Effect of Cu Addition to Zn-12Al Alloy on Thermal Properties and Wettability on Cu and Al Substrates

TOMASZ GANCARZ, JANUSZ PSTRUŚ, SYLWIA MOSIŃSKA, and SYLWIA PAWLAK

The thermal properties, electrical resistivity, thermal linear expansion and tensile strength of a new high-temperature lead-free solder based on a eutectic Zn-Al alloy with 0.5, 1.0, or 1.5 at. pct Cu added were studied. Wettability studies on Cu substrate were performed with flux at 773 K (500 °C) for 60, 180, 240, 900, 1800, and 3600 seconds, and for 480 seconds at 733 K, 753 K, 773 K, 793 K, and 823 K (460 °C, 480 °C, 500 °C, 520 °C, and 550 °C, respectively). The experiment was designed to demonstrate the effect of the addition of Cu on the kinetics of the formation and growth of the CuZn, Cu_5Zn_8, $CuZn_4$, and Al_4Cu_9 phases, which were identified by X-ray diffraction analysis. Wetting tests were also performed on the Al substrate, for 15 and 30 seconds at 773 K and 793 K (500 °C and 520 °C, respectively). Very low contact angles on Al pads were obtained. The electrical resistivity of Zn-Al-Cu alloys was slightly higher than that of the ZnAl eutectic alloy. The present results are discussed with respect to the available literature on Zn-Al and Zn-Al-Cu alloys.

I. INTRODUCTION

THE development of modern technology and the production of more advanced electronic devices has caused an increase in the demand for new construction materials and thus stimulated the development of new materials combining single and multiple elements. Lead-free soldering was, and still is, a great challenge for many industries, and it requires not only the development of new solder, but also of fluxes, and potentially even changes in the manufacturing processes. The electrical and electronics industries have developed replacements using the addition of alloying elements to lead-free and tin-based soft solder that melts at 503 K (230 °C).[1–5] However, the automotive and cooling industries have used solders with higher melting points.[6] Therefore, an important task is to develop new solders with appropriate wetting properties, melting points, mechanical strength, etc.

In response to market demand from the aerospace, automotive, and electronics industries, solder alloys for use at temperatures up to 623 K (350 °C) have been developed, on the basis of eutectic ZnAl alloys with added Ag,[6] In,[7] and Cu.[8,9] The major contribution of the Vianco team,[10] which worked on alloys in the temperature range above 573 K (300 °C), is noteworthy. Yet their new ecological alloys still did not yield very

good results, so further research has been conducted by Takaku,[11] Kang,[12] and Savaskan,[13] to improve the alloy properties. The proposed eutectic ZnAl alloys have a higher melting point, of 654 K (381 °C), after the addition of Cu, and they demonstrate good corrosion resistance and high mechanical strength.[8–10] The intermetallic phases (IMPs) in the Cu-Zn system have a very important role in the joining of metals.[11–14] Therefore, the formation of IMP layers on a Cu substrate has a significant impact on the properties of the joints.

The aim of this study was to characterize Zn-Al-Cu alloys in terms of melting temperature, coefficient of linear expansion, electrical resistivity, tensile strength, contact angles, and spreading area on Cu and Al substrates, and to determine the effect of Cu in a ZnAl alloy on the formation of IMPs, during the soldering process on Cu substrates.

II. EXPERIMENTAL

The alloys were prepared using pure (99.999 pct) Zn, Al, and Cu in an argon-filled glove box, with oxygen and with a moisture level below 1 ppm. The studied alloys were based on eutectic ZnAl with the addition of 0.5, 1.0, and 1.5 at. pct Cu; their final compositions are shown in Table I. Transition temperatures for the solder alloys were determined from heating curves obtained by differential scanning calorimeter (DSC) measurement at a heating rate of 10 K/min (°C/min) under an argon gas flow at 40 mL/min, using an Al_2O_3 cell. Electrical resistivity measurements were performed using the 4-point method with a Keithley 6220 current source (with an accuracy of 100 mA), coupled with a Keithley 2182 nanovoltmeter (range 10 mV, with an accuracy of 1 nV). The experiment was designed for temperatures

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from 303 K to 423 K (30 °C to 150 °C), and the sample was held for 3 h at each temperature step. The thermal expansion coefficient was measured using a TMA Netzsch Pegasus for a temperature range from 223 K to 473 K (−50 °C to 200 °C), at a heating rate of 2 K/min (°C/min), with a gas flow of 20 mL/min, and a force of 0.1 mN.[6] The soldered joint was formed by wetting the joined materials with solder during the soldering process. Therefore, the study of the properties of the solders is based on an assessment of their ability to wet the solder materials under certain conditions. Wettability was measured using the sessile drop method as described previously.[14] The wetting test was performed using 0.5 g of solder. The Al and Cu plates were cleaned by acetone, and the process was conducted using flux at Alu33 in a protective atmosphere of nitrogen, at temperatures from 723 K to 823 K (480 °C to 550 °C, respectively). The spreading area of the solder was evaluated after cooling, using the graphical method described previously.[15] Selected samples were cut and cross-section tested using a scanning electron microscope (SEM, FEI ESEM XL30) with EDS, and X-ray diffraction (XRD) was conducted to identify the phases present.[16] Mechanical tests were conducted using an INSTRON 6025 testing machine of Zwick/Roell. The conditions of testing were in accordance with EN ISO 6892-1:2009, with a strain rate of 0.00025 1/s at room temperature. The samples for mechanical tests were cast in graphite crucibles heated to above 723 K (450 °C) and allowed to cool freely to room temperature. They were then machined into samples suitable for tensile measurements.

III. RESULTS AND DISCUSSION

The values obtained for the melting point of the Zn-Al-Cu alloys are shown in Table I. The addition of Cu to the eutectic ZnAl initially increased the melting temperature, but increased Cu concentration in the alloy decreased the melting temperature when nearing to the composition of ternary eutectic Al-Cu-Zn.[7] The obtained alloys met the criterion for high-temperature lead-free solder proposed by Vianco[10] because the melting temperature was above 623 K (350 °C). The electrical resistivity measurements are presented in Figure 1, which shows the difference in the resistivity of pure Zn, the eutectic ZnAl alloy, and the ZnAl with Cu alloys. With increased Cu, the electrical resistivity of the eutectic ZnAl alloy also increased. In comparison to the data on electrical resistivity for ZnAl with In,[7] the

values obtained here are lower. The linear expansion of ZnAl alloys with added Cu shows the same pattern as the electrical resistivity, with increased Cu in alloys increasing the CTE. The CTE values are presented in Table II. The atomic volume of Zn is 9.16 cm^3/mol, Al is 10.0 cm^3/mol, and Cu is 7.11 cm^3/mol. These values suggest that the addition of Cu should reduce the electrical resistivity. However, in the present case, the electrical resistivity and CTE increased with the Cu concentration, which is interpreted as Cu failing to dissolve in the ZnAl matrix and Cu-Zn intermetallic phases forming instead. Kang et al.[12] observed a similar effect of increased electrical resistivity with the addition of Cu in alloys. The Zn-Al-Cu solder exhibited an electrical resistivity of 5.5 to 7.0 $\mu\Omega$ cm at room temperature, which was lower than that of the Sn-37Pb solder (14.25 $\mu\Omega$ cm[18]). The obtained electrical resistivity and CTE for ZnAl with Cu are similar to those for ZnAl with Ag,[6] which were 24.03, 25.27, and 29.75 cm^3/mol for 0.5, 1.0, and 1.5 pct Ag, respectively.

The microstructure and XRD analyses of the cast alloys are presented in Figure 2. With increasing amounts of Cu in the alloys, more Cu-Zn precipitates formed. The precipitates were analyzed and identified, using XRD, as β—CuZn, γ—Cu$_5$Zn$_8$, ε—CuZn$_5$, and γ'—Al$_4$Cu$_9$ (Figure 2(b)). Because the microstructure did not differ for ZnAl with 0.5, 1.0, and 1.5 (at. pct) Cu alloys, only the microstructure for ZnAl with 1.5 Cu is
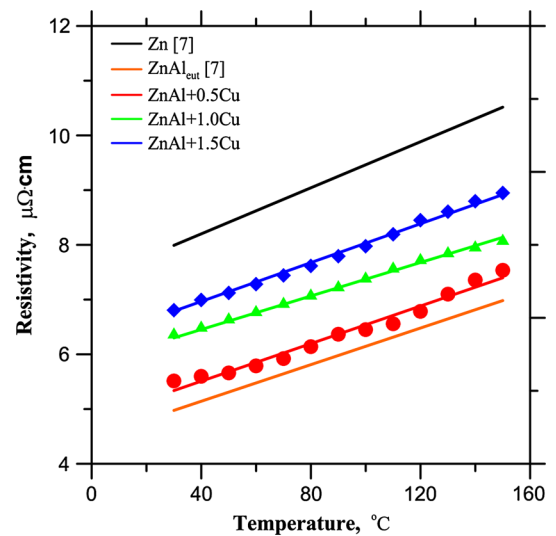
Fig. 1—Electrical resistivity *vs* temperature of pure Zn,[7] eutectic ZnAl,[7] and ZnAl with Cu alloys.

**Table I. The Compositions of the Studied Alloys with Melting Points Determined by DSC**

Alloys	Chemical Composition		Melting Temperature [K (°C)]
	(At. Pct)	(Wt Pct)	
ZnAl(eut)	Zn12Al	Zn5.3Al	656.7 (383.7)
ZnAl + 0.5Cu	Zn12Al0.5Cu	Zn5.3Al0.52Cu	663.2 (390.2)
ZnAl + 1.0 Cu	Zn12Al1.0Cu	Zn5.3Al1.04Cu	662.1 (389.1)
ZnAl + 1.5Cu	Zn12Al1.5Cu	Zn5.3Al1.57Cu	657.9 (384.9)

Table II. The CTEs and Tensile Strengths of Zn-Al-Cu Alloys

Alloy (At. Pct)	Temperature Range [K (°C)]	CTE (10^{-6} K^{-1})	Tensile Strength (MPa)
Zn	223 to 473 (−50 to 200)	29.87 ± 0.32	—
Zn-12Al	223 to 473 (−50 to 200)	23.97 ± 0.16	122.7 ± 7.4
Zn-12Al-0.5Cu	223 to 473 (−50 to 200)	24.55 ± 0.23	183.1 ± 9.5
Zn-12Al-1.0Cu	223 to 473 (−50 to 200)	26.21 ± 0.21	221.6 ± 10.7
Zn-12Al-1.5Cu	223 to 473 (−50 to 200)	28.86 ± 0.24	268.3 ± 8.1
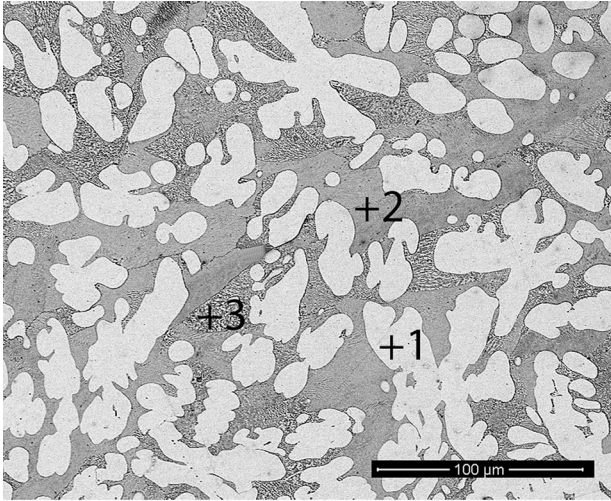
(a)
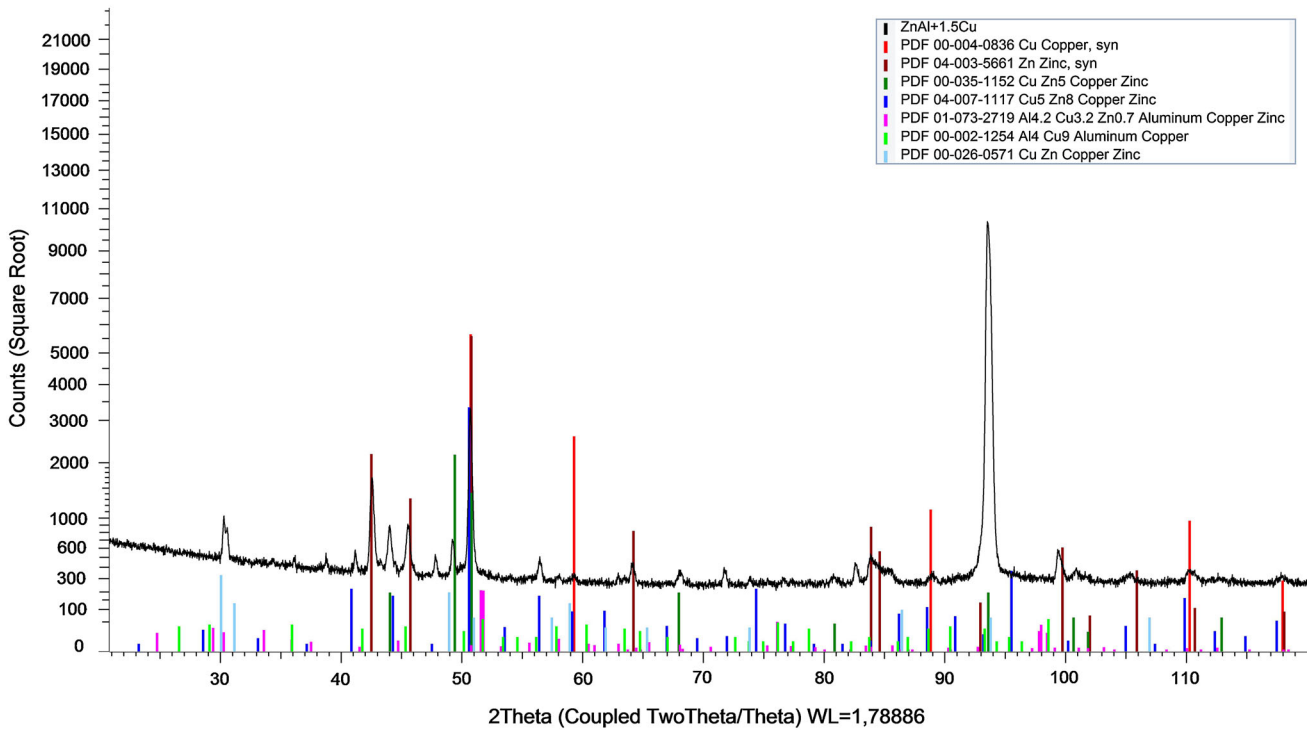
(b)

Fig. 2—Microstructure (*a*) and XRD analysis (*b*) of ZnAl + 1.5Cu as-cast.

shown in Figure 2(a). The interposition of Cu in ZnAl alloys is intended to create IMP precipitates that block the formation of IMP layers on the substrate in the wetting test, as observed with the addition of Ag to ZnAl.[6] The values of ultimate tensile strength (UTS) are summarized in Table II. Measurements for R_m

(tensile strength) were obtained using tensile testing. The highest value of tensile strength was observed for ZnAl with 1.5 pct Cu. Due to the high brittleness of samples, the obtained elongation was less than 1 pct for all alloys. The obtained R_m (268.3 MPa) for ZnAl + 1.5Cu is more than twice the highest (122.7 MPa) for eutectic ZnAl. The increase in tensile strength is caused by the creation of precipitates of β, γ, ε, and γ', as shown on the microstructure and proved by XRD analysis presented in Figure 2(b). The mechanical tests show a trend of increasing tensile strength as Cu is increased in ZnAl alloys. For 3 pct Cu, the tensile strength is 304 MPa, as reported in Reference 19.
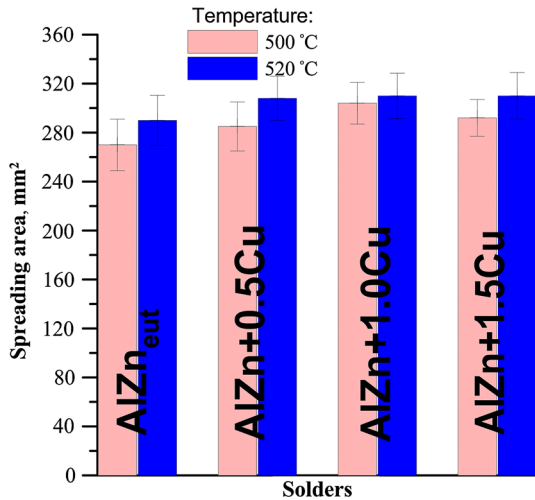
After characterizing Zn-Al-Cu solders in terms of DSC, CTE, electrical resistivity, and microstructure, and following mechanical tests, we proceeded with the process of wetting the solder on Cu and Al substrates. Figure 3 shows the spreading area of ZnAl + Cu alloys on the Al substrate after 15 seconds, at 773 K and 793 K (500 °C and 520 °C, respectively). The spreading area of ZnAl alloys with Cu is slightly higher than for eutectic ZnAl[14] at both temperatures. There was no explicit trend in the effect of the added Cu on the spreading area. The obtained spreading area at 793 K (520 °C) was greater than that at 773 K (500 °C). The short time used for the wetting test was dictated by the
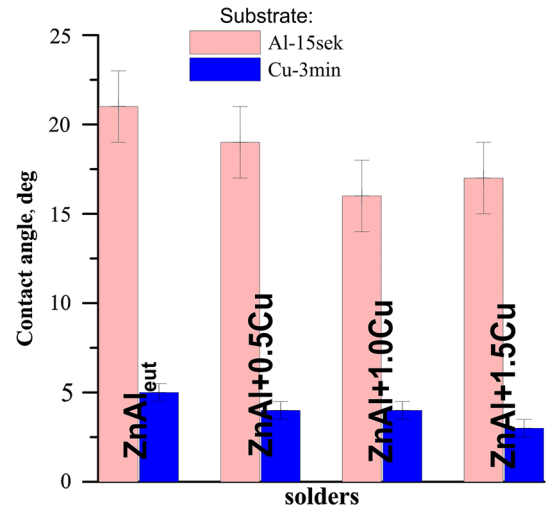

Fig. 3—Spreading area of 0.5 g liquid eutectic ZnAl[14] and ZnAl with Cu solders on Al pads after 15 s at 773 K (500 °C) and 793 K (520 °C), respectively.

Fig. 5—Contact angle of eutectic ZnAl[15] and ZnAl + Cu on Cu and Al substrates after 3 min or 15 s at 773 K (500 °C).
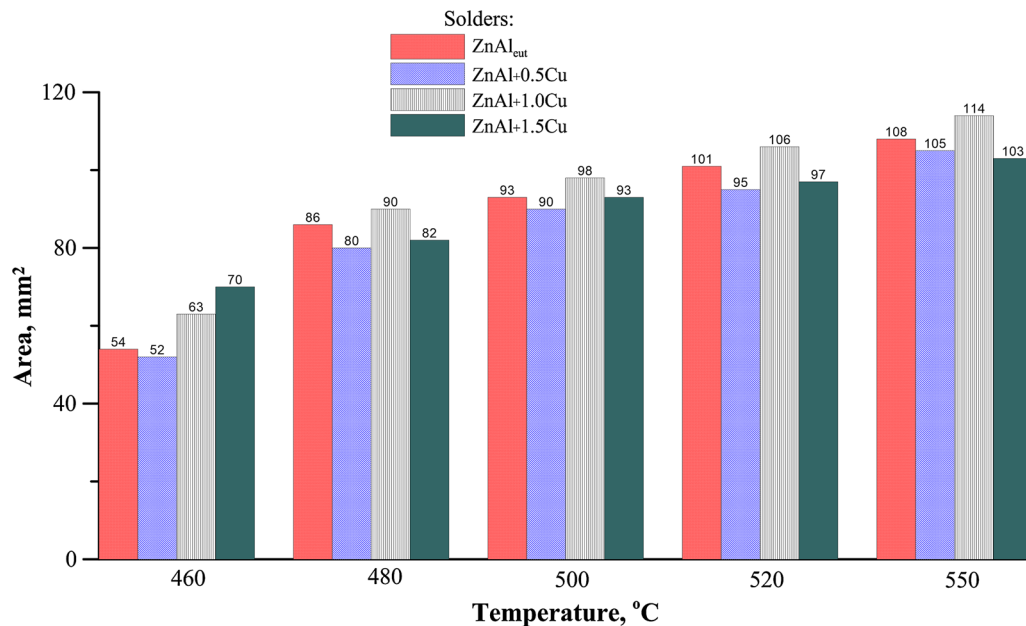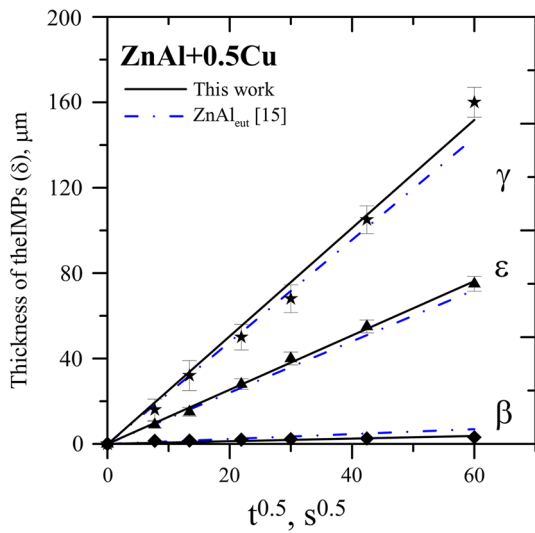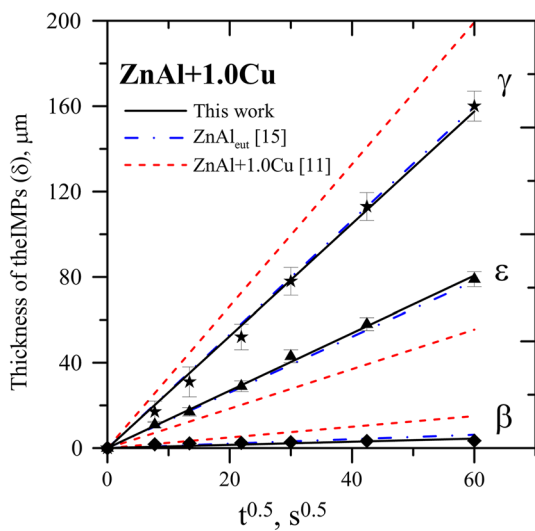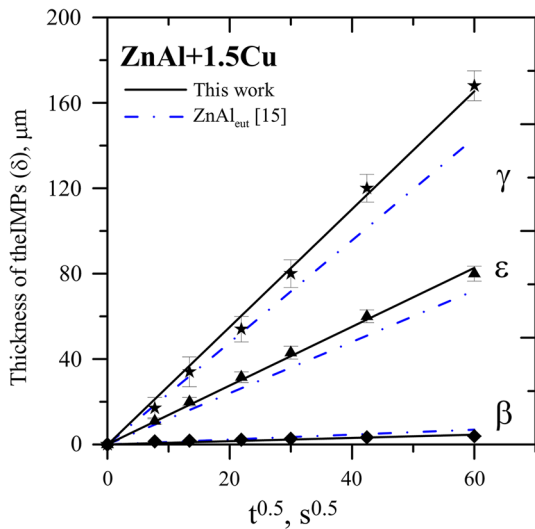

Fig. 4—Spreading area of 0.5 g liquid ZnAl and ZnAl with Cu solder after 8 min at 733 K, 753 K, 773 K, 793 K, and 823 K (460 °C, 480 °C, 500 °C, 520 °C, and 550 °C), respectively.

(a)

(b)

(c)

Fig. 6—Thickness of IMPs *vs* time for (*a*) ZnAl + 0.5 pct Cu compared with eutectic ZnAl,[15] (*b*) ZnAl + 1.0Cu compared with literature data[11] for ZnAl + 1.0Cu,[15] for eutectic ZnAl, and (*c*) ZnAl + 1.5 pct Cu compared with eutectic ZnAl,[15] all at 773 K (500 °C).

Table III. Properties of IMP Growth During Soldering on a Cu Substrate, Using Liquid Zn-12Al Alloys with Added Cu, Calculated from the Straight Line Shown in Fig. 6

ZnAl + Cu	0.5	1.0	1.5
IMP		$K \times 10^{-6}$ (m/s$^{1/2}$)	
β	0.061	0.073	0.076
ε	1.270	1.344	1.377
γ	2.533	2.628	2.760

complete consumption of the Al substrate by the solder, which is presented in Figure 12.

Figure 4 shows the spreading area on Cu for eutectic ZnAl and ZnAl alloys with added Cu, after 480 seconds at 733 K, 753 K, 773 K, 793 K, and 823 K (460 °C, 480 °C, 500 °C, 520 °C, and 550 °C, respectively). With increasing temperature in the wetting test, the spreading area of the solders increased. Comparing the spreading area obtained for the ZnAl alloys with Ag[6] at 773 K (500 °C) for 480 seconds to that of the ZnAl alloys with Cu, the investigated alloys show higher wettability of the Cu substrate. The contact angle of the eutectic ZnAl with added Cu on the Cu and Al substrates is presented in Figure 5. The value is within the scope required for good wetting.[20] Generally, the addition of Cu to eutectic ZnAl reduced the contact angle, but further increasing the Cu content in the alloy did not result in a further decrease of the angles. The contact angle on the Al substrate corresponded to complete wetting. A reduced contact angle on the Al substrate was observed as Cu content in the ZnAl alloys was increased.

Figure 6 presents the growth of IMPs *vs* time at 773 K (500 °C) for ZnAl with Cu alloys. The thickness of IMPs increased slightly with the addition of Cu. The data for ZnAl + 1.0Cu show good agreement with the literature,[11,15] but the γ—Cu$_5$Zn$_8$ phase shows a lower growth rate. After 60 minutes, the ZnAl with Cu alloys at 60 minutes does not show so great an increase in the growth of the γ phase as does the ZnAl with Ag alloys.[6] Table III shows the value of the coefficient k obtained from the fitting of a straight line to experimental data (the thickness of IMPs is shown in Figure 6, which records the growth rate of the IMPs). As Cu content in the ZnAl alloys was increased, the growth rate of the formation of IMPs increased slightly or remained the same. The obtained values for the ZnAl + 1.0Cu alloy were as follows: β—0.073, ε—1.344, and γ—2.628; the data reported in the literature were β—0.256, ε—0.947, and γ—3.400.[11] The obtained growth rate is higher for the ε phase and lower for the β and γ phases, compared to that obtained in Reference 11 and almost identical to
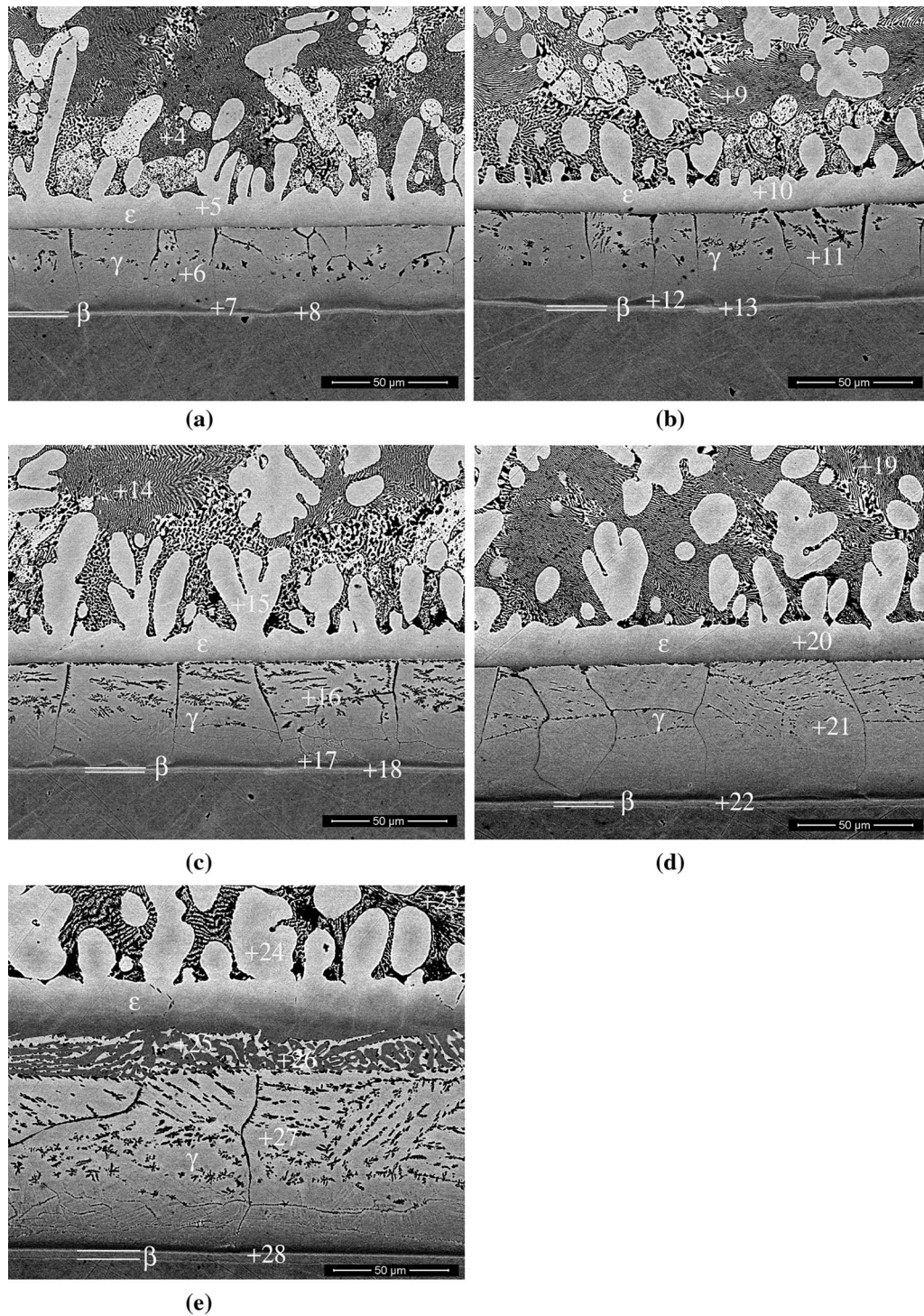
Fig. 7—Microstructure of ZnAl + 1.5Cu on Cu substrate after 480 s at (*a*) 773 K (460 °C), (*b*) 753 K (480 °C), (*c*) 773 K (500 °C), (*d*) 793 K (520 °C), and (*e*) 823 K (550 °C).

the values obtained in Reference 15, which are shown in Figure 6(b).

Because the values obtained for contact angle, spreading area, and thickness of IMPs with the changes of concentration of the addition of Cu to eutectic ZnAl were similar, further studies were performed on the ZnAl + 1.5Cu alloy.

Figure 7 presents the microstructure of soldered joints for the ZnAl + 1.5 pct Cu alloy on the Cu substrate after soldering for 8 minutes at a temperature range from 733 K to 823 K (460 °C to 550 °C, respectively). The results show that processes occurring at the interface between the solder and pad correspond to the presence of a rich intermetallic phase from the Cu-Zn
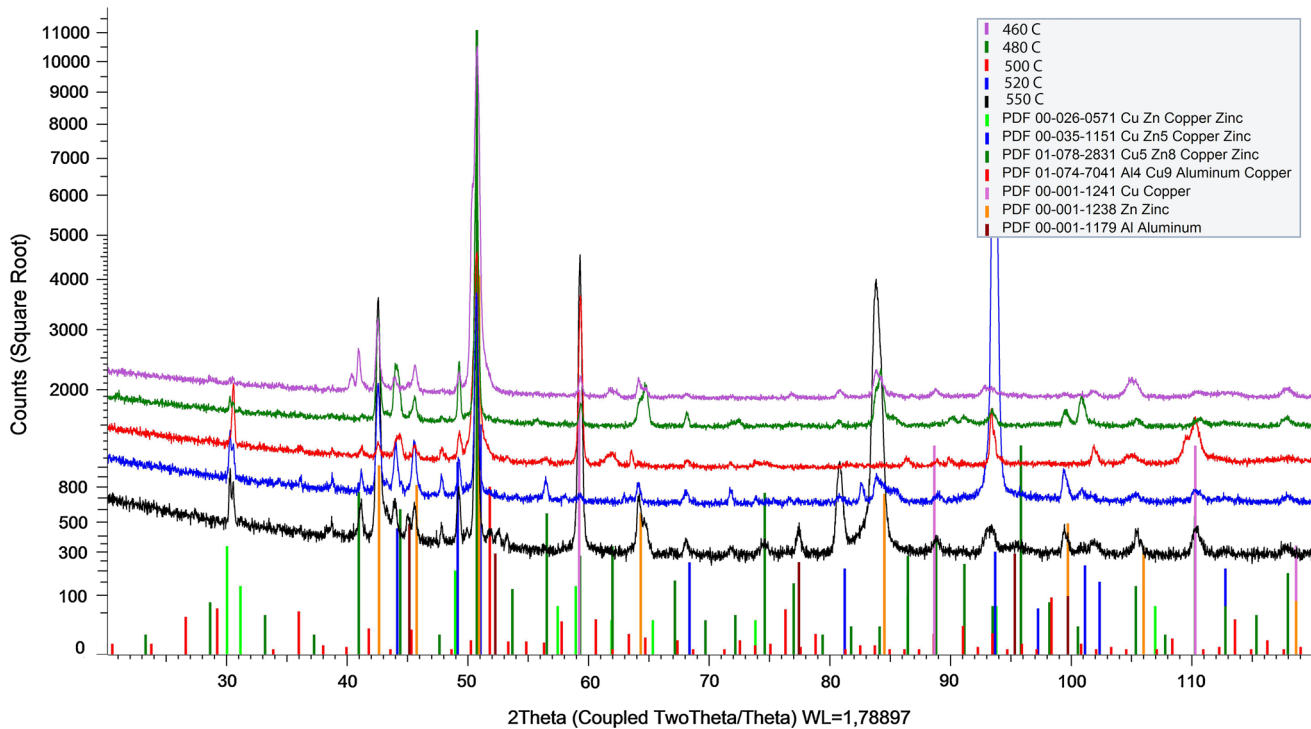
Fig. 8—XRD analysis of ZnAl + 1.5Cu on Cu substrate in the soldering test after 480 s at 733 K, 753 K, 773 K, 793 K, and 823 K (460 °C, 480 °C, 500 °C, 520 °C, and 550 °C, respectively).

system. When the solder has been melted, the processes occurring at the interface between the solder and pad can be divided into two stages. The first involves the dissolution of copper by liquid zinc, and the second comprises crystallization and peritectic reactions. The ε—CuZn$_4$ phase crystallizes first, followed by the γ—Cu$_5$Zn$_8$ and β—CuZn phases. The microstructure of the interface, which can be divided into three intermetallic layers, is presented in Figure 7. Beginning with the Cu substrate, the layers are, sequentially, the CuZn, Cu$_5$Zn$_8$, and CuZn$_4$ phases. The achieved results are consistent with the results reported in the literature.[6,11,15] Figure 7 shows that, with increasing temperature, the IMP layers increase and were largest at 823 K (550 °C). The visible scallop on the solder side is the CuZn$_4$ phase, which diffuses into the solder and increases the number of precipitates in the depths of the solder.

The presence of IMP of β—CuZn, γ—Cu$_5$Zn$_8$, and ε—CuZn$_4$ was confirmed by XRD, as shown in Figure 8 and by EDS analysis (Table IV). The Cu$_5$Zn$_8$ phase showed the highest growth, the nature of which is different from that of the CuZn and CuZn$_4$ phases. In the case of the γ phase, there is mixed diffusion, of the volumetric and grain boundaries. The growth of the γ phase was described in Reference 15 for Cu/solder/Cu joints, where the solder was eutectic ZnAl. In our case, for the growth rate shown in Figure 9, the β and ε phases do not exhibit growth at 823 K (550 °C), which indicates that we are dealing with mixed diffusion. Therefore, the increase of the β and ε phases is controlled by volume diffusion. The same growth behavior of the phases with increasing temperature

was observed by Reference 11 for eutectic ZnAl and eutectic ZnAl with 1.0 pct Cu. The size of the growth of the IMP layer for the ZnAl + 1 pct Cu alloy was very similar to that obtained in this work. Similar IMP growth results for ZnAl alloys with 0.5 pct Ag have been reported in Reference 6. At 823 K (550 °C), differences in the nature of the transition between the γ and ε phases were observed. As observed from EDS analysis, the growth of the γ phase was increasingly dependent on Al$_9$Cu$_4$, not just on Cu$_5$Zn$_8$. The same characteristics of changes at the interface of the γ and ε phases were observed in Reference 6. It can be concluded that the nature of the changes in the growth of the γ phase is not affected by the addition of Cu to eutectic ZnAl, but rather only by temperature. According to the Al-Cu-Zn phase diagram,[17] the γ phase dissolved the Al at 823 K (550 °C), and the stream of diffusion of Cu from the substrate (which is much higher than the diffusion of Zn from solder[6]) is maintained by creating a γ phase consisting of Cu$_5$Zn$_8$ and Al$_9$Cu$_4$.

The observed activation energies of growth are shown in Figure 10. From these activation energies, it follows that the γ—Cu$_5$Zn$_8$ phase has the lowest activation energy (27 kJ/mol), albeit slightly higher than that of ε—CuZn$_4$ at 27.5 kJ/mol, and the β—CuZn phase has the highest activation energy (34.5 kJ/mol). Comparing the obtained activation energies with those reported in[11], ZnAl + 1.0 pct Cu has higher values for the β and γ phases, at 48.8 and 36.7 kJ/mol, respectively, and the lowest activation energy for ε at 16.5 kJ/mol. The authors of Reference 11 reported that the ε phase for ZnAl + 1.0 pct Cu had the lowest activation energy. For the ZnAl with Cu alloys, and in Reference 6, for

Table IV. EDS Results from Zn-12Al-1.5Cu on Cu and Al Substrates, at the Positions Indicated in Figs. 2, 7, 11, and 12

	Al^K	Cu^K (At. Pct)	Zn^K
1	3.23	16.27	80.5
2	12.53		87.47
3	12.47	3.84	83.69
4	20.26	3.92	75.83
5	4.05	18.06	77.89
6	15.69	43.62	40.69
7	20.06	49.34	30.6
8	5.71	58.53	35.76
9	20.81	4.25	74.94
10	5.1	19.49	75.41
11	18.01	44.71	37.28
12	22.59	50.86	26.55
13	6.94	57.24	35.83
14	18.82	4.2	76.98
15	5.51	20.27	74.22
16	15.57	43.84	40.59
17	21.49	49.17	29.34
18	8.04	55.77	36.19
19	22.39	3.74	73.87
20	6.78	21.05	72.17
21	15.38	42.38	42.24
22	7.84	61.66	30.51
23	25.47	4.09	70.44
24	6.38	21	72.61
25	9.65	39.02	51.33
26	28.03	41.87	30.1
27	13.35	42.66	43.99
28	11.45	59.12	29.43
29	36.36	2.15	61.5
30	67.49		32.51
31	63.86	0.64	35.5
32	63.27	2.54	33.64
33	40.64	2.78	56.58
34	17.89	1.8	80.31
35	66.34	2.64	28.79
36	46.86	2.02	51.12

Fig. 9—Growth phases of CuZn$_4$, Cu$_5$Zn$_8$, and CuZn for ZnAl + 1.5Cu alloy on the Cu pad with a wetting time of 480 s at the temperatures of 733 K, 753 K, 773 K, 793 K, and 823 K (460 °C, 480 °C, 500 °C, 520 °C, and 550 °C, respectively).

Fig. 10—Arrhenius plot of the activation energy of each layer type at the interface between molten ZnAl + 1.5Cu solder and the substrate Cu.

ZnAl + 0.5Ag, the γ phase had the lowest activation energy. However, for the eutectic alloy ZnAl, the ε phase has the lowest activation energy, at 29.5 kJ/mol[6] or 20.0 kJ/mol.[11] This phenomenon may occur because the addition of Ag or Cu to the eutectic ZnAl alloy contributes to the formation of IMPs of Ag-Zn and Cu-Zn/Al-Cu precipitates, resulting in the highest concentration of Zn on the interface between the solder and substrate and enabling easier creation of γ phase layers.

Figures 11 and 12 present the microstructure of the ZnAl solder alloy containing 1.5 at. pct Cu on an Al substrate after soldering at 773 K (500 °C) for 15 and 30 seconds, respectively. Based on the alloy microstructures of the soldered joints, the addition of Cu to eutectic ZnAl causes an increase in the dissolution of Al by the liquid solder compared to ZnAl with In.[7] The compositions of Al, Cu, and Zn, as determined by EDS at the points noted in Figures 11 and 12, are shown in Table IV. Al from the substrate is present in the solder as precipitates rich in Al (point 35 in Figure 12). The
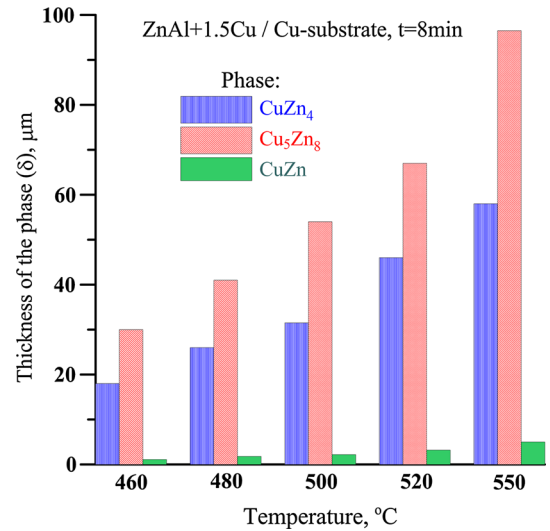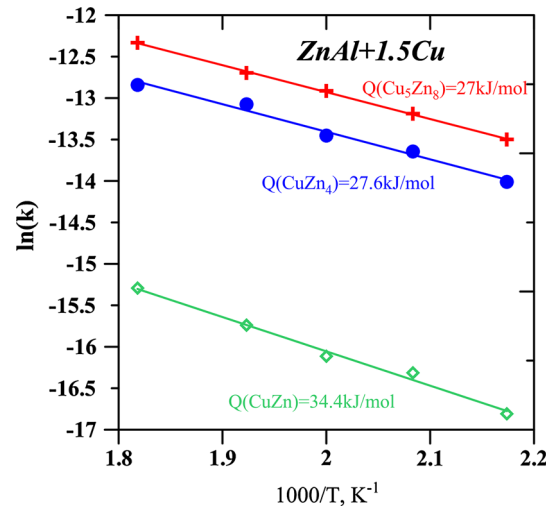
EDS analysis shows that, during soldering, the solder dissolves the Al substrate and the Al diffuses into the drop. At the interface between the solder and the Al substrate (point 30 in Figure 11), it was observed that the Al was dissolved in liquid solder. After soldering for 30 s, the Al substrate was completely dissolved at the point of contact with the solder (see Figure 12). Dissolution of Al by Zn is consistent with the Al-Zn phase diagram,[17] which shows that, at 773 K (500 °C), approximately 30 pct of the Al dissolved in the ZnAl alloy. The temperature of the wetting test was selected so that both the Al and Cu substrates could be used. XRD measurements are presented in Figure 13, for
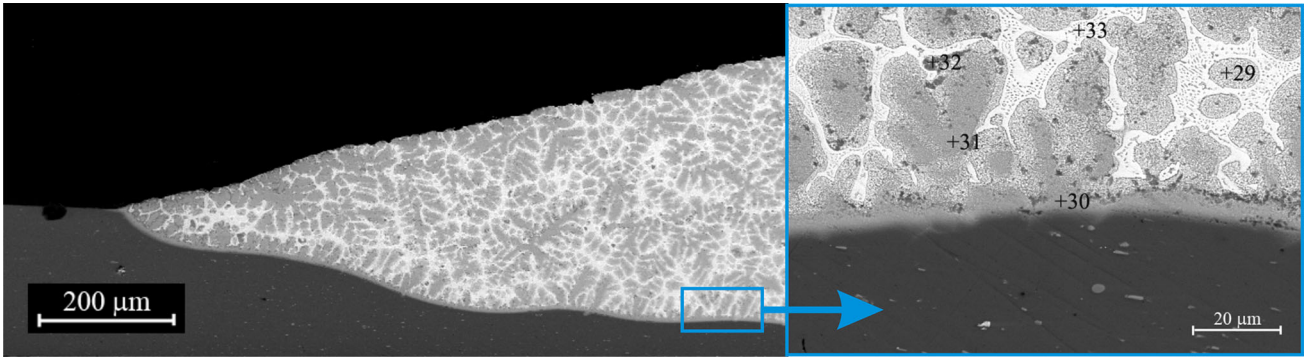
Fig. 11—The microstructure of a cross section of ZnAl + 1.5Cu solder on Al substrate after soldering for 15 s at 773 K (500 °C).
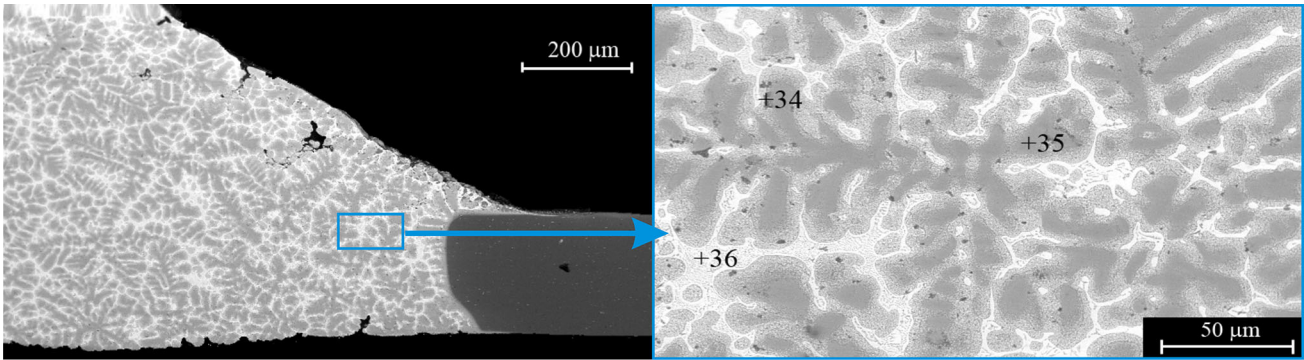

Fig. 12—The microstructure of a cross section of ZnAl + 1.5Cu solder on Al substrate after soldering for 30 s at 773 K (500 °C).
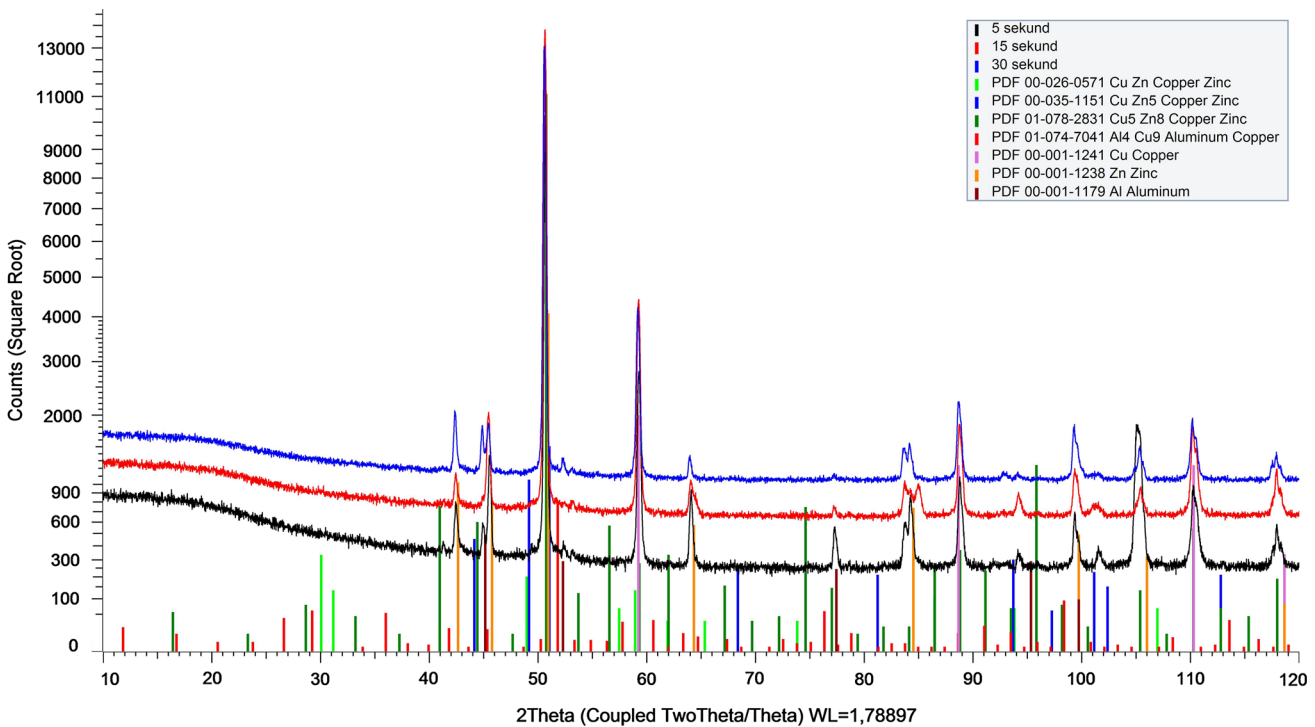

Fig. 13—XRD analysis of ZnAl + 1.5Cu on Al substrate for soldering test after 5, 15, and 30s at a temperature of 773 K (500 °C).

soldering for 5, 15, and 30 seconds at 773 K (500 °C) on the Al substrate. Over time, the ε phase peak decreased.

IV. CONCLUSIONS

Solder alloys based on eutectic ZnAl with an additional alloy element of 0.5 to 1.5 pct Cu were developed for applications in high-temperature electronics. DSC results showed that the addition of 0.5, 1.0, and 1.5 pct Cu to the eutectic ZnAl alloy influenced the melting temperature only slightly. The solders had a liquid melting range of 657 K to 663 K (384 °C to 390 °C). The electrical resistivity was increased by the addition of Cu to the eutectic ZnAl alloy. Measurements of the coefficient of thermal expansion (CTE) showed a linear increase throughout the tested temperature range. The CTE and mechanical test results showed that the addition of copper to the eutectic ZnAl alloy increases the thermal expansion and tensile strength. The wettability tests showed that the spreading area of ZnAl + 1.5 at. pct Cu on a Cu substrate was the largest at 823 K (550 °C). These tests also showed that the temperature affects of the formation and growth of some intermetallic phases, such as Cu_5Zn_8. The results of the calculations showed that the activation energy increases in the order of $Q(CuZn) > Q(CuZn_4) > Q(Cu_5Zn_8)$. The growth of $CuZn$ and $CuZn_4$ phases during soldering is controlled by volume diffusion, and by mixed diffusion for the Cu_5Zn_8 phase. The thickness of the Cu_5Zn_8 layer increases rapidly from 733 K to 823 K (460 °C to 550 °C), but the growth of the other layers proceeds much more slowly.

Solders based on the eutectic ZnAl with Cu additives are much better in wetting an Al substrate compared to a Cu substrate in the soldering test. They have a lower contact angle (for Cu, this is approximately 20 deg and for Al it is approximately 4 deg) and, most of all, a larger spreading area (Cu approximately 90 mm^2 and Al approximately 300 mm^2). The melting point of Cu is higher than that of Al, which results in the formation of IMPs in the Cu-Zn system and the dissolution of Al in the Al-Zn system, as shown by the phase diagram.[17] Generally, small additions of Cu to eutectic ZnAl improves solder wetting properties for both Cu and Al substrates.

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