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Laser brazing molybdenum using two titanium base fillers

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Abstract. Brazing Mo using Ti and Ti-15-3 foils has been investigated in the experiment. For traditional furnace brazing, solidification shrinkage voids cannot be completely removed from the joint even the brazing temperature increased to 2013 K and 160 μm thick Ti foil applied in brazing. Similar results are observed from the joint using Ti-15-3 filler. In contrast, the quality of laser brazed joint is much better than that of furnace brazed joint. A sound joint is achieved after laser brazing. Tensile strengths of 418 and 373 MPa are obtained from laser brazed joints at the power of 800 W and travel speed of 5 mm/s using Ti and Ti-15-3 fillers, respectively. All laser brazed joints are fractured at the brazed zone and cleavage dominated fractures are widely observed from their fractographs. The Ti base fillers show potential in laser brazing Mo substrate.

Keywords: laser brazing; molybdenum; titanium base fillers; microstructure

1. Introduction

Molybdenum (Mo) has the high melting point of 2890 K, and the ability of Mo to withstand high-temperatures without softening makes it useful in applications that involve intense heat (Smith 1990, Davis 1990). For example, the Mo shield is used in impregnated dispenser cathode applied for high-power microwave vacuum electronic device. The high-power impregnated dispenser cathodes was made by infiltration of barium calcium aluminate (BCA) into the porous *W* matrix, and it was shielded by using a miniature Mo tube, which was brazed to the Mo support (Bao 2007, Lin *et al.* 2011, Lin *et al.* 2012).

YAG (Yttrium-Aluminum Garnate) laser is featured high energy density and low heat input, so the distortion of workpiece is minimized after joining (Vancil *et al.* 2005). Traditional YAG laser is difficult to weld Mo due to high melting point of Mo. Laser brazing provides an alternative approach to join Mo using the filler metal with lower melting point. However, selection of filler metal in brazing the miniature tube and Mo support is important (Hiraoka *et al.* 1996, Singh *et al.* 2009, Liu *et al.* 2010). There are many fillers are applied in brazing Mo such as Ag, Cu, Pd, Ti etc (Hiraoka *et al.* 1992, Humpston *et al.* 1993, Lin *et al.* 2012, Schwartz 1995, Zang *et al.* 2009). Key

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issues in selecting brazing filler metal(s) include high-temperature resistance and low vapor pressure of the braze alloy. The BCA impregnated dispenser cathode is heated to 1323 K in operation, so the filler metal must be strong enough to resist temperature up to 1323 K without vaporization. Melting point of Ti is 1943 K, and the β-Ti is completely soluble with Mo (Massalski 1990). Therefore, Ti filler is a potential candidate in brazing Mo (Olsen 1990). The purpose of this research is focused on laser brazing Mo using two Ti-based filler metals, Ti and Ti-15-3. Traditional furnace brazing Mo using Ti and Ti-15-3 foils is also included for comparison's purpose. Microstructures and selected bonding strengths of brazed joints are evaluated in the experiment.

2. Experimental procedure

Mo plates were machined with the dimension of 10 mm × 10 mm × 1.5 mm. All joined surfaces were ground by SiC papers up to grit 1000 and then ultrasonically cleaned by acetone prior to brazing. Ti and Ti-15-3 foils were chosen as braze alloys. Thickness of Ti and Ti-15-3 (Ti-15V-3Cr-3Al-3Sn, in *wt*%) foils was 400 μm. Yb-YAG laser with wavelength of 1030 nm made by Trumpf, Germany and its maximum power of 1000 W was applied in the experiment. Laser brazing was carried out in air with the Ar flow protection. A high-tempertaure furnace with the *W* mesh heating elements was used in the experiment for comparison's purpose. Dead load of 290 g was applied during furnace brazing. The heating rate of furnace was kept at 0.1 K/s under Ar protective atmosphere. Furnace brazing conditions of two filler foils were summarized in Table 1.

Cross-sections of brazed joints were cut by a low-speed diamond saw and subsequently examined by using an electron probe microanalyzer (EPMA) equipped with the wavelength dispersive spectroscope (WDS). The operation voltage was kept at 15 kV, and the minimum spot size was

Table 1 Summary of furnace brazing conditions used in the experiment

Filler metal	Brazing temperature	Brazing time	Thickness of filler
Ti	1953, 1983, 2013 K	600 s	40, 80, 120, 160 μm
Ti-15-3	1873, 1903 K	600 s	400 μm

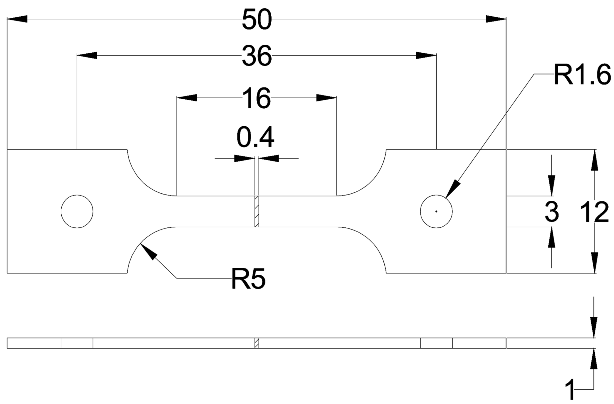

Fig. 1 Schematic diagram of tensile test specimen with the dimension of millimetre (mm)

1 μm. Tensile tests of laser brazed specimens were performed according to ASTM E8 specification, and the schematic diagram of tensile test specimen was illustrated in Fig. 1. Failure analyses of fractured surfaces were conducted using the scanning electron microscope (SEM) secondary electron image (SEI).

3. Results and discussion

Fig. 2 shows EPMA BEIs and WDS analysis results of traditional furnace brazed joints using Ti and Ti-15-3 fillers, respectively. According to Fig. 2(a), the Ti filler cannot braze Mo substrate well

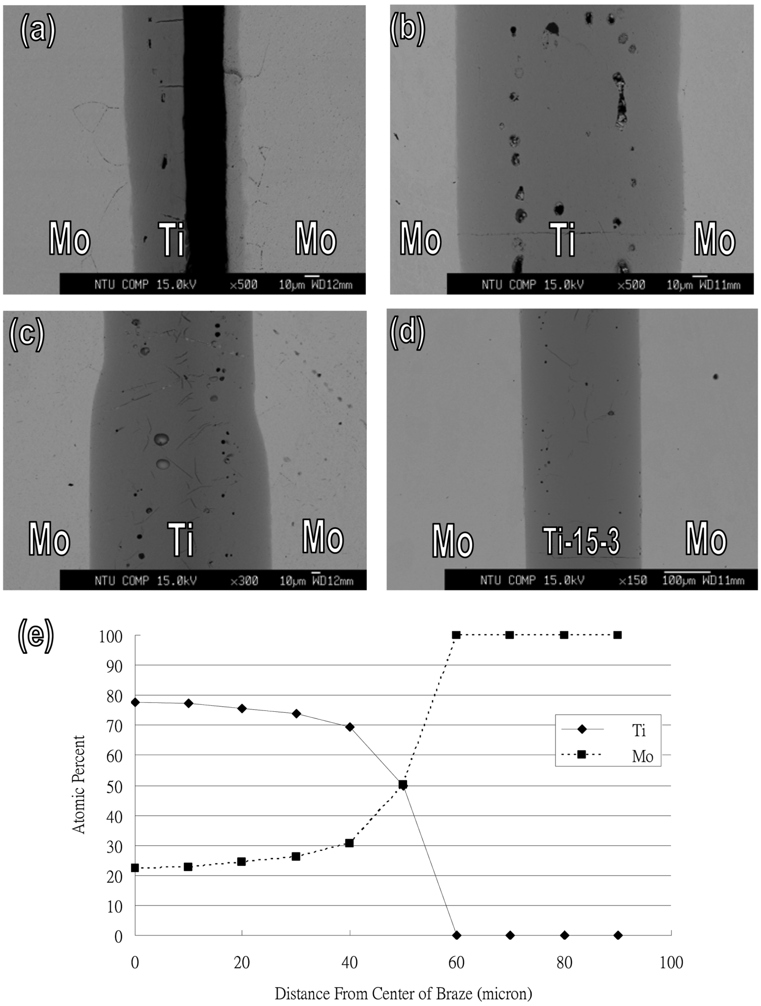

Fig. 2 EPMA BEIs and WDS analysis results of (a) Mo/Ti (40 μm)/Mo joint brazed at 1953 K for 600 s, (b) Mo/Ti (120 μm)/Mo joint brazed at 1983 K for 600 s, (c) Mo/Ti (160 μm)/Mo joint brazed at 2013 K for 600 s, (d) Mo/Ti-15-3 (400 μm)/Mo joint brazed at 1903 K for 600 s and (e) WDS analyses across the joint of (b)

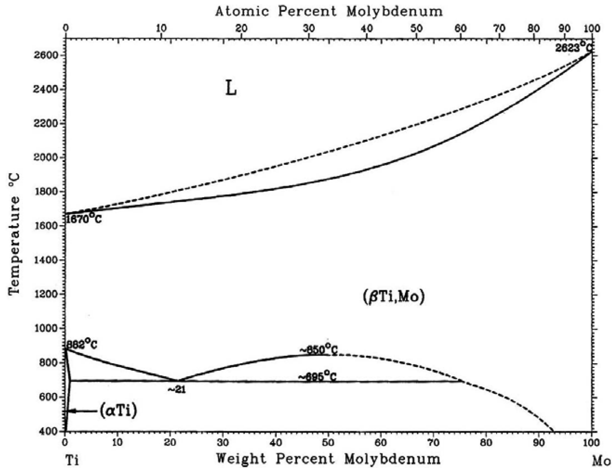

Fig. 3 Mo-Ti binary alloy phase diagram (Massalski 1990)

at 1953 K, which is higher than the melting point of Ti, 1943 K (Massalski 1990). The joint is separated into two pieces after brazing. Increasing the brazing temperature and thickness of Ti filler metal improve the quality of brazed joints as illustrated in Figs. 2(b) and 2(c). However, solidification shrinkage voids cannot be completely removed from the joint even the brazing temperature increased to 2013 K and 160 μm thick Ti filler applied in brazing. Similar to Ti brazed joint, solidification shrinkage voids are observed from the joint using Ti-15-3 filler even with thickness of 400 μm as displayed in Fig. 2(d).

According to Mo-Ti binary alloy phase diagram shown in Fig. 3, the β-Ti is completely soluble with Mo. (Massalski 1990) The Mo substrate is readily dissolved into the Ti-rich melt during brazing, and results in increasing both solidus and liquidus temperatures of the Ti-rich melt. It is consistent with EPMA analysis results of the joint brazed at 1983 K for 600 s using a 120 μm thick Ti filler as shown in Fig. 2(e). The Ti-rich braze is alloyed with 22 at% Mo at the center of braze, and the Mo content of Ti-rich braze is increased with increasing the distance from center of the brazed. Both solidus and liquidus temperatures of the Ti-rich braze are increased due to the braze melt alloyed with the Mo content. The isothermal solidification of Ti-rich melt during brazing significantly deteriorates quality of the brazed joint (Lin *et al.* 2012). Rapidly isothermal solidification of the Ti-rich melt leads to the brazed joint containing solidification shrinkage voids. The lack of Ti-rich melt during brazing cannot be improved by either increasing the brazing temperature from 1953 K to 2013 K or increasing thickness of Ti foil from 40 μm to 160 μm. Similar result is obtained from the brazed joint using Ti-15-3 filler foil. Because furnace brazed joints using two Ti-based fillers are too weak to perform tensile tests, there is no tensile test data available from the experiment. Accordingly, furnace brazing Mo substrate using two Ti base fillers is not an appropriate approach.

Fig. 4 shows EPMA BEIs and WDS analysis results in atomic percent of laser brazed specimen using Ti foil at laser power of 800 W and travel speed of 5 mm/s. Different from the traditional furnace brazing using Ti filler, a sound joint is obtained from laser brazing. According to the WDS chemical analysis results across the joint, the Ti-rich melt is alloyed with approximately 20 at% Mo as displayed in Fig. 4. Dissolution of Mo substrate into the Ti-rich braze in laser brazing is similar

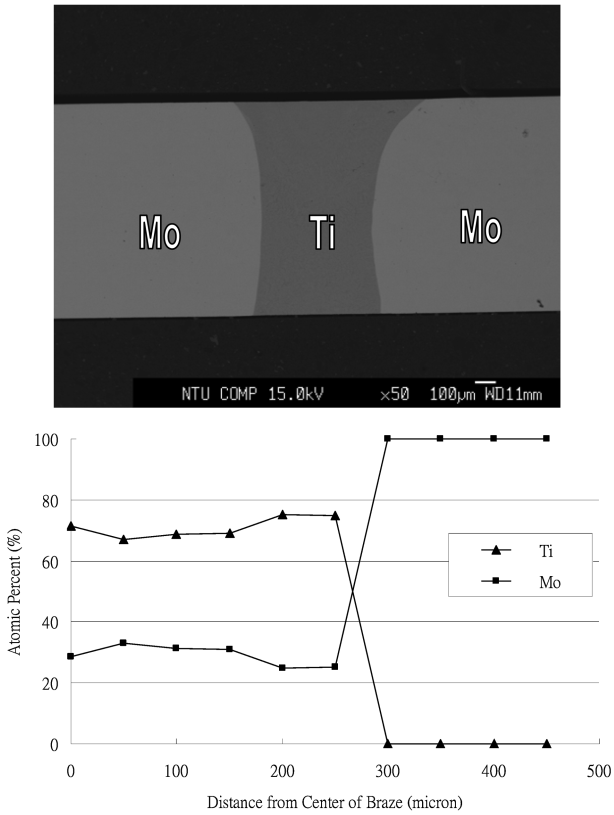

Fig. 4 EPMA BEI and WDS analysis results in atomic percent of laser brazed specimen using Ti filler foil at 800 W for 5 mm/s

to that in furnace brazing as compared between Figs. 2 and 4. Different from the furnace brazed specimen, isothermal solidification of the laser brazed joint is not observed due to presence of intensive laser beam heating the joint. Brazing temperature of laser-heated joint is much higher than liquidus temperature of the Ti-rich melt, and the Ti-rich braze melt is not solidified until termination of the laser beam irradiation. Because Mo is completely soluble with Ti, the Ti-rich melt readily wets the Mo substrate. Accordingly, a sound joint is achieved after laser brazing.

Fig. 5 shows EPMA BEIs and WDS analysis results in atomic percent of laser brazed specimen using Ti-15-3 foil with the laser power of 800 W and travel speed of 5 mm/s. Similar to the laser brazed joint using Ti foil, the quality of laser brazed joint is much better than that of furnace brazed one. Based on the WDS chemical analysis result across the joint, the Ti-rich melt is mainly alloyed with approximately 19 at% Mo and 17 at% *V* as displayed in Fig. 5. There is porosity in the brazed joint as indicated by an arrow in Fig. 5. It is resulted from vaporization of low melting point ingredient in Ti-15-3 filler during laser brazing. It is expected that bonding strength of Ti-15-3 brazed joint is deteriorated in the test.

Table 2 shows average tensile strengths of laser brazed joints using two Ti-based filler foils. Tensile strength of the Mo substrate is 627 MPa. Tensile strengths of 418 and 373 MPa are obtained from laser brazed joints with the laser power of 800 W and travel speed of 5 mm/s using Ti and Ti-15-3

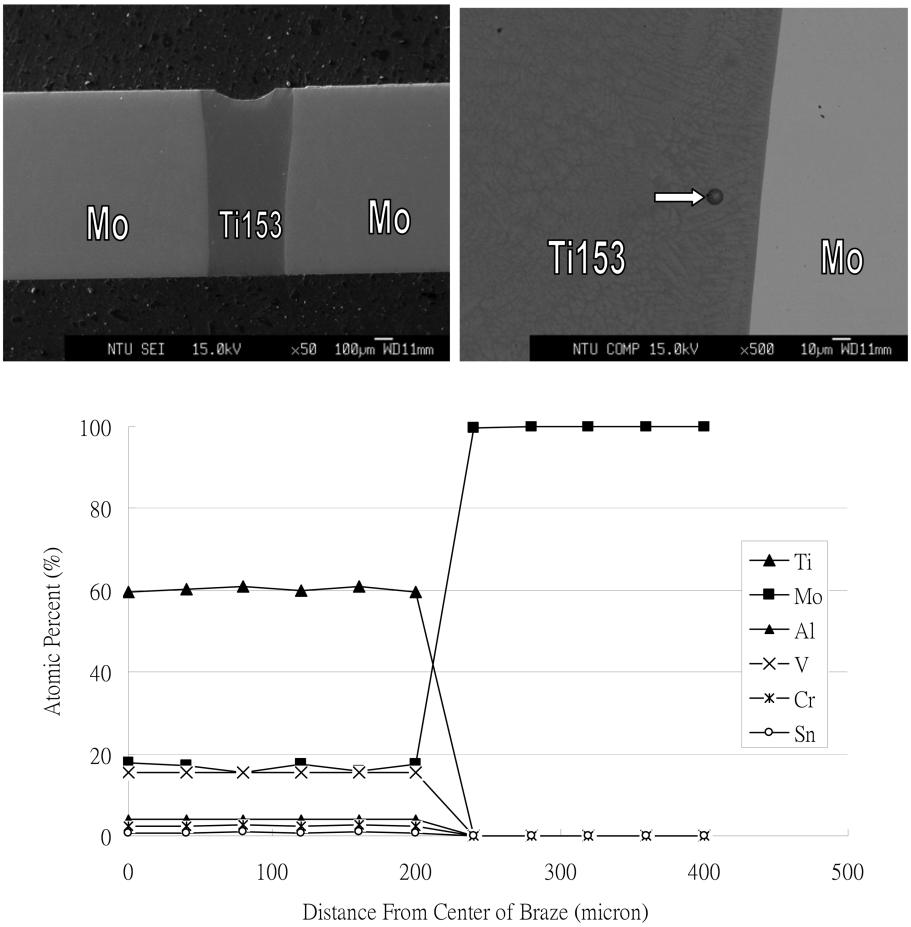

Fig. 5 EPMA BEIs and WDS analysis results in atomic percent of laser brazed specimen using Ti-15-3 filler foil at 800 W for 5 mm/s

Table 2 Average tensile strengths of laser brazed joints and Mo substrate

Tensile specimen	Laser power (W)	Travel speed (mm/s)	Average tensile strength (MPa)
Mo/Ti/Mo	800	5	418
Mo/Ti-15-3/Mo	800	5	373
Mo substrate	-	-	627

filler, respectively. Tensile strengths of laser brazed joints exceed 60% of Mo substrate. Higher average tensile strength of Ti brazed joint is observed from the experiment. It is deduced that lower tensile strength of Ti-15-3 brazed joint is resulted from the presence of porosity in the laser brazed joint.

Fig. 6 shows SEM BEI cross-sections and SEI fractographs of laser brazed joints using two Ti-based fillers after tensile tests. All laser brazed joints are fractured at the brazed zone (Figs. 6(a) and 6(c)), and cleavage dominated fractures are widely observed from their fractographs (Figs. 6(b) and

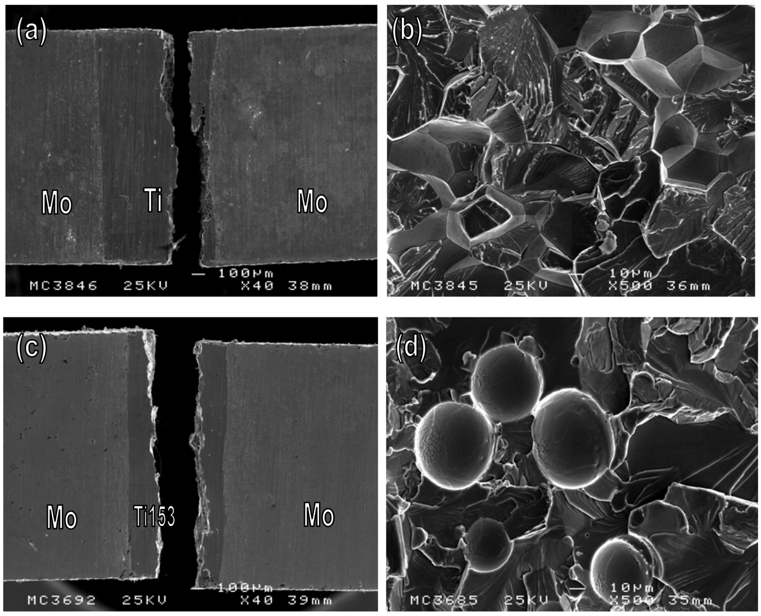

Fig. 6 SEM BEI cross-sections and SEI fractographs of laser brazed joints at 800 W and 5 mm/s after tensile tests using (a,b) Ti filler, (c,d) Ti-15-3 filler

6(d)). Porosities are observed from the fractograph using Ti-15-3 filler as illustrated in Fig. 6(d). In contrast, there is no porosity in the fractograph using Ti filler (Fig. 6(b)). Accordingly, the Ti filler is superior to Ti-15-3 filler in laser brazing Mo substrate.

4. Conclusions

Laser brazing Mo using Ti and Ti-15-3 foils has been investigated in the experiment. Traditional furnace brazing Mo using two Ti base foils is also included for comparison's purpose. Important conclusions are summarized below:

1. For the furnace brazed joint, solidification shrinkage voids cannot be completely removed from the joint even the brazing temperature increased to 2013 K and 160 μm thick Ti foil applied in brazing. Similarly, isothermal solidification shrinkage voids are observed from the joint using Ti-15-3 foil even with the thickness of 400 μm. Therefore, furnace brazing Mo substrate using two Ti base fillers is not suitable.
2. The quality of laser brazed joint is superior to that of furnace brazed one, and a sound joint is achieved after laser brazing. Tensile strengths of 418 and 373 MPa are obtained from laser brazed joints at the laser power of 800 W and travel speed of 5 mm/s using Ti and Ti-15-3 fillers, respectively. Tensile strengths of laser brazed joints exceed 60% of Mo substrate.
3. All laser brazed joints are fractured at fillers, and cleavage dominated fractures are widely observed from their fractographs. There are porosities in Ti-15-3 brazed joint due to vaporization of low melting point ingredient in Ti-15-3 filler during laser brazing. Accordingly, the Ti filler is superior to Ti-15-3 filler in laser brazing Mo substrate.

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