons: firstly, there is more Bi content, which hinders the diffusion and migration of Cu atoms; second, because the hot-end temperature is relatively high, the hot-end IMC is relatively faster than that of the cold end. The growth coefficients of the IMCs at the cold and hot interfaces of Sn58Bi-0.75Ni/Cu solder joints are $2.78 \times 10^{-6} \mu\text{m}^2/\text{s}$ and $4 \times 10^{-6} \mu\text{m}^2/\text{s}$, respectively. The growth coefficients of the IMCs at the cold and hot interfaces of Sn58Bi/Cu solder joints are $3.36 \times 10^{-6} \mu\text{m}^2/\text{s}$ and $7.11 \times 10^{-6} \mu\text{m}^2/\text{s}$, respectively, which indicates that the addition of Ni nanoparticles could inhibit the thermomigration of solder joints. This is because the addition of Ni nanoparticles makes the presence of a Ni_3Sn_4 compound in the solder, which can inhibit the movement of Sn atoms to the Cu substrate and inhibit the growth rate of the IMC layer, thus weakening the influence of the thermomigration effect on the solder joint structure. The k value in this paper is significantly lower than that in the conclusions of Li et al. [38], at 120°C , which is consistent with the growth constant law.

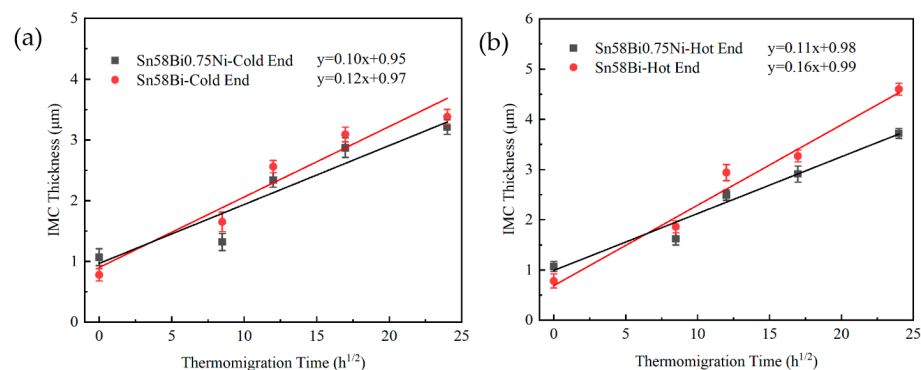


Figure 12. Square root relationship between IMC layer thickness and thermal loading time. (a) cold end; (b) hot end.

4.3. Mechanical Properties of Solder Joints Under Thermal Loading

The shear strength curve of Sn58Bi- x Ni composite solder/Cu solder joint under thermal loading is shown in Figure 13. Figure 13 indicates that the shear strength of the solder joints diminishes as the duration of thermal loading increases. The solder joint's shear strengths for the Sn58Bi-0.75Ni/Cu solder connection are 45.5 MPa at 0 h and 25.5 MPa at 576 h, respectively. This is 43.9% less than the solder joint's thickness without thermal loading. When the thermal loading time for Sn58Bi/Cu solder joints is 0 h, the solder joints' shear strength is 38.6 MPa. After 576 h of heat loading, the solder joint's shear strength drops to 19.6 MPa, a 49.2% decrease from its pre-loading value. The main reason for the decrease in shear mechanical properties of solder joints under thermal loading is caused by defects such as voids and cracks [3,25]. Adding Ni nanoparticles can block the migration of solder joints, reduce the occurrence of defects such as micro-voids and micro-cracks, and improve the shear strength of solder joints compared with base solder.

The shear fracture morphology of the Sn58Bi-0.75Ni/Cu solder joint under thermal loading is shown in Figure 14. EDS analysis results of micro-area components are shown in Table 2. At the initial point where the thermal loading time is 0 h, thermomigration in the solder joints has not yet occurred, and the shear fracture surface of the solder joints is characterized by numerous torn edges. The locally enlarged picture shows small cleavage

facets, which are brittle and ductile mixed fractures dominated by quasi-cleavage. The solder junction A region's shear fracture structure is a (β -Sn + Bi phase) eutectic structure + $(\text{Cu, Ni})_6\text{Sn}_5$. This suggests that the transition area between the soldering seam and IMC layer is where the shear fracture happened, as shown Figure 14a. When the thermal loading time is 144 h, the shear fracture of the solder joint has a large number of torn edges, and there are secondary cracks on the torn edges, showing brittle fracture. The shear fracture structure of the solder joint B region is composed of a Sn58Bi eutectic structure and $(\text{Cu, Ni})_6\text{Sn}_5$. This suggests that the shear fracture happens in the area where the IMC layer and the soldering seam meet, as shown in Figure 14b. When the thermal loading time is 576 h, the shear fracture has a large number of "rock sugar" sections, the fracture surface is clean and smooth, and the number of secondary cracks increases, which is a typical intergranular brittle fracture. The fracture mechanism of the solder joint shear fracture is a brittle fracture. The shear fracture structure of the solder joint C region is $(\text{Cu, Ni})_6\text{Sn}_5$. From Figure 14c, one can see that the site of the fracture has shifted further toward the IMC layer. This is consistent with the gradual increase in hardness of solder joints from the hot end to the cold end, as studied by Wei et al. [17].

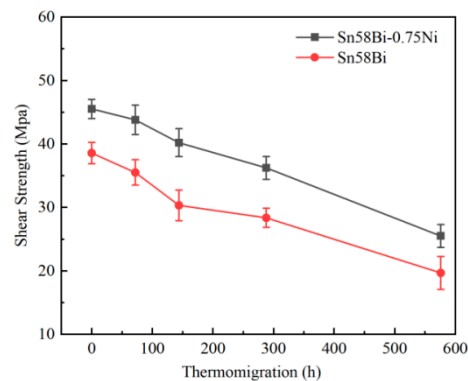


Figure 13. Solder joint shear strength under thermal loading.

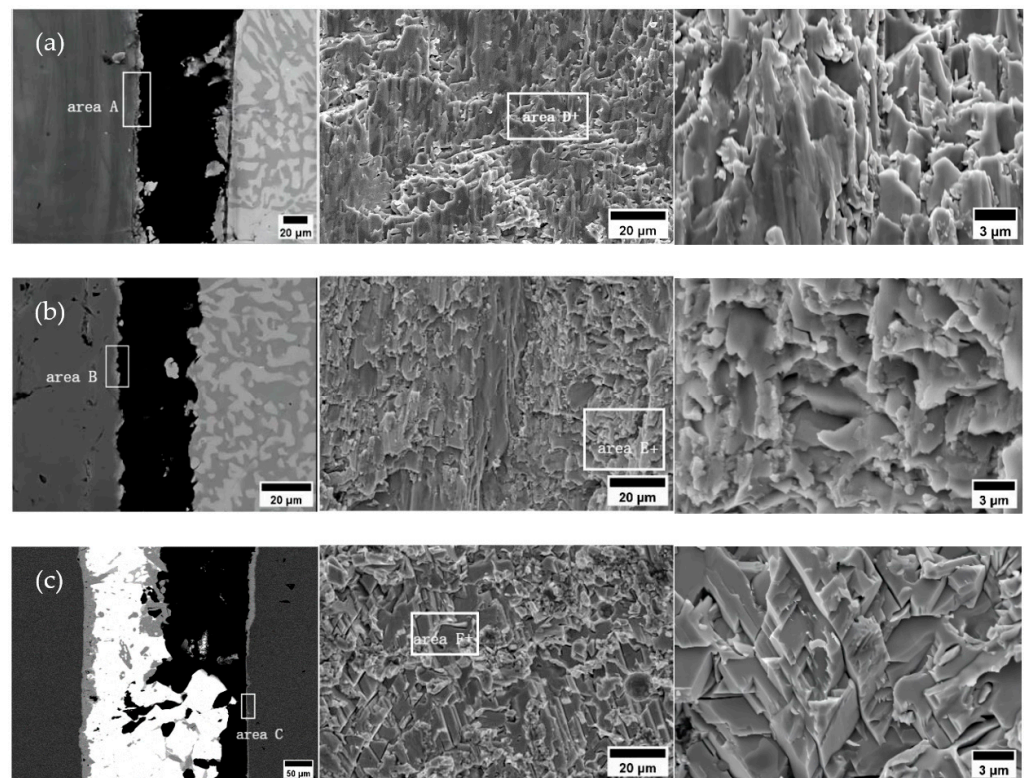


Figure 14. Shear fracture morphology of solder joints under thermal loading. (a) 0 h; (b) 144 h; (c) 576 h.

Table 2. EDS analysis results of micro-area components in Figure 14 (at%).

No.	Sn	Bi	Cu	Ni
A	49.1	20.3	30.4	0.2
B	46.1	10.6	42.8	0.5
C	44.2	0	55.4	0.4
D	70.9	26.4	2.1	0.6
E	62.8	15.1	19.5	2.6
F	21.2	0	78.6	0.2

In summary, with the increase in thermal loading time, the solder joint shear fracture path moves from the transition zone composed between the soldering seam and the IMC layer to the IMC layer dominated by $(\text{Cu}, \text{Ni})_6\text{Sn}_5$, and the shear fracture mechanism changes from the brittle and tough mixed fracture dominated by quasi-cleavage to the brittle fracture dominated by a large number of “rock sugar” sections and secondary cracks.

5. Conclusions

1. Introducing an appropriate quantity of Ni nanoparticles can enhance the microstructure of the composite solder, mitigate the coarsening of Bi-phase segregation, and essentially maintain its melting point and conductivity. Basically, its melting point conductivity does not change, and its wettability and tensile strength is improved. For instance, at 190 °C, the spread area of the Sn58Bi-0.5Ni composite solder reaches 43.4 mm², which is a 37.8% increase compared to the base solder. Additionally, the tensile strength of the Sn58Bi-0.75Ni composite solder is 59.7 MPa, with an elongation of 54.6%, marking improvements of 15.5% and 21.8%, respectively, over the base solder.
2. The IMC thickness at this interface for the Sn58Bi-0.75Ni/Cu solder joints measures 3.72 µm, which is 247.7% higher than the thickness without thermal stress, yet it is considerably thinner compared to the 4.6 µm IMC thickness observed at the hot-end interface of the base solder.
3. Incorporating Ni nanoparticles can enhance the longevity of solder joints. At a thermal loading duration of 576 h, the shear strength of the Sn58Bi-0.75Ni/Cu solder joint reaches 25.5 MPa, surpassing the base solder’s strength by 30.1%. The fracture path shifts from the transition area between the solder and the IMC layer to within the IMC layer itself. Concurrently, the fracture mechanism transitions from a mix of brittle and tough fractures, primarily characterized by quasi-cleavage, to a predominantly brittle fracture, marked by numerous “rock sugar”-like structures and secondary cracks.

Despite SnAgCu solder’s irreplaceable advantages and its status as the most mainstream solder in the current electronics packaging industry, the demand for low-temperature soft solders in consumer electronics is growing. The Sn-58Bi/Cu solder joint, which is the core of this paper’s research, has already attracted the attention of companies both domestically and internationally due to its excellent comprehensive performance. We will further investigate the grain orientation changes in Sn-58Bi/Cu solder joints during thermomigration, providing a solid theoretical foundation for the study of low-temperature lead-free solder joints.

Author Contributions: Conceptualization, Y.F. and K.Z.; Methodology, Y.F.; Software, Y.F., W.C. and J.W.; Validation, J.W.; Formal analysis, Y.F. and W.C.; Investigation, Y.F., W.C., J.W. and Y.W.; Resources, K.Z.; Data curation, Y.F., J.W. and Y.W.; Writing—original draft, Y.F. and W.C.; Writing—review & editing, Y.F. and K.Z.; Visualization, Y.W.; Supervision, K.Z.; Project administration, K.Z.; Funding acquisition, K.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (grant No. U1604132); the Leading Talent in Basic Research in Central Plains (grant No. ZYYCYU202012130); the Henan Province International Science and Technology Cooperation Project (Key Project) (grant No. 241111521400); the China Postdoctoral Science Foundation (grant No. 2023M741037); and the

Provincial and Ministerial Co-construction of Collaborative Innovation Center for Non-Ferrous Metal New Materials and Advanced Processing Technology, Henan Province, China.

Data Availability Statement: The data used to support the findings of this study are included within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

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