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The Evolution of Interfacial Intermetallic Compound Growth and Solder Joint Strength of Sn-40Pb/Cu under Thermal Aging

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ABSTRACT

A solder joint serves as a mechanical support and heat dissipator in an electronics board. Thus, logically, there is a need for high reliability. The reliability of solder joints in electronic systems is an issue that affects all aspects of the production and use stages. In any aspect of packaging technology, the reliability of solder joints plays an important role in determining the lifetime of electronic devices. In this study, the intermetallic formation and solder joint strength of a conventional Sn-Pb solder were investigated. The solder joints were prepared at 250 ^{o}C with a soldering time of 1 min. The solder joints were aged at various temperatures and times. Aging was performed at 50, 100 and 150 ^{o}C for 100, 250 and 500 h. For intermetallic observation, the solder joint was cross-sectioned and mounted in epoxy resin. After polishing, the surface was observed using a Scanning Electron Microscope (SEM) for intermetallic study. The joint strength was measured using an Instron machine and the fracture surface was observed using a SEM. For a low aging temperature and duration, a Cu_6Sn_5 intermetallic compound was formed with a scalloped morphology. This intermetallic structure was transformed into a flat structure at higher aging temperatures and durations. As aging progressed, another thin and flat intermetallic layer formed near the Cu interface. The intermetallic compound was identified as Cu_3Sn. The solder joint strength degraded at a later stage of aging owing to the excessive growth of the intermetallic.

Being brittle in nature and having higher volume fraction compared to the bulk solder, these intermetallics weaken the solder joint strength. A solder joint break occurred at the Cu_6Sn_5 intermetallic/solder interface under all aging conditions.

Keywords: Shear strength; Intermetallic; Sn-Pb Solder; Cu-Sn; Fracture

INTRODUCTION

Currently, owing to health and environmental concerns, lead-free solders are widely used in the semiconductor industry to provide electronic connections. Although lead-free solder joints are generally used for conventional purposes, Pb-based solders are still used in certain critical sectors. These sectors include aerospace and aviation, energy, and data servers [1]. Hence, the reliability of solder joints is critical [2,3]. Although Sn-Pb solder is the first choice in the electronics industry, the toxicity of Pb to the environment and human health prevents its widespread use [4,5].

Interfacial continuity between the solder and the substrate is provided by the nucleation and subsequent growth of intermetallic compounds at the interface. Under the impact of thermal aging, the interfacial intermetallic layers thicken and change from a scallop morphology to a more planar. This results in a reduction in the joint strength as aging continues [6].

Although the formation of these interface intermetallics is desirable to help attain good bonding between the substrate and solder, there are some drawbacks. The intermetallics are quite brittle, and excessive thickness may degrade the interfacial strength and mismatch in physical properties such as the thermal expansion coefficient and elastic modulus [7].

As reported, the interfacial microstructure plays an important role in the reliability of solder joints owing to its brittleness nature [8-12]. Because the reliability losses in many electronic systems are identified with the failure of solder joints rather than device malfunction, an increasing number of concerns are focused on solder joint reliability [13]. To develop a reliable solder joint, it is desirable to better understand the morphology of the intermetallic phase as aging progresses.

Since Sn-Pb solders are tin-based, the interaction between the solders and the Cu substrate produces Cu-Sn intermetallics. For liquid tin/copper and many liquid-tin alloy/copper interconnects, Cu_6Sn_5 intermetallic forms almost immediately upon contact of the liquid solder with solid copper. The formation of Cu_6Sn_5 intermetallic is well documented [14-21]. Subsequently, under solid-state aging at high temperatures, a second Cu_3Sn layer below the Cu_6Sn_5 phase is formed [22,23]. The initial formation of Cu_6Sn_5 and the subsequent formation of Cu_3Sn are due to the diffusion of Cu into the bulk solder (Sn). These intermetallic compounds are necessary for good metallurgical bonding. However, their excess volume and growth may significantly affect the reliability [24].

At the Cu_3Sn/Cu interface, Kirkendall voids may have formed which has detrimental effects on the reliability of the joints [25,26]. Therefore, interfacial intermetallic formation requires a deeper understanding of the form of phase evolution. The formation of intermetallics at the solder/substrate interface is directly related to the strength of the solder joint. Hence, it is crucial to obtain a comprehensive understanding of the mechanical properties of Cu-Sn intermetallics in Sn-40Pb solder joints.

The intermetallic effects on joint strength have been reported by many researchers. Hu et al. [6] observed that with increasing aging time, the shear strength of the Sn37Pb/Cu solder decreased. This could be attributed to either an increase in the brittle intermetallic layer or grain coarsening of the Sn-rich phase in the solder. Choudhury and Ladani [24] reported for Sn-3.5Ag/Cu system that an increase in volume fraction of intermetallics from 40 to 60 % increased the shear strength. However, when the volume fraction reached 80 %, with the presence of Cu_3Sn intermetallic, the strength decreased.

Although Pb-free solder has been gradually used to replace traditional Sn-Pb solder and has been widely used in industry, some products inevitably still use a mixture of Sn-Pb and Pb-free solder to transition from Sn-Pb to Pb-free solder. Therefore, it is very important to understand the reliability of Sn-Pb solders in terms of intermetallic formation, growth, and solder joint strength.

In this research, Sn-40Pb solder was soldered to a Cu substrate and the solder joint was aged at 50, 100 and 150 °C for 100, 250 and 500 h. The solder joint was studied for its interface intermetallic formation and solder joint strength. Subsequently, the fracture path and facture surface morphology were also examined.

METHODS

The Sn-40Pb solder was melted to 400 ºC and poured into a mold to make a disc 6 cm in diameter and 3 mm in thickness. Then, the disc was ground to a thickness of 2 mm using 320 grid silicon carbide coated paper. The disc was sliced into a cylinder with a mass around 0.5 g using a puncher (5 mm in diameter). The solder was placed on a copper substrate and melted at 250 ˚C using $ZnCl_2$ flux. The solder/copper substrate interaction process was performed on a hot plate. The solder and copper substrate were allowed to react for 1 min and then allowed to cool on the hot plate. The samples were then cleaned and placed in an oven for aging. Aging was performed at 50, 100 and 150 °C for 100, 250, and 500 h. These aging temperatures were chosen based on literature for solders such as Sn-Ag-Cu and Sn-Ag [27-29].

The samples were then crossed sectioned and mounted in epoxy resin. The mounted samples were polished with 320, 400, 600, 800, 1000, 1200, 1500, and 2000 silicon carbide (SiC)-coated papers to smoothen the surface. The mounted samples were polished using 6 micron and 1 micron diamond paste. The solder/copper substrate intermetallic was then observed under a Scanning Electron Microscope (SEM).

Several magnifications were performed depending on the total intermetallic thickness. For each sample, 8-10 micrographs were obtained.

For the joint strength study, dog-bone-shaped copper specimens consisting of copper substrate arms were fabricated by machining, as shown in Figure 1. After machining, they were cleaned with 320 grit silicon-carbide coated paper. The dog-bone-shaped copper plates were then cut in the middle to form two parts. Next, approximately 0.2 g of solder alloy was sandwiched between the two copper substrates.

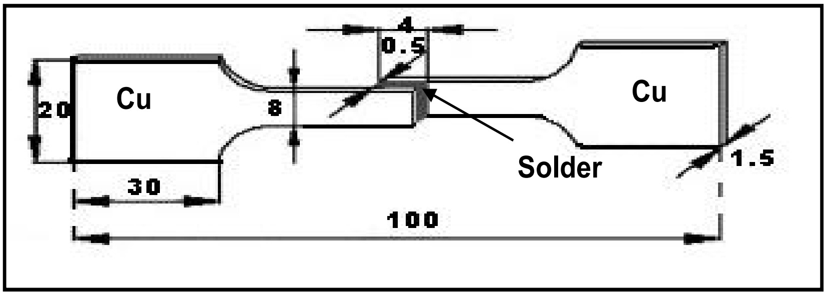

Figure 1: Single lap dog-bone shape [30,31].

After applying $ZnCl_2$ flux to the solderable area of the Cu substrates, the system was placed on a hotplate and subsequently heated to a maximum temperature of 250 °C. After soldering, the specimens were left to cool and cleaned using soap.

Soldered samples were placed in an oven at various temperatures and for various durations similar to the intermetallic studies. For each aging condition, six samples were tested, with one sample allocated for the intermetallic study. The lap area (8 x 4) mm^2 and initial length (l_o) of 4 mm were used as input data for the stress/strain calculations. In this test, the load was applied parallel to the solder joint layer at a crosshead speeds of 0.2 mm/min and the test performed at room temperature. The values of the maximum stress at fracture (failure) were recorded.

The relationship between intermetallic formation and shear strength was investigated and discussed. After the tensile test, the specimens were examined using FEVPSEM to observe the mode of fracture in the ductile or brittle fracture mode.

RESULTS AND DISCUSSION

Intermetallic formation

This section explains the formation of an intermetallic layer at the Cu substrate interface when solder samples were aged at various temperatures and durations. The formation of intermetallic compound (IMC) layers at the interface is an indication of good bonding between the solder and the substrate. In most cases, reaction products (e.g., intermetallic compound layers) are formed at the soldered interfaces. Figure 2 shows the intermetallics formed for the as-soldered and aged solder joints at 50 °C for the Sn-40Pb solder. The interaction between Cu and Sn produced a Cu_6Sn_5 intermetallic compound. According to Tu [32], the formation of the Cu_6Sn_5 phase is attributed to the interstitial diffusion of Cu into Sn. Thick intermetallic growth degrades interface integrity, owing to the brittle nature of intermetallic compounds and mismatches in physical properties such as the thermal expansion coefficient and elastic modulus.

When the solid-state aging duration increased, the scallop structure increased in size, and the scallop Cu_6Sn_5 started to penetrate bulk solder.

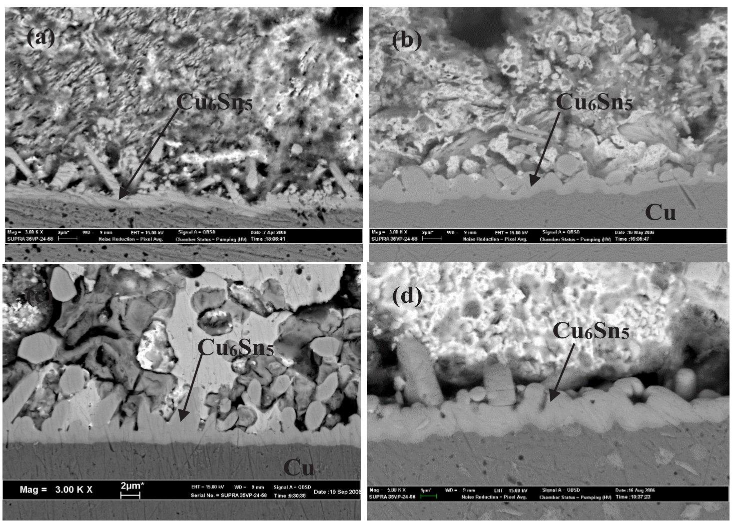

Figure 2: Interface intermetallic morphology changes for Sn-40Pb aging at 50 °C for: a) 0 h, b) 100 h, c) 250 h, d) 500 h.

The interfacial reaction of the solders with the Cu substrate continued during the thermal aging. This is evidenced by the morphology change and thickness increase of the intermetallic phase compared to the as-soldered state.

When aging was performed at 100 °C, a thick scallop morphology of the Cu_6Sn_5 intermetallic compound was observed (Figure 3(a)). When the aging duration was increased to 250 h, the thick scallop structure started to transform into a flat layer (Figure 3(b)). The transformation from a scalloped to a flat surface may be attributed to changes in the interfacial energy, as reported by Tu *et al* [33]. The scalloped morphologies have larger interfacial areas than the flat interfaces. Therefore, the intermetallic layer converted to a flat morphology to minimize the interfacial energy.

As aging progressed (Figure 3(c)), a second layer near the Cu substrate started to form. The contrast of this layer is distinguishable. This layer was identified as Cu_3Sn. Cu_3Sn has a darker contrast with a more planar morphology. The Cu_3Sn intermetallic, which was formed after Cu_6Sn_5 was formed by a solid-state reaction to satisfy the requirements of local equilibrium. The formation of Cu_6Sn_5 intermetallic at the later stage of aging was explained by Liu and Lee [34] using Eq.(1). Excess Cu from the substrate promoted the thickening of the Cu_3Sn intermetallic phase at a later stage of aging.

$$Cu_6Sn_5 + 9Cu \rightarrow 5Cu_3Sn \tag{1}$$

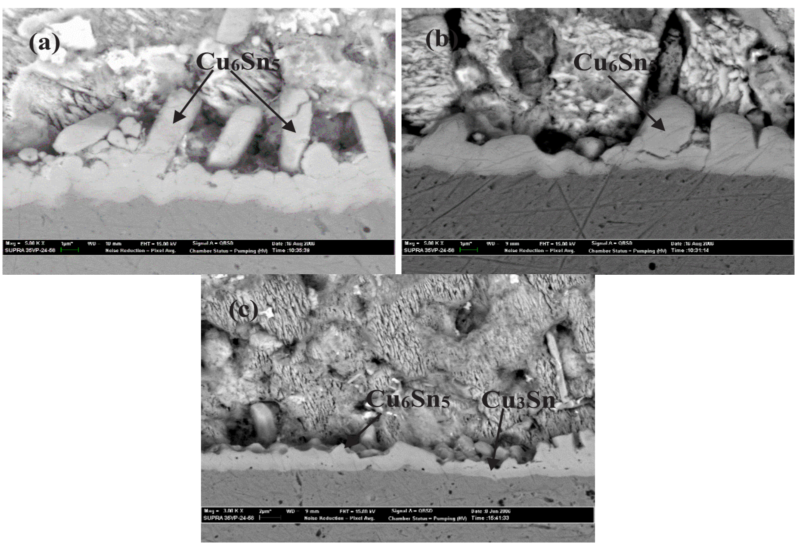

Figure 3: Interface intermetallic morphology changes for Sn-40Pb aging at 100 °C for: a) 100 h, b) 250 h, c) 500 h.

The formation of the Cu_3Sn layer is illustrated in Figure 4. At an aging temperature of 150 °C, the growth of both Cu_6Sn_5 and Cu_3Sn was significant. The thickness of Cu_6Sn_5 and Cu_3Sn and the total Cu-Sn IMC (Cu_6Sn_5 + Cu_3Sn) region increased with aging time.

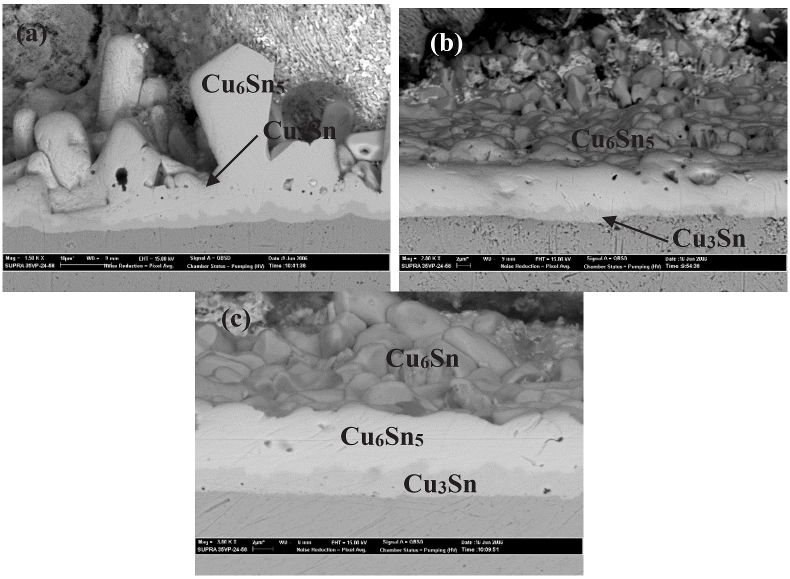

Figure 4: Interface intermetallic morphology changes for Sn-40Pb aging at 150 °C for: a) 100 h, b) 250 h, c) 500 h.

Influence of Aging Temperature and Time on Shear Strength Solder Joints

In general, excessive growth of intermetallic compounds formed at the interface is one of the main causes of breakdown in solder joints. They play a role in mechanically bonding solder and substrate, but their brittle nature may hinder the long-term reliability of solder joints [35]. Generally, in all solder joints, as the intermetallic layer grows thick, the shear strength decreases. This is the same phenomenon observed in all other Sn-based solder/Cu joint systems [13].

Figure 5 shows the shear strength of the Sn-40Pb solder joint. After thermal aging at 50 and 100 °C, the strength did not show significant degradation for up to 500 h. The values remained between 17 and 19 MPa and 19 and 20 MPa for 50 and 100 °C, respectively.

The solder joint strength began to degrade significantly when aging was performed at 150 °C. After 100 h of ageing, the shear strength increased to 19.5 MPa. Further aging for 250 and 500 h, shear strength reduces to 15.5 and 12.3 MPa, respectively. This degradation in shear strength may be due to morphological changes in the Cu_6Sn_5 intermetallic from the scallop-type to the planar-type. Furthermore, the thick Cu_3Sn intermetallic phase may have contributed to the degradation. The formation of these intermetallics increases the Sn-depletion zone near the interface, which may degrade the solder joint strength.

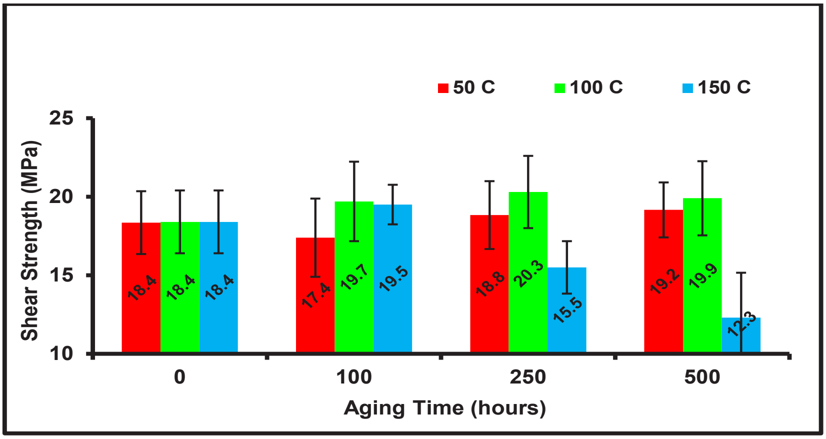

Figure 5: The effect of aging time on the shear strength of Sn-40Pb solder joint with Cu.

Shear strength reduction is caused primarily by the growth of interfacial layers and the formation of new intermetallics at longer aging times. The maximum joint strength generally occurs when the intermetallic layer thickness is the smallest. For Sn-40Pb/Cu, the joint degradation in shear strength is mainly due to the increasing roughness of the solder/Cu_6Sn_5 interface and the stress concentration at the reaction layer.

Fracture Path in Sn-40Pb/Cu Solder Joint

Figure 6 shows the cross section of the fracture plane at different aging temperatures and times. A fracture path was observed between the Cu_6Sn_5 intermetallic and the bulk solder, regardless of the solder layer thickness or aging conditions.

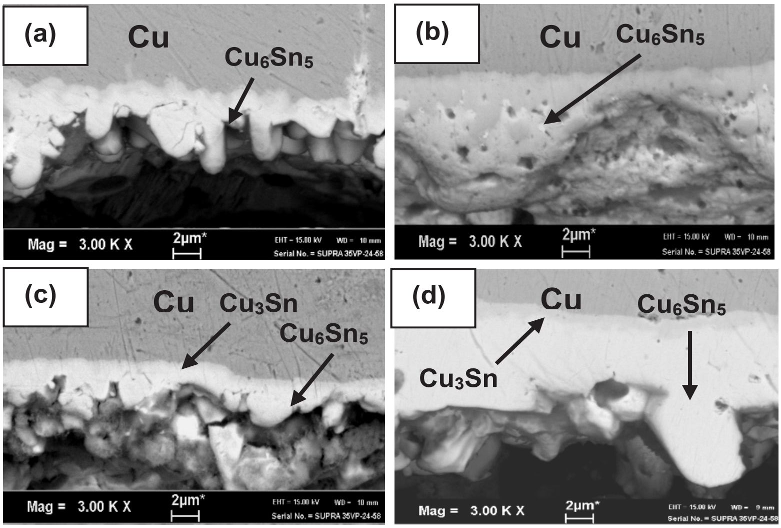

Figure 6: FEVPSEM backscattered image of Sn-40Pb/Cu solder joint break: (a) at room temperature, (b) aged at 50°C for 500 h, (c) aged at 100°C for 500 h and (d) aged at 150°C for 500 h.

The fracture propagated along the intermetallic/solder interface under all soldering conditions. A study by Lee and Chen [36] on Sn-40Pb/Cu joints observed a different type of fracture mode under tensile loading. They reported that solder joints stored at high temperatures for a short duration cracked at the intermetallic-solder interface. As the ageing time of the solder joint increased, a fracture path occurred at the Cu/intermetallic interface (150 °C, 626 h). This change can be attributed to the large number of copper atoms diffusing into the intermetallic, resulting in many fine and closed Kirkendall voids forming in the Cu near the intermetallic, making the Cu locally weaker. They concluded that Kirkendall voids formed by the diffusion of Cu atoms were the main reason for decrease in adhesive strength after long-term storage. Kirkendall voids were not observed in this study because the ageing duration was limited to 500 h.

Fracture Surface Morphology of the Solder Joint

Figure 7 shows the fracture surfaces off the Sn-40Pb/Cu solder joints before and after aging. The SEM fracture surface for as-soldered joint is shown in Figure 7(a). the surface exhibits many typical cups. These cups show evidence of a large amount of plastic deformation along the loading direction and means that the ductile fracture occurred as the shear load was applied to the reflowed solder joint. The plastic deformation on the shear fracture surface for the as-soldered solder joint in Figure 7(a) indicates that the shear fracture in the as-soldered solder joint can occur through Sn-40Pb solder by micro-void diffusion. Before aging, many large cups were observed, and as aging progressed, the cup became smaller, indicating a reduction in the ductile mode. This explains the reduction in tensile strength as aging progresses.

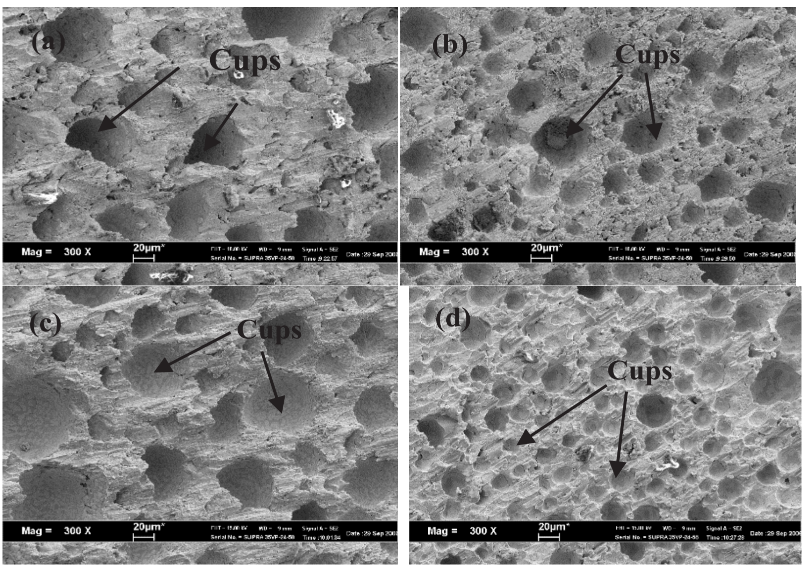

Figure 7: Fracture surface (a) Room temperature (b) 50 °C after 100 h (c) 100 °C after 100 h (d) 150 °C after 500 h.

CONCLUSION

The morphology and joint strength of Cu and Sn-40Pb solder interfaces during solid-state aging were investigated. The intermetallic layer formed consist of' Cu_6Sn_5, which forms adjacent to the bulk solder. At a later stage of aging, Cu_3Sn began to form an interface with the Cu substrate. Cu_6Sn_5 developed with a scalloped morphology, whereas Cu_3Sn grew as an undulating planar layer in phase with Cu_6Sn_5. The Cu_6Sn_5 layer transforms from a scalloped to a planar morphology as aging progresses owing to the minimization of the interfacial energy. The solder joint strength significantly degraded during the later stage of aging and at higher aging temperatures. This is because of the excessive growth of intermetallic compounds. Solder joint break-down occurs at the intermetallic/solder interface for all aging conditions. The fracture surface indicates a ductile failure mode at the stages of aging (bigger cups) and a brittle mode at the later stage of aging (smaller cups).

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