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Characterization of Transient Liquid-Phase Bonded Joints in a Copper-Beryllium Alloy with Silver-base Interlayer

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Transient liquid-phase diffusion bonding was employed to join copper-beryllium alloy using three silver-base interlayers. The bonding process was carried out at different temperatures under argon and vacuum atmospheres for various hold times. Interfacial microstructures were examined by scanning electron microscopy. Microhardness, tensile, and fatigue tests were used for evaluating the mechanical properties. Maximum tensile strength of 156.45 MPa was obtained for bonds processed at 780 °C. Fatigue strength of bonds fabricated in vacuum was higher than those of bonds prepared in argon atmosphere. The diffusion of the main elements from the interlayers into the base metal was the main controlling factor pertaining to the microstructural evolution of the joint interface.

Keywords copper-beryllium alloy, microstructure, transient liquid-phase diffusion bonding

1. Introduction

Copper-beryllium alloys are preferred in critical applications ranging from miniature electronic connectors to aircraft bushings to oil field drill tooling applications, as well as plastic and die cast mold tooling and non-sparking hand tools (Ref 1). Among the various types of copper-beryllium alloys, precipitation-hardening copper-beryllium alloy (C17200) is widely used in different springs because of its low elastic module and high strength. The alloy usually contains a third element (cobalt or nickel) to produce solid solution and dispersion beryllide particles in the matrix (Ref 2). In general, applied procedures for joining of the copper-beryllium alloy are limited for some reasons such as high conductivity and severe oxidation damage at high temperatures (Ref 3). In addition, the precipitation-hardened material suffers from coarsening, and thereby from loss of strength through high temperature joining processes. This loss of properties can result in premature failure in service both within and outside of the weld. The purpose of this article, therefore, is to develop a joining process for the copper-beryllium alloy that will reduce the effect of this softening. Many of the problems of welded joints for the alloy can be overcome by transient liquid-phase diffusion bonding (Ref 4-6). For a given operating temperature, the joining method relies on the time required to complete the isothermal solidification to prevent the formation of brittle phases (Ref 7). Therefore, transient liquid-phase diffusion bonding method was used to join copper-beryllium alloy with different Ag-base interlayers. Microstructural and compositional changes were characterized and hardness was measured in different bond regions. The analysis was coupled with the strength and fatigue measurements of the specimens.

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2. Experimental Procedures

Transient liquid-phase diffusion bonds were made between two similar copper-beryllium alloys (C17200) using three Ag-base filler metals. The thickness of the interlayers was 100 μm. The nominal composition of the base metal and the interlayers are shown in Tables 1 and 2, respectively. Surface cleaning was performed by removing surface oxides, oils and greases in an acetone solution. The bonding operation and heat treating of the specimens were carried out in argon and vacuum atmospheres according to Fig. 1. A range of optimum temperatures, 720 and 780 °C, was set as diffusion temperatures for different holding times. The heating and cooling rates were 20 °C/min and 30 °C/min, respectively. The uniaxial compression load of 0.5 MPa was applied along the longitudinal direction of the specimens. The microstructure of the bond area was examined using scanning electron microscope (Cam Scan 2300MV). Microhardness measurements at the interface of the base metal and filler alloys were carried out with Vickers hardness scale. Tensile and fatigue tests were accomplished according to ASTM D1002-72 at a strain rate of 3.28×10^{-4} s^{-1} (Ref 8).

3. Results and Discussion

The effect of the interlayer composition on the rate of isothermal solidification is studied by SEM micrographs shown in Fig. 2. The SEM micrographs revealed that the eutectic constituents were bordered on two sides adjacent to the copper alloy by isothermally solidified regions as the amount of Ag,

Cu, and Sn increased in the interlayer. Considering the phases, the average eutectic width was measured using SEM and plotted against the bonding time for each bonding temperature, as shown in Fig. 3. It is seen that the isothermal solidification rate enhanced as the bonding temperature increased from 720 to 780 °C. The increase in diffusivity of the alloying elements at the bonding temperatures is attributed to increase in solid-state diffusion rate of Ag, Sn, Zn, and Cd, since this is the rate-controlling factor during the isothermal solidification process. An incomplete isothermal solidification of the liquid interlayer occurred in the specimen bonded at the lower temperature. This resulted in the formation of continuously distributed eutectic constituents of Ag- and Cu-rich phases in the joints. In contrast to the situation at 780 °C, using Ag-base interlayer with higher amount of Ag resulted in a semi-complete isothermal solidification. However, an increase in the bonding temperature resulted in the formation of bigger eutectic constituents and solid solution in the bonds. The matrix present at the interface of the bonds are mostly Cu-rich solid solution containing Ag and Sn in BVAg-18a and Ag, Zn, and Cd in both BAg-1 and BAg-1a resulting from the dissolution of the base metal and the interdiffusion of the alloying elements. A typical microstructure of the bonded area of the base metal using BVAg-18 interlayer

Table 1 Chemical composition of the copper-beryllium alloy

	Chemical composition, wt.%				
Alloy	**Cu**	**Be**	**Ni**	**Co**	**Pb**
C17200	Bal.	1.92	0.50	0.10	0.10

Table 2 Chemical composition of the interlayers

	Chemical composition, wt.%				
Interlayer	**Ag**	**Cu**	**Zn**	**Cd**	**Sn**
BVAg-18	54	32	…	…	14
BAg-1	44.5	15	16	24.5	…
BAg-1a	51.562	15	16	17.438	…

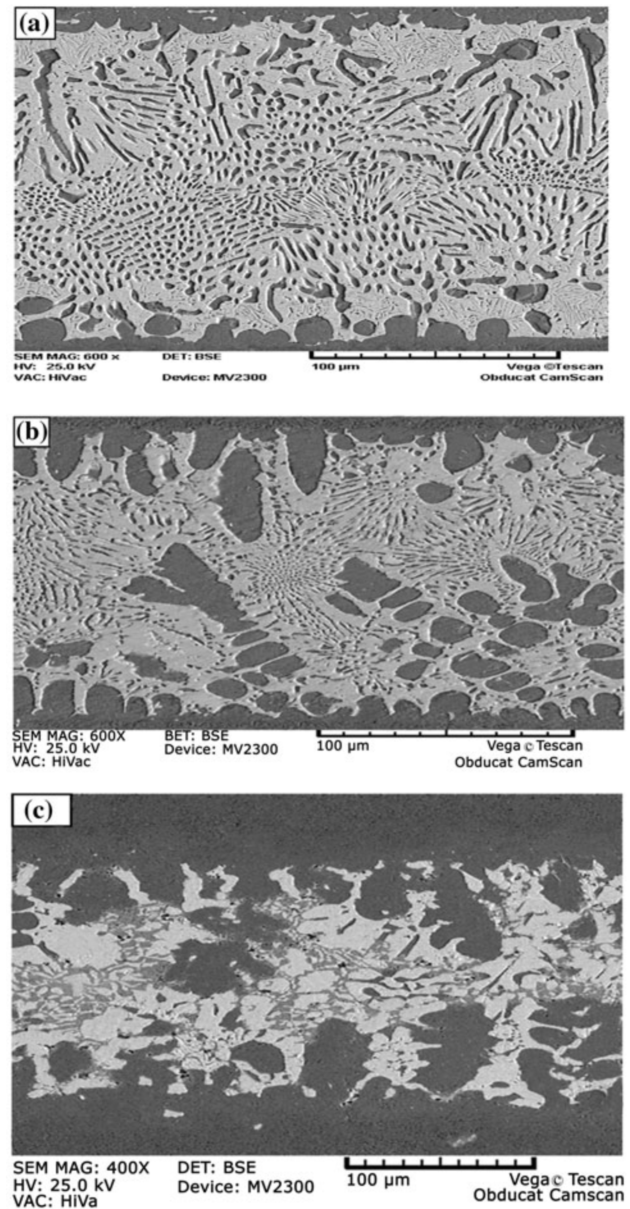


Fig. 2 SEM microstructure of the copper-beryllium alloy bonded at 780 °C for 20 min using (a) BAg-1a, (b) BAg-1, and (c) BVAg-18

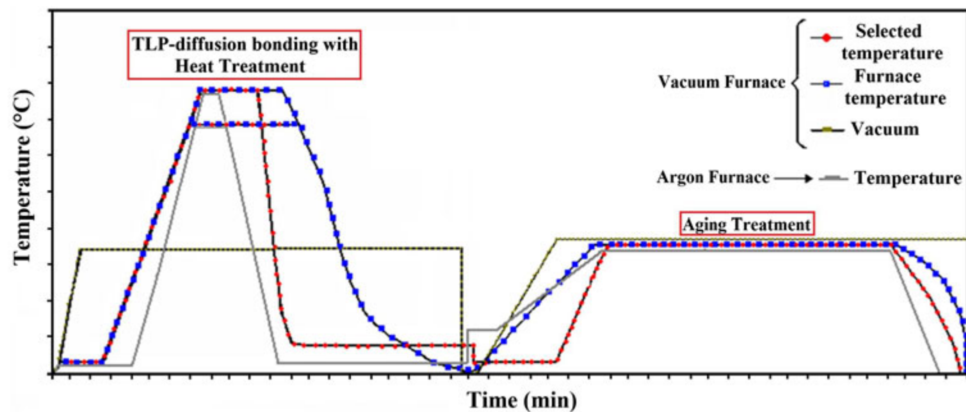


Fig. 1 Cycle of transient liquid-phase diffusion bonding of the copper-beryllium alloy

showed that it consists of three distinct microstructural zones, before completion of isothermal solidification (Fig. 4). One of them is athermally solidified zone (ASZ), which consists of eutectic microconstituents. This area is formed because of insufficient time for isothermal solidification completion. The second area is isothermally solidified zone (ISZ), which consists of a solid-solution phase occurred by interdiffusion between the substrate and the interlayer during holding at the bonding temperature. The third area is diffusion-affected zone (DAZ), which consists of precipitates due to Ag-base interlayer elements diffusion into the base metal (BM) during the bonding operation.

The optimum hardness was achieved for the specimens bonded with BVAg-18 in vacuum of 2.0 Pa (Fig. 5). Lower hardness of the ASZ nearby the isothermal solidification zone associated with the absence of intermetallics and the presence of Ag-rich solid solution resulting from the dissolution and interdiffusion of the main elements. The higher hardness of the joints can be attributed to the higher soaking of the alloying elements, e.g., Ag and Sn in the bond interface. It is important to note that voids and porosities were observed in bonds fabricated in argon atmosphere (see Fig. 6). The voids were formed because of oxidation of the base metal and interlayer with argon impurities during the bonding process. In the present study, diffusion of Ag and Sn which have high diffusivity compared to substitutional solutes is believed to be an isothermal solidification rate controlling factor during the bonding operation. Thus an increase in the diffusivity of the elements with an increase in the bonding temperature results in a reduction in the isothermal solidification time. Diffusivity of Ag, Cd, and Sn into Cu follows an Arrhenius behavior and thus will occur in shorter time at the higher temperature. In addition to considering the diffusivity in the bulk copper, one must also consider diffusivity at the solid-liquid interface and any partitioning that will occur with precipitation of solid second phases. At the higher bonding temperature as the bonding time increased, the interlayer thickness significantly decreased (see Table 3). As it is seen, increasing the bonding time from 2 to 20 min has a considerable effect on the interlayer thickness. This can be attributed to the distribution of Ag, Cd, Zn, and Sn in the faying surface of the alloy and the diffusion zone with regards to the type of interlayer. In this case, dissolution stage occurred at the preliminary steps of the bonding because the solute concentrations at the interface vary with the bonding time and the bonding temperature. The dissolution process was hindered by intermetallic phases, which might form between the low melting constituent and the primary solid solution. In two of the filler metal systems, transient liquid-phase diffusion bonding involves more than the dissolution of the base metal and its isothermal solidification that accompanies diffusion of the solute. For example, BAg-1a filler alloy contains solid solutions of (Cu, Ag, and Zn), (Ag, Cu, and Zn) and β″ phases (intermetallic compounds) (Ref 9, 10). In this regard, quantitative investigation on the presence of intermetallics and modeling of the process for the special alloy will be presented elsewhere.

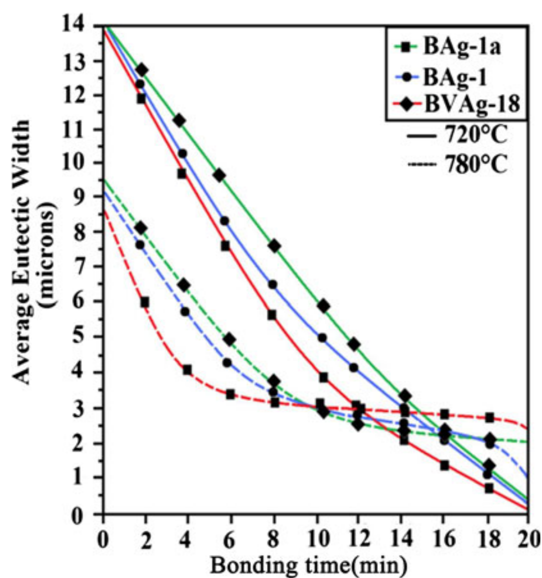


Fig. 3 Variation in average eutectic width, bonding time, and bonding temperature

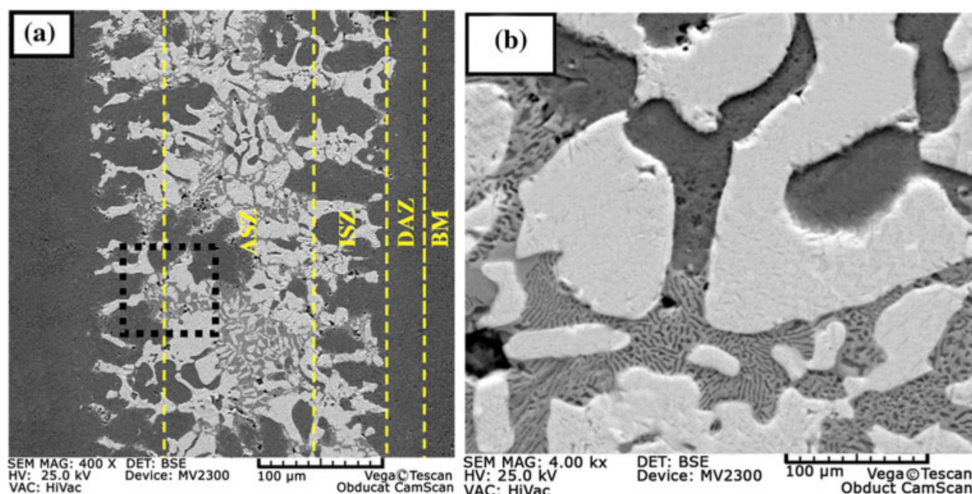


Fig. 4 SEM microstructure, high magnification of the bond region, and x-ray energy dispersive analysis of the specimens prepared at 780 °C for 20 min in vacuum using BVAg-18

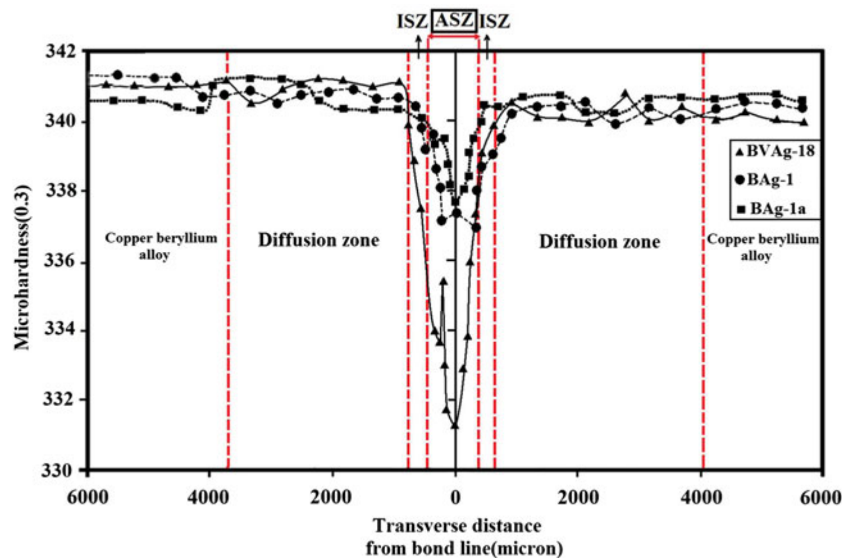


Fig. 5 Microhardness profiles as a function of distance from the centreline for bonds prepared at 780 °C in vacuum

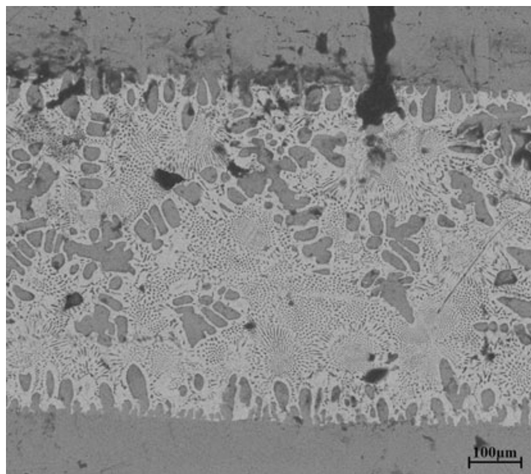


Fig. 6 The presence of voids at the interface of bonds fabricated in argon atmosphere

Tensile test results showed that weakest tensile strength of the bonds occurred for the specimens prepared in argon atmosphere. For this case, voids within the bond region were responsible in weakening of the joint area. Figure 7 shows the relationship between tensile strength of the joints and diffusion bonding atmosphere. Note that transient liquid-phase diffusion bonding at 780 °C for 20 min under argon atmosphere, followed by aging at 350 °C for 3 h results a significant drop in tensile strength to 151.3 MPa. This suggests that the bonding atmosphere can lead to a decrease in strength of the parent metal. A comparison of tensile strengths of the specimens bonded in various times is shown in Fig. 8. It is obvious that the bond strengths of the alloy are quite different at the bonding temperatures, ranged from 117.5 to 156.45 MPa. Because the compositions at the interface are within the respective solubility limits, the increase in the strength of the specimen is due to the solid solution strengthening at the bonding interfaces. It is also clear that the deformation during transient liquid-phase diffusion bonding increases from 1.87 to 11.08% with increase in temperature from 720 to 780 °C. In all specimens, failure was

Table 3 Thickness of the interlayers for bonds fabricated at 780 °C in different times

	Interlayer thickness, μm		
Bonding time, min	**BAg-1a**	**BAg-1**	**BVAg-18**
2	85 ± 0.1	81 ± 0.2	78 ± 0.1
10	80 ± 0.4	73 ± 0.35	73 ± 0.3
15	68 ± 0.25	59 ± 0.1	54 ± 0.15
20	57 ± 0.25	52 ± 0.15	41 ± 0.35

observed outside the bond interface close to the diffusion zone indicating that the DAZ was the weakest within the joint. The plot about the strength also shows that strength of the specimens strongly depended on the bonding temperature. In the copper-beryllium alloy, however, a critical bonding temperature was expected due to interplay between increase in diffusivity of the interlayer elements and increase in maximum widening of the liquid.

The optimum fatigue strength was achieved for bonds prepared at 780 °C for 20 min in vacuum using BVAg-18 filler metal. The test results for two atmospheres are shown in Fig. 9. The majority of specimens failed from surface sites remote from the bond line. The initiation sites were typically displaced from the bond line by approximately 0.8 mm or greater and almost equally divided between the parent material. It was seen that fatigue life of the alloy bonded in argon is lower than that of joined in vacuum. The fatigue test results also showed that when specimens were under low stress, fracture occurred on the corner of the joints. However, fatigue failures in the low-cycle and high-cycle regimes were often dominated by the crack initiation processes, which were strongly influenced by the salient features and bonding end products in the microstructure. In addition, both brittle and ductile fractures appeared in the bonds (see Fig. 10). In the fracture surface, the conventional ductile fracture process generated the regions with dimples, whereas the faceted regions were generated by an intergranular fracture mechanism. Initial cracks produced in the fine phase and expanded to other areas of the bond.

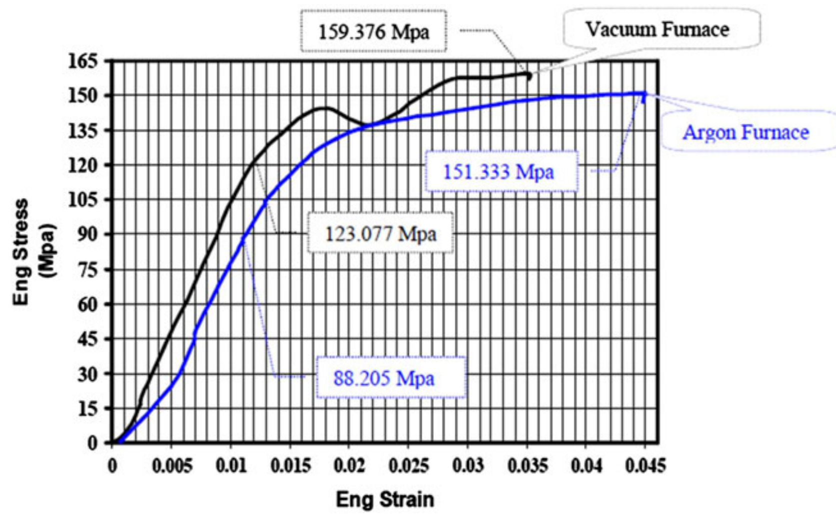


Fig. 7 Effect of bonding atmosphere on tensile strength of bonds fabricated at 780 °C for 20 min

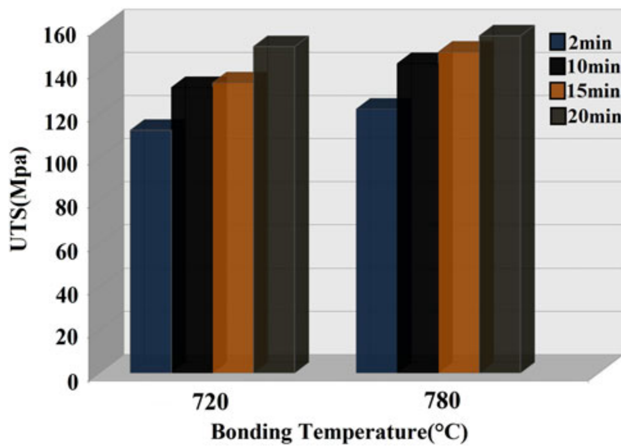


Fig. 8 Effect of bonding time on tensile strength of specimens prepared at 720 and 780 °C

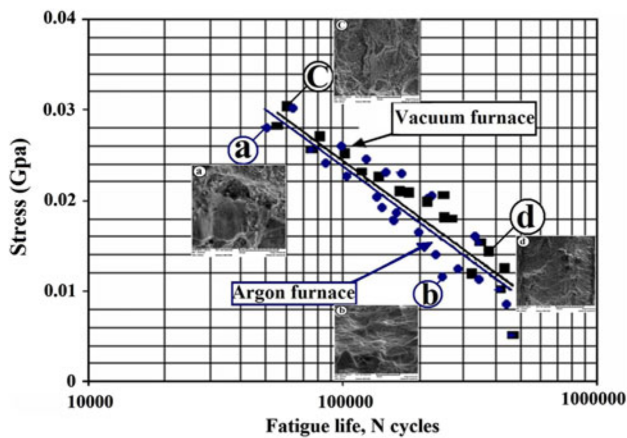
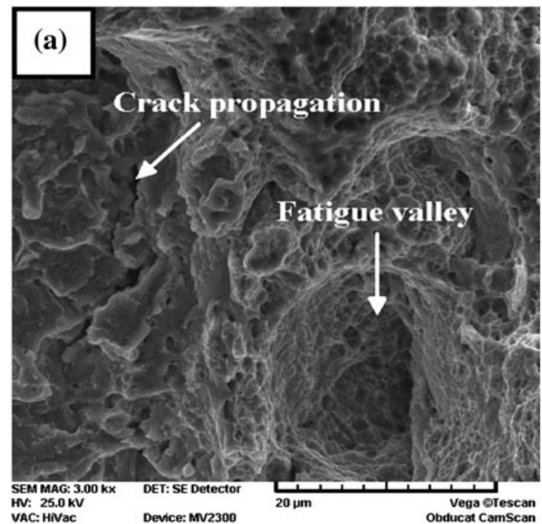


Fig. 9 *S-N* curves of bonds prepared at 780 °C for 20 min in vacuum and argon atmospheres



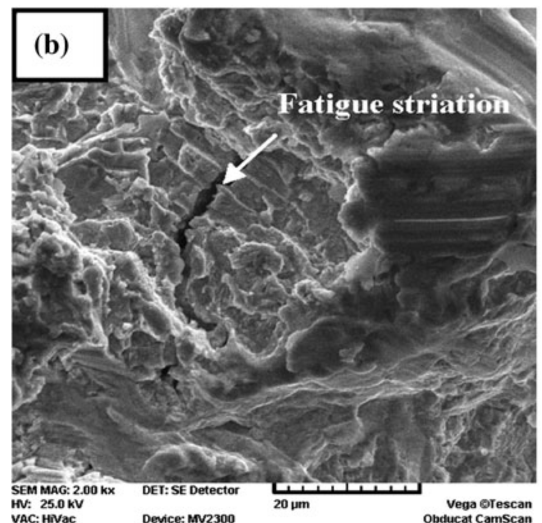


Fig. 10 Micrograph of fracture surface for bonds fabricated at 780 °C for 20 min. (a) Ductile fracture, and (b) brittle fracture

4. Conclusions

In this study, microstructural evolution of a copper-beryllium alloy was investigated when using different Ag-base interlayers and optimum bonding parameters are presented. The important findings are as follows:

(1) The microstructural studies revealed that the cross section of the interlayer decreased with increasing temperature and diffusion time. Optimum hardness was achieved in both argon and vacuum at the higher bonding temperature.
(2) There was a critical bonding temperature to minimize the required time for isothermal solidification. Decreasing of isothermal solidification rate at bonding temperature of 780 °C can be attributed to enrichment of residual liquid with some filler metal alloying elements, particularly, Sn and Cd, during dissolution and isothermal solidification.
(3) Fatigue life of bonds prepared at 780 °C for 20 min in vacuum was more than that of bonds fabricated in argon atmosphere. In both low and high stresses, brittle and ductile fracture occurred. Fractography of the specimens showed that majority of cracks in the interface were intergranular.

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