Arch. Metall. Mater. **71** (2026), 2, 597-600

DOI: https://doi.org/10.24425/amm.2026.158849

CHAN YANG LEE[1,2], MIN CHUL OH[2], GEON HONG KIM[2], BYUNGMIN AHN[1,3*]

EFFECT OF COMPOSITIONAL DESIGN IN Ag-Cu-BASED BRAZING ALLOYS ON MICROSTRUCTURE AND Cu-STS JOINING CHARACTERISTICS

In this study, a copper-silver-phosphorus-tin brazing filler metal with reduced silver content was designed to facilitate the oxide removal and to enable fluxless brazing. Based on the thermodynamic phase diagram analysis, the silver and tin contents were fixed, and the influence of phosphorus content on microstructures and the joint strength was investigated. Increased phosphorus content resulted in a higher fraction of copper-phosphorus intermetallic phases. The filler metal containing 65 wt.% copper, 10 wt.% silver, 5 wt.% phosphorus, and 20 wt.% tin exhibited excellent wettability and a stable interfacial microstructure at 900°C. In addition, it achieved superior joint strength compared with a commercial copper-phosphorus filler metal and showed performance comparable to that of a conventional silver-based filler metal. These results demonstrate the potential of the developed filler metal as a cost-effective solution for the copper-stainless steel cooling pipe applications.

Keywords: Filler metal; Brazing; Hybrid interface; Interfacial microstructure; Mechanical strength

1. Introduction

The increasing power density in electronic systems driven by artificial intelligence and high-performance computing has increased the demand for reliable copper-stainless steel dissimilar metal joining in liquid-cooled servers [1]. For such practical need, brazing is widely adopted because it provides hermetic sealing and metallurgical bonding at relatively low temperatures with minimal damage to the base materials [2,3]. However, the conventional silver-based brazing filler metals involve high material cost and typically require flux to remove chromium oxide layers on stainless steel surfaces, raising concerns related to corrosion and process complexity [4-6]. Therefore, in this study, a low-silver Cu–Ag–Sn–P quaternary brazing filler metal was designed by reducing the silver content and introducing tin and phosphorus. In particular, P was incorporated to promote oxide reduction and improve wettability, thereby enabling flux-free copper-stainless steel brazing [7,8]. The performance of the developed filler metal was evaluated to assess its potential as an alternative to conventional Ag–Cu-based brazing alloys.

2. Experimental

In this study, a low-silver brazing filler metal for fluxless brazing applications was designed based on thermodynamic calculations using FactSage, as shown in Fig. 1. Copper was selected as the base composition, and the tin content was fixed at 20 wt.% to suppress excessive softening of the copper substrate and limit the formation of tin-rich intermetallic compounds, while the silver content was set to 10 wt.% to ensure economic feasibility and facilitate liquid formation. The phosphorus content was determined with reference to the eutectic composition of the copper-phosphorus binary system (8.3 wt.% phosphorus). Based on this criterion, two filler metal compositions containing 5 wt.% phosphorus (hypoeutectic) and 10 wt.% phosphorus (hypereutectic) were selected. The finalized copper-silver-tin-phosphorus filler metal compositions are summarized in TABLE 1 together with those of commercial filler metals for comparison. The microstructures and phase constituents of the developed filler metals were analyzed by scanning electron microscopy (SEM) and X-ray diffraction (XRD). Brazing was conducted at 900°C with a holding time of 30 min using copper and stainless steel plates (15 mm × 25 mm × 1 mm) in a lap-joint configuration with a joint clearance of 0.1 mm. After brazing,

1 AJOU UNIVERSITY, DEPARTMENT OF MATERIALS SCIENCE AND ENGINEERING, SUWON, KOREA
2 MECHANICAL CONVERGENCE SYSTEM CENTER(INSTITUTE FOR ADVANCED ENGINEERING, YONGIN, KOREA
3 AJOU UNIVERSITY, DEPARTMENT OF ENERGY SYSTEMS, RESEARCH, SUWON, KOREA

* Corresponding author: byungmin@ajou.ac.kr

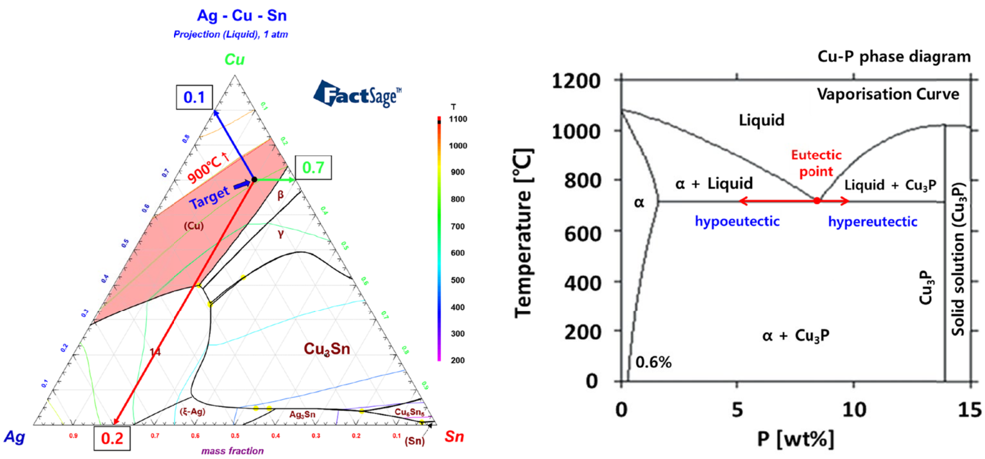


Fig. 1. Composition design of low-Ag Cu–Ag–Sn–P filler metals based on FactSage calculations and the Cu–P phase diagram

TABLE 1

Composition of designed and commercial filler metals

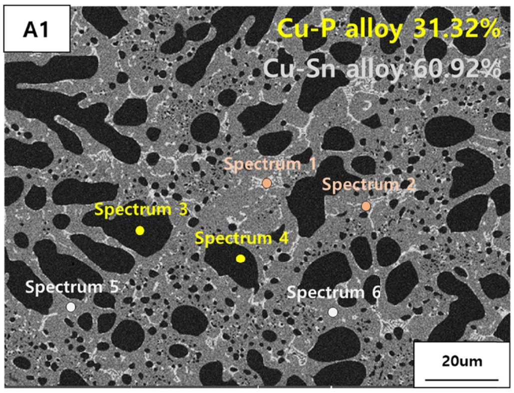
Filler metal name	Composition (wt.%)					
	Cu	Ag	P	Sn	Zn	Ni
A1	65	10	5	20	—	—
A2	60	10	10	20	—	—
BCuP-5	80	15	5	—	—	—
BAg-4	30	40	—	—	28	2

the joint microstructures and the strengths were evaluated to correlate the microstructural characteristics with the mechanical performance and to compare the developed filler metals with a commercial brazing alloy.

3. Results and discussion

Based on the designed brazing filler metal compositions with different phosphorus contents, the microstructural evolution of the alloys was investigated by SEM, as summarized in Fig. 2. For both compositions, the microstructures mainly consisted of Ag-Sn, Cu-Sn, and Cu-P phases, with the fraction of Cu-P phases strongly dependent on phosphorus content. In the alloy containing 5 wt.% P, the microstructure was dominated by Cu-Sn phases, while Cu-P phases were sparsely distributed. EDS analysis revealed that the Cu–Sn phase had an atomic Cu:Sn ratio of approximately 3:1, corresponding to Cu_3Sn. This behavior is attributed to the relatively low Sn content and the higher thermodynamic stability of Cu_3Sn compared with Cu_6Sn_5, as reflected by its lower formation enthalpy (–7.81 kJ/mol vs. –3.2 to –4 kJ/mol), leading to its preferential formation under the present composition conditions [9,10]. The Cu-P phase was mainly identified as Cu^3P, which is thermodynamically stable even at low temperatures [11]. Owing to the limited phosphorus content, the overall fraction of Cu-P phases remained low, resulting in a relatively homogeneous microstructure. In contrast, increasing the phosphorus content to 10 wt.% shifted the alloy composition into the P-rich hypereutectic region of the Cu-P binary system, where solidification occurred in the liquid + Cu-P two-phase region. Consequently, the fraction of the Cu-P phases increased significantly, and the Cu-P intermetallic compounds such as Cu_3P and CuP_2 formed at an early stage and were coarsely distributed in the final microstructure.

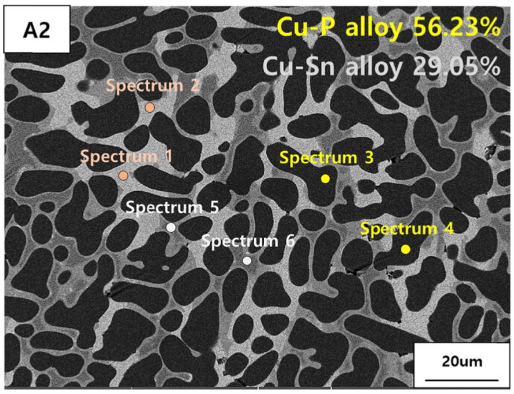
XRD analysis was conducted to investigate changes in alloying behavior and phase formation as a function of phosphorus content, and the results are summarized in Fig. 3. The diffraction patterns were collected over a 2θ range of 20-60°. Overall, a clear change in phase constitution was observed with increasing phosphorus content. At 5 wt.% P, diffraction peaks of the Cu matrix were dominant, while Cu-P-related peaks were weak, indicating suppressed Cu-P compound formation and the development of a continuous Cu or Cu-Sn-based matrix. In contrast, the alloy containing 10 wt.% P exhibited reduced Cu matrix diffraction intensity with enhanced Cu_3P peaks, indicating a Cu_3P-dominated phase constitution. Distinct CuP_2 and Cu_6Sn_5 peaks were observed only at this phosphorus content. The formation of CuP_2 indicates a transition toward P-rich Cu-P intermetallic compounds, which are brittle and can degrade joint reliability under thermal stress [12]. In addition, preferential Cu consumption by Cu-P phases reduces Cu availability for reaction with Sn, leading to localized Sn-rich regions where brittle η-Cu_6Sn_5 forms [13]. Fig. 4 presents the SEM analysis and joint strength results of Cu-stainless steel joints brazed with the developed filler metals. SEM observations show that the A1 alloy forms a uniform and continuous joint interface without observable defects. Phosphorus distribution toward the stainless steel interface indicates effective oxide removal and improved wettability. In addition, the filler metal diffuses into the stainless steel region containing Fe and Cr, implying sufficient melt



Light gray				
Elements	Spectrum 1		Spectrum 2	
	Wt.%	At.%	Wt.%	At.%
Ag	73.02	69.93	79.6	81.13
Sn	18.25	15.88	20.4	18.87
Cu	8.73	14.19		

Black				
Elements	Spectrum 3		Spectrum 4	
	Wt.%	At.%	Wt.%	At.%
Cu	96.44	96.91	81.61	68.39
P	0.73	1.51	18.39	31.61
Sn	2.83	0.99		
Ag	0.98	0.58		

Dark gray				
Elements	Spectrum 5		Spectrum 6	
	Wt.%	At.%	Wt.%	At.%
Cu	66.92	78.9	62.55	67.98
Sn	29.55	18.65	33.73	29.63
Ag	3.53	2.45	3.72	2.38



Light gray				
Elements	Spectrum 1		Spectrum 2	
	Wt.%	At.%	Wt.%	At.%
Ag	73.5	73.1	78.8	80.31
Sn	22.7	20.5	21.2	19.69
Cu	3.8	6.4		

Black				
Elements	Spectrum 3		Spectrum 4	
	Wt.%	At.%	Wt.%	At.%
Cu	81.8	70.13	55.0	37.33
P	16.4	28.95	45.0	62.67
Sn				
Ag	1.8	0.92		

Dark gray				
Elements	Spectrum 5		Spectrum 6	
	Wt.%	At.%	Wt.%	At.%
Cu	39.7	55.12	38.5	53.78
Sn	59.0	43.84	59.8	44.77
Ag	1.3	1.04	1.7	1.45

Fig. 2. SEM micrographs showing the microstructural evolution of Cu–Ag–Sn–P filler metals with different phosphorus contents

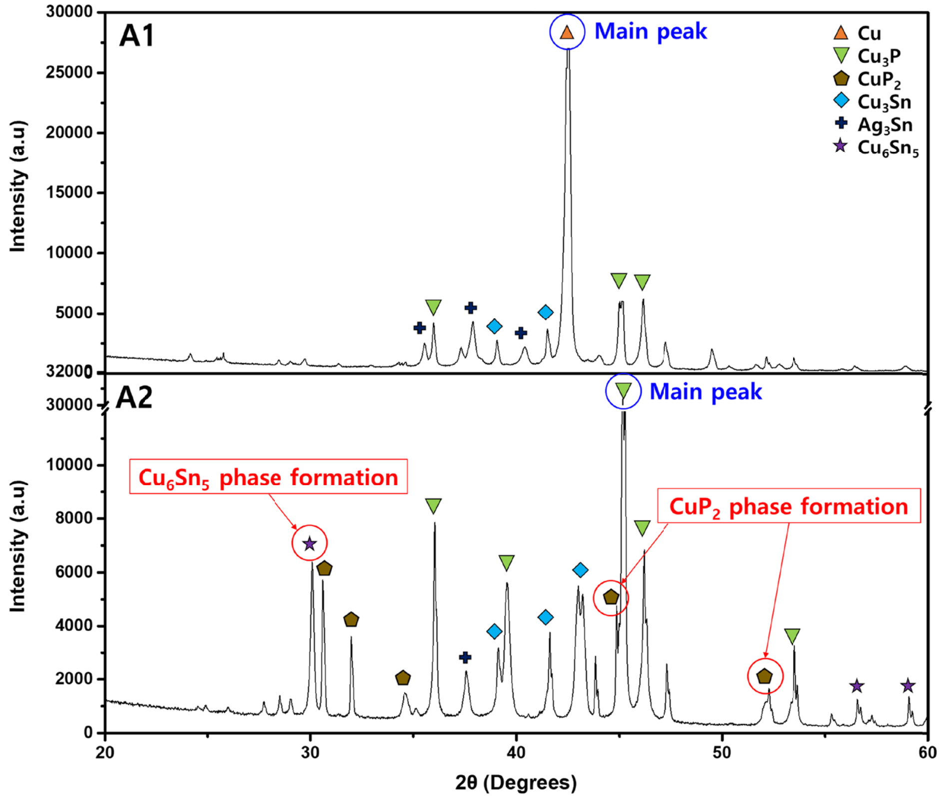


Fig. 3. XRD patterns of Cu–Ag–Sn–P filler metals with different phosphorus contents

fluidity and active interfacial reactions. In contrast, the A2 alloy exhibited a discontinuous and irregular interface, along with generally limited diffusion of the filler metal, which can be attributed to suppressed interfacial reactions due to reduced melt fluidity. These interfacial characteristics are consistent with the joint strength results, where the A1 alloy showed the highest strength, while the A2 alloy exhibited relatively lower strength.

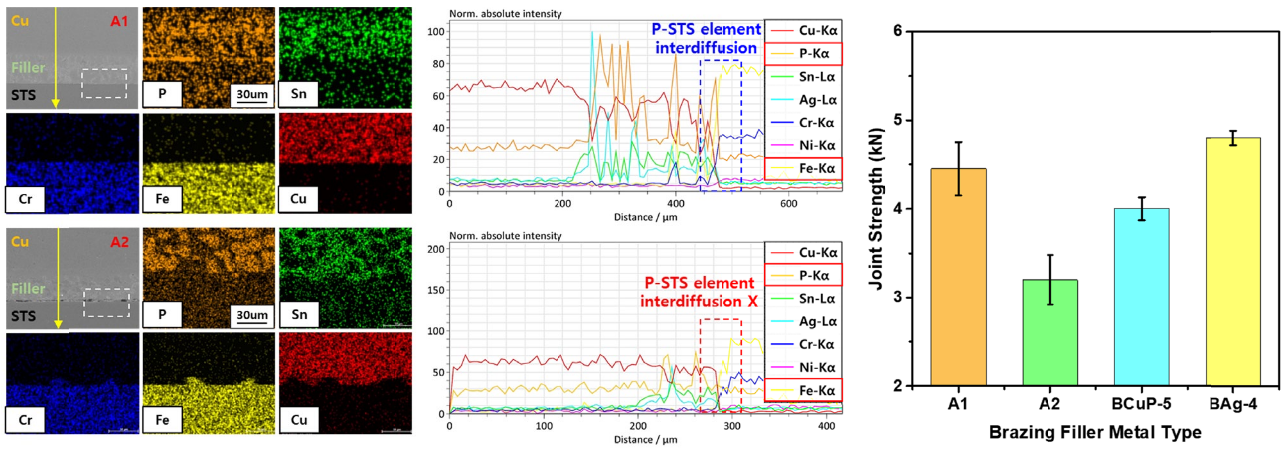


Fig. 4. Joint strength and SEM microstructures of Cu-stainless steel brazed joints. Yellow line: line scan; white boxes: analysis regions

4. Conclusions

In this study, the effects of the phosphorus content on the microstructure and joint strength of Cu–Ag–Sn–P filler metals for fluxless brazing were investigated. At 5 wt.% P, a uniform joint interface and improved wettability were achieved through effective reduction of the chromium oxide layer on the stainless steel. In addition, the relatively low phosphorus content suppressed excessive formation of Cu–P intermetallic compounds, allowing the formation of a continuous Cu or Cu–Sn-based matrix, which contributed to stable melt flow and homogeneous joint formation. In contrast, increasing the P content to 10 wt.% caused an excessive formation of P-rich brittle phases such as CuP_2 and Cu_6Sn_5, resulting in degraded melt fluidity and joint reliability. Consequently, the A1 alloy containing 5 wt.% P exhibited a superior joint strength compared with the commercial BCuP-5 and a performance comparable to the BAg-4, despite its lower Ag content, demonstrating its potential as an alternative filler metal for high-reliability fluxless brazing applications.

Acknowledgments

This work was supported by the Technology Innovation Program (or Industrial Strategic Technology Development Program-Technology Independent Advanced Packaging Technology Development) (RS-2025-02220485, Securing low-temperature bonding materials and process reliability within 50% of non-pressure low-bending deformation for high-density 85×85 mm^2 large-area FCBGA package linked to market demand) funded by the Ministry of Trade, Industry and Energy (MOTIE, Korea)

REFERENCES

[1] D. Al Kez, A.M. Foley, F. Wong, B.M. Hasan Wong, A. Dolfi, G. Srinivasan, Thermodynamic assessment of energy systems for sustainable applications. Sustainable Energy Technologies and Assessments **82**, 104511 (2025).

[2] S.C. Hong, S.Y. Park, D.H. Jung, J.H. Lee, W.J. Kim, J.P. Jung, Characteristics of brazed joints using Cu–P based filler metals. Journal of the Korean Welding and Joining Society **30**, 501-506 (2012).

[3] M.S. Khan, Y.N. Zhou, Laser joining of dissimilar materials: A brief review. Manufacturing Letters **36**, 44-45 (2023).

[4] S.C. Hong, J.K. Park, J.H. Oh, J.H. Lee, W.J. Kim, J.P. Jung, Microstructural characteristics of Cu–P brazed joints. Journal of the Korean Welding and Joining Society **29**, 660-664 (2011).

[5] A.M. Aminazada, A.M. Hadian, F. Ghasimakbari, Microstructure and mechanical properties of brazed joints. Procedia Materials Science **11**, 672-678 (2015).

[6] S. He, Y.A. Shen, B. Xiong, F. Huo, J. Li, J. Ge, Z. Pan, W. Li, C. Hu, H. Nishikawa, Microstructure evolution and mechanical behavior of Cu–Sn intermetallic compounds. Journal of Materials Research and Technology **21**, 2352-2361 (2022).

[7] L. Hardwick, P. Webb, R. Goodall, Design of higher temperature copper brazing filler metals with reduced brittle phase content. Materials Today Communications **35**, 105524 (2023).

[8] N.A.M. Zahri, F. Yusof, Y. Miyashita, T. Ariga, A.S.M.A. Haseeb, N.H. Jamadon, N.L. Sukiman, Brazing of porous copper foam/copper with amorphous Cu–9.7Sn–5.7Ni–7.0P (wt%) filler metal: interfacial microstructure and diffusion behavior. Welding in the World (2019).

[9] H. Flandorfer, U. Saeed, C. Luef, A. Sabbar, H. Ipser, Thermodynamic investigation of Cu–Sn intermetallic compounds. Thermochimica Acta **459**, 34-39 (2007).

[10] G. Ghosh, M. Asta, Phase stability and thermodynamics of Cu–Sn intermetallics. Physical Review B **71**, 014113 (2005).

[11] S. Boone, O.J. Kleppa, Thermochemistry of copper phosphides. Thermochimica Acta **202**, 113-119 (1992).

[12] C.-F. Yu, H.-C. Cheng, First-principles study on phase stability and brittleness of Cu–P intermetallic compounds. Metals **15**, 369 (2025).

[13] M.I.I. Ramli, M.A.A.M. Salleh, M.M.A.B. Abdullah, N.S.M. Zaimi, A.V. Sandu, P. Vizureanu, A. Rylski, S.F.M. Amli, Growth behavior and mechanical properties of Cu6Sn5 intermetallic compounds. Materials **15**, 1451 (2022).