UNIVERSITI PUTRA MALAYSIA

MORPHOLOGICAL AND MECHANICAL CHARACTERISATION OF BI-AG ALLOY AS HIGH TEMPERATURE LEAD FREE SOLDER

MAHDI NAHAVANDI

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By

MAHDI NAHAVANDI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

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DEDICATION

Firstly, this thesis is dedicated to my beloved parents, Mohammad Ali Nahavandi & Rogayeh Sorayaie, who have always been on my side in spite of the little time I have been able to devote for them especially during these three years. They have never failed to give me moral and financial support especially during my master studies and finishing my thesis.

Secondly, I am dedicating this thesis to my beloved siblings, Mahdiyeh and Naemeh Nahavandi for their endless kindness and supports.

Thirdly, this thesis is dedicated to my fiancé, Faranak Baserfalak, who has been very understanding and helpful.

Forthly, this thesis is dedicated to my Supervisor Dr. Azmah Hanim Mohamed Ariff who taught me to learn and without whom the completion of this work wouldn't be possible.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master Science.

MORPHOLOGICAL AND MECHANICAL CHARACTERISATION OF BI-AG ALLOY AS HIGH TEMPERATURE LEAD FREE SOLDER

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April 2014

Chairman: Azmah Hanim Binti Mohamed Ariff, PhD

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In welding and metallurgical processes, solder is used to join two or more metallic surfaces. Today, the use of solder in modern microelectronic technology is ubiquitous. Lead solder has been widely used in the semiconductor industry for a long time. In soldering process, demands for elevated temperature application are increasing and they require large amount of lead in solder alloys like Pb-5Sn. Due to the lead toxicity, an impetus has been provided towards the development of lead-free solders by worldwide environmental legislation that prohibited the use of lead in solders. Despite numerous studies on lead free solders in recent years, only limited number of research are available on high-temperature lead-free alternative solders. Bismuth based alloys, zinc based alloys, and tin based alloys have been introduced as a tailored lead-free alternatives under consideration to substitute Pb-Sn solder alloys. Therefore, this research focused on several candidate alloys (Bi-1.5-2.5-3.5 wt.% Ag) as alternative solders in order to replace the high lead solders. To reach this end, candidates of Bi-Ag alloys with different mass compositions were put in oven at 160°C for 0, 100, 200, 350, and 500 hours . Morphological characterizations such as, grain growth behavior, Cu-rich particles size behavior in solder bulk and wetting angle formed between the solder alloys on copper plate during aging process, were performed by Optical Microscope (OM) and Scanning Electron Microscope (SEM). Area elemental analysis was performed using Energy Dispersive X-ray (EDX). Candidates of Bi-Ag alloy joint's behavior and resistance were investigated using single lap-shear test method by 10 kN universal testing machine. Failed areas were investigated by optical microscope and SEM-EDX. It was observed that wt% of Bi and Ag, and aging time affected the overall results of shear test and isothermal aging process. By increasing percentages of Ag in solder

matrix, the length of Cu-rich particle size and grain boundary grooving thickness increased. Also by increasing percentages of Ag in solder matrix and gaging time, wetting angle decreased. For shear test results, by adding of Ag content in solder matrix, the maximum shear stress and shear strain at maximum shear stress were also increased. The highest maximum shear stress and strain were observed at Bi-3.5 wt.% Ag with the value of 13.355 MPa and 44.136, respectively. Furthermore, the lowest maximum shear stress and strain were observed at Bi-1.5 wt.% Ag with the value of 11.032 MPa and 24.955, respectively.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PENCIRIAN MORFOLOGI DAN MEKANIKAL ALOI BI-AG SEBAGAI PATERI BEBAS PLUMBUM SUHU TINGGI

Oleh

MAHDI NAHAVANDI

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Dalam proses kimpalan dan metalurgi, pateri digunakan untuk menggabungkan dua atau lebih permukaan logam. Kini, penggunaan pateri dalam teknologi mikroelektronik moden sentiasa ada. Pateri plumbum telah digunakan secara meluas dalam industri semikonduktor sejak dahulu lagi. Dalam proses pematerian, permintaan bagi aplikasi suhu tinggi semakin meningkat dan ianya memerlukan jumlah plumbum yang besar dalam aloi pateri seperti Pb-5Sn. Disebabkan ketoksikan plumbum, dorongan telah diperuntukkan ke arah pembangunan pateri bebas plumbum oleh undang-undang alam sekitar seluruh dunia yang melarang penggunaan plumbum di dalam pateri. Walaupun banyak kajian terhadap pateri bebas plumbum yang dijalankan sejak kebelakangan ini, kajian mengenai pateri alternatif bebas plumbum suhu tinggi adalah terhad. Aloi berasaskan bismut, aloi berasaskan zink, dan aloi berasaskan timah telah diperkenalkan sebagai alternatif bebas plumbum disesuaikan dalam pertimbangan untuk menggantikan pateri aloi Pb-Sn. Oleh itu, kajian ini memfokuskan beberapa pilihan aloi (Bi-1.5-2.5-3.5Ag) sebagai pateri alternatif untuk menggantikan pateri plumbum tinggi. Untuk mencapai tujuan ini, pilihan aloi Bi-Ag dengan komposisi berbeza dimasukkan ke dalam ketuhar pada 160^{o}C untuk tempoh 0, 100, 200, 350, and 500 jam. Ciri-ciri dan kajian morfologi seperti perilaku pertumbuhan butiran, perilaku saiz partikel kaya tembaga. Dalam pateri pukal dan sudut pembasahan terbentuk di antara aloi

pateri pada plat tembaga semasa proses penuaan, telah dijalankan menggunakan Mikroskop Optik (OM) dan Mikroskop Elektron Pengimbas (SEM). Analisis unsur kawasan dilakukan menggunakan Penyebaran Tenaga Sinar-X (EDX). Selain itu, perilaku sendi dan rintangan aloi Bi-Ag telah dikaji menggunakan kaedah ujian pusingan ricih tunggal dengan 10 kN mesin uji universal. Tambahan pula, kawasan yang gagal telan dikaji dengan mikroskop optic dan MEP- PTS. Adalah diperhatikan bahawa wt% Bi dan Ag, dan masa penuaan mempengaruhi hasil keseluruhan ujian ricih dan proses penuaan isotermal. Dengan kenaikan peratus Ag di dalam logam pateri, pajang saiz partikel kaya tembaga dan ketebalan belahan sempudan butiran menigkat. Kenaikan pertus Ag dalam matriks pateri dan masa penuaan turut mengurangkan sudut basahan. Untik keputusan ujikaji ricih, nlai maksimum tekanan ricih dan tegangan ricih turut meningkat dengan pertambahan dungan. Nilai tertinggi yang dicapai oleh maksimum tekanan ricih dan tegangan ricih apabila Bi-3.5wt.%Ag adalah 13.355 Mpa dan 44.136. Manakala, nilai terendah yang dicapai oleh maksimum tekanan ricih dan tegangan ricih apabila Bi-1.5 wt.%a Ag adalah 11.032 MPa dan 24.955.

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I certify that a Thesis Examination Committee has met on 15/4/2014 to conduct the final examination of Mahdi Nahavandi on his thesis entitled " morphological and mechanical characterisation of Bi-Ag alloy as high temperature lead free solder" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science (Materials Engineering).

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LIST OF ABBREVIATIONS

BGA	Ball Grid Array
CNS	Central Nervous System
DBS.P	Pin Plastic Power DIL-Bent-SIL
EDX	Energy Dispersive X-ray spectroscopy
ENIG	Electroless nickel immersion gold
FESEM	Field-emission scanning electron microscopy
FEEPMA	Field-emission electron probe microanalyser
ICs	Internal Circuits
IMC	Intermetallic Compound
ITMA	Institute of Advanced Technology
JEDEC	Joint Electronic Devices Engineering Council
NCMS	National Centre of Manufacturing Science
OM	Optical Microscope
OSP	Organic Solderability preservative
PLCC	Plastic Leaded Chip Carrier
RE	Rare Earth
RMA	Rosin mildly activated
RoHS	Restriction of Hazardous Substances
RPM	Revolution per minute
SEM	Scanning Electron Microscopy
SLI.P	Pin Plastic Power Single-in-Line
T_m	Melting point

UBM	Under Bump Metallization
UTS	Ultimate Tensile Strength
XRD	X-ray diffractometer

CHAPTER 1

INTRODUCTION

1.1 Background of the Research

Solders are generally described as fusible alloys with liquids temperature below 400°C (750°F). Solder is a filler metal with a low melting point. In welding and metallurgical processes, solder is used to join two or more metallic surfaces. In other words, it is using low melting temperature metals to stick to the surfaces to be soldered together. Solder materials are used for many applications, including electronic assemblies, in which solder covers mechanical and physical properties like thermal and electrical. In general, elements which are frequently used in solder alloys are Plumbum (T_m=328°C), Silver (T_m=961ºC), Bismuth (T_m =271.5ºC), Indium (T_m =160 ºC), Antimony (T_m = 630.5 ºC), and Cadmium (T_m =321.2ºC) (Palenzona 1971; Yatsenko et al. 1983; Karakaya and Thompson 1987; Karakaya and Thompson 1993; Okamoto 2012). Pb-Sn alloys are widely used as a solder in the electronics industry (Hwang 2004). Recently, there is a great need within the avionics, military, oil exploration, telecommunications, and automotive industries for solders. For these applications, solders perform reliably at higher temperatures and come close to or exceed the melting point of tin-lead eutectic (Dash 2006).

High percentages of Pb in conventional solder alloys (95Pb-5Snor 90Pb -10Sn) are used for high temperature application such as die attach solders in power semiconductor packaging. However, low percentages of Pb are used for normal consumer electronics such as laptops, cell phones, and electronic toys. Majority of these products, are releasing in landfill within a few months or years because of having short service life. The lead can penetrate into the drinking water and poison humans' health. In July 2006, The European Parliament and Council agreed to the Restriction on the Use of Hazardous Substances in Electrical and Electronic Equipment Directive, which bans the use of lead, or plumbum (Pb). Also, Japan as one of the paramount electronic products producers, required all new electronic products to be lead free solder from January 2005. These directives encourage the development of high-temperature lead-free solders (Hwang 2004).

Selecting an alternative high temperature lead-free solution involves two main properties, mechanical and electrical behavior. A typical lead-free high temperature solder replacement is eutectic Au-20Sn. This alloy is a hard solder with a melting temperature of 280°C which will be within range of applications for high temperature lead free solders (George et al. 2011). Hard solders have higher melting temperature and higher yield stress than Pb-5Sn. However, the cost of gold (Au) and lack of suitable mechanical properties limits its implementation. Other lead-free solutions such as Bi-5Sb have the proper thermodynamic properties, but they lack sufficient mechanical and electrical properties to be considered as a suitable high temperature replacement (Song et al. 2009). The addition of antimony to bismuth increases the strength of the material while increasing its brittleness and resistivity. A number of promising lead-free materials such as Sn-Ag-Cu alloys i.e., have been developed as replacements for the (near-) eutectic Sn-Pb solders in mainstream applications, despite the fact that there is still no 'drop-in' alternative for the traditional Pb-Sn alloy (Živković et al. 2008). Despite extensive studies on lead-free solder alternatives in recent years, direct replacement for the Pb-Sn near-eutectics have not been introduced yet (Evans et al. 2007; Zeng et al. 2012).

1.2 Problem Statement

Current high temperature solders (Pb-5Sn) are used for lots of applications, such as attachment of power semiconductors, flip chip packages, heat resistant vehicles, packages, aerospace, and variety of intrusive procedures are being used in the medicine. Environmental concerns after usage and throwing away are also driving research in this area. The concern about toxicity and health hazards means that leaded solders should be replaced with lead-free solders as soon as possible.

Prohibiting the use of lead containing solders in many industries was applied from 1st of July 2006. Recently, a new alloy system, Bi-Ag, has been considered as the replacement for high Pb solders for high-temperature applications (e.g., 95Pb-5Sn, with a melting range from 308 °C to 312 °C)(Song et al. 2007). Therefore, this research focused on several candidate alloys (Bi-1.5-2.5-3.5 wt.%Ag) as alternative solders in order to replace the high lead solders. To achieve this end, the morphology and mechanical properties of candidate alloys should be investigated under real conditions and these solders must be cautiously applied for high temperature applications step by step.

1.3 Research Objectives

The main objectives of this research are:

1. To investigate the morphology of Bi-Ag (three different weight percentages of Ag 1.5, 2.5, and 3.5) solders on Cu substrates subjected to isothermal aging at 160°C.

2. To evaluate the mechanical and morphological solder joints strength using single lap-shear test method by 10 kN universal testing machine.

1.4 Scope of Study

In this research, candidates of Bi-Ag alloys with different wt.% compositions were put in oven at 160°C at various duration of times. Characteristics and morphological investigations such as grain growth behavior, Cu-rich particles size behavior in solder bulk and wetting angle formed between the solder alloys on copper plate, during aging process, were done by Optical Microscope (OM) and Scanning Electron Microscope (SEM). Area elemental analysis was performed using Energy Dispersive X-ray (EDX). Moreover, candidates of Bi-Ag alloy joint's behavior and resistance were investigated using single lap-shear test method by 10 kN universal testing machine. Furthermore, failed areas were investigated by optical microscope and SEM-EDX.

1.5 Layout of the Thesis

This thesis is primarily divided into five chapters:

Chapter 1 introduces the explanation of background of research, problem statements, research objectives and scope of this research.

Chapter 2 provides a literature review of solder infrastructure and soldering, definition of electronic packaging, lead and leaded solders, health and environmental concerns with lead, high temperature solder, lead free solder materials and their essential properties, brief introduction of Bi-Ag alloys as a tailored candidate for high temperature lead-free solder, bismuth and effects of bismuth in solders, silver and effects of silver in solders, shear test study in solders, and thermal aging study in solders.

Chapter 3 explains in detail the methodology which were done in this study. Three stages of material development and making solder rod, samples for isothermal aging process and analysis, single-lap shear joint sample preparation, performing shear test and microstructural analysis, are explained in this chapter.

Chapter 4 explains the results, discussions and analyses on the experimental data of the effect of isothermal aging process on microstructural changes of Bi-Ag solder alloys. Furthermore, the effect of Ag on the mechanical properties and failed mode of Bi-Ag solder compositions which were investigated by single-lap shear test method, visual, optical microscope and SEM-EDX observations, are described in detail in this chapter.

Chapter 5 concludes the main findings in relations to the objectives of the research. Also this chapter gives some suggestions and recommendations for future research on the development of Bi-Ag solder as a high temperature lead-free solder alloys.

REFERENCES

Allenby, B. (1993). "An assessment of the use of lead in electronics assembly." Circuit World 19: 25-25.

Amore, S., E. Ricci, G. Borzone and R. Novakovic (2008). "Wetting behaviour of lead-free Sn-based alloys on Cu and Ni substrates." Materials Science and Engineering: A 495(1): 108-112.

Astm, D. (2010). 1002–10 Standard Test Method for Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal-to-Metal)-ASTM, International.

Benjamin, J. (1976). "Mechanical alloying." Scientific American 234(5): 40-48.

Chen, C.-m., K.-j. Wang and K.-c. Chen (2007). "Isothermal solid-state aging of Pb–5Sn solder bump on Ni/Cu/Ti under bump metallization." Journal of alloys and compounds 432(1): 122-128.

Chen, Z., Y. Shi, Z. Xia and Y. Yan (2003). "Properties of lead-free solder SnAgCu containing minute amounts of rare earth." Journal of electronic materials 32(4): 235-243.

Dash, M. R. (2006). "Thermo-mechanical Durability Assessment and Microstructural Characterization of 95.5 Pb2Sn2. 5Ag High Temperature Solder."

Deng, X., G. Piotrowski, J. Williams and N. Chawla (2003). "Influence of initial morphology and thickness of Cu6Sn5 and Cu3Sn intermetallics on growth and evolution during thermal aging of Sn-Ag solder/Cu joints." Journal of electronic materials 32(12): 1403-1413.

Dharma, I., G. B. Budi, M. H. A. Shukor and T. Ariga (2009). "Wettability of low silver content lead-free solder alloy." Materials transactions 50(5): 1135-1138.

Doelman, P. and L. Haanstra (1979). "Effect of lead on soil respiration and dehydrogenase activity." Soil Biology and Biochemistry 11(5): 475-479.

Evans, J. W., W. Engelmaier, D. Kwon and J. Y. Evans (2007). A guide to lead-free solders: physical metallurgy and reliability, Springer Germany.

Gayle, F. W., G. Becka, A. Syed, J. Badgett, G. Whitten, T.-Y. Pan, A. Grusd, B. Bauer, R. Lathrop and J. Slattery (2001). "High temperature lead-free solder for microelectronics." JOM 53(6): 17-21.

George, E., D. Das, M. Osterman and M. Pecht (2011). "Thermal cycling reliability of lead-free solders (SAC305 and Sn3. 5Ag) for high-temperature applications." Device and Materials Reliability, IEEE Transactions on 11(2): 328-338.

Goyer, R. A. (1993). "Lead toxicity: current concerns." Environmental Health Perspectives 100: 177.

Guo, F., J. Lee, S. Choi, J. Lucas, T. Bieler and K. Subramanian (2001). "Processing and aging characteristics of eutectic Sn-3.5 Ag solder reinforced with mechanically incorporated Ni particles." Journal of electronic materials 30(9): 1073-1082.

Hamilton, C., P. Snugovsky and M. Kelly (2007). Have High Cu Dissolution Rates of SAC305/405 Alloys Forced a Change in the Lead Free Alloy Used during PTH Processes? Proceedings of PanPacific Microelectronics Symposium.

Hassam, S., E. Dichi and B. Legendre (1998). "Experimental equilibrium phase diagram of the Ag–Bi–Sn system." Journal of alloys and compounds 268(1): 199-206.

Hibbeler, R. (2000). Mechanics of Materials. Prentice Hall, Upper Saddle River.

Humpston, G. and D. M. Jacobson (2004). Principles of soldering, ASM International Materials Park, OH.

Hwang, J. S. (2004). "Solder technologies for electronic packaging and assembly." Electronic Packaging and Interconnection Handbook: 6.1-6.83.

Jeon, S.-j., S. Hyun, H.-J. Lee, J.-W. Kim, S.-S. Ha, J.-W. Yoon, S.-B. Jung and H.-J. Lee (2008). "Mechanical reliability evaluation of Sn-37Pb solder joint using high speed lap-shear test." Microelectronic Engineering 85(10): 1967-1970.

Karakaya, I. and W. Thompson (1987). "The Ag-Pb (Silver-Lead) System." Bulletin of Alloy Phase Diagrams 8(4): 326-334.

Karakaya, I. and W. Thompson (1993). "The Ag-Bi (Silver-Bismuth) System." Journal of phase equilibria 14(4): 525-530.

Kim, H., M. Zhang, C. M. Kumar, D. Suh, P. Liu, D. Kim, M. Xie and Z. Wang (2007). Improved drop reliability performance with lead free solders of low Ag content and their failure modes. Electronic Components and Technology Conference, 2007. ECTC'07. Proceedings. 57th, IEEE.

Krause, M., M. Muller, M. Petzold, S. Wiese and K.-J. Wolter (2008). Scaling effects on grain size and texture of lead free interconnects—investigations by electron backscatter diffraction and nanoindentation. Electronic Components and Technology Conference, 2008., ECTC 2008, 58th, IEEE.

Kwak, H. and T. Hubing (2007). "Technical report: cvel-07-001 an overview of advanced electronic packaging technology."

Lavoisier, A. L. (1965). Elements of chemistry: in a new systematic order, containing all the modern discoveries, DoverPublications. com.

Lee, H.-T., H.-S. Lin, C.-S. Lee and P.-W. Chen (2005). "Reliability of Sn–Ag–Sb lead-free solder joints." Materials Science and Engineering: A 407(1–2): 36-44.

Lee, J., K. Kim, K. Suganuma, M. Inoue and G. Izuta (2007). "Thermal properties and phase stability of Zn-Sn and Zn-In alloys as high temperature lead-free solder." Materials transactions 48(3): 584.

Lee, Y.-H. and H.-T. Lee (2007). "Shear strength and interfacial microstructure of Sn–Ag–xNi/Cu single shear lap solder joints." Materials Science and Engineering: A 444(1–2): 75-83.

Lu, S., F. Luo, J. Chen and K. Li (2009). The effects of Bi on physical and microstructural characteristics of Sn-Ag-Cu lead-free solders. Physical and Failure Analysis of Integrated Circuits, 2009. IPFA 2009. 16th IEEE International Symposium on the, IEEE.

Ma, H., J. C. Suhling, P. Lall and M. J. Bozack (2006). Reliability of the aging lead free solder joint. Electronic Components and Technology Conference, 2006. Proceedings. 56th, IEEE.

McCluskey, F., M. Dash, Z. Wang and D. Huff (2006). "Reliability of high temperature solder alternatives." Microelectronics Reliability 46(9): 1910-1914.

McCormack, M. and S. Jin (1994). "Improved mechanical properties in new, Pb-free solder alloys." Journal of electronic materials 23(8): 715-720.

Monsalve, E. (1984). Lead Ingestion Hazard in Hand Soldering Environments, DTIC Document.

Nahavandi, M., M. A. Hanim, Z. Ismarrubie, A. Hajalilou, R. Rohaizuan and M. S. Fadzli (2014). "Effects of Silver and Antimony Content in Lead-Free High-Temperature Solders of Bi-Ag and Bi-Sb on Copper Substrate." Journal of electronic materials 43(2): 579-585.

Ohnishi, T. and T. Taguchi (2012). LEAD-FREE SOLDER, EP Patent 2,277,657.

Okamoto, H. (2012). "Bi-Sb (Bismuth-Antimony)." Journal of Phase Equilibria and Diffusion 33(6): 493-494.

Palenzona, A. (1971). "The ytterbium-cadmium system." Journal of the Less Common Metals 25(4): 367-372.

Pan, J., B. J. Toleno, T. C. Chou and W. J. Dee (2006). "The effect of reflow profile on SnPb and SnAgCu solder joint shear strength." Soldering & surface mount technology 18(4): 48-56.

Pandher, R. and T. Lawlor (2009). "Effect of Silver in common lead-free alloys." Cookson Electronics Assembly Materials.

Park, J. Y., J. S. Ha, C. S. Kang, K. S. Shin, M. I. Kim and J. P. Jung (2000). "Study on the soldering in partial melting state (1) analysis of surface tension and wettability." Journal of electronic materials 29(10): 1145-1152.

Pecht, M. (1999). Handbook of Electronic Packaging Design, Marcel-Dekker, New York**:** 754-765.

Sharif, A., M. Islam and Y. Chan (2004). "Interfacial reactions of BGA Sn–3.5% Ag–0.5% Cu and Sn–3.5% Ag solders during high-temperature aging with Ni/Au metallization." Materials Science and Engineering: B 113(3): 184-189.

Shen, Y.-L., N. Chawla, E. Ege and X. Deng (2005). "Deformation analysis of lap-shear testing of solder joints." Acta materialia 53(9): 2633-2642.

Shi, Y., W. Fang, Z. Xia, Y. Lei, F. Guo and X. Li (2010). "Investigation of rare earth-doped BiAg high-temperature solders." Journal of Materials Science: Materials in Electronics 21(9): 875-881.

Shiue, R.-K., L.-W. Tsay, C.-L. Lin and J.-L. Ou (2003). "A study of Sn-Bi-Ag-(In) lead-free solders." Journal of materials science 38(6): 1269-1279.

Song, J.-M., H.-Y. Chuang and T.-X. Wen (2007). "Thermal and tensile properties of Bi-Ag alloys." Metallurgical and Materials Transactions A 38(6): 1371-1375.

Song, J.-M., H.-Y. Chuang and Z.-M. Wu (2007). "Substrate dissolution and shear properties of the joints between Bi-Ag alloys and Cu substrates for high-temperature soldering applications." Journal of electronic materials 36(11): 1516-1523.

Song, J.-M., G. Lan, T.-S. Lui and L.-H. Chen (2003). "Microstructure and tensile properties of Sn–9Zn–xAg lead-free solder alloys." Scripta materialia 48(8): 1047-1051.

Song, J. M., H. Y. Chuang and Z. M. Wu (2006). "Interfacial reactions between Bi-Ag high-temperature solders and metallic substrates." Journal of electronic materials 35(5): 1041-1049.

Song, K. X., Y. F. Yan, L. F. Feng, X. X. Guo and K. Tang (2009). Effect of the Content of Cu on Solderability and Mechanical Properties of Bi5Sb Solder Alloy. Materials Science Forum, Trans Tech Publ.

Suganuma, K. (2001). "Advances in lead-free electronics soldering." Current Opinion in Solid State and Materials Science 5(1): 55-64.

Suganuma, K., S. J. Kim and K. S. Kim (2009). "High-temperature lead-free solders: Properties and possibilities." JOM Journal of the Minerals, Metals and Materials Society 61(1): 64-71.

Suh, D., D. W. Kim, P. Liu, H. Kim, J. A. Weninger, C. M. Kumar, A. Prasad, B. W. Grimsley and H. B. Tejada (2007). "Effects of Ag content on fracture resistance of Sn–Ag–Cu lead-free solders under high-strain rate conditions." Materials Science and Engineering: A 460: 595-603.

Suryanarayana, C. (2001). "Mechanical alloying and milling." Progress in Materials Science 46(1): 1-184.

Xu, L., J. H. Pang, K. H. Prakash and T. Low (2005). "Isothermal and thermal cycling aging on IMC growth rate in lead-free and lead-based solder interface." Components and Packaging Technologies, IEEE Transactions on 28(3): 408-414.

Yatsenko, S., A. Semyannikov, H. Shakarov and E. Fedorova (1983). "Phase diagrams of binary rare earth metal-indium systems." Journal of the Less Common Metals 90(1): 95-108.

Zeng, G., S. McDonald and K. Nogita (2012). "Development of high-temperature solders: Review." Microelectronics Reliability 52(7): 1306-1322.

Živković, D. T., A. I. Kostov, I. P. Janković and M. L. Stojanović (2008). "Application of high temperature lead-free solder materials in medicine." Metalurgija 14(4): 271-277.