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MICROSTRUCTURAL DEGRADATION MECHANISMS IN LEAD-FREE SOLDER ALLOYS FOR HIGH-RELIABILITY ELECTRONICS: SYSTEMATIZED REVIEW AND BIBLIOMETRIC ANALYSIS

Gilberto Tadashi Kondo[1]; José Carlos Boareto[2]; Paulo Antônio Pereira Wendhausen[3]

[1]PGMAT/UFSC • [2]Embraer • [3]Federal University of Santa Catarina

Objective

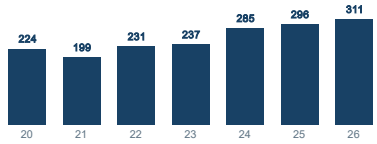
Analyze the evolution and structure of scientific literature on microstructural degradation mechanisms in lead-free solders, using bibliometric methods to identify publication trends, influential authors, collaboration patterns, leading research topics, and future research opportunities.

Methodology

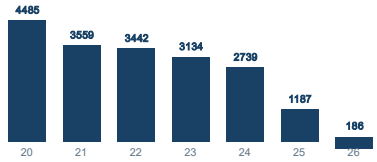
Systematized review (2020–2026): Scopus, WoS, SMTA and IMAPS. 1,793 unique records; 231 screened; 119 selected; 93 full texts retrieved and analyzed.

Bibliometric overview | 1,793 unique records

Publications by year



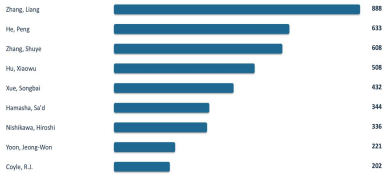
Citations by publication year



Most prolific authors

Zhang, Liang	42
Zhang, Shuye	27
Yoon, Jeong-Won	27
Ma, H. T.	26
Wang, Fengjiang	25
Nishikawa, Hiroshi	24
Tian, Yanhong	24
He, Peng	23

Impact | article citations



Most frequent keywords

Intermetallic compound	273
Microstructure	209
Solder joint	182
Lead-free solder	134
Mechanical property	132
Reliability	116
Shear strength	107
Interfacial reaction	88

Keyword co-occurrence



Experimental mapping | 93 articles analyzed

01 Solder alloys

SAC alloys (Sn-Ag-Cu)	68
Third-generation alloys	32
Low-melting-point alloys	24
Low- or zero-silver alloys	15
Sn-Pb reference	14
Experimental alloys / composites	12

02 Reliability tests

Thermal cycling	48
Isothermal aging	42
Shear testing	36
Thermal shock	18
Tensile / microtensile	16
Electromigration	11
Drop / impact	8
HALT/HASS	2

03 Components / specimens

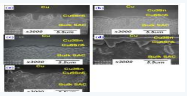
Area array (BGA/LGA/CSP)	52
Solder joints / test specimens	28
Chip passives (C/R)	18
Integrated circuits (QFP/SOIC/QFN)	9
PTH (connectors)	2
Electromechanical / magnetic	1

04 Characterization

SEM	85
EDS	78
Optical microscopy	40
EBSD	34
XRD	22
Micro-CT / radiography	12

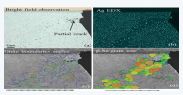
Article frequencies; categories are not mutually exclusive. Source: authors' analysis of the reviewed corpus.

Microstructural degradation mechanisms | 93 articles



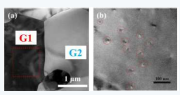
SAC305, SAC105, Sn-Bi, Sn-Cu, SAC-Bi
KIM et al., 2019

IMC growth and coarsening
≈85 · 91%
Cu_6Sn_5/Cu_3Sn layers thicken; Ag_3Sn coarsens; interfacial embrittlement.



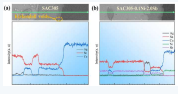
SAC305, SAC105, Sn-Bi, SAC-Bi-Sb-Ni
BEN ROMDHANE et al., 2021

Crack initiation and propagation
≈65 · 70%
Thermomechanical fatigue; intergranular or interfacial crack growth.



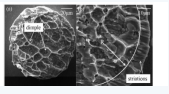
SAC family, Sn-3.5Ag, Sn-Cu
BELYAKOV et al., 2021*

β-Sn recrystallization
≈45 · 48%
Subgrains develop into HAGBs, promoting intergranular cracking.



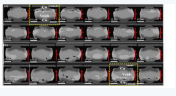
SAC305, Sn-58Bi, Sn-0.7Cu, SN100C
WANG et al., 2024

Kirkendall voids
≈38 · 41%
Unequal Cu/Sn diffusion produces voids in Cu_3Sn or at interfaces.



SAC305, SAC387, Sn-58Bi, Sn-3.5Ag
LI et al., 2020

Creep and ductile fracture
≈32 · 34%
Time-dependent deformation and dimples; fatigue–creep interaction.



SAC305, Sn-58Bi, Cu-pillar, flip-chip
CHEN et al., 2024

Electromigration and polarity
11 · 12%
Cu/Sn migration; cathodic voids and anodic IMC growth.

Approximate frequencies; overlapping categories. Images adapted by cropping from the cited articles.

Synthesis and implications

Metallurgical trends — SAC305 remains a reference alloy; Bi/Sb/Ni-doped SAC and Sn-Bi alloys are gaining attention. Composition and microstructure govern reliability.

Research gaps — HALT/HASS: 2 studies in the combined category (<3%); electromechanical/magnetic components: 1 study. Both remain underrepresented.

Experimental patterns — Thermal cycling and isothermal aging dominate studies of BGA/area-array packages, mainly characterized by SEM, EDS and EBSD.

Dissertation contribution — This mapping supports a methodology to evaluate third-generation lead-free alloys, with future validation under severe loading conditions.

REFERENCES

ALAKAYLEH, M. et al. The effect of micro-alloying and surface finishes on thermal cycling of doped SAC. Materials, 15(19), 6759, 2022.

KIM, S. H. et al. IMC growth mechanisms of SAC305 lead-free solder on different surface finishes. SMTA Int., 2019, p. 573–580.

BELYAKOV, S. A. et al. Microstructure and damage evolution during thermal cycling of SAC with Sb. J. Electron. Mater., 50(3), 825–841, 2021.

LI, J. et al. The thermal cycling reliability of copper pillar solder bump in flip chip. Microelectron. Reliab., 104, 113543, 2020.

BEN ROMDHANE, E. et al. Early microstructural evolution and intergranular crack propagation in SAC solders. Microelectron. Reliab., 126, 114288, 2021.

PADUA, R. et al. Impact of graphene addition on IMC and mechanical properties of SnBi alloys. Mater. Des., 238, 112701, 2026.

CHEN, C. et al. Mechanistic insights into direction-modulated electromigration failures in SnAg microbumps. Intermetallics, 190, 109160, 2026.

WANG, Y. et al. Ni and Sb improve the microstructure and reliability of SAC305 alloy. Vacuum, 231, 113782, 2025.

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