Research Article

Mohammad A. Gharaibeh*

Isothermal aging effect on SAC interconnects of various Ag contents: Nonlinear simulations

https://doi.org/10.1515/jmbm-2024-0020
received August 25, 2024; accepted October 05, 2024

Abstract: The mechanical behavior of the tin (Sn)–silver (Ag)–copper (Cu) (SAC) lead-free solders is strongly influenced by the isothermal aging due to the evolution of the microstructure and mechanical properties. This study aims to examine the influence of pre-isothermal aging at 100°C on the mechanical behavior of different SACN05 alloys with different silver content including N = 1, 2, 3 and 4% by applying nonlinear finite element analysis. The mechanical properties, including elastic and inelastic properties, of the SAC systems with various Ag percentages are gathered from the literature and incorporated in thorough thermomechanical simulations. In addition to the unaged solders condition, two aging periods, 6 and 12 months, are studied. The computational results showed that the mechanical response of pre-aged SACN05 solders is significantly influenced by the aging duration and silver content. Specifically, interconnects with higher Ag percentage are shown to be more resistive to aging and expected to have lower thermally induced inelastic deformations, strains, and strain energies. Therefore, better thermal fatigue performance and improved failure resistance is potentially expected. However, the pre-isothermally aged SACN05 solders generally exhibit lower resistance to the accumulations of inelastic strains and strain energies. Thus, it is probable that pre-aged SACN05 solders will demonstrate deterioration in thermal fatigue performance compared to unaged interconnects. Nonetheless, the aged SAC solder systems could be an innovative solution for designing electronic devices regularly exposed to shock and impact loading as the aging process significantly reduces the brittleness of the SnAgCu alloys.

Keywords: SAC alloys, isothermal aging, finite element simulations, thermal fatigue

*** Corresponding author: Mohammad A. Gharaibeh,** Department of Mechanical Engineering, Faculty of Engineering, The Hashemite University, Zarqa, 13133, Jordan, e-mail: mohammada_fa@hu.edu.jo

Nomenclature

Symbol	Description
s_o	initial value of deformation resistance [MPa]
Q/R	activation energy/universal gas constant [K]
A	pre-exponential factor [s^{-1}]
ζ	stress multiplier [-]
m	strain rate sensitivity of stress [-]
h_o	hardening–softening constant [MPa]
$\hat{s}$	coefficient for saturation value of deformation resistance [MPa]
n	strain rate sensitivity of the saturation value [-]
a	strain rate sensitivity of the hardening–softening [-]
SAC	tin (Sn)–silver (Ag)–copper (Cu)

1 Introduction

During their service life, electronic devices are continuously exposed to mechanical and thermomechanical loading conditions that can result in solder interconnect failures. Notably, 55% of electronic device failures are attributed to temperature and thermal cycling loadings [1]. For this reason, numerous experimental, numerical, and analytical investigations [2–6] have been overseen to accurately evaluate and characterize the reliability of electronic assemblies under thermal cycling conditions.

Solder alloys are primarily divided into two groups: lead-based (Pb-based) and lead-free (Pb-free) solders [7]. Pb-based solders incorporate a specific amount of lead (Pb) with tin (Sn) to create the widely used tin–lead (SnPb) alloy. However, due to the toxic nature of lead, its use in electronics was significantly limited at the beginning of the twenty-first century [8]. This regulatory shift compelled the industry to adopt lead-free solder alternatives. Among too many, the tin–silver–copper (Sn–Ag–Cu) alloy, commonly referred to as tin (Sn)–silver (Ag)–copper (Cu) (SAC) solder, has gained considerable attention because of its superior mechanical, electrical, and thermal properties, making it a highly suitable replacement for the traditional eutectic SnPb solders [9–12].

In practice, the silver content in SAC alloys is expected to significantly influence their mechanical properties, mechanical behavior, and thermal fatigue resistance [13]. Kariya *et al.* [14] reported in their experimental studies that SAC solders with high Ag content exhibit increased shear strength due to the formation of Ag_3Sn brittle intermetallic compounds (IMCs). Terashima *et al.* [15] investigated the effect of Ag content in SAC alloys on the thermal fatigue of flip–chip components through reliability experiments. Their findings indicated that solders with lower Ag content had a much higher failure rate compared to those with higher Ag content, although the failure mode, *i.e.*, crack initiation and propagation, remained unchanged.

Table 1: Modulus of elasticity of SACN05 at various loading temperatures [19,20]

Temperature (°C)	Modulus of elasticity [GPa]			
	SAC 105	SAC 205	SAC 305	SAC 405
25	36.5	42.1	45.0	48.9
50	33.2	39.6	41.5	44.3
75	29.0	35.8	38.4	40.0
100	25.6	30.4	33.7	36.7
125	20.2	26.3	31.1	31.5

Hassan *et al.* [16], Lall *et al.* [17,18], and Basit *et al.* [19–21] examined the stress–strain relationships of SAC alloys with varying silver percentages to determine their mechanical properties. Their results demonstrated that higher Ag content in the solder leads to a stiffer (higher modulus of elasticity) and stronger joints (improved yield and tensile strengths). Gharaibeh and Al-Oqla [22] explored the thermal reliability of SAC solders of various Ag contents using nonlinear finite element analysis (FEA) simulations and showed that the solders with higher silver presence are more likely to have higher resistance to the accumulation of inelastic deformations and strains. Therefore, improved thermal reliability is expected for the SAC with higher silver content. These trends were corroborated by additional studies in the literature [23,24].

The aging mechanisms of lead-free solders affect their microstructure, fatigue performance, and cracking and breaking mechanics [25–27]. Particularly, isothermal aging can significantly degrade key mechanical properties of lead-free solder joints, including the elastic modulus, yield strength, and ultimate tensile strength [28,29]. Additionally, aging can severely impact the creep behavior of solder, leading to a substantial increase in the creep strain rate [30–32]. These changes in the behavior of lead-free solders can adversely affect the reliability of electronic devices.

Table 2: Anand parameters for SACN05 for unaged and 6 and 12 months' aging durations at 100°C [19,20]

Parameter	Units	SAC105			SAC205		
		No aging	6 months	12 months	No aging	6 months	12 months
s_o	MPa	7.5	2.90	2.89	16.5	5.20	5.0
Q/R	K	8,850	8,850	8,850	9,090	9,090	9,090
A	sec^{-1}	6,900	8,250	9,000	4,300	4,900	5,200
ξ	[-]	4	4	4	4	4	4
m	[-]	0.215	0.160	0.160	0.238	0.177	0.177
h_o	MPa	137,500	60,000	58,750	169,000	75,000	73,300
$\hat{s}$	MPa	25.1	18.9	17.9	29	21.6	19.94
n	[-]	0.0062	0.00115	0.001	0.0087	0.00145	0.0013
a	[-]	1.96	2.21	2.22	1.84	2.09	2.10
Parameter	**Units**	**SAC305**			**SAC405**		
		No aging	**6 months**	**12 months**	**No aging**	**6 months**	**12 months**
s_o	MPa	21.0	5.8	5.4	23.65	6.20	6.14
Q/R	K	9,320	9,320	9,320	9,580	9,580	9,580
A	sec^{-1}	3,501	4,110	4,210	3,175	3,725	3,800
ξ	[-]	4	4	4	4	4	4
m	[-]	0.250	0.18	0.18	0.263	0.184	0.184
h_o	MPa	180,000	77,540	73,708	183,000	80,000	79,840
$\hat{s}$	MPa	30.2	21.9	21.4	31.3	22.2	23
n	[-]	0.0100	0.0016	0.001	0.0110	0.0018	0.0014
a	[-]	1.78	2.05	2.06	1.77	2.01	2.01

Therefore, it is essential to consider the effect of the aging process, *i.e.*, aging durations and temperature, as they can significantly affect the creep coefficients [33–35] even at room temperatures [36–38]. Therefore, when performing finite element (FE) computations, variations in mechanical properties, such as material constants, must be incorporated in the simulation procedure to guarantee accurate predictions of solder damage. This approach enables the most precise evaluation of solder damage parameters, thereby ensuring reliable assessments of electronic assemblies [39–41]. In addition to FEA, there are plenty of other numerical methods that are available for solving complex engineering problems [42–52].

Clearly, the silver content and the pre-aging process are expected to play a crucial role in determining the mechanical properties of SAC interconnects, influencing their failure mechanisms and, consequently, their thermal fatigue performance. Therefore, the goal of this study is to compare how different pre-aging durations affect the mechanical and creep responses of four common SnAgCu solder alloys – SAC105, SAC205, SAC305, and SAC405 – using three-dimensional nonlinear simulations. The research also seeks to investigate the correlation between pre-isothermal aging, solder inelastic strain, stored inelastic strain energy, and therefore the solder thermal fatigue life. Reputable literature sources are first consulted to gather the mechanical and material parameters of the SAC solders both before and after aging for 6 and 12 months at 100°C. These parameters are then utilized in the FEA simulations. The results of this investigation offer valuable insights into the influence of pre-isothermal aging on the behavior of SAC solders, contributing to the understanding of reliability of electronic assemblies.

This article is structured to start with a detailed description of the research problem of the pre-aged SAC solders and all the factors considered in this investigation. Subsequently, it outlines the FE modeling approach employed in the study. This article then proceeds to deliver a thorough discussion on the mechanical response of pre-aged SAC solders, examining the effects of pre-aging duration on solder behavior, in terms of the hysteresis loops, inelastic strains, and inelastic strain energy densities. At the end, this study presents concluding remarks, general statements, and potential future recommendations for designing endured electronic assemblies.

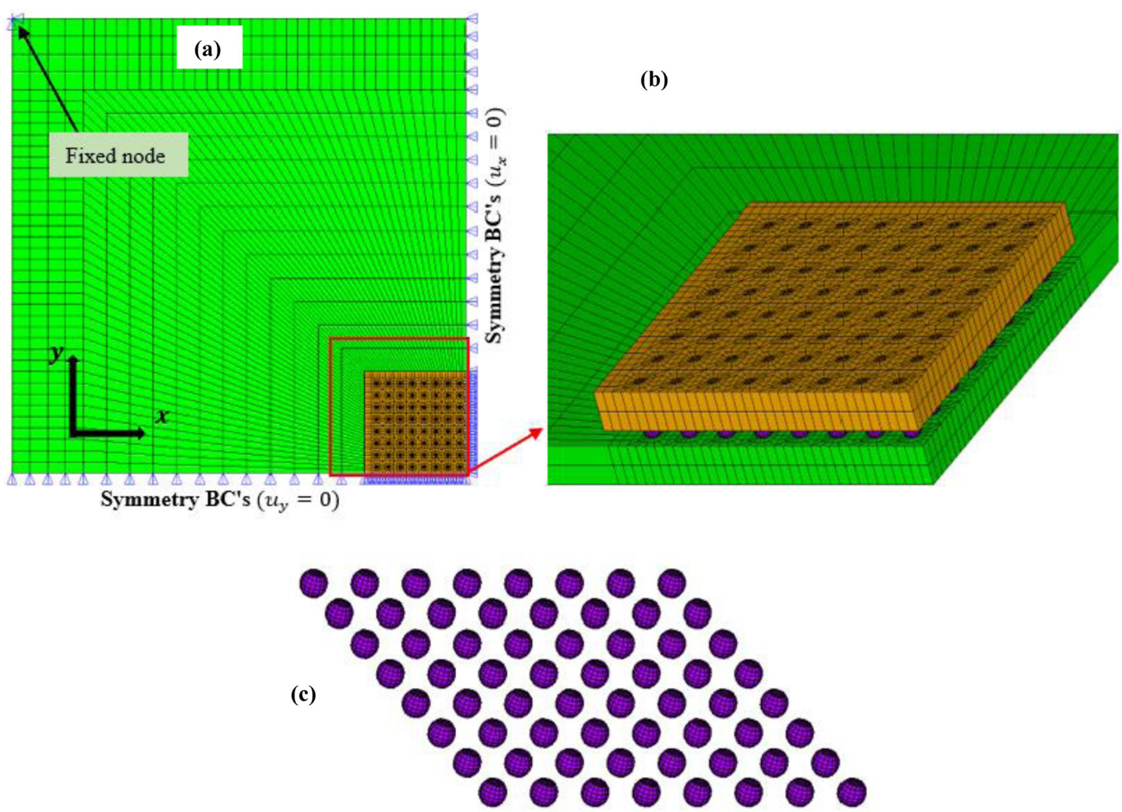

Figure 1: FE model details: (a) quarter model and symmetry BCs, (b) zoomed in isometric view, and (c) solder quarter array layout.

Table 3: Elastic properties of the board, IC component, and the solder Cu pad [53]

Material property	Board	IC component	Cu pads
Modulus of elasticity [GPa]	23.0	22.0	117.0
Poisson's ratio [-]	0.16	0.3	0.33
Density [kg/m^3]	3,000	2,000	8,800
Coefficient of thermal expansion [ppm/°C]	*X*, *Y* = 14.5 *Z* = 67.2	16.2	17.6

2 SnAgCu solders under aging

The primary objective of this research is to examine the impact of isothermal aging on four common lead-free SAC alloy compositions: 98.5Sn-1.0Ag-0.5Cu (SAC105), 97.5Sn-2.0Ag-0.5Cu (SAC205), 96.5Sn-3.0Ag-0.5Cu (SAC305), and 95.5Sn-4.0Ag-0.5Cu (SAC405). The SACN05 alloys have different Ag percentages ranging from $N = 1.0$ to 4.0%, while the Cu content of 0.5% remains unchanged. The Sn content varies matching to the Ag amounts in the alloy. As stated earlier, it is widely recognized that the aging process in SAC alloys notably alters their mechanical properties such as the modulus of elasticity, as well as in their creep constants, *i.e.*, Anand parameters. Thus, it is crucial to accurately account for these changes when conducting numerical analyses of the thermomechanical fatigue performance of SAC solder.

Basit *et al.* [19,20] conducted extensive experimental studies to estimate the mechanical properties of SACN05 when subjected to isothermal aging at a constant temperature of 100°C for various durations, including 6 and 12 months. In these studies, the stress–strain relationships of both unaged and aged SAC solders were determined through tensile testing experiments. These experiments considered various strain rates, including 1, 0.1, and 0.01 msec, as well as five loading temperatures of 25, 50, 75, 100, and 125°C. From the resulting stress–strain curves, values for the modulus of elasticity, yield strength, ultimate tensile strength, and Anand creep parameters were derived. The collected data on the elastic modulus and Anand coefficients for SACN05 solder interconnects under various conditions are presented in Tables 1 and 2, respectively. As noted, aging causes large degradations in the material properties, *i.e.*, elastic modulus and ultimate strength, of the SAC solders with different Ag amounts especially at high loading temperatures. This degradation is resulting from the microstructural coarsening of the aged SAC solders. Also, the number of IMC particles decreases during aging, while the average diameter of the particles increases significantly. However, the SAC

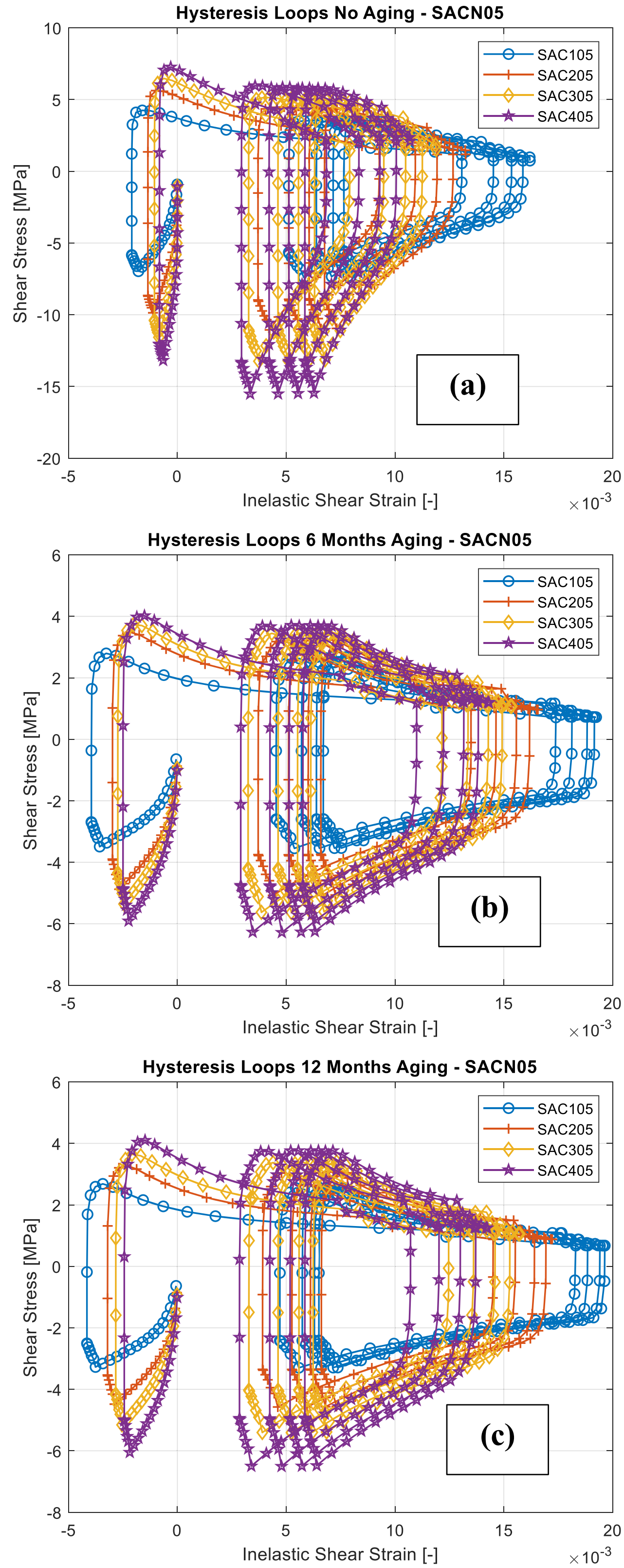

Figure 2: Hysteresis loops of the SACN05 solders for various aging periods: (a) unaged, (b) 6 months, and (c) 12 months.

systems with high silver content are showing high resistance to aging-lead degradation in the mechanical properties as well as in the microstructure.

To precisely evaluate the thermomechanical behavior of pre-aged SACN05 lead-free solders, the material data from Tables 1 and 2 are integrated into the FEA simulations of thermal cycling performed in this study. Subsequently, the mechanical response of the pre-isothermally aged SACN05 interconnects is thoroughly evaluated and discussed, with particular attention to solder stresses, strains, and accumulated inelastic strain energy densities.

3 FE modeling

The current study utilizes a comprehensive nonlinear FEA performed using ANSYS Mechanical Pro Version 2021 to precisely determine the mechanical response of pre-isothermally aged SACN05 solder joints subjected to thermal cycling. The electronic assembly considered in this study features a square printed circuit board (PCB) measuring 76 × 76 × 1 mm^3, with a centrally located integrated circuit (IC) package (13 × 13 × 1 mm^3) comprising a 16 × 16 full area array of SACN05 solder balls. Thanks to the symmetrical properties of the problem, only a one-quarter FE model is considered. Symmetry boundary conditions are directly imposed on the cut planes of symmetry, and the FE model is fully constrained at a single node located at the corner of the PCB to prevent rigid body motions.

In the meshing process, a mapped three-dimensional mesh using hexahedron SOLID185 elements is created. This model is demonstrated in Figure 1. For material modeling, only linear elastic mechanical properties are applied to the PCB, the IC, and the Cu pads, as listed in Table 3. However,

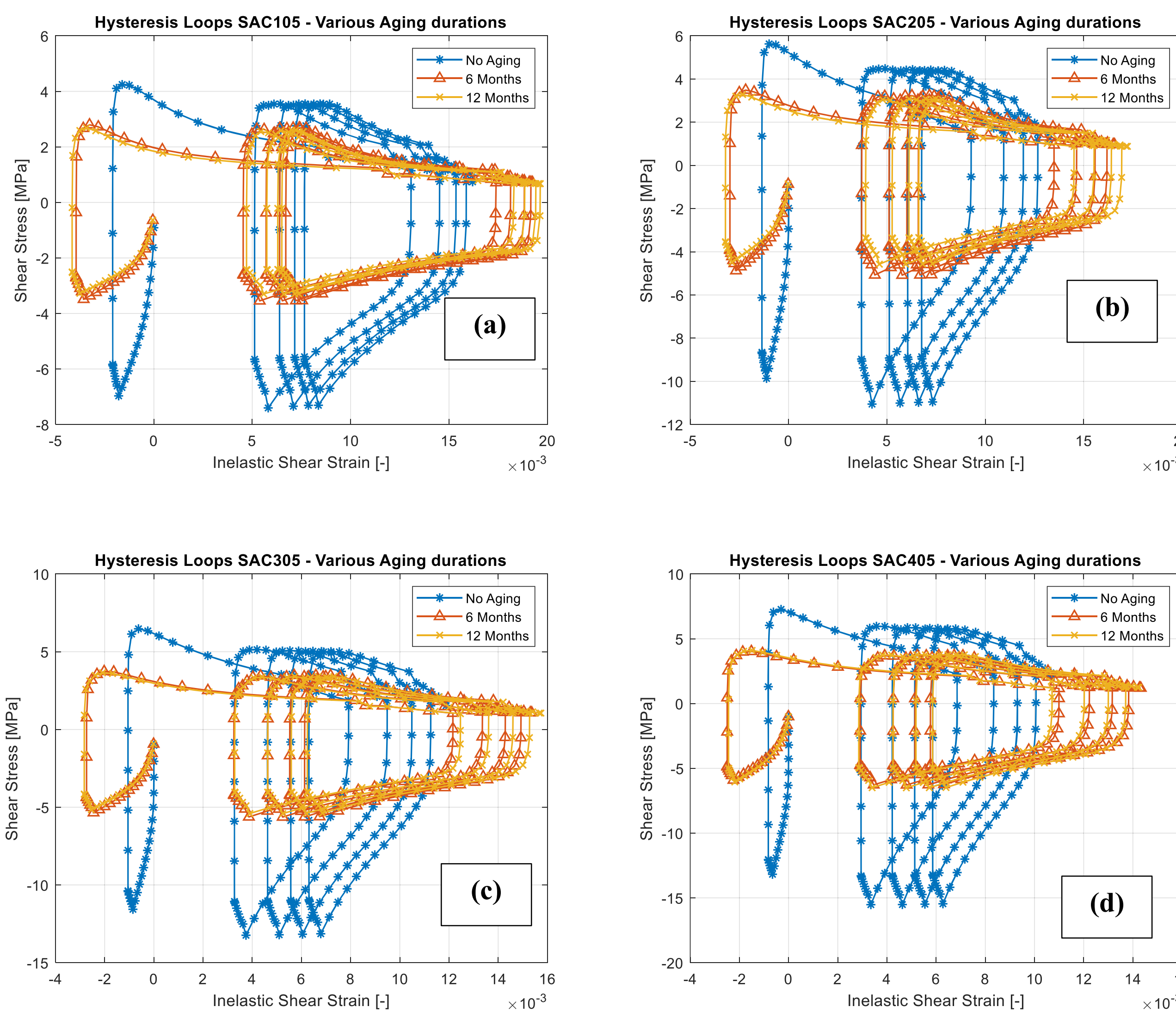

Figure 3: Hysteresis loop plots to show the effect of the aging condition on the response of (a) SAC105, (b) SAC205, (c) SAC305, and (d) SAC405.

for the SACN05 solders, the previously described elastic and inelastic mechanical properties are used (refer to Tables 1 and 2). During the nonlinear simulations, the Newton–Raphson algorithm was used in the ANSYS simulations.

Thermomechanical simulations of five complete thermal cycles of −40/125°C with 20 min ramp and 15 min dwell are executed. In this thermomechanical simulation, room temperature is selected as the stress-free temperature and large deformations

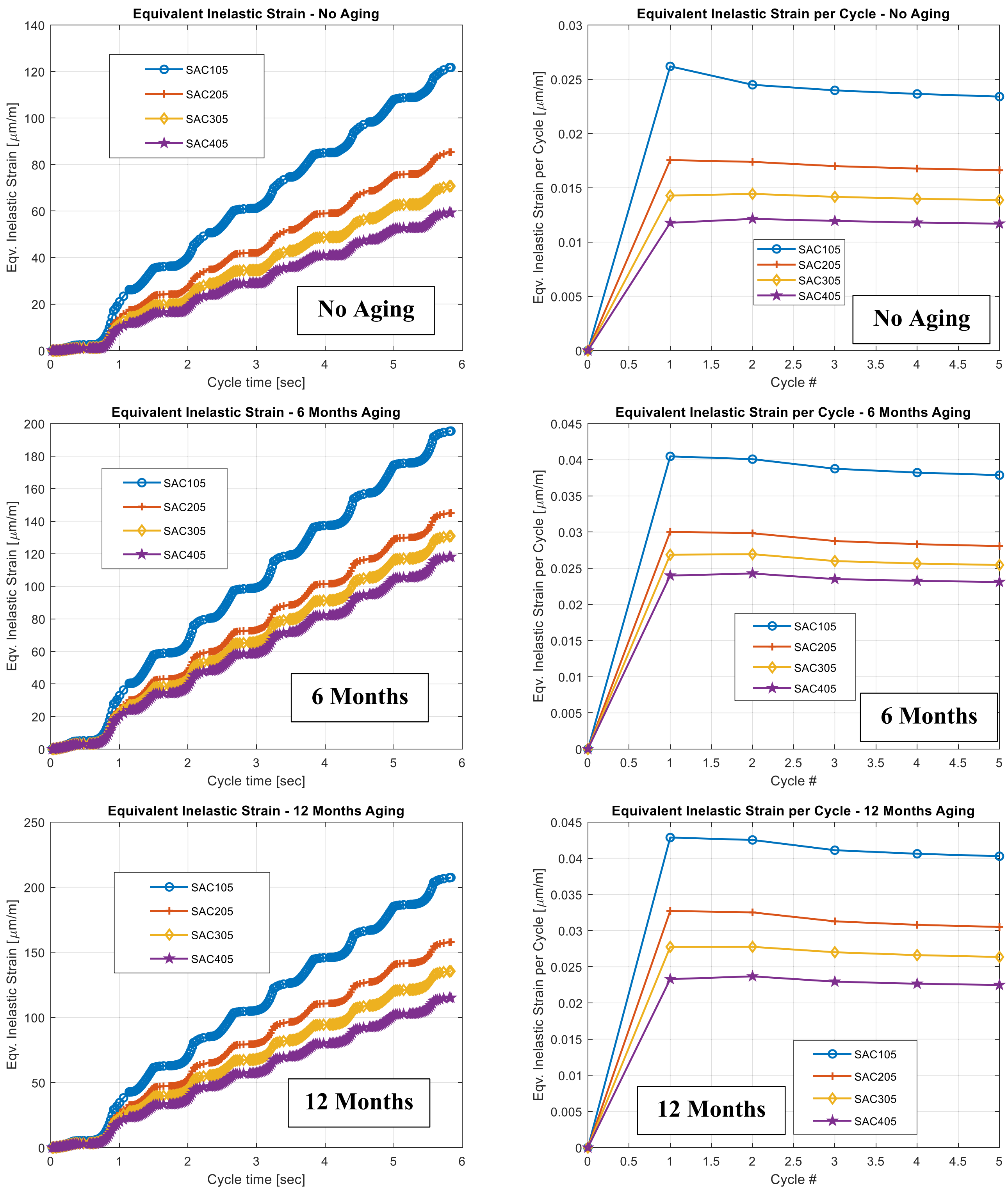

Figure 4: Equivalent inelastic strains of the SACN05 solders (left) *vs* cycle time and (right) per cycle for different aging durations.

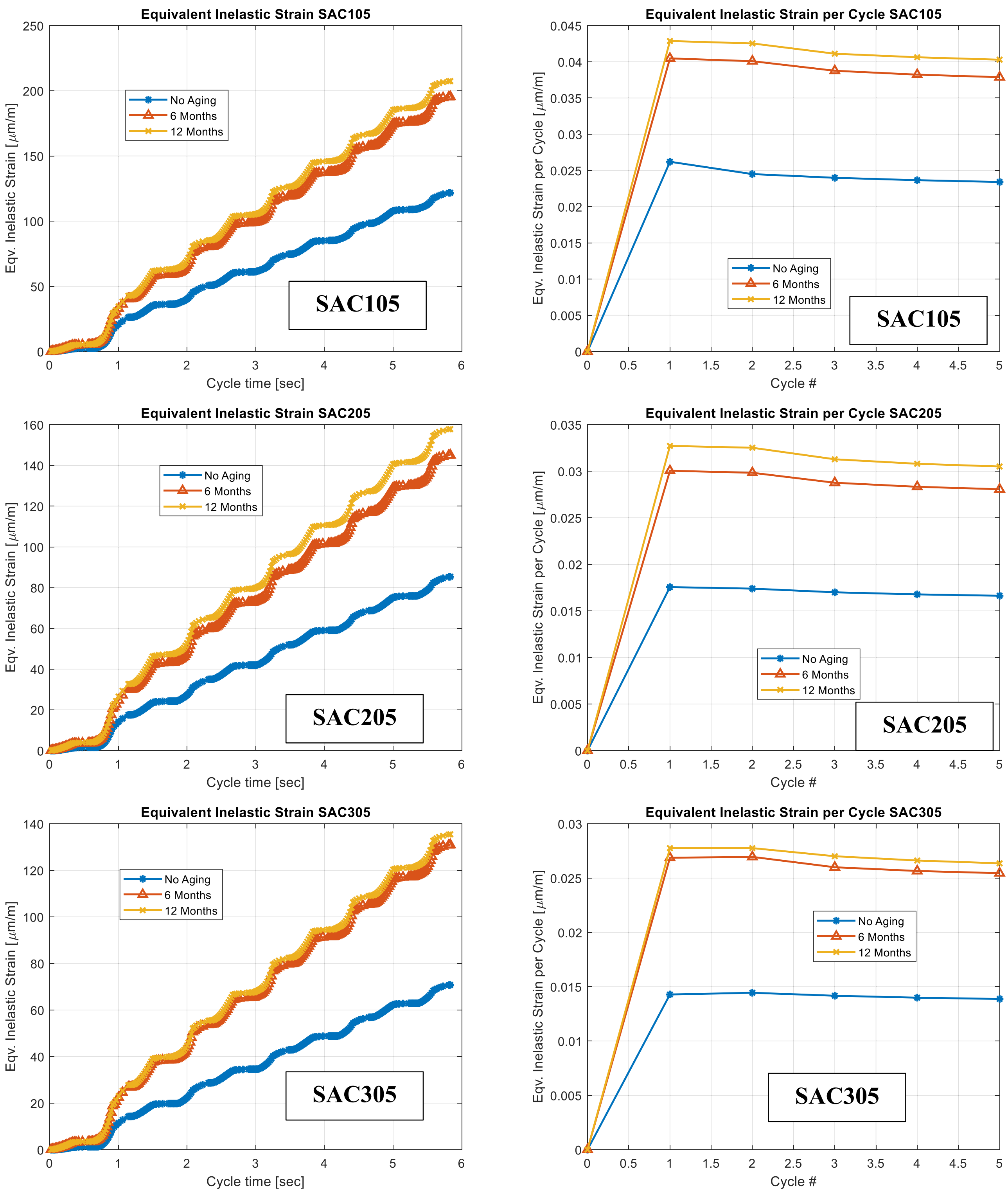

Figure 5: Equivalent inelastic strain plots to show the effect of the aging condition on the response of SACN05.

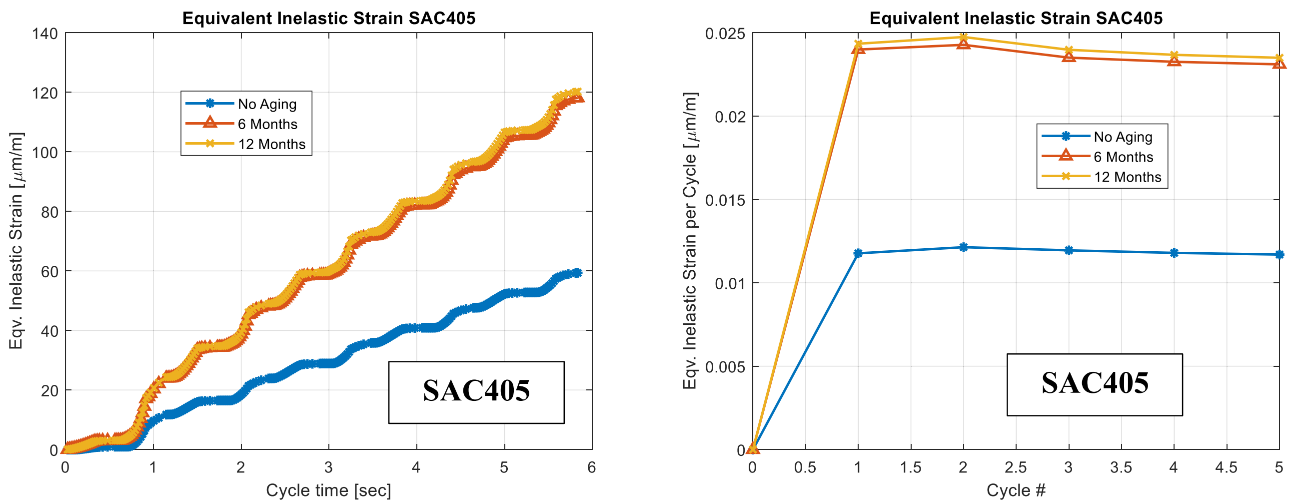

Figure 5: (*Continued*)

option is turned on. Accordingly, the in-plane shear stress, in-plane shear strains, equivalent inelastic strains, and the inelastic strain energy density SACN05 solders are extracted and thoroughly evaluated.

4 Results and discussions

As stated earlier, this work aims to numerically investigate and compare the effect of isothermal aging on the mechanical performance of the SAC105 and SAC305 interconnects when subjected to thermal cycling. The comparison is based on solder's stress–strain relationship, *i.e.*, hysteresis loops, the equivalent inelastic strains, and the inelastic strain energy density.

4.1 Hysteresis loops

Figure 2 shows the results of the solder's in-plane shear stress *vs* inelastic in-plane shear strains of the SACN05 solders at different aging durations. For all conditions, with and without aging, the increase in silver content within the solder composition leads to a narrower range of inelastic shear strain, indicating lesser inelastic deformations, while the range of shear stress significantly expands because the SAC with higher Ag content are generally stiffer, *i.e.*, higher modulus of elasticity values. This implies that higher levels of stress are necessary to induce inelastic deformations in the high Ag solder. Conversely, solders with lower silver content, aged or unaged, exhibit a wider range of inelastic strains and comparatively smaller stress ranges because the SAC with low Ag content are more compliant. Consequently, even minor stress levels can result in substantial inelastic deformations in the solders with lower silver presence. As a result, solders with reduced silver content, such as SAC105 and SAC205, are more prone to accelerated degradation and consequently have shorter thermal fatigue life spans compared to solders with higher silver content like SAC305 and SAC405 when they are all having the same aging conditions. However, solders with increased silver content tend to be brittle and stiffer, leading to poorer fatigue performance under drop and impact loading conditions. On the contrary, SAC105 and SAC205 are ductile and are therefore expected to exhibit better performance in shock and impact loading scenarios.

Figure 3 shows the effect of the aging condition on the hysteresis loop relations of various SACN05 systems. Apparently, SACN05 solders without exposure to aging are experiencing smaller inelastic shear strains and deformations; however, larger shear stress ranges. Therefore, a high amount of stress is required to induce inelastic deformations in the unaged SACN05 solder. Nevertheless, when aging is present, the inelastic shear strain range becomes wider, and the shear stresses are smaller. This could demonstrate that low stresses could possibly cause larger permanent and inelastic deformations in the aged interconnect. For both aging durations, *e.g.*, 6 and 12 months, the solder's inelastic shear strains and shear stresses are slightly changed, or most likely remaining unchanged. Consequently, the aged solders are probably maxed out on inelastic deformations and hence more vulnerable to fatigue failures. In summary, the aged SACN05 solders are expected to have higher degradation and quicker failure rates than the unaged interconnects, but the presence of the silver in the solder could significantly improve the fatigue performance of the aged and unaged interconnects.

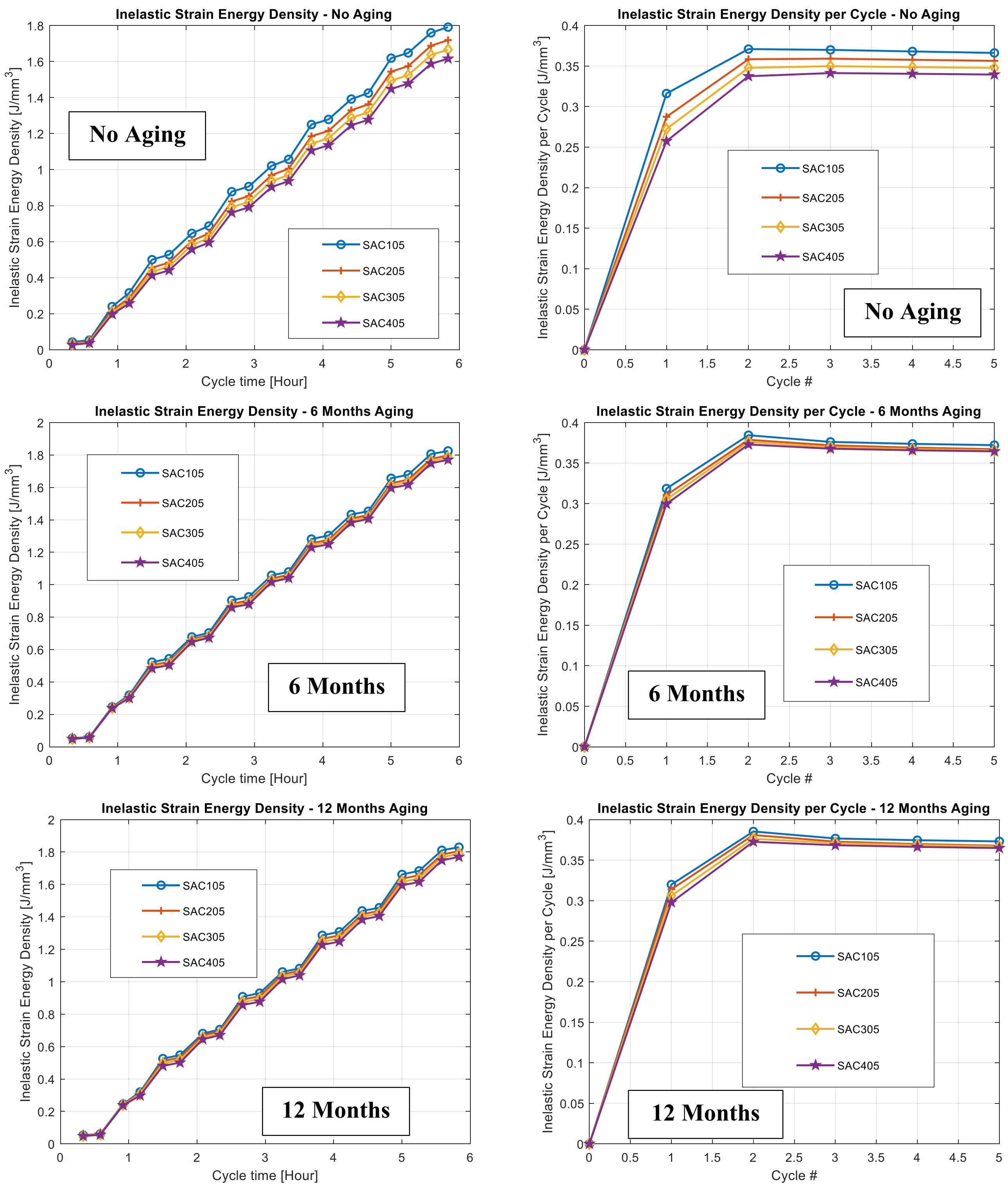

Figure 6: Inelastic SED accumulated in the SACN05 solders (left) *vs* cycle time and (right) per cycle for different aging durations.

4.2 Equivalent inelastic strain

In the process of the lifetime evaluation of solder interconnects, strain-based fatigue models, like Coffin–Mason's (CM) rule [54,55], are commonly used to calculate the fatigue life performance of the interconnect. In the CM, the equivalent inelastic strain of the joint is mainly used as the evaluation metric. The CM model is expressed as follows:

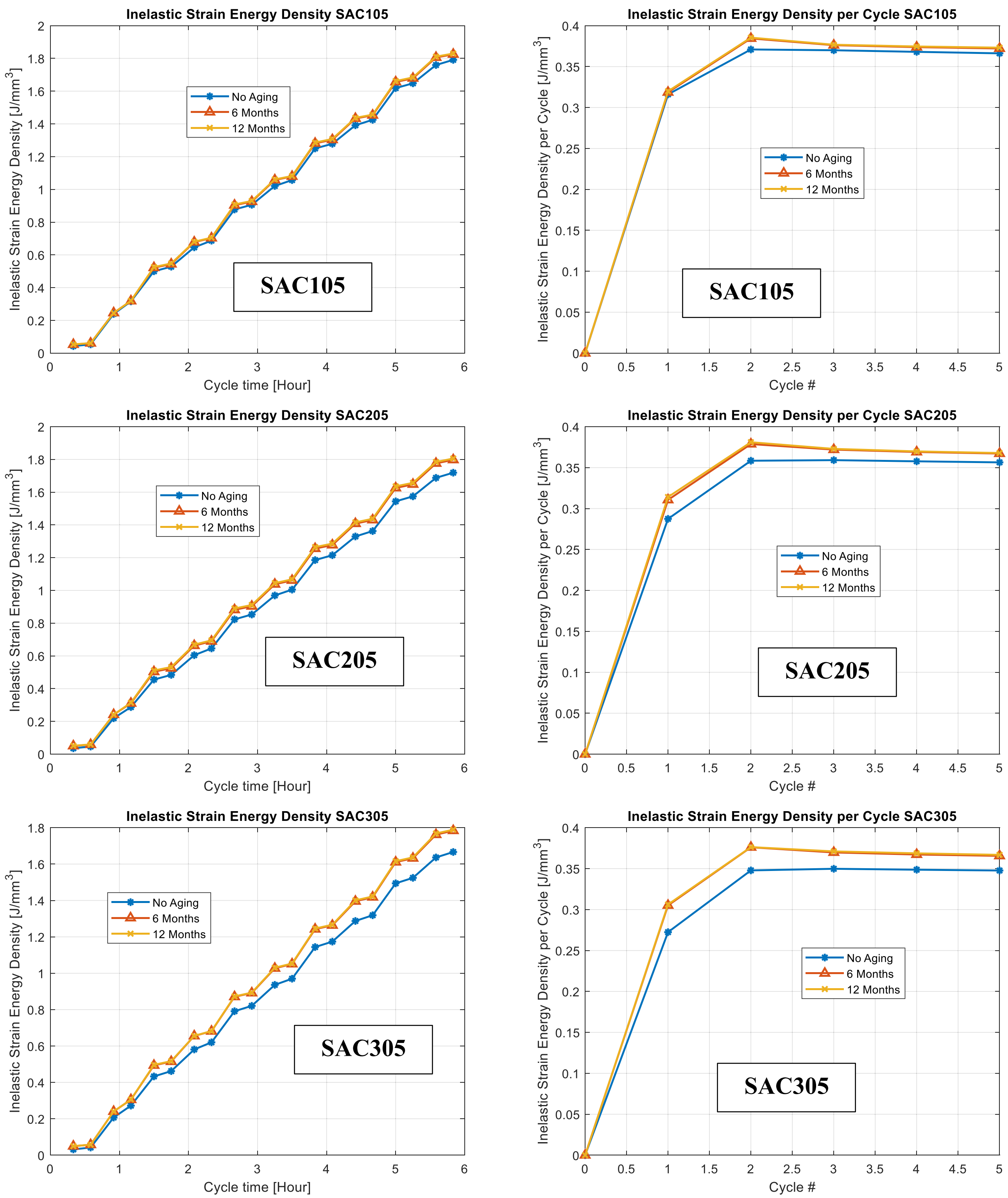

Figure 7: Inelastic SED accumulation plots to show the effect of the aging condition on the response of SACN05.

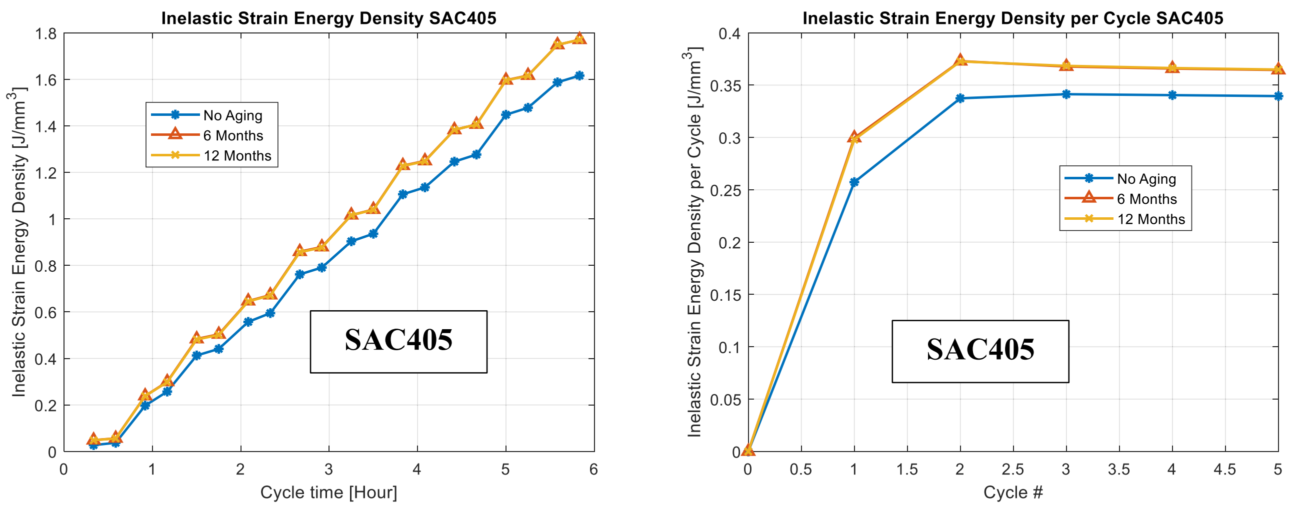

Figure 7: (*Continued*)

$$(2N_F)^c = \frac{\Delta\varepsilon_p}{2\gamma}, \tag{1}$$

where γ is the fatigue ductility coefficient, c is the fatigue ductility exponent, $\Delta\varepsilon_p$ is the plastic strain range from the cyclic equilibrium, and N_F is the fatigue life. This study closely investigates the SACN05 solders cyclic equivalent inelastic strains to further correlate that to the expected fatigue life.

Figure 4 plots the results of the SACN05 equivalent inelastic strain results *versus* the cycling time and the equivalent inelastic strain results per cycle at the end of each thermal cycle considering various aging intervals. The inelastic strain results here depict that for solders with low Ag percentages, the equivalent inelastic strains are considerably larger, for aged and unaged configurations. Thus, shorter thermal fatigue life is probable for the SACN05 solders with low Ag content, with and without pre-isothermal aging, such as SAC105 and SAC205, while the high Ag solders such as SAC305 and SAC405, aged or not, are expected to have improved thermal fatigue performance.

Figure 5 shows the effect of the aging condition on the SACN05 solder's equivalent plastic strain results *versus* the cycling time and the equivalent plastic strain results per cycle. Evidently, the equivalent inelastic strains are higher for solders with pre-aging conditions and much smaller for the non-aged SACN05 interconnects. Hence, shorter solder thermal fatigue life is expected for the aged configuration. Additionally, for the aging durations of 6 and 12 months, the change in the solder's equivalent inelastic strains is small especially for high Ag solders. This actually could mean that the aged solders are maxed out on inelastic deformations, and therefore, they are more susceptible to fatigue failures.

In summary, the pre-aged SACN05 solders are generally projected to have higher degradation rate and quicker failures than the non-aged solders but the solders with higher silver content could have improved fatigue performance in both aged and unaged cases.

4.3 Inelastic strain energy density

In addition to strain-based modeling, energy-based fatigue life models, like Darveaux's model [56], are widely used to evaluate the fatigue performance of electronic assemblies. In Darveaux's law, the inelastic strain energy density of the interconnect is used as the estimation metric. In fact, the inelastic strain energy density, measured by energy per unit volume, represents the absorbed energy by the material before it fractures and often called the plastic work. The Darveaux's model is expressed as follows:

$$N_F = K_1(\Delta W)^{K_2} + \frac{a}{K_3(\Delta W)^{K_4}}, \tag{2}$$

where K_1 to K_4 are the crack growth correlation coefficients, a is the solder crack length, ΔW is the accumulated inelastic strain energy density per cycle along the crack propagation, and N_F is the fatigue life. It is important to mention here that the first and the second terms of Eq. (2) are the power law relations for the crack initiation and propagation rates of Darveaux's model, respectively [57]. This study explores the SACN05 systems' cyclic inelastic strain energy density (inelastic SED) due to thermomechanical loads.

Figure 6 presents the inelastic strain energy density *versus* cycling time and the cyclic inelastic strain energy density per cycle of the SACN05 solders with different aging periods. Seemingly, the solder inelastic strain energy density is higher for SAC systems with lower Ag amounts and lower for high Ag content systems in all aged and unaged configurations. Thus, the solders with high Ag content such as SAC305 and SAC405 are likely to have improved thermal fatigue life characteristics. Thus, more possible solder damage and quicker failures are expected in the aged systems. However, the difference in the inelastic SED is minor probably because for SAC with low Ag content, the inelastic strains are larger (lower stresses) but in the high Ag SACs, the stresses are larger (lower inelastic strains), which might cause the difference in the inelastic SED to cancel out, and this becomes more effective in the aged SACN05 systems. For this reason, this study highly recommends the use of the CM rule while evaluating the fatigue life of SACN05 with pre-aging conditions.

Figure 7 displays the effect of the aging condition on the SACN05 solder's inelastic strain energy density results *versus* the cycling time and the inelastic strain energy density results per cycle. Clearly, the periods of aging lead to higher accumulation of inelastic strain energy density in the SACN05 interconnects. Thus, more possible solder damage and quicker failures are expected in the aged configuration. Nevertheless, for the aging durations of 6 and 12 months, the change in the solder's inelastic strain energy is small in all Ag contents in the solders.

In summary, the aged solders are generally expected to fail quickly when exposed to thermal cycling loads. However, the solders with higher silver content could have improved fatigue performance in both aged and unaged cases. To confirm such numerical analysis results, it is recommended to perform experimental reliability tests of aged SACN05 for better quantification of the fatigue performance of pre-isothermally aged lead-free SACN05 interconnects.

Finally, this article endorses the use of unaged tin–silver–copper solders with higher silver content for designing electronic packages subjected to thermal cycling loading. Nonetheless, this study advises the use of low silver content tin–silver–copper solders or pre-aged tin–silver–copper solders of high Ag percentages for electronic devices repetitively susceptible to mechanical shock and impact loadings.

5 Conclusions

This study has introduced a complete 3-D nonlinear FEA to examine the impact of pre-isothermal aging at 100°C, with aging periods ranging from 6 to 12 months, on the mechanical behavior and the expected thermomechanical fatigue performance of SACN05 alloys with different silver content including N = 1, 2, 3 and 4%. The mechanical properties of SACN05 solders, including elastic and inelastic properties, were collected and incorporated into the nonlinear FE simulations, accordingly. The findings proved that the mechanical behavior of pre-aged SACN05 solders is remarkably influenced by both the duration of aging and the silver content. Particularly, interconnects with higher silver percentages exhibit greater resistance to aging and are anticipated to display reduced thermally induced inelastic deformations, strains, and strain energies. This suggests a potential for improved thermal fatigue performance and enhanced resistance to failure. Conversely, pre-isothermally aged SACN05 solders generally showed reduced resistance to the accumulation of inelastic strains and inelastic strain energies. Consequently, it is likely that pre-aged SACN05 solders may exhibit a decline in thermal fatigue performance compared to their unaged counterparts. On the other hand, the aged SAC solder systems could serve as an innovative solution for designing electronic devices that are frequently subjected to shock and impact loading, as the aging process effectively mitigates the brittleness of the SnAgCu alloys.

Acknowledgement: The author wishes to deeply thank the Hashemite University for providing the necessary tools for this research.

Funding information: No funding was received.

Author contribution: Mohammad A. Gharaibeh: The author confirms the sole responsibility for the conception of the study, presented results and manuscript preparation.

Conflict of interest: The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Data availability statement: Data used in this paper will be made available upon a reasonable request.

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