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Item Type	Article
Authors	Atieh, A.M.;Khan, Tahir I.
Citation	Atieh AM and Khan TI (2014) Effect of interlayer configurations on joint formation in TLP bonding of Ti-6Al-4V to Mg-AZ31. IOP Conference Series: Materials Science and Engineering. 60, conference 1.
DOI	<a href="https://doi.org/10.1088/1757-899X/60/1/012036">https://doi.org/10.1088/1757-899X/60/1/012036</a>
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Download date	2026-03-08 13:06:02
Link to Item	<a href="http://hdl.handle.net/10454/12047">http://hdl.handle.net/10454/12047</a>



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**Citation:** Atieh AM and Khan TI (2014) Effect of interlayer configurations on joint formation in TLP bonding of Ti-6Al-4V to Mg-AZ31. IOP Conference Series: Materials Science and Engineering. 60, conference 1.

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## Effect of interlayer configurations on joint formation in TLP bonding of Ti-6Al-4V to Mg-AZ31

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**Abstract.** In this research work, the transient liquid phase (TLP) bonding process was utilized to fabricate joints using thin (20 $\mu$ m) nickel and copper foils placed between two bonding surfaces to help facilitate joint formation. Two joint configurations were investigated, first, Ti-6Al-4V/CuNi/Mg-AZ31 and second, Ti-6Al-4V/NiCu/Mg-AZ31. The effect of bonding time on microstructural developments across the joint and the changes in mechanical properties were studied as a function of bonding temperature and pressure. The bonded specimens were examined by metallographic analysis, scanning electron microscopy (SEM), and X-ray diffraction (XRD). In both cases, intermetallic phase of CuMg<sub>2</sub> and Mg<sub>3</sub>AlNi<sub>2</sub> was observed inside the joint region. The results show that joint shear strengths for the Ti-6Al-4V/CuNi/Mg-AZ31 setup produce joints with shear strength of 57 MPa compared to 27MPa for joints made using the Ti-6Al-4V/NiCu/Mg-AZ31 layer arrangement.

### 1. Introduction

The Ti-6Al-4V alloy has a high specific strength, good oxidation resistance, and high elastic modulus which makes it an attractive choice for aerospace, marine, and oil and gas industries [1–3]. The magnesium alloy Mg-AZ31 is a light structural alloy, with a high specific strength, good formability, and recently has been found to be suitable for use in the automotive industry [4–6]. However, differences in the physical properties of these alloys (e.g. melting point for Ti-6Al-4V is 1650° C and 680° C for AZ31) make the joining of these dissimilar alloys a great challenge. Transient Liquid Phase Bonding (TLP) process has been used to join various advanced metals and alloys [7–10]. In previous work [11,12] three eutectic forming interlayers based on nickel, copper and aluminum were tested to enhance joint formation between Ti-6Al-4V and Mg-AZ31. It was found that the nickel foil was the most suitable eutectic former and it gave the highest bond shear strength (39 MPa) compared to the copper and aluminum foils. However, the copper foil produced a eutectic liquid at a temperature below the eutectic temperature for Ni-Mg ( $T_{E\text{ Mg-Cu}} = 485^\circ\text{C}$  and  $T_{E\text{ Mg-Ni}} = 512^\circ\text{C}$ )[13,14]. Therefore, in order to take advantage of the lower eutectic temperature of Cu and the better joint quality produced using nickel foils a combination of both foils may produce fewer hard intermetallic phases inside the joint region and give better joint shear strengths. In this study, bonds were made between Ti-6Al-4V and Mg-AZ31 using a combination of nickel and copper as eutectic forming interlayers.

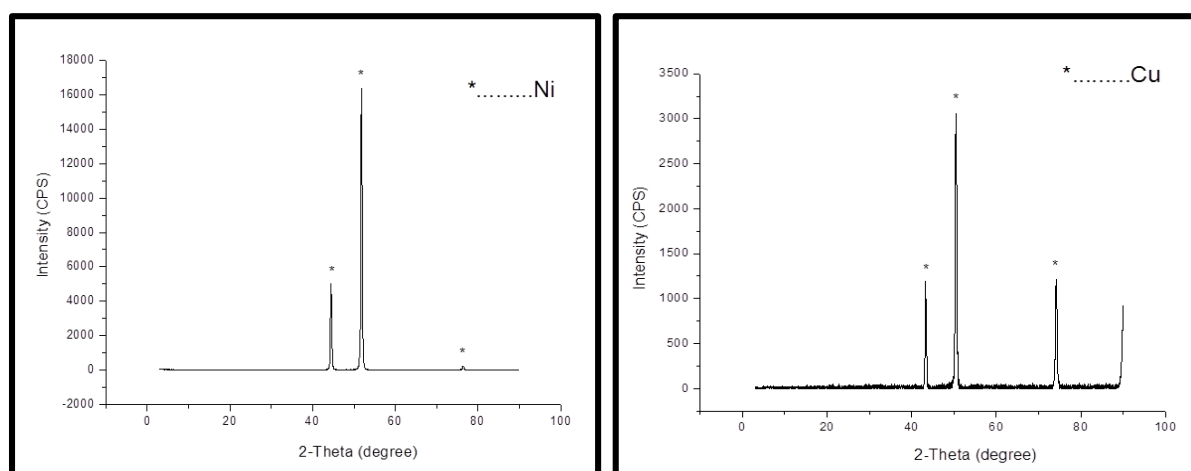


## 2. Materials and experimental work

Commercially available Ti-6Al-4V and Mg-AZ31 alloys were obtained from William Gregor Ltd (London, UK) and from Goodfellow (Cambridge, UK) respectively. The alloys were received in the form of extruded rods with 10 mm diameter; the specimens were cut to 5 mm thick sections, ground and polished down to 1000 grit surface finish followed by rinsing and cleaning in an acetone bath. The chemical composition of these alloys obtained by WDS analysis is shown in Table 1. The Ni and Cu foils are cut into a dimension of 10x10 mm square pieces. Prior to diffusion bonding, the Ti-6Al-4V samples were pickled in diluted HCl (20% HCl-80% distilled water) for 3 minutes, the Ni and Cu foils were pickled for 1 minute to remove surface oxides and degreased in acetone solution. Figure 1 shows the XRD spectrum for the as received Ni and Cu foils.

**Table 1:** Chemical composition (wt%) of Ti-6Al-4V and Mg-AZ31 using the WDS analysis.

Alloy	Al	V	Fe	Zn	Ni	Mn	Mg	Ti
<b>Ti-6Al-4V</b>	6.70	4.44	0.17	0.05	0.02	0.02	0.00	Rem.
<b>Mg-AZ31</b>	2.82	0.01	0.00	1.10	0.00	0.13	Rem.	0.00



**Figure 1.** XRD spectra for Ni and Cu foils as received.

TLP bonding was carried out in a vacuum chamber with a pressure of  $4 \times 10^{-4}$  Torr (0.053 Pa). Induction heating was used with heating rate of  $50^\circ\text{C}/\text{min}$ . A bonding pressure of 0.35 was applied to provide surface to surface contact and to hold the specimens together. For microstructural characterization the bonded samples were prepared by grinding and then polished using 0.25 micron diamond suspension. SEM micrographs were taken by JEOL JXA 8200 electron microprobe analyzer equipped with wavelength dispersive X-ray spectroscopy (WDS) and energy dispersive X-ray spectroscopy (EDS) for composition analysis. A Vickers micro-hardness test was carried out using a Shimadzu mini-load micro-hardness tester. A micro-hardness profile was established with 600  $\mu\text{m}$  on each side and 50 g of load. The shear strength measurements were carried out using a 25kN load-cell tensile testing machine (Tinius Olsen H25KS) at a cross head-speed of 0.5mm/min. X-ray diffraction

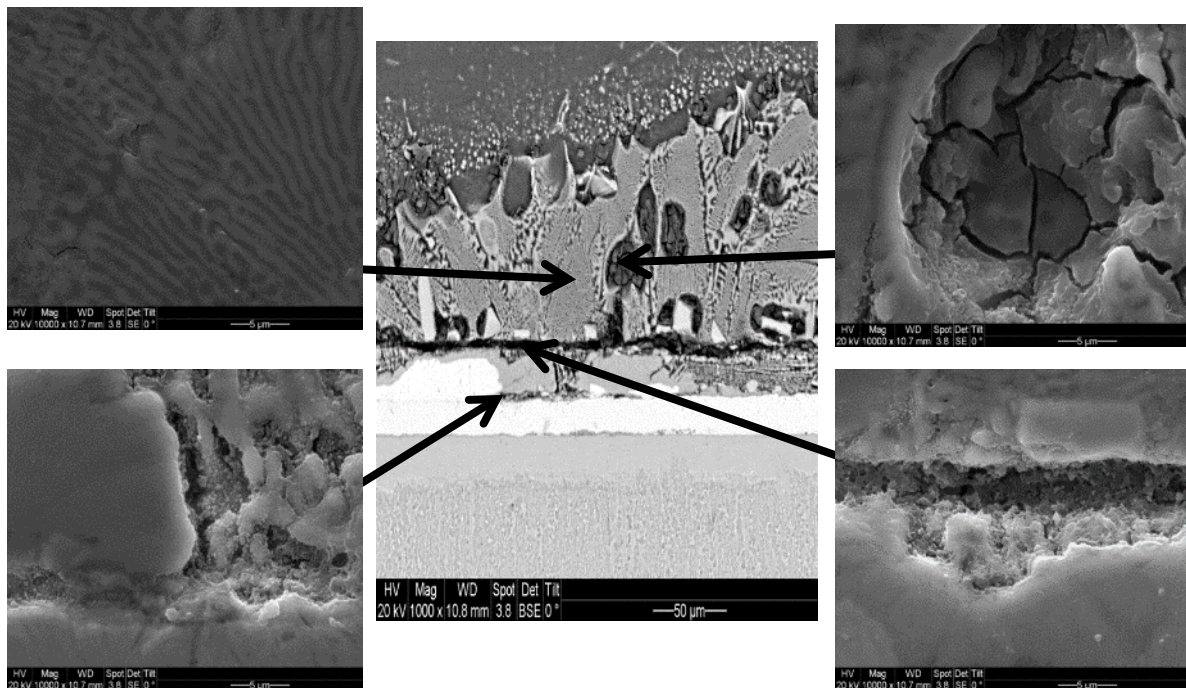
(XRD) of fractured surface was performed to study the phase composition and intermetallic compounds formed inside joint region. A Rigaku Multiflex CuK  $\alpha$  radiation source with a step size  $0.1^\circ$  and step time 5 s was used at 40 kW and 20 mA over a  $2\theta$  scanning range of  $10-90^\circ$ . Joints were made using interlayer configurations Ti-6Al-4V/CuNi/Mg-AZ31 and Ti-6Al-4V/NiCu/Mg-AZ31.

### 3. Results and discussion

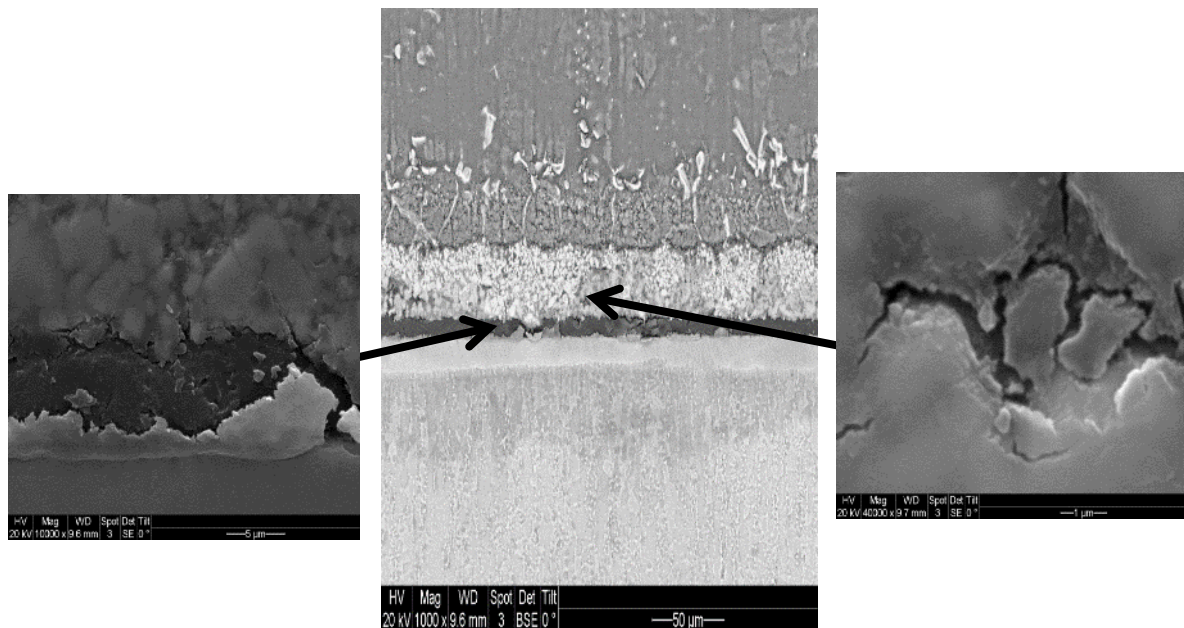
#### 3.1. Microstructural development

The SEM micrograph of joint interface for Ti-6Al-4V/NiCu/Mg-AZ31 made at  $515^\circ\text{C}$  bonding temperature, 0.35 MPa bonding pressure for 10 min bonding times is shown in figure 2. At bonding times of less than 10 minutes joints could not be made and were seen to fail between Ni and Ti-6Al-4V interface. This was attributed to the absence of eutectic liquid formation at the Ni/Ti-6Al-4V interface although evidence of liquid formation was seen between Cu and Mg. At 10 minutes bonding time, the Cu-Mg eutectic formed and reacted with the Ni interlayer, then it started to dissociate and formed a small amount of liquid.

The SEM micrograph of joint interface for Ti-6Al-4V/CuNi/Mg-AZ31 made at  $515^\circ\text{C}$  bonding temperature, 0.35 MPa bonding pressure for 20 min bonding times is shown in figure 3. At bonding times less than 20 minutes all bonds failed to join, and failure was seen at the Cu foil on both sides between Ni-Cu and Cu/Ti-6Al-4V interface. This was attributed to the short bonding time preventing the Ni eutectic liquid from wetting and reacting with the Cu foil.



**Figure 2.** BSE-SEM micrographs of Ti-6Al-4V/NiCu/Mg-AZ31 joint interface after bonding at  $515^\circ\text{C}$  and 0.35 MPa for 10 min [15].

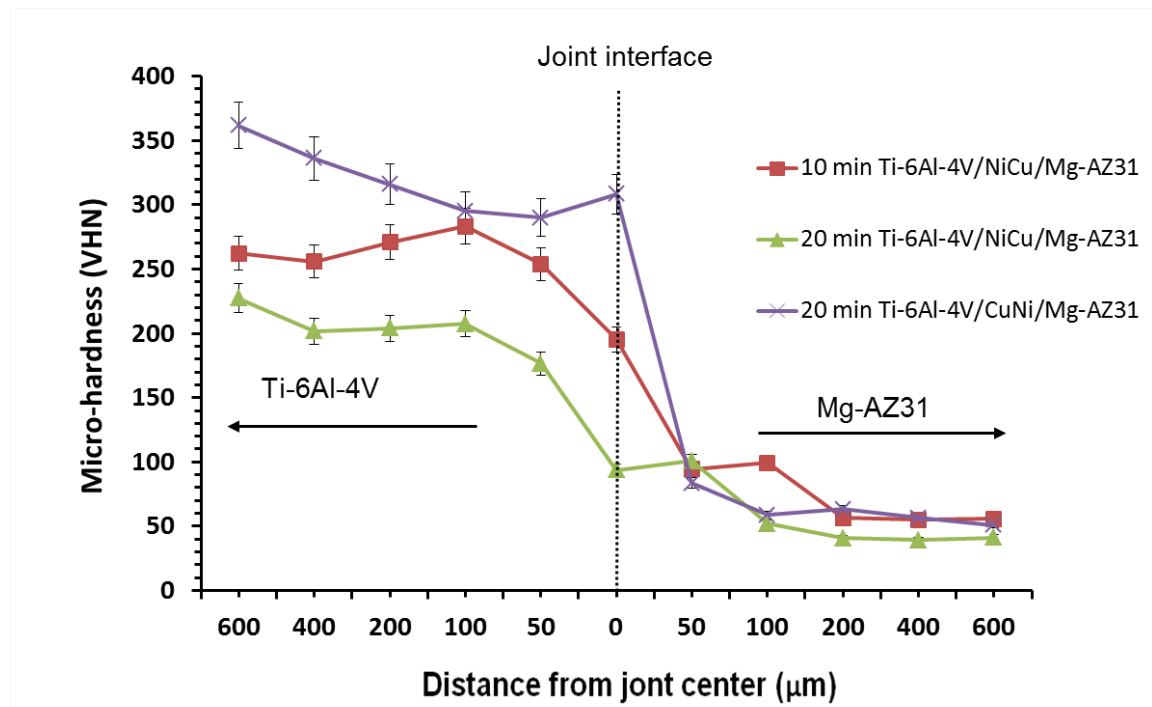


**Figure 3.** BSE-SEM micrographs of Ti-6Al-4V/CuNi/Mg-AZ31 joint interface after bonding at 515°C and 0.35 MPa for 20 min [15].

### 3.2. Mechanical properties of the joint

Micro-hardness profiles for joint interface as a function of time are shown in figure 4. This profile can give a good indication on the nature of phases and intermetallics formed inside joint region. For the Ti-6Al-4V/NiCu/Mg-AZ31 configuration, as the bonding times increased from 10 to 20 minutes, at bonding time of 10 minutes a smooth transition between the two parent alloys was noticed from 250 VHN to 60 VHN. Comparing the two interlayer configurations at the same bonding time and pressure, it was observed that the Ti-6Al-4V/CuNi/Mg-AZ31 configuration resulted in higher hardness profile on both sides of joint interface towards Ti-6Al-4V and Mg-AZ31. The maximum hardness observed was at the joint center and a value of 308 VHN was recorded. After 200 μm inside Mg-AZ31 the micro-hardness profiles for the 10 minutes Ti-6Al-4V/NiCu/Mg-AZ31 and 20 minutes Ti-6Al-4V/CuNi/Mg-AZ31 measured the same value with an average of 56 VHN.

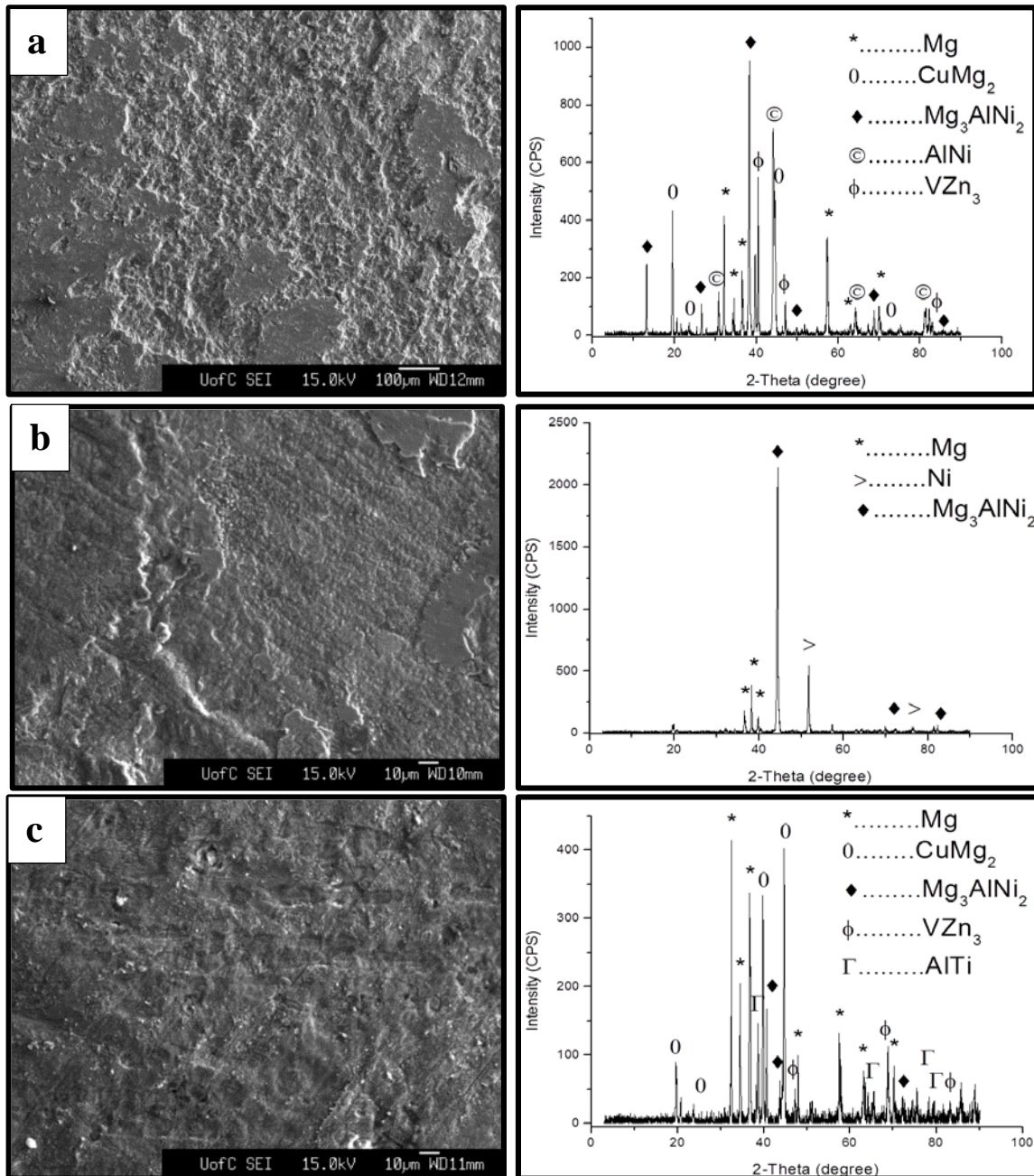
For joints produced using Ti-6Al-4V/NiCu/Mg-AZ31 setup; the bond shear strength was 27 MPa. However, increasing the bonding time to 20 minutes resulted in a decrease in shear strength to 18 MPa. This decrease in shear strength was attributed to the change in Cu-Mg eutectic concentration before complete reaction with Ni was possible. For a longer bonding time, a higher volume of Cu-Mg eutectic formed leaving less eutectic available to wet the Ni/Ti-6Al-4V interface. However, for Ti-6Al-4V/CuNi/Mg-AZ31 even the bond time less than 20 minutes failed to achieve a joint, the 20 minutes resulted in higher shear strength of 57 MPa which is twice the strength obtained for joints made using the Ti-6Al-4V/NiCu/Mg-AZ31 setup.



**Figure 4.** Micro-hardness profile for joint made at 515°C, 0.35 MPa for different bonding times.

### 3.3. Fracture surface and XRD spectra

The SEM micrograph and XRD spectra achieved from Mg-AZ31 fractured surface are shown in figures 5. The complexity of the system made difficult to identify the phases formed and the intermetallics inside joint region where 7 elements are reacting with each other to form the bonds. However, the application of XRD spectra with WDS and EDS allowed the prediction of phases formed. In the Ti-6Al-4V/NiCu/Mg-AZ31 configuration, at bonding time of 10 minutes 5 major compounds were detected on the fractured surface, only two was common with the fractured surface obtained for 20 minutes which are Mg and Mg<sub>3</sub>AlNi<sub>2</sub>. Mixed failure mode of brittle and ductile was observed. Those two observations suggested that the fracture path propagated between the reactions layers and contained both Cu and Ni. However, CuMg<sub>2</sub> was not detected at 20 minutes bonding time which suggested the decrease in Cu eutectic towards the formation of Ni eutectic as the bonding time progress. For the Ti-6Al-4V/CuNi/Mg-AZ31 setup, the formation of CuMg<sub>2</sub> and Mg<sub>3</sub>AlNi<sub>2</sub> intermetallics was observed. Furthermore AlTi was detected at the Mg-AZ31 fracture surface, this suggested that the diffusion of Ti towards the joint interface and the fracture propagated close to Ti-6Al-4V interface. However, only ductile fracture mode was observed in the Ti-6Al-4V/CuNi/Mg-AZ31 set up.



**Figure 5.** SEM micrograph and XRD spectra for Mg-AZ31 fractured surface for bond made 515°C, 0.35 MPa, and 20 minutes for a) Ti-6Al-4V/NiCu/Mg-AZ31 at 10 minutes b)Ti-6Al-4V/NiCu/Mg-AZ31 at 20 minutes c) Ti-6Al-4V/CuNi/Mg-AZ31 20 minutes.

#### 4. Conclusion

In this study the TLP bonding process was used to join Ti-6Al-4V to Mg-AZ31 using double foil of Ni and Cu. The results showed that different configurations resulted in different minimum bonding times to achieve a joint. When the joint configuration was Ti-6Al-4V/NiCu/Mg-AZ31, a bonding time of 10 minutes was sufficient to achieve a joint. However for the Ti-6Al-4V/CuNi/Mg-AZ31 configuration it required 20 minutes to achieve a suitable joint. The maximum shear strength obtained was 57 MPa for the Ti-6Al-4V/CuNi/Mg-AZ31 bonds made at 515°C, 0.35 MPa and 20 minutes. The formation of Mg and Mg<sub>3</sub>AlNi<sub>2</sub> were detected at all joints and the fracture mode was mixed brittle-ductile for the Ti-6Al-4V/NiCu/Mg-AZ31 joints and ductile for the Ti-6Al-4V/CuNi/Mg-AZ31 joints.

#### 5. Acknowledgment

The authors would like to acknowledge The German Jordanian University, NSERC Canada for the financial support for this research.

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