Effect of Thermal Aging on the Microstructure Evolution and Solder Joint Reliability in Hard Disk Drive Under Mechanical Shock

Hongtao Chen, Chunqing Wang, Mingyu Li, and Dewen Tian

Abstract—The effect of thermal aging on the microstructure evolution and solder joint reliability in hard disk drive (HDD) under mechanical shock was investigated. Significant coarsening of Ag$_5$Sn particles was found in SnAgCu solder, and Au$_6$Sn$_5$ intermetallic compound (IMC) changed from needle-type to layer-type during aging. For as-soldered SnAgCu solder joints after mechanical shock, the cracks were initiated in AuSn$_3$ at the corner of the solder joints, and mainly propagated along the thin Ni$_3$Sn$_4$ IMC layer. After aging at 150 °C for 21 days, the cracks were mainly propagated along the solder, Ni$_3$Sn$_4$, Au–Sn–Ni–Cu, and Au–Cu–Sn. The significant coarsening of microstructure was found in SnPb solder joints, and only microcracks were found on the surfaces of as-soldered and aged solder joints after mechanical shock.

Index Terms—Aging, hard disk drive (HDD), mechanical shock, solder joint reliability.

I. INTRODUCTION

UNDER the pressure of increasing fierce competition in data storage industry, hard disk drive (HDD) manufacturers try to adopt every possible advanced technology to increase the capacity and performance of HDD and reduce the cost at the same time. The current bonding methods to make electrical connection for hard disk drive magnetic head include soldering, gold-to-gold interconnection, and anisotropic conductive film bonding [1], [2]. Solder reaction is one of the oldest metallurgical processes for joining metal parts, and solder is widely used for the interconnection and packaging in modern microelectronic technology today. The solder joints not only transfer electrical signals, but also maintain the mechanical integrity. The performance and quality of solder joints are crucial to the overall functioning of the assembly. With the increasing demand and popularity of mobile HDDs, laptop computers, and MP3 players with large capacity, the solder joint reliability under mechanical shock loading in the handheld electronic products has drawn tremendous attention [3]–[13]. If solder joints can withstand the mechanical shock due to the accidental drops from certain heights or occasional bangs with hard surfaces directly influences the confidence and acceptance of customers and successful long-term commercialization.

Generally, the shock level experienced by handheld electronic products when dropped onto the ground ranges from several hundred G to thousands of G depending on the drop height, mass of the electronic devices, impact orientation, and so on [4], [14]–[16]. Pang et al. evaluated the flip chip on-board solder joints with both experiment and finite-element analysis (FEA) [5]. The plastic strain of solder joints was investigated, and the fatigue life of solder joints under drop loading was predicted. Zhao et al. measured the whole deformation field of the ball grid array (BGA) specimen using laser moiré interferometry, and then calculated corresponding inelastic strain field [6]. They found that at elevated temperature, both vibration and shock induce significant inelastic shear deformation, thus shortening the fatigue life of solder joints. Mishiro et al. evaluated the solder joint reliabilities of BGAs and chip size packages under drop impacts, and the authors found that the stress in a solder joint differs depending on the package structure, even if the motherboard strain is the same, and underfilling eases the motherboard strain and disperses the stress concentrated on a solder joint [7]. Irving and Liu studied the free drop test performance of portable IC package by implicit transient dynamics FEA, and the modeling results show that the higher the solder joints, the higher the impact stress [8]. To investigate the board level solder joint reliability performance during the drop test, Tee et al. studied the comprehensive dynamic response of printed circuit board (PCB) and solder joints with a multichannel real-time electrical monitoring system, and simulated with a novel input acceleration method [9]–[11]. Their results show that the mechanical shock causes the multiple PCB bending or vibration, which induces the solder joint fatigue failure. The solder joint reliability under mechanical shock was also one of the serious concerns of HDD manufacturers. One solder joint failure may lead to the fatal breakdown of the whole HDD. In this paper, the solder joints in HDDs are not quite different from the common solder joints in electronic packaging regarding solder materials and dimension, but the two pads are vertical to adapt to the requirement of HDD magnetic head structure, not parallel like the common BGA solder joints. During the field service or storage, the morphology and composition of the intermetallic
II. EXPERIMENTAL PROCEDURE

The thicknesses of Au and Ni surface finish on horizontal Cu pad were 0.5 μm and 2 μm, respectively, while the Au and Ni thicknesses on vertical Cu pad were 0.8 μm and 0.2 μm, respectively. Sn3.5Ag0.75Cu (SAC) solder balls with a 0.12-mm diameter were soldered onto rectangular pads with a dimension of 110 μm x 138 μm by Nd:YAG laser with 23-mJ pulse energy. Sn63Pb37 solder was also used for the purpose of comparison. Samples were aged at 125 °C up to 21 days. The samples were sectioned, ground, and polished with 0.1 μm diamond suspension after being mounted in epoxy, and then were slightly etched with 2 vol.% HCL + 98 vol.% C2H5OH solution for several seconds to distinguish the different phases. A JSM 6301F scanning electron microscope (SEM) equipped with an energy dispersive X-ray spectrometer (EDX) was used to characterize the microstructure. GHI system LSM-100 horizontal shock machine, as shown in Fig. 1, was used to perform the mechanical shock test. A head stack assembly (HSA) was mounted on a 2.5-in HDD to perform the mechanical shock. Potential energy for the impact is stored in high capacity springs, which are pre-loaded by pneumatic pressure. A fixture designed according to the requirement of HDD structure was mounted on the mounting table, and these springs drive the fixture to which HDD was attached with four screws at the corners in vertical direction impact against a high effective mass seismic anvil. The combination of impact velocity, programmer characteristics, and driven mass dictates the energy transfer to the table and product. An adjustable trigger release device decouples the table and product from the pneumatic actuator, and the mechanical shock was performed in the horizontal direction. An accelerometer was installed on the fixture near the mounting screw to record the corresponding impact pulse during the mechanical shock. A typical measured shock pulse used for the mechanical shock is shown in Fig. 2, the duration and peak acceleration were one millisecond and 1000 G (G = 9.8 m/s²), respectively [15], [16]. The schematic diagram of the mechanical shock test is shown in Fig. 3. Ten samples with total 60 solder joints were used for mechanical shock at a time. The electrical resistance and appearance of solder joints after mechanical shock were checked to confirm the failure. The fractographic morphology after mechanical shock was observed and analyzed by PHI-680 Auger electron spectroscopy (AES), and the acceleration voltage and beam current under the analysis conditions were 10 keV and 1 nA, respectively.

III. MICROSTRUCTURE EVOLUTION DURING AGING

For SAC solder joints, as shown in Fig. 4(a) and (b), in the initial as-soldered state, randomly distributed needle-type AuSn₄ IMC was formed at the interface after laser heating. The trace that AuSn₄ was dissolved into solder bulk can be clearly seen on the top of AuSn₄ needle-type IMC. As the aging time went on, as shown in Fig. 4(c)–(h), the needles of AuSn₄ cant coarsening of Ag₃Sn particles was pronounced in the solder IMC layer during aging, but its composition cannot be determined accurately. In addition, the significant coarsening of Ag₃Sn particles was pronounced in the solder
bulk, and the Ag$_3$Sn particles could be embedded in the AuSn$_4$ IMC at the interface sometimes. Furthermore, the AuSn$_4$ IMC needles were occasionally found in the solder bulk after aging for 21 days.

For SnPb solder joints, as shown in Fig. 5(a) and (b), the needle-type AuSn$_4$ IMC was formed in the as-soldered state, and enwrapped by the Pb-rich phase. It is interesting to note that the needle type IMCs are much thinner than those formed in the SAC solder joints, and it maybe because that the limited Sn supply near the interface after excessive reaction with Au and the separation of Pb-rich phases in SnPb solder joints resulted in the thinner AuSn$_4$ IMC needle at the interface, while the Sn supply in SAC solder, which is a high-tin based solder alloy, is adequate to sustain the growth of the needles at the interface. Significant coarsening of the Sn and Pb phases took place during aging, as shown in Fig. 5(c)–(h), and only few Pb-rich phases were found in the solder bulk after aging for 21 days. A (Au, Ni)Sn$_4$ IMC layer with about 5 wt% Ni was formed at the interface, and the thickness of this IMC layer increased with the aging time. Similar phenomenon was also observed by other researchers [18], [19]. Based on the thermodynamic calculations, it is assumed that with 10 at.% of Ni dissolved in the (Au, Ni)Sn$_4$ compound, its Gibbs-free energy is decreased by 3-kJ/g atoms [20]. Then it is natural for (Au, Ni)Sn$_4$ to seek more Ni at the interface to decrease the Gibbs-free energy. The Pb-rich phases were developed on the top of the (Au, Ni)Sn$_4$ IMC because of the large consumption of Sn in the metallurgical reaction with Au metallization. Furthermore, similar to what happened in the SAC solder joints, a thin IMC layer containing Au, Sn, Ni, and Cu was also developed under (Au, Ni)Sn$_4$ IMC layer during aging. The Cu in the Au–Sn–Ni–Cu IMC indicates that Cu diffused through Ni layer and was involved into the IMC formation process. It is assumed that the Ni has a columnar structure, which offers the pathway for Cu diffusion [21]. It is worth noting that the Au–Sn–Ni–Cu IMC pikes had extended from Au–Sn–Ni–Cu IMC into (Au, Ni)Sn$_4$ IMC layer, as shown in Fig. 5(f) and (h).
IV. CRACKS AFTER MECHANICAL SHOCK

For the SAC solder joints in the as-soldered state, 49 out of 60 solder joints failed. The failed solder joints indicate a brittle fracture behavior. It is known that the strain rate in mechanical shock is very high [17], [22], [23]. The force required to deform the solder increases significantly when the strain rate is increased. The solder alloy behaves as a strong material owing to the strain-rate hardening, and then the magnitudes and distributions of the stresses in solder joints are totally different from the thermal cycling, in which low cycle fatigue is the main failure mode [24], [25]. The IMC formed at the interface will subject to significantly higher stress in mechanical shock test than in the thermal cycling, and then cracks will initiate and propagate more easily in the brittle IMCs [26]. As clearly shown in Fig. 6(a) and (b), the cracks were initiated in AuSn IMC at the corner of solder joints in the as-soldered state, but the cracks were not propagated in the AuSn IMC. As shown in Fig. 7(a) and (c), some solder joints were detached completely from pads after mechanical shock, and the typical fractography appears to be flat, which indicates a brittle fracture behavior. A detailed examination of the fractography at the solder side and pad side by AES, as shown in Fig. 7(b) and (d), reveals that the fracture occurred mainly through the thin NiSn IMC layer. NiSn was determined to be very brittle by hardness and fracture toughness [27], and then fracture tends to occur through it under mechanical shock. It is worth noting that the cracks rarely occur through the AuSn IMC where the cracks were initiated. It seems like that NiSn is more susceptible to crack under mechanical shock loading. After aging for 21 days, the IMCs tend to change from needle-type to layer-type and become ternary or quaternary due to the continuous diffusion of metal elements during solid state aging. 53 out of 60 SAC solder joints failed after mechanical shock test. The solder joints become more susceptible to failure in mechanical shock after aging. The cracks were also initiated in AuSn like the as-soldered state, but the propagation behavior of cracks became more complicated because the Au and Cu were involved in the IMC formation at the interface during thermal aging. From the typical fractography at the solder side after mechanical shock, as shown in Fig. 8(a) and (b), the solder and NiSn were found on the fracture surface. On the pad side, as shown in Fig. 8(c)–(f), solder, Ni3Sn4, Au–Sn–Ni–Cu and Au–Cu–Sn with a faceted morphology were found on the fractured surface. These thin IMCs are too thin to be distinguished in the cross-sectional images of the solder joints.

For all the tested SnPb solder joints, no electrical resistance change was found after the mechanical shock. It is shown in Fig. 9(a), only micro-cracks were observed at the interface between the solder and the horizontal pad in the as-soldered joints. It indicates that SnPb solder joints have a higher resistance to mechanical shock compared with SAC solder joints, which have a higher modulus and lower ductility [28], [29]. After aging...
for 21 days, as shown in Fig. 9(b), the volume of solder joint is found to be reduced due to the excessive reaction of Sn in SnPb solder with Au metallization. Micro-cracks were located on the upper part above horizontal pad compared to as-soldered solder joints. Obviously, cracks were initiated on the top of (Au, Ni)Sn$_4$ IMC layer, which had grown to a large thickness after aging for 21 days.

V. CONCLUSION

1) For the SAC solder joints, as the aging time went on, the needles of AuSn$_4$ IMC in the as-soldered state coalesced at the corner of the joints, and IMC at the interface.

2) For the SnPb solder joints, the needle type IMCs in the as-soldered state are much thinner than those formed in the SAC solder joints, and significant coarsening of the Sn and Pb phases took place during aging. Only few Pb-rich phases were found in the solder bulk after aging for 21 days, and most of the Pb-rich phases were developed on the top of (Au, Ni)Sn$_4$ IMC at the interface.

3) A thin IMC layer containing Au, Sn, Ni, and Cu was developed under (Au, Ni)Sn$_4$ IMC layer in SnPb solder joints during aging. Cu could diffuse through Ni layer and was involved into the IMC formation process.

4) For the as-soldered SAC solder joints, the cracks were initiated in the AuSn$_4$ at the corner of the joints, and mainly propagated along the thin Ni$_3$Sn$_4$ IMC layer after 1000-g/1 ms mechanical shock. The solder joints become more susceptible to failure in mechanical shock after aging, and the propagation path of cracks becomes complicated due to the change of the composition and morphology of the IMCs. As for the SAC solder joints after aging for 21 days, solder, Ni$_3$Sn$_4$–Au–Sn–Cu and Au–Cu–Sn with a faceted morphology were found on the fractured surface after the mechanical shock.

5) For all the tested SnPb solder joints, no resistance change was found after mechanical shock. It indicates that SnPb solder joints have a higher resistance to mechanical shock compared with SAC solder joint due to its ductility.

REFERENCES


Hongtao Chen received the M.S. and Ph.D. degree in material science and engineering from Harbin Institute of Technology, Harbin, China, in 2003 and 2007, respectively. He is currently a Postdoctoral Fellow in the Electronics Production Technology Laboratory, Helsinki University of Technology, Espoo, Finland. His research interests are interfacial metallurgical reactions in solder joints and solder joint reliability under different loading conditions such as thermal cycling and mechanical shock.

Chunqing Wang received the Ph.D. degree in materials science and engineering from the Harbin Institute of Technology (HIT), Harbin, China, in 1989. He is a Professor with HIT. He has been working on research concerning microjoining technology for electronics packaging, reliability analysis of interconnection, etc. He is now the Vice Director of the State Key Laboratory of Advanced Welding Production Technology.

Dr. Wang is a Senior Member of Chinese Institute of Electronics (CIE) and Vice President of the advisory committee of SMT and CIE.

Mingyu Li studied in the School of Materials Science and Engineering, Harbin Institute of Technology (HIT), China starting in 1989 and received the Ph.D. degree in 2001. He is currently a Professor at the Shenzhen Graduate School of HIT. His research area includes electronic interconnection processes, special joining technology, and electronic interconnection materials.

Dewen Tian received the B.S. degree in material science and engineering from the Harbin Institute of Technology, Harbin, China, in 2003 and 2005, respectively. He currently pursing the Ph.D. degree in material science and engineering at the Harbin Institute of Technology.

His research interests are micro-droplet soldering, time-dependent spreading, and solidification processes of solder droplets on pads.