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Effect of Strain Rate on Tensile Behavior of Sn-9Zn-xAg-ySb; {(x, y) = (0.2, 0.6), (0.2, 0.8), (0.6, 0.2), (0.8, 0.2)} Lead-Free Solder Alloys

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Abstract

The tensile properties of Sn-9Zn-xAg-ySb; {(x, y) = (0.2, 0.6), (0.2, 0.8), (0.6, 0.2), (0.8, 0.2)} lead-free solders were investigated. All the test samples were annealed at 150˚C for 1 hour. The tests are carried out at room temperature at the strain rate of 4.17×10^{-3} s^{-1}, 20.85×10^{-3} s^{-1}, and 208.5×10^{-3} s^{-1}. It is seen that the tensile strength increases and the ductility decrease with increasing the strain rate over the investigated range. From the strain rate change test results, the strain sensitivity values are found in the range of 0.0831 to 0.1455 due to the addition of different alloying elements.

Keywords

Lead-Free Solder, Strain Rate, Strain Sensitivity, Ductility, Tensile Properties

1. Introduction

Lead-based solder alloys are using for a long time in electronic and optoelectronic packaging all over the world due to their excellent wetting property, decent melting temperature, suitable electrical and mechanical properties, and low cost [1] [2]. Due to the toxicity of lead, it pollutes the groundwater and causes lead poisoning. Therefore, it is harmful to human beings and to the environment, and its use is prohibited [3]-[10]. Because of environmental and health perturbation, legislations, environmental regulations like Waste Electrical and Electronic Equipment (WEEE), Restriction of the use of Hazardous Substances (RoHS), and marketing forces at home and abroad made the electronics industries restless about the lead-free solder alloys to replace the traditional lead-based solders [11]-[18]. The researchers are giving the most attention to the Sn-Ag and

Sn-Zn alloys, because of their excellent performance, reliability, cost, and resource. In comparison with Sn-Ag solders Sn-Zn solders have many benefits, such as low melting point (198˚C), satisfactory mechanical strength, low cost, and available supply. So there is a great opportunity to think about the Sn-Zn solder [19]-[27]. Sn-Zn-based solder alloys may be a good alternative to lead-based solders because of their better mechanical properties. The mechanical properties of Sn-9Zn eutectic alloy is better than that of traditional solder alloys and it has a lower melting point of 199.8˚C [28]. As the Sn-9Zn eutectic alloy has many advantages, it is predicted as a suitable replacement for leaded solder alloys. Nowadays a large number of studies on Sn-9Zn-xNi [29], Sn-9Zn-(Cu & Al) [30], Sn-9Zn-xAg [31], Sn-9Zn-xCr [32], Sn-9Zn-xGa [33], Sn-9Zn-xBi [34], Sn-9Zn-xAl and Sn-9Zn-xCu [35], are done to find out an alternative of Sn-Pb alloys. But Sn-9Zn eutectic alloy has some negative points, such as worst corrosion behavior, poor oxidation resistance, and low wettability than the Sn-Pb eutectic solder [36]. Due to these poor behaviors, Sn-9Zn eutectic alloy cannot occupy the position of Sn-Pb solders [37] [38]. Despite so many weak sides, using of Sn-9Zn eutectic alloy is spreading day by day. So further studies are required to investigate its material properties such as melting temperature, solderability, creep resistance, thermal fatigue, corrosion behavior, mechanical strength, ductility, and so on. The mechanical properties of a solder alloy are very significant, as such properties determine the thermal fatigue and fracture of the solder joint. Therefore, it is necessary to investigate the solder's mechanical properties (tensile strength, yield strength, and ductility). The aim of this study is to investigate the tensile properties of Sn-9Zn-0.2Ag-0.6Sb, Sn-9Zn-0.2Ag-0.8Sb, Sn-9Zn-0.6Ag-0.2Sb and Sn-9Zn-0.8Ag-0.2Sb solders under different test conditions. Especially the effects of strain rate at room temperature on the tensile properties are examined.

2. Experimental Procedure

2.1. Preparation of the Samples

Raw materials for preparing the alloys, pure tin (99.5 wt%), pure zinc (99.5 wt %), pure silver (99.5 wt%), and pure antimony (99.5 wt%) are available in the local market. At the first calculated amount of tin, zinc, silver, and antimony are weighted. Then tin is placed in a clay graphite crucible and melted in a muffle furnace at the temperature of 250˚C for 10 minutes. After melting the tin, zinc, silver, and antimony are added and the temperature is upgraded to 500˚C for 10 minutes. The melted solder alloy was chill cast in the preheated (300˚C) cast iron mold having the dimension of 250 mm × 10 mm × 10 mm followed by cooling in the air. Each solder is cast as a rectangular ingot. Before casting, the melt was homogenized by stirring at 500˚C.

2.2. Heat Treatment

The as-cast alloys are sectioned and annealed at the temperature of 150˚C for 60 minutes followed by furnace cooling to remove the micro-segregation effects. Then the tensile test samples are prepared from the ingots of the solder. The dimensions of the samples are gauge length 8 mm, thickness 2 mm, and width 3 mm as shown in Figure 1.

2.3. Tensile Tests

The tensile test is performed in a Universal Testing Machine (brand: Hounsfield, SR. No. H10KS-0572) at three different cross-head speeds: 2, 10, and 100 mm/min which are equal to the nominal strain rates of 4.17×10^{-3}, 20.85×10^{-3} and $208.5 \times 10^{-3}\ s^{-1}$ respectively. The test is carried out up to the failure of the samples at room temperature. Test curves only for one sample of each alloy are presented here as typical test curves; those for the other samples exhibited a similar shape and appearance and are not given. The averages of three consistent test results are taken as the tensile value for the corresponding alloy.

3. Results and Discussion

The chemical compositions of the alloys are measured with BRUKER S1TITAN Handheld XRF Analyzer, shown in Table 1 (wt%).

3.1. Effect of Strain Rate on Ultimate Tensile Strength

The investigation was conducted with four alloys. All the test samples are annealed at 150˚C for 1 hour and a significant effect is observed. Table 2 summarizes the results of the tensile tests and each datum is the average of the results of the three samples. In two alloys (alloy-1, alloy-2) Sb content was varied and in the other two alloys (alloy-3, alloy-4) Ag content was varied. The tensile tests were conducted at three strain rates ($4.17 \times 10^{-3}\ s^{-1}$, $20.85 \times 10^{-3}\ s^{-1}$, and $208.5 \times 10^{-3}\ s^{-1}$). It is very clear that the strain rate plays an important role and affects

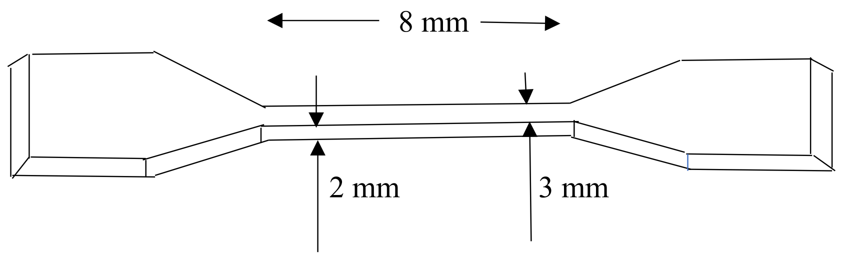


Figure 1. Dimensions of the tensile specimen.

Table 1. Chemical compositions of the solder alloys (wt%).

Solder alloy	Zn	Ag	Sb	Sn
(Alloy-1) Sn-9Zn-0.2Ag-0.6Sb	9.354	0.182	0.524	89.940
(Alloy-2) Sn-9Zn-0.2Ag-0.8Sb	8.980	0.187	0.673	90.160
(Alloy-3) Sn-9Zn-0.6Ag-0.2Sb	9.780	0.720	0.190	89.310
(Alloy-4) Sn-9Zn-0.8Ag-0.2Sb	8.780	0.750	0.185	90.285

Table 2. Tensile properties at different strain rates.

Solder alloy	Annealing temp. and time	Strain rate (s^{-1})	Tensile strength (MPa)	Yield stress (MPa)	Elongation (%)
(Alloy-1) Sn-9Zn-0.2Ag-0.6Sb	150˚C, 1 hour	4.17×10^{-3}	36	27.06	36.22
		20.85×10^{-3}	40.92	34.6	33.53
		208.5×10^{-3}	49.79	45.23	29.17
(Alloy-2) Sn-9Zn-0.2Ag-0.8Sb	150˚C, 1 hour	4.17×10^{-3}	26.82	24	46.35
		20.85×10^{-3}	36.97	34	44.54
		208.5×10^{-3}	47.84	44.83	42.08
(Alloy-3) Sn-9Zn-0.6Ag-0.2Sb	150˚C, 1 hour	4.17×10^{-3}	33	26.23	45.50
		20.85×10^{-3}	43.73	38	41.97
		208.5×10^{-3}	54.79	48.58	22.93
(Alloy-4) Sn-9Zn-0.8Ag-0.2Sb	150˚C, 1 hour	4.17×10^{-3}	35	28.33	61.38
		20.85×10^{-3}	46.67	38.97	32.36
		208.5×10^{-3}	59.73	51	28.49

stress levels. The ultimate tensile strength (UTS) increases with increasing the strain rate over the investigated range at room temperature as shown in **Figure 2**.

Table 2 and **Figure 3** show that alloy-1 with less Sb displays higher tensile strength than alloy-2 with more Sb all over the strain rates. On the other hand, alloy-4 having more Ag displays higher tensile strength than alloy-3 having less Ag.

An approximate linear relevance is performed between the tensile strength and the strain rate as shown in **Figure 4**. The strength-strain rate relationship follows the equation given below:

$$\sigma = k\dot{\varepsilon}^{m} \tag{1}$$

where σ is the tensile strength, $\dot{\varepsilon}$ is the strain rate, k is a constant, and m is called the strain rate hardening exponent or strain sensitivity [39]. The values of m, k, and R^2 are obtained from the logarithmic plotting of Equation (1) as shown in **Figure 4** and those are summarized in **Table 3**.

The value of m for Sn-37Pb is much greater than that of these four investigated lead-free solders [40]. As the value of m describes the ability to stop necking, the lead-free solders are lower capable to arrest necking [41]. As the values of m are less than 0.3, superplastic behavior will not occur in these lead-free solders [42]. The obtained results are in good agreement with the previous results [43] [44].

3.2. Effect of Strain Rate on Ductility

Figure 5 displays the variation of % elongation with the strain rate of the alloys. It was observed that at the strain rate for which the ultimate tensile strength is maximum, the ductility values of the alloys go through the minimum.

Table 3. Stress-strain characteristics of the alloys.

Solder Alloy	*m*	*K*	R^2
Sn-9Zn-0.2Ag-0.6Sb	0.0831	56.63	0.999
Sn-9Zn-0.2Ag-0.8Sb	0.1455	61.46	0.973
Sn-9Zn-0.6Ag-0.2Sb	0.1274	68.24	0.973
Sn-9Zn-0.8Ag-0.2Sb	0.1346	75.14	0.978

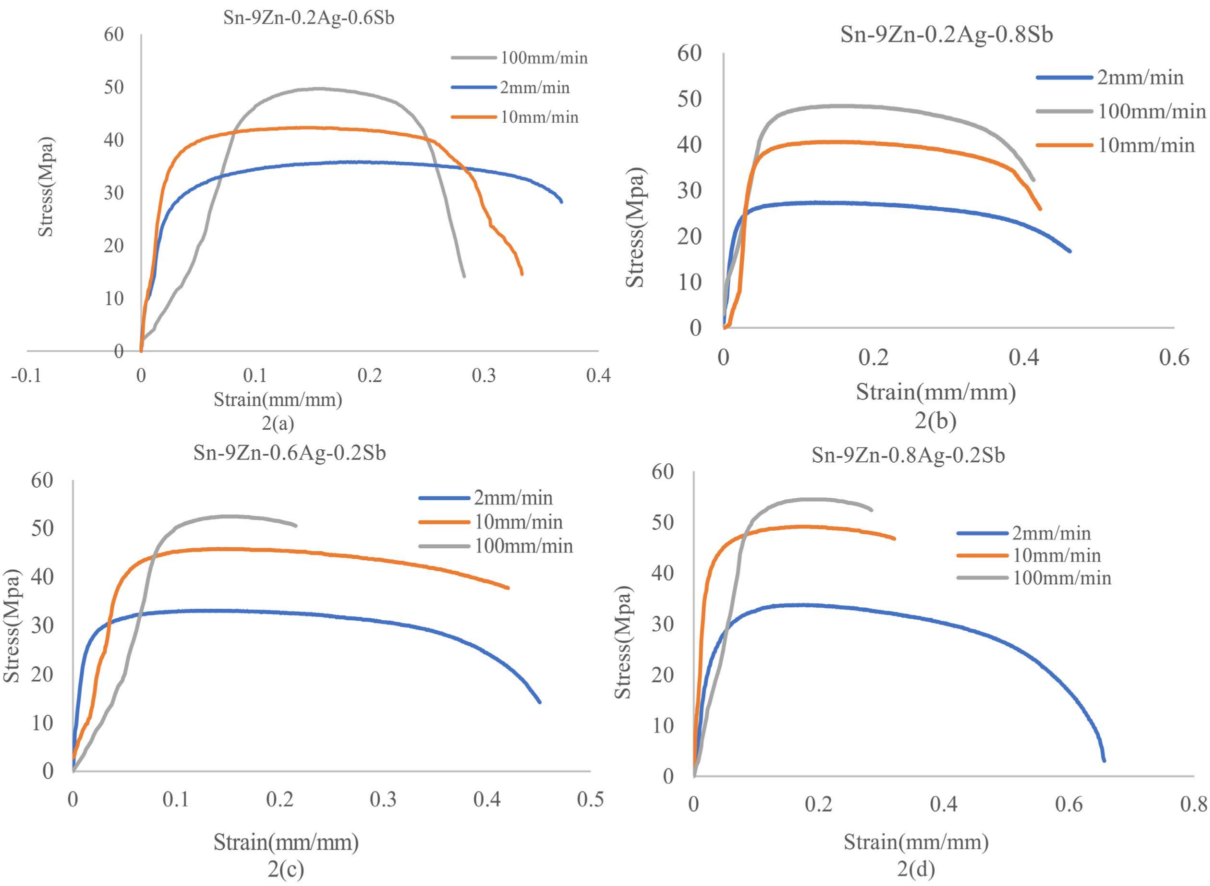
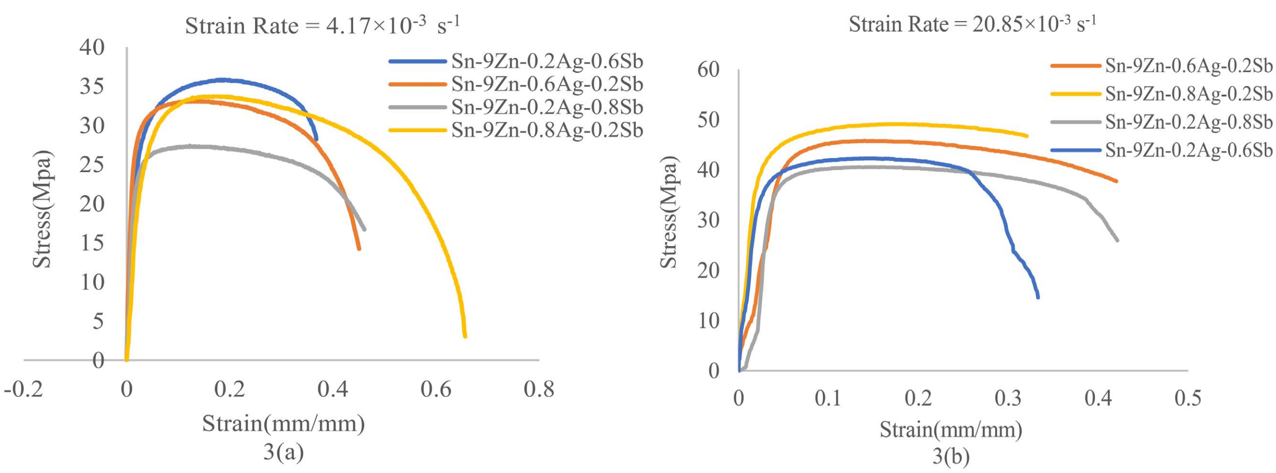


Figure 2. Typical stress-strain curves at room temperature showing the effect of different strain rates (a) alloy-1, (b) alloy-2, (c) alloy-3, (d) alloy-4.



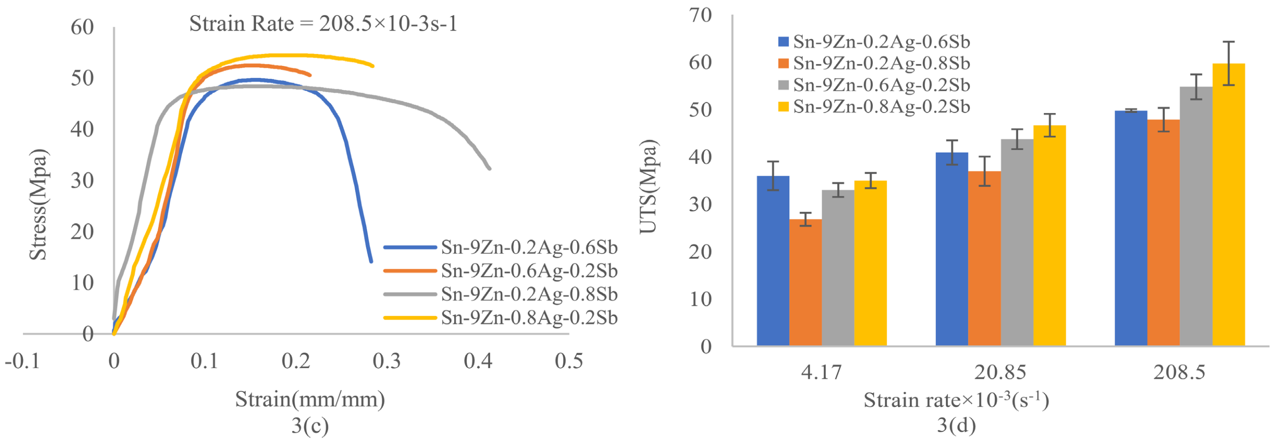


Figure 3. Typical stress-strain curves (a-c) of the alloys at the different strain rates (a) Strain rate 4.17×10^{-3} s^{-1} (b) 20.85×10^{-3} s^{-1} (c) 208.5×10^{-3} s^{-1} and (d) average UTS values at various strain rates.

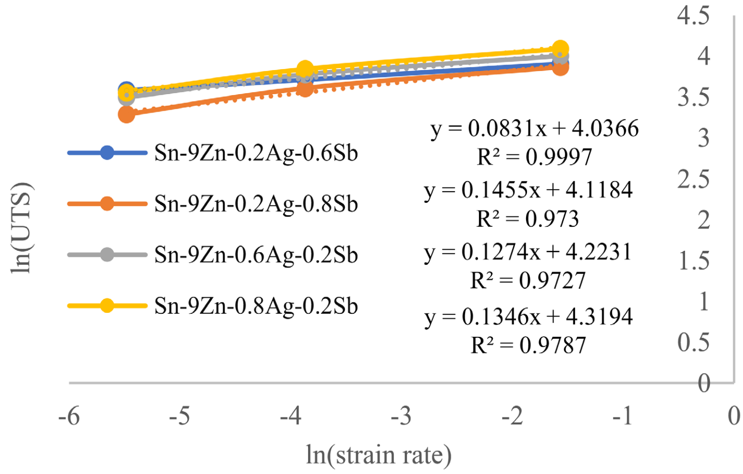


Figure 4. Ln-Ln plot of UTS versus strain rate.

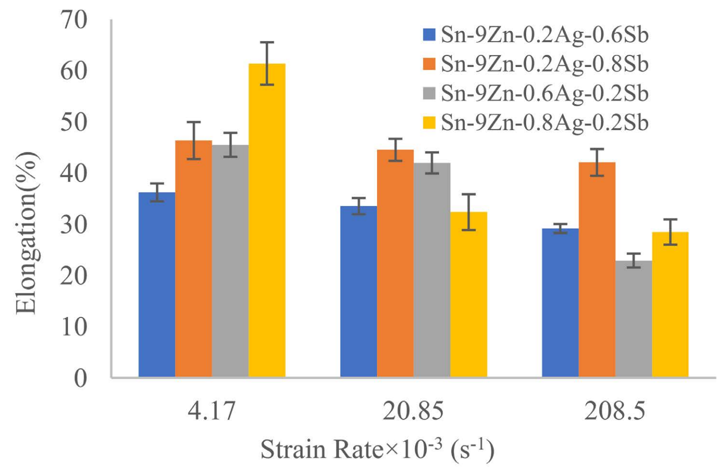


Figure 5. Ductility (% elongation)—strain rate curves of investigated alloys.

3.3. Effect of Strain Rate on Yield Strength

The yield strength-strain rate curves of the alloys are plotted in **Figure 6**. It is

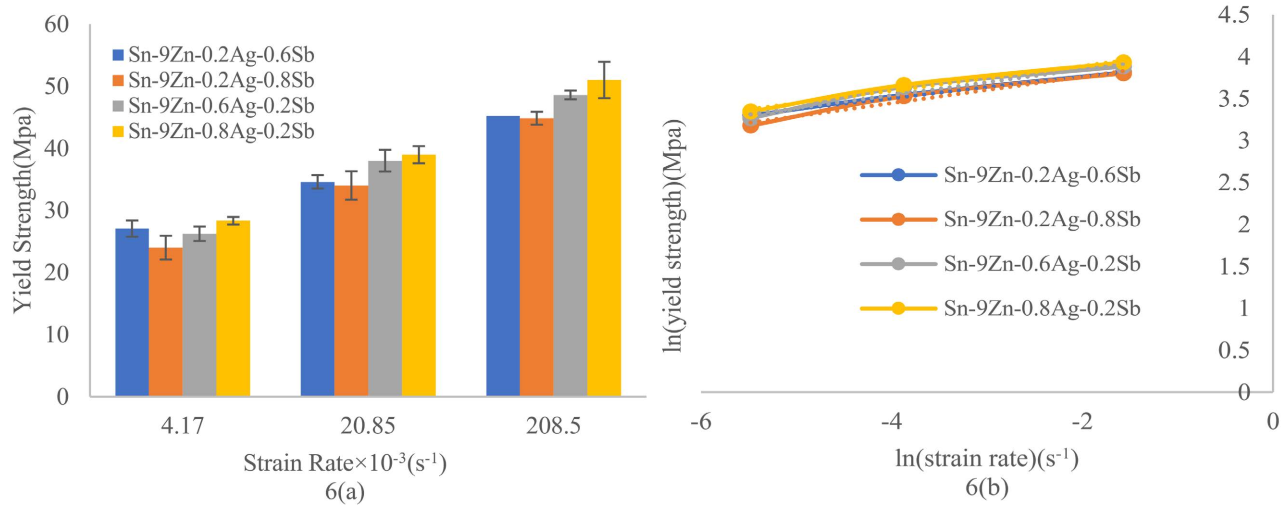


Figure 6. Yield strength-strain rate curves of investigated alloys (a) average yield strength values at different strain rates (b) Ln-Ln plot of average yield strength versus strain rate.

found that the yield strength (2% proof strengths) of the alloys increases with strain rates. The trend is very similar to that of ultimate tensile strengths. In all the alloys the maximum yield strength was attained at a strain rate of $208.5 \times 10^{-3}\ s^{-1}$. The yield strength of alloy-1 is higher than that of alloy-2 and the yield strength of alloy-4 is higher than that of alloy-3 all over the strain rates.

4. Conclusions

The tensile properties of Sn-9Zn-0.2Ag-0.6Sb, Sn-9Zn-0.2Ag-0.8Sb, Sn-9Zn-0.6Ag-0.2Sb, and Sn-9Zn-0.8Ag-0.2Sb are investigated under the strain rates $4.17 \times 10^{-3}\ s^{-1}$, $20.85 \times 10^{-3}\ s^{-1}$ and $208.5 \times 10^{-3}\ s^{-1}$. The results are summarized as follows:

1) Tensile strength and yield strength increase with the strain rate within the investigated range.

2) The trend of the yield strength is very similar to that of tensile strength.

3) Ductility decreases with increasing the strain rate.

4) The strain sensitivity m is 0.0831 for Sn-9Zn-0.2Ag-0.6Sb, 0.1455 for Sn-9Zn-0.2Ag-0.8Sb, 0.1274 for Sn-9Zn-0.6Ag-0.2Sb and 0.1346 for Sn-9Zn-0.8Ag-0.2Sb.

5) All the values of m are less than 0.3, so superplastic behavior will not occur in any of the lead-free solders investigated in this study.

6) Further investigation of the tensile properties of these solder alloys at different temperatures and strain rates is needed to understand the thermodynamic hardening response in more detail.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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