

Effect of Alloying Elements on Electrochemical Corrosion Behavior, Microstructure, Wettability and Thermal Performance of Bismuth-Tin Based Alloys

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ABSTRACT

Microstructure, wettability behavior, corrosion parameters, thermal properties of quaternary bismuth- tin based alloy have been investigated using different experimental techniques. Induced lattice microstrain of $Bi_{60}Sn_{40}$ alloy increased after adding Sb-Zn or Sb-Ag or Al-Cd or Al-Cu. Contact angle of $Bi_{60}Sn_{40}$ alloy increased after adding Sb-Zn or Sb-Ag or Al-Cd or Al-Cu. A significant change (28%) occurred in contact angle of $Bi_{60}Sn_{40}$ alloy after adding Al-Cd. Corrosion rate of $Bi_{60}Sn_{40}$ alloy decreased after adding Sb-Zn or Sb-Ag but it increased after adding Al-Cd or Al-Cu. The melting temperature of $Bi_{60}Sn_{40}$ alloy varied after adding alloying elements. The $Bi_{50}Sn_{40}Al_5Cd_5$ alloy has the lowest melting temperature. Some properties of $Bi_{60}Sn_{40}$ alloy improved after adding Sb-Zn or Sb-Ag elements which make them useful for different industrial applications.

Keywords: Corrosion Behavior, Wettability, Microstructure, Melting Point, Thermal Performance, Pasty Range, Bismuth-Tin Alloys

I. INTRODUCTION

Bismuth is used in alloys to lower the melting point as in industry applications such as thermal switches. Much research was done for studying microstructure, electrical, mechanical and thermal properties of bismuth- lead/ bismuth-tin eutectic alloys, bismuth- lead- tin, bismuthlead- tin- cadmium, tin- antimony with other elements additions [1-11]. The microstructure and microhardness of rapidly solidified foils of the Sn-58 wt. % Bi alloy was studied [12]. The Sn-Bi eutectic alloy nanoparticle consisted of the tetragonal phase of tin and the rehombohedral phase of bismuth [13]. The Bi-Sn eutectic alloy has a good soldering property such as low point, mechanical properties, melting adequate wettability and cost [14]. Splat quenching caused a metastable shift of the solubility limit in Sn-Bi alloys containing 15, 20 and 25 % bismuth [15]. The ductility of the binary Bi-Sn eutectic solders has significantly improved by adding small amount of Ag [16]. The phase formation during rapid solidification of the

undercooled droplets Bi-Sn system at ambient pressure and of the thermal behavior of droplet samples under hydrostatic pressure conditions in an attempt to identify the structure and the operative solidification kinetics were studied [17]. The microstructural development of eutectic alloys Bi-Sn and In-Sn during high temperature deformation was studied and reported [18]. The aim of our research was to study the effect of quaternary alloying elements on microstructure, electrochemical corrosion behavior and soldering properties of bismuthtin alloy.

II. METHODS AND MATERIAL

High purity (more than 99.5 %) bismuth, tin, antimony, zinc, silver, aluminum, cadmium and copper were melted in a muffle furnace to use in the production ingots from $Bi_{60}Sn_{40}$, $Bi_{50}Sn_{40}Sb_7Zn_3$, $Bi_{50}Sn_{40}Sb_7Ag_3$, $Bi_{50}Sn_{40}Al_5Cd_5$ and $Bi_{50}Sn_{40}Al_8Cu_2$ alloys. The resulting ingots were turned and re-melted four times to increase the homogeneity. Long ribbons of ~ 3 mm width and

~90 µm thickness were prepared by melt spinning technique. The surface velocity of the roller was 31.4 m/s giving a cooling rate of $\sim 3.7 \times 10^5$ K/s. The samples then cut into convenient shape for the measurements using double knife cuter. Microstructure of used samples was performed using scanning electron microscope (JEOL JSM-6510LV, Japan) and Shimadzu X-ray Diffractometer (Dx-30, Japan) of Cu-Ka radiation with λ =1.54056Å at 45 kV and 35 mA and Ni– filter in the angular range 2θ ranging from 0 to 100° in continuous mode with a scan speed 5 deg/min. Thermal analysis were obtained using SDT Q600 (V20.9 Build 20) instrument made in U. S. A with heating rate 10 k/min in the temperature range from 50-400 °C. All the samples have the same mass, which is 2 mg. The polarization studies were performed using Gamry Potentiostat/Galvanostat with a Gamry framework system based on ESA 300.

III. RESULTS AND DISCUSSION

A. Microstructure

Figure 1a shows x-ray diffraction patterns of Bi₆₀Sn₄₀ alloy which have lines corresponding to hexagonal bismuth phase and tetragonal tin phase. Stared base line at ~ 240 counts and the range of random atoms distribution (amorphousity area) stared from 0 to 35°. X-ray diffraction patterns of Bi₅₀Sn₄₀Sb₇Zn₃ alloy which have lines corresponding to hexagonal bismuth phase and tetragonal tin phase as shown in Figure 1b. That meant that, antimony and zinc atoms dissolved in matrix alloy formed a solid solution. Adding 7% antimony and 3% zinc improve crystallinty which indicated by peak intensity and decreased amorphous region (0- 28°) with formed a small phases in it\ or undetected phases. X-ray diffraction patterns of Bi₅₀Sn₄₀Sb₇Ag₃ alloy which have lines corresponding to hexagonal bismuth phase and tetragonal tin phase as shown in Figure 1c. That meant that, antimony and silver atoms dissolved in matrix alloy. Adding 7% antimony and 3% silver caused little enhanced in $Bi_{60}Sn_{40}$ crystallinty. X-ray diffraction patterns of Bi50Sn40Al5Cd5 alloy which have lines corresponding to hexagonal bismuth phase and tetragonal tin phase as shown in Figure 1d. That meant that, aluminum and cadmium atoms dissolved in matrix alloy. Adding 5% aluminum and 5% cadmium enhance Bi₆₀Sn₄₀ crystallinty. X-ray diffraction patterns of

 $Bi_{50}Sn_{40}Al_8Cu_2$ alloy which have lines corresponding to hexagonal bismuth phase, tetragonal tin phase and CuSn intermetallic phase as shown in Figure 1e. That meant that, aluminum and cadmium atoms dissolved in matrix alloy. Adding 8% aluminum and 2% copper improve $Bi_{60}Sn_{40}$ crystallinty and decreased amorphous region. The analysis of x-ray diffraction patterns, (peak intensity, peak broadness, peak position, area under peaks, phases and Miller indices), is shown in Table 1 (a, b, c, d and e). The estimated crystal size is given by Scherer equation [19] and then listed in Table 1f.

Lattice microstrain will be related to both diffraction lines broadening as well as line shift compared with the initial state. From the relation between full widths half maximum (β) and 4tan θ [20, 21] as shown in Figure 1f, the induced internal lattice microstrain of used alloys was determined and then listed in Table 1g. Lattice microstrain of Bi₆₀Sn₄₀ alloy increased after adding quaternary elements, Sb-Zn or Sb- Ag or Al- Cd or Al-Cu, that is because Sb, Ag or Sb, Zn or Al, Cd or Al, Cu atoms dissolved in matrix alloy effected on its structure.









alloy



alloy





Table 1a:- x-ray	diffraction	analysis	of Bi ₆₀	$_{0}Sn_{40}$	alloy
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2θ 4.8' Int % FHWM Area Phase hel 91.866 1.07205 3.94 1.152 11.29 Bi 312 27.1398 3.28574 100 0.2755 22.535 Bi 012 31.9555 2.0773 4.686 0.1755 100.58 S.0 200 A* Int.% FHWM Area Phase hkl 37.973 2.3664 3.547 0.2362 27.13 S.0 220 A* Int.% FHWM Area Phase hkl 43.7598 0.0644 3.547 0.2362 7.13 S.0 220 A* Int.% FHWM Area Phase hkl 44.8202 0.22223 3.76 0.1574 48.42 Bi 201 30.933 2.9722 45.13 0.1968 8.28 Sn 301 31.9732 2.79921 7.541 0.171 A.429 Sn 101 52.121 1.64355 1.626 0.1574								89.6991	1.09314	6.77	0.6298	7.86	Bi	306	
17.1398 32.8574 100 0.2755 225.35 Bi 012 30.5471 2.92656 44.63 0.2755 100.58 Sn 200 31.9955 2.7973 46.86 0.1966 7.5.42 Sn 101 37.9723 2.36964 35.47 0.2362 85.31 Bi 104 43.7598 2.06873 14.05 0.2362 27.13 Sn 220 20 d.A° Int.% FHWM Area Phase hkl 44.8002 2.02222 37.6 0.1574 48.42 Bi 211 2.264 10.0 0.2362 60.63 Bi 102 55.946 1.66369 11.36 0.1968 18.28 Sn 301 31.9732 2.79921 75.41 0.1717 34.29 Sn 101 61.1275 1.51611 2.68 0.3149 15.86 1004 44.763 2.02467 30.46 0.1968 15.39 Sn 200 16.51	20	d A°	Int.%	FHWM	Area	Phase	hkl	91.866	1.07205	3.94	1.152	11.29	Bi	312	
10 10 20 Table 1c: x-ray diffraction analysis of Bi _{sg} Sn _{db} Sb ₇ Ag; alloy 31.9955 2.7973 46.86 0.1968 75.42 Sn 101 37.0723 2.36964 35.47 0.2362 68.51 Bi 100 37.0723 2.36964 35.47 0.2362 71.3 Sn 200 d A° Int.% FHWM Area Phase hkl 43.7598 2.06873 10.05 0.3362 27.13 Sn 200 d A° Int.% FHWM Area Phase hkl 45.8564 19754 9.25 0.433 3.27.77 Bi 113 27.1674 3.28246 100 0.2362 Phase hkl 55.2461 1.64255 16.26 0.1574 2.09 Sn 301 37.9076 2.3753 67.02 0.2362 Phase hkl 61.1275 1.5141 2.60 0.1574 2.09 Bi 116 43.3768 2.0267 83.44 0.319 <td>27.1398</td> <td>3.28574</td> <td>100</td> <td>0.2755</td> <td>225.35</td> <td>Bi</td> <td>012</td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td><u>I</u></td>	27.1398	3.28574	100	0.2755	225.35	Bi	012							<u>I</u>	
31 31 955 2.973 46 60 1988 75.42 Sn 101 alloy 379732 2.36964 53.47 0.2362 85.32 Bi 104 43.7598 2.06673 14.05 0.2362 27.13 Sn 220 2.0 d.A° Int.% FHWM Arca Plase hki 44.8002 2.0222 3.7.6 0.1574 48.42 Bi 113 27.1674 3.28246 100 0.2362 8.5 200 55.9446 1.64255 16.26 0.1574 48.42 Bi 107 3.7976 2.37353 67.02 0.263 Bi 104 61.1275 1.51611 2.08 0.3149 1.86 Bi 107 3.79776 2.37353 67.02 0.203 40.63 Bi 104 62.1275 1.4049 17.16 0.1574 22.09 Bi 116 43.766 2.07344 63.84 0.3149 63.84 101	30.5471	2.92656	44.63	0.2755	100.58	Sn	200	Table 1	e. x-ray (liffractio	on analysi	s of Bia	SnuSh	$-\Delta\sigma_{2}$	
37.9723 2.36964 35.47 0.2362 68.51 Bi 104 43.7598 2.06873 14.05 0.2362 25.713 Sn 220 0 d.A* Im.% FHWM Area Phase hki 44.8202 2.02222 37.6 0.1574 48.42 Bi 211 22.41 3.96736 68.52 0.00 0.12 Bi 003 45.8654 1.9784 9.25 0.433 3.277 Bi 113 27.167 3.8284 100 0.2362 60.63 Bi 0.02 55.9464 1.64255 16.26 0.1984 8.88 n.01 3.97972 2.79921 75.41 0.173 3.29 Sn 101 59.2961 1.55848 5.38 0.3149 1.89 Bi 116 43.7368 2.0267 83.44 31.45 Bi 110 61.1275 1.51611 2.68 0.3149 6.9 Bi 202 50.3781 46.40 0.50 Bi 116 43.7368 2.0267 83.44 3.145 Bi <td< td=""><td>31.9955</td><td>2.7973</td><td>46.86</td><td>0.1968</td><td>75.42</td><td>Sn</td><td>101</td><td>Tuble I</td><td>c. A luy c</td><td>mmucu</td><td>11 analysi</td><td>15 OI DI5</td><td>00114000</td><td>1163</td></td<>	31.9955	2.7973	46.86	0.1968	75.42	Sn	101	Tuble I	c. A luy c	mmucu	11 analysi	15 OI DI 5	00114000	1163	
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44 8202 2.02222 37.6 0.1374 48.42 Bi 211 22.41 3.96736 68.52 0.001 0.12 Bi 003 45 8654 1.97854 9.25 0.433 32.77 Bi 013 27.1674 3.28246 100 0.262 60.63 Bi 012 55.121 1.66369 11.36 0.1574 20.93 Sn 301 31.9732 2.79921 75.41 0.1771 34.29 Sn 101 59.9461 1.64255 1.52 0.1574 20.93 Sn 301 31.9732 2.79921 75.41 0.1771 34.29 Sn 101 62.1275 1.49409 17.16 0.1574 22.09 Bi 116 43.7368 2.06976 30.46 0.1968 15.39 Sn 220 63.6578 1.46181 5.46 0.3149 6.9 Bi 200 27.54 1.3149 6.349 Bi 202 70.7542 1.316 1.12 0.1574 4.20 2.14 811 113 7.7374 1.316	43.7598	2.06873	14.05	0.2362	27.13	Sn	220	20	d A°	Int.%	FHWM	Area	Phase	hkl	
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48.703 1.86907 25.17 0.3346 68.86 Bi 202 30.5933 2.9225 45.13 0.1968 22.8 Sn 200 55.2121 1.66309 11.36 0.1968 18.28 Sn 301 31.9732 2.79921 75.41 0.1771 34.29 Sn 101 59.2864 1.64255 16.26 0.1574 20.39 Sn 300 37.9076 2.37353 67.02 0.2362 40.63 Bi 104 61.1275 1.5161 2.68 0.3149 6.9 Bi 205 39.6466 2.27334 62.26 0.1968 1.45 Bi 110 62.1575 1.44402 30.55 0.1968 49.17 Sn 321 45.188 1.98044 81.22 0.3149 69.39 Bi 210 67.1356 1.312 6.30 0.551 36.21 Sn 421 55.9801 1.46267 26.06 0.2755 1.21 Sn 301 72.9657 1.2616 2.82 0.3149 1.72 Bi 255 1.5042	45.8654	1.97854	9.25	0.433	32.77	Bi	113	27.1674	3.28246	100	0.2362	60.63	Bi	012	
55.2121 1.66309 11.35 0.1988 18.28 Sn 301 31.9732 2.79921 75.41 0.1771 34.29 Sn 101 55.9846 1.64255 16.26 0.1574 20.93 Sn 31.9732 2.79921 75.41 0.1771 34.29 Sn 101 55.9846 1.64255 16.26 0.1344 6.9 Bi 107 37.9076 2.37335 67.02 0.2362 40.63 Bi 110 61.1257 1.51611 2.68 0.3149 6.9 Bi 116 43.7368 2.02467 85.84 0.3149 62.39 Bi 211 64.5163 1.4442 30.551 3.621 Sn 420 55.2854 1.66166 17.26 0.2755 18.21 Sn 301 7.19365 1.3126 8.03 0.511 3.621 Sn 421 55.2854 1.66166 17.26 0.2755 18.43 Sn 301 7.9352 1.201751 0.314 9.727 Bi 125 59.2153 1.56042 15.86	48.7203	1.86907	25.17	0.3346	68.86	Bi	202	30.5933	2.92225	45.13	0.1968	22.8	Sn	200	
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	55.2121	1.66369	11.36	0.1968	18.28	Sn	301	31 9732	2 79921	75.41	0.1771	34.29	Sn	101	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	55.9846	1.64255	16.26	0.1574	20.93	Sn	301	37.0076	2.77252	67.02	0.1771	40.63	Di	101	
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	59.2961	1.55848	5.38	0.3149	13.86	Bi	107	37.9070	2.37333	07.02	0.2302	40.05		104	
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	61.1275	1.51611	2.68	0.3149	6.9	Bi	205	39.6466	2.2/334	62.26	0.1968	31.45	B1	110	
$ \begin{array}{c} 63.6578 & 1.46181 & 5.46 & 0.3149 & 14.06 & Sn & 400 & 44.763 & 2.02467 & 85.84 & 0.3149 & 69.39 & Bi & 211 \\ \hline 64.5163 & 1.44442 & 30.55 & 0.1968 & 49.17 & Sn & 321 & 45.8189 & 1.98044 & 31.22 & 0.3149 & 25.24 & Bi & 113 \\ \hline 67.4003 & 1.38946 & 4.04 & 0.2362 & 7.8 & Bi & 018 & 47.719 & 1.86901 & 48.81 & 0.3542 & 44.39 & Bi & 202 \\ \hline 71.9365 & 1.3216 & 8.03 & 0.551 & 36.21 & Sn & 420 & 55.9801 & 1.64267 & 26.06 & 0.2755 & 12.21 & Sn & 301 \\ \hline 72.9657 & 1.2966 & 7.1 & 0.1574 & 9.15 & Sn & 411 & 55.9801 & 1.64267 & 26.06 & 0.2755 & 18.43 & Sn & 301 \\ \hline 73.3333 & 1.26163 & 2.82 & 0.3149 & 7.27 & Bi & 125 & 59.2153 & 1.56042 & 15.86 & 0.3936 & 16.02 & Bi & 107 \\ \hline 79.352 & 1.20752 & 10.31 & 0.1968 & 16.6 & Sn & 312 & 61.01 & 1.51875 & 3.07 & 0.09 & 0.72 & Bi & 205 \\ \hline 81.2294 & 1.18429 & 1.24 & 0.4723 & 4.8 & Bi & 208 & 62.4077 & 1.48805 & 46.11 & 0.1968 & 23.29 & Bi & 116 \\ \hline 85.1387 & 1.13963 & 3.76 & 0.7872 & 24.21 & Bi & 119 & 63.6117 & 1.46276 & 9.29 & 0.3149 & 7.51 & Sn & 400 \\ \hline 87.0591 & 1.11936 & 2.86 & 0.3936 & 9.2 & Bi & 217 & 64.464 & 1.44582 & 62.22 & 0.1771 & 28.29 & Sn & 321 \\ \hline 89.1342 & 1.09769 & 5.68 & 0.192 & 12.09 & Bi & 306 & 67.3895 & 1.38966 & 1.3926 & 1.337 & 0.2362 & 14.37 & Bi & 214 \\ 94.3053 & 1.09769 & 5.68 & 0.192 & 12.61 & Sn & 521 & 75.47 & 1.25968 & 4.23 & 0.09 & 0.99 & Bi & 125 \\ \hline 75.474 & 1.0240 & 5.94 & 0.192 & 12.61 & Sn & 521 & 75.47 & 1.25968 & 4.23 & 0.09 & 0.99 & Bi & 125 \\ \hline 77.139 & 3.28044 & 100 & 0.1968 & 36.27 & Bi & 012 & 91.755 & 1.07394 & 12.28 & 0.3149 & 9.92 & Bi & 125 \\ \hline 77.139 & 3.28044 & 100 & 0.1968 & 36.27 & Bi & 012 & 91.7564 & 1.0281 & 25.84 & 0.1968 & 13.05 & Sn & 312 \\ \hline 73.9547 & 2.3707 & 50.81 & 0.1374 & 15.72 & Bi & 101 & 97.558 & 1.0491 & 3.84 & 0.09 & 0.9 & Sn & 332 \\ \hline 39.6161 & 2.27502 & 54.19 & 0.1574 & 15.72 & Bi & 101 & 97.558 & 1.0491 & 3.84 & 0.09 & 0.9 & Sn & 332 \\ \hline 39.6161 & 2.27502 & 54.19 & 0.1574 & 15.72 & Bi & 101 & 97.558 & 1.0491 & 3.84 & 0.09 & 0.9 & Sn & 332 \\ \hline 39.6161 & 2.27502 & 54.19 & 0.1574 & 15.72 & Bi & 101 & 97.558 $	62.1275	1.49409	17.16	0.1574	22.09	Bi	116	43.7368	2.06976	30.46	0.1968	15.39	Sn	220	
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	63.6578	1.46181	5.46	0.3149	14.06	Sn	400	44.763	2.02467	85.84	0.3149	69.39	Bi	211	
67.4003 1.38946 4.04 0.2362 7.8 Bi 018 48.7219 1.86901 48.81 0.3542 44.39 Bi 202 70.7542 1.3316 11.12 0.1574 14.32 S52854 1.66166 17.26 0.2755 12.21 Sn 301 72.9657 1.2966 7.1 0.1574 9.15 Sn 411 55.9801 1.64267 26.06 0.2755 18.43 Sn 301 75.3333 1.26163 2.82 0.3149 7.27 Bi 125 59.2153 1.56042 15.86 0.3936 16.02 Bi 107 79.352 1.0315 0.316 0.4723 4.8 Bi 208 62.077 1.4805 46.11 0.1968 3.29 Bi 116 87.0591 1.11936 3.76 0.7872 24.21 Bi 119 63.6117 1.46276 9.29 0.149 5.8 0.192 1.64446 1.44582 62.22 0.1771 28.29 Sn 321 89.5669 1.09441 5.93 <td< td=""><td>64.5163</td><td>1.44442</td><td>30.55</td><td>0.1968</td><td>49.17</td><td>Sn</td><td>321</td><td>45.8189</td><td>1.98044</td><td>31.22</td><td>0.3149</td><td>25.24</td><td>Bi</td><td>113</td></td<>	64.5163	1.44442	30.55	0.1968	49.17	Sn	321	45.8189	1.98044	31.22	0.3149	25.24	Bi	113	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	67.4003	1.38946	4.04	0.2362	7.8	Bi	018	48.7219	1.86901	48.81	0.3542	44.39	Bi	202	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	70.7542	1.3316	11.12	0.1574	14.32	B1	214	55.2854	1.66166	17.26	0.2755	12.21	Sn	301	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	71.9365	1.3126	8.03	0.551	36.21	Sn	420	55,9801	1.64267	26.06	0.2755	18.43	Sn	301	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	72.9657	1.2966	/.1	0.15/4	9.15	Sn D:	411	59 2153	1 56042	15.86	0.3936	16.02	Bi	107	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	/5.3333	1.20103	2.82	0.3149	1.27	B1 Cm	125	61.01	1.50042	2.07	0.5750	0.72	Di Di	205	
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	19.352	1.20752	10.31	0.1908	10.0	Sn Di	200	01.01	1.310/3	3.07	0.09	0.72		203	
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	01.2294	1.18429	1.24	0.4723	4.8	DI	208	62.4077	1.48805	46.11	0.1968	23.29	B1	116	
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	87.0501	1.13903	2.86	0.7872	0.2	Bi	217	63.6117	1.46276	9.29	0.3149	7.51	Sn	400	
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	89 1342	1.11750	2.00 5.68	0.3730	12.09	Bi	306	64.4464	1.44582	62.22	0.1771	28.29	Sn	321	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	89 5669	1.09441	5.00	0.172	11.45	Bi	306	67.3895	1.38966	13.73	0.2362	8.32	Bi	018	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	91 7129	1.07433	5.18	0.3149	13 33	Bi	312	70.7525	1.33163	23.7	0.2362	14.37	Bi	214	
95.3808 1.04249 5.18 0.2362 10 Sn 332 73.0033 1.29603 14.57 0.2362 8.84 Sn 411 97.5634 1.02406 5.94 0.192 12.61 Sn 521 75.47 1.25968 4.23 0.09 0.99 Bi 125 Table 1b:- x-ray diffraction analysis of Bi ₅₀ Sn ₄₀ Sb ₇ Zn ₃ 81.2279 1.18431 5.45 0.4723 6.61 Bi 208 81.2279 1.18431 5.45 0.4723 6.61 Bi 208 84.9137 1.14207 14.02 0.2362 8.5 Bi 119 87.1714 1.11821 5.45 0.4723 6.6 Bi 217 2Θ d A° Int.% FHWM Area Phase hkl 89.1172 1.09877 13.88 0.2362 8.42 Bi 306 27.1339 3.28644 100 0.1968 36.27 Bi 012 91.7556 1.07394 12.28 <td>94.3053</td> <td>1.05151</td> <td>2.04</td> <td>0.2362</td> <td>3.94</td> <td>Bi</td> <td>128</td> <td>72.173</td> <td>1.30888</td> <td>19.23</td> <td>0.551</td> <td>27.2</td> <td>Sn</td> <td>411</td>	94.3053	1.05151	2.04	0.2362	3.94	Bi	128	72.173	1.30888	19.23	0.551	27.2	Sn	411	
97.5634 1.02406 5.94 0.192 12.61 Sn 521 75.47 1.25968 4.23 0.09 0.99 Bi 125 Table 1b:- x-ray diffraction analysis of Bi ₅₀ Sn ₄₀ Sb ₇ Zn ₃ alloy 79.3064 1.2081 25.84 0.1968 13.05 Sn 312 alloy 79.3064 1.2081 25.84 0.1968 13.05 Sn 312 alloy 79.3064 1.2081 25.84 0.1968 13.05 Sn 312 alloy 79.3064 1.2081 5.45 0.4723 6.61 Bi 208 VEV FHWM Area Phase hkl 89.1172 1.09877 13.88 0.2362 8.42 Bi 306 2.92666 35.26 0.2362 15.34 Sn 200 94.59 1.0491 3.84 0.09 9.9 Bi 312 30.546 2.92666 35.26 0.2362 Sn 101 <td>95.3808</td> <td>1.04249</td> <td>5.18</td> <td>0.2362</td> <td>10</td> <td>Sn</td> <td>332</td> <td>73.0033</td> <td>1.29603</td> <td>14.57</td> <td>0.2362</td> <td>8.84</td> <td>Sn</td> <td>411</td>	95.3808	1.04249	5.18	0.2362	10	Sn	332	73.0033	1.29603	14.57	0.2362	8.84	Sn	411	
Table 1b:- x-ray diffraction analysis of Bi ₅₀ Sn ₄₀ Sb ₇ Zn ₃ 79.3064 1.2081 25.84 0.1968 13.05 Sn 312 Table 1b:- x-ray diffraction analysis of Bi ₅₀ Sn ₄₀ Sb ₇ Zn ₃ 79.3064 1.2081 25.84 0.1968 13.05 Sn 312 alloy 79.3064 1.2081 25.84 0.1968 13.05 Sn 312 alloy 79.3064 1.2081 25.84 0.1968 13.05 Sn 312 20 d A° Int.% FHWM Area Phase hkl 81.127 1.09877 1.0491 3.84 0.402 8.42 Bi 312 2.92666 35.26 0.2362 15.34 Sn 200 <th cols<="" td=""><td>97.5634</td><td>1.02406</td><td>5.94</td><td>0.192</td><td>12.61</td><td>Sn</td><td>521</td><td>75.47</td><td>1.25968</td><td>4.23</td><td>0.09</td><td>0.99</td><td>Bi</td><td>125</td></th>	<td>97.5634</td> <td>1.02406</td> <td>5.94</td> <td>0.192</td> <td>12.61</td> <td>Sn</td> <td>521</td> <td>75.47</td> <td>1.25968</td> <td>4.23</td> <td>0.09</td> <td>0.99</td> <td>Bi</td> <td>125</td>	97.5634	1.02406	5.94	0.192	12.61	Sn	521	75.47	1.25968	4.23	0.09	0.99	Bi	125
Table 1b:- x-ray diffraction analysis of Bi ₅₀ Sn ₄₀ Sb ₇ Zn ₃ alloy 1.2001 2.0.1 0.110.0 <th colspa<="" td=""><td></td><td></td><td></td><td></td><td></td><td>1</td><td></td><td>79 3064</td><td>1 2081</td><td>25.84</td><td>0 1968</td><td>13.05</td><td>Sn</td><td>312</td></th>	<td></td> <td></td> <td></td> <td></td> <td></td> <td>1</td> <td></td> <td>79 3064</td> <td>1 2081</td> <td>25.84</td> <td>0 1968</td> <td>13.05</td> <td>Sn</td> <td>312</td>						1		79 3064	1 2081	25.84	0 1968	13.05	Sn	312
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Table 1	h. v-rav	diffracti	on analys	is of Ri-	Sn. Sh	-7n-	81 2270	1.2001	5.45	0.1700	6.61	Di Di	208	
$\begin{array}{ c c c c c c c c c c c c c c c c c c c$	Tuble 1	D. Aluy	ammacu	allow	15 01 D15	05114050	/2113	01.2279 94.0127	1.10431	14.02	0.4723	0.01	DI D:	200	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $			i	anoy				07.1714	1.14207	14.02	0.2302	0.5	DI	119	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$		T	1	1				87.1714	1.11821	5.45	0.4723	6.6	B1	217	
27.1339 3.28644 100 0.1968 36.27 Bi 012 91.7556 1.07394 12.28 0.3149 9.92 Bi 312 30.546 2.92666 35.26 0.2362 15.34 Sn 200 94.59 1.0491 3.84 0.09 0.9 Sn 332 31.9344 2.80252 39.13 0.1574 11.35 Sn 101 95.3959 1.04236 11.77 0.2362 7.14 Sn 332 37.9547 2.3707 50.81 0.1378 12.9 Bi 104 97.5548 1.02412 11.68 0.24 9.72 Sn 521 39.6161 2.27502 54.19 0.1574 15.72 Bi 110 43.7766 2.06797 16.01 0.2362 6.97 Sn 220 A alloy	20	d A°	Int.%	FHWM	Area	Phase	hkl	89.1172	1.09877	13.88	0.2362	8.42	Bi	306	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	27.1339	3.28644	100	0.1968	36.27	Bi	012	91.7556	1.07394	12.28	0.3149	9.92	Bi	312	
31.9344 2.80252 39.13 0.1574 11.35 Sn 101 95.3959 1.04236 11.77 0.2362 7.14 Sn 332 37.9547 2.3707 50.81 0.1378 12.9 Bi 104 97.5548 1.02412 11.68 0.24 9.72 Sn 521 39.6161 2.27502 54.19 0.1574 15.72 Bi 110 43.7766 2.06797 16.01 0.2362 6.97 Sn 220 20 A4.7808 2.0239 43.91 0.2362 19.11 Sn 220 20 alloy alloy 11.57 44.7808 2.0239 43.91 0.2362 19.11 Sn 220 20 alloy alloy 10.9 11.57 0.2362 8.61 Bi 113 <t< td=""><td>30.546</td><td>2.92666</td><td>35.26</td><td>0.2362</td><td>15.34</td><td>Sn</td><td>200</td><td>94.59</td><td>1.0491</td><td>3.84</td><td>0.09</td><td>0.9</td><td>Sn</td><td>332</td></t<>	30.546	2.92666	35.26	0.2362	15.34	Sn	200	94.59	1.0491	3.84	0.09	0.9	Sn	332	
37.9547 2.3707 50.81 0.1378 12.9 Bi 104 97.5548 1.02412 11.68 0.24 9.72 Sn 521 39.6161 2.27502 54.19 0.1574 15.72 Bi 110 43.7766 2.06797 16.01 0.2362 6.97 Sn 220 44.7808 2.0239 43.91 0.2362 19.11 Sn 220 45.8833 1.97781 19.77 0.2362 8.61 Bi 113 48.7704 1.86727 35.89 0.2165 14.32 Bi 202 2Θ d A° Int.% FHWM Area Phase hkl 56.0277 1.64139 15.43 0.2362 6.72 Sn 301 22.3795 3.9727 20.49 0.4723 37.01 Bi 003 59.2999 1.5584 11.81 0.2362 5.14 Bi 107 27.1793 3.28105 100 0.2362 90.3 Bi 012	31.9344	2.80252	39.13	0.1574	11.35	Sn	101	95.3959	1.04236	11.77	0.2362	7.14	Sn	332	
39.6161 2.27502 54.19 0.1574 15.72 Bi 110 43.7766 2.06797 16.01 0.2362 6.97 Sn 220 44.7808 2.0239 43.91 0.2362 19.11 Sn 220 45.8833 1.97781 19.77 0.2362 8.61 Bi 113 48.7704 1.86727 35.89 0.2165 14.32 Bi 202 20 d A° Int.% FHWM Area Phase hkl 56.0277 1.64139 15.43 0.2362 6.72 Sn 301 22.3795 3.9727 20.49 0.4723 37.01 Bi 003 59.2999 1.5584 11.81 0.2362 5.14 Bi 107 27.1793 3.28105 100 0.2362 90.3 Bi 012	37,9547	2.3707	50.81	0.1378	12.9	Bi	104	97.5548	1.02412	11.68	0.24	9.72	Sn	521	
39.0101 22.7302 34.19 0.1374 13.72 B1 110 43.7766 2.06797 16.01 0.2362 6.97 Sn 220 44.7808 2.0239 43.91 0.2362 19.11 Sn 220 45.8833 1.97781 19.77 0.2362 8.61 Bi 113 48.7704 1.86727 35.89 0.2165 14.32 Bi 202 20 d A° Int.% FHWM Area Phase hkl 56.0277 1.64139 15.43 0.2362 6.72 Sn 301 22.3795 3.9727 20.49 0.4723 37.01 Bi 003 59.2999 1.5584 11.81 0.2362 5.14 Bi 107 27.1793 3.28105 100 0.2362 90.3 Bi 012	39.6161	2 27502	54 19	0.1574	15.72	Bi	110							1	
43.7700 2.00797 10.01 0.2302 0.97 Sil 220 Fraine fil x-ray unfraction analysis of Bi ₃ 03140/RisCus 44.7808 2.0239 43.91 0.2362 19.11 Sn 220 alloy 45.8833 1.97781 19.77 0.2362 8.61 Bi 113 48.7704 1.86727 35.89 0.2165 14.32 Bi 202 2Θ d A° Int.% FHWM Area Phase hkl 56.0277 1.64139 15.43 0.2362 6.72 Sn 301 22.3795 3.9727 20.49 0.4723 37.01 Bi 003 59.2999 1.5584 11.81 0.2362 5.14 Bi 107 27.1793 3.28105 100 0.2362 90.3 Bi 012	12 7766	2.27502	16.01	0.1374	6.07	Sn	220	Tabla 1	d• - v rov	diffracti	on analys	is of Ri	Sn. Al	Cd	
44.7808 2.0239 43.91 0.2362 19.11 Sn 220 alloy 45.8833 1.97781 19.77 0.2362 8.61 Bi 113 48.7704 1.86727 35.89 0.2165 14.32 Bi 202 2Θ d A° Int.% FHWM Area Phase hkl 56.0277 1.64139 15.43 0.2362 6.72 Sn 301 22.3795 3.9727 20.49 0.4723 37.01 Bi 003 59.2999 1.5584 11.81 0.2362 5.14 Bi 107 27.1793 3.28105 100 0.2362 90.3 Bi 012	45.7700	2.00797	10.01	0.2302	0.97		220		u x-ray	unnacu	011 anaiys		5001140741	.5CU5	
45.8833 1.97/81 19.77 0.2362 8.61 Bi 113 48.7704 1.86727 35.89 0.2165 14.32 Bi 202 20 d A° Int.% FHWM Area Phase hkl 56.0277 1.64139 15.43 0.2362 6.72 Sn 301 22.3795 3.9727 20.49 0.4723 37.01 Bi 003 59.2999 1.5584 11.81 0.2362 5.14 Bi 107 27.1793 3.28105 100 0.2362 90.3 Bi 012	44./808	2.0239	43.91	0.2362	19.11	Sn	220			ć	uloy				
48.7704 1.86727 35.89 0.2165 14.32 Bi 202 20 d A° Int.% FHWM Area Phase hkl 56.0277 1.64139 15.43 0.2362 6.72 Sn 301 22.3795 3.9727 20.49 0.4723 37.01 Bi 003 59.2999 1.5584 11.81 0.2362 5.14 Bi 107 27.1793 3.28105 100 0.2362 90.3 Bi 012	45.8833	1.97781	19.77	0.2362	8.61	Bi	113								
56.0277 1.64139 15.43 0.2362 6.72 Sn 301 22.3795 3.9727 20.49 0.4723 37.01 Bi 003 59.2999 1.5584 11.81 0.2362 5.14 Bi 107 27.1793 3.28105 100 0.2362 90.3 Bi 012	48.7704	1.86727	35.89	0.2165	14.32	Bi	202	20	d A°	Int.%	FHWM	Area	Phase	hkl	
59.2999 1.5584 11.81 0.2362 5.14 Bi 107 27.1793 3.28105 100 0.2362 90.3 Bi 012	56.0277	1.64139	15.43	0.2362	6.72	Sn	301	22.3795	3.9727	20.49	0.4723	37.01	Bi	003	
	59.2999	1.5584	11.81	0.2362	5.14	Bi	107	27.1793	3.28105	100	0.2362	90.3	Bi	012	
62.2443 1.49156 20.9 0.3936 15.16 Bi 116 30.5751 2.92395 39.2 0.1968 29.5 Sn 200	62.2443	1.49156	20.9	0.3936	15.16	Bi	116	30.5751	2,92395	39.2	0.1968	29.5	Sn	200	
64.5636 1.44347 29.61 0.2165 11.81 Sn 321 31 9142 2.80425 47.07 0.2165 38.96 Sn 101	64.5636	1.44347	29.61	0.2165	11.81	Sn	321	31 9142	2.80425	47.07	0.2165	38.96	Sn	101	

85.1493

1.13951

4.86

0.6298

5.64

Bi

119

8.37

6.04

5.99

214

411

312

37.8705

39.6137

43.7945

2.37578

2.27516

2.06717

35.63

21.91

16.27

0.2755

0.2362

0.2362

37.53

19.78

14.69

Bi

Sn

Sn

70.8319

72.1252

79.4731

1.33033

1.30963

1.20599

14.42

6.94

6.88

0.3149

0.4723

0.4723

1270

Bi

Bi

Sn

104

110

220

44.8698	2.0201	29.3	0.2755	30.87	Bi	211
45.8473	1.97928	12.26	0.3149	14.77	Bi	113
48.7795	1.86694	13.04	0.2362	11.78	Bi	202
55.2365	1.66301	8.19	0.3149	9.87	Sn	301
56.0549	1.64066	10.54	0.2165	8.72	Bi	024
59.2589	1.55938	6.85	0.2558	6.7	Bi	107
62.3788	1.48867	15.9	0.4723	28.71	Sn	112
64.5026	1.44469	15.95	0.2362	14.4	Sn	321
67.4439	1.38867	4.83	0.4723	8.73	Bi	018
70.81	1.33069	4.9	0.09	1.71	Bi	214
72.35	1.30611	2.84	0.09	0.99	Sn	411
79.4057	1.20684	3.73	0.4723	6.74	Sn	312
85.2375	1.13856	2.72	0.9446	9.83	Bi	119
89.5286	1.09478	2.85	0.9446	10.29	Bi	306
91.8855	1.07188	3.43	0.576	10.22	Bi	312

Table 1e: - x-ray diffraction analysis of $Bi_{50}Sn_{40}Al_8Cu_2$ alloy

20	d A°	Int.%	FHWM	Area	phase	hkl
21.2911	4.17325	67.82	0.1968	59.04	CuSn	
23.8654	3.72861	8.37	0.6298	23.32	Bi	101
27.163	3.28299	100	0.2165	95.76	Bi	012
30.6045	2.92121	43.25	0.1771	33.88	Sn	200
31.9551	2.80076	42.86	0.1968	37.31	Sn	101
37.8122	2.3793	37.7	0.2558	42.66	Bi	104
39.6386	2.27378	37.68	0.1574	26.24	Bi	110
43.7676	2.06838	18.02	0.2755	21.96	Sn	220
44.7946	2.02332	37.86	0.1968	32.96	Bi	211
45.651	1.98733	8.83	0.3149	12.3	Bi	113
48.7426	1.86827	22.81	0.1771	17.87	Bi	202
55.211	1.66372	7.39	0.3149	10.29	Sn	301
56.006	1.64198	10.83	0.2755	13.2	Bi	024
59.253	1.55952	7.07	0.3149	9.84	Bi	107
62.099	1.49471	16.43	0.1181	8.58	Sn	112
63.5925	1.46315	4.76	0.3149	6.63	Sn	400
64.4889	1.44497	21.57	0.3542	33.8	Sn	321
67.4061	1.38935	4.12	0.4723	8.61	Bi	018
70.7828	1.33113	8.24	0.3936	14.34	Bi	214
72.1503	1.30923	7.71	0.3542	12.08	Sn	411
73.0073	1.29597	5.04	0.3149	7.01	Sn	411
79.3299	1.2078	7.66	0.3149	10.67	Sn	312
85.1251	1.13977	3.63	0.7872	12.63	Bi	119
89.447	1.09557	3.59	0.6298	10.01	Bi	306
91.7617	1.07389	4.92	0.2362	5.14	Bi	312
95.4735	1.04172	2.81	0.4723	5.86	Sn	332
97.4781	1.02472	3	0.768	13.76	Sn	521

Table 1f:-crystal size of Bi and Sn in used alloys

Alloys	(Bi) τ A°	$(Sn) \tau A^{\circ}$
$\mathrm{Bi}_{60}\mathrm{Sn}_{40}$	372.55	445.04
$Bi_{50}Sn_{40}Sb_7Zn_3$	337.28	300.9
$Bi_{50}Sn_{40}Sb_7Ag_3$	490.63	478.75
$Bi_{50}Sn_{40}Al_5Cd_5$	330.3	416.96
$Bi_{50}Sn_{40}Al_8Cu_2$	317.01	346.12

Table (1g):-lattice microstrain of used alloys

Alloys	Lattice microstrain
	x 10 ⁻³
$Bi_{60}Sn_{40}$	0.3
$Bi_{50}Sn_{40}Sb_7Zn_3$	3.7
$Bi_{50}Sn_{40}Sb_7Ag_3$	0.4
$Bi_{50}Sn_{40}Al_5Cd_5$	2.5
$Bi_{50}Sn_{40}Al_8Cu_2$	1.6

Scanning Electron Micrographs Analysis

Scanning electron micrograph of Bi₆₀Sn₄₀ alloy, Figure 2a, shows the bismuth grain is majority as white color with different size, shape and orientations with large grain of tin as minority black color. Also scanning electron micrograph of Bi₅₀Sn₄₀Sb₇Zn₃ alloy, Figure 2b, shows the bismuth grain as majority white color with different size, shape and orientations with tin grains as minority black color. That is mean; adding antimony and zinc to Bi₆₀Sn₄₀ alloy caused a refinement grain size with increased homogeneity of it. Also small grain appeared as bright white color. Scanning electron micrograph of Bi₅₀Sn₄₀Sb₇Ag₃ alloy given in Figure 2c shows that, bismuth grain as majority white color with different size, shape and orientations with tin grains as minority black color. Adding antimony and silver to Bi₆₀Sn₄₀ alloy caused refinement to grain size with increased homogeneity of it. Many grains appeared as bright white color. Also very smooth dendrite from bright white color grains appeared. Scanning electron micrograph of Bi50Sn40Al5Cd5 alloy given in Figure 2d shows that, white color bismuth grain as lamellar structure (texture) with different size, shape and orientations with black color tin grains as dendrite

structure. Adding aluminum and cadmium to $Bi_{60}Sn_{40}$ alloy caused more homogeneity of both phases. Scanning electron micrograph of $Bi_{50}Sn_{40}Al_8Cu_2$ alloy,

Figure 2e, shows the white color bismuth grains with different size, shape and orientations and black color tin grains. Also bright white color grains are disturbed in matrix alloy. Adding aluminum and copper to $Bi_{60}Sn_{40}$ alloy caused more homogeneity of both phases.



Figure 2a:-SEM of Bi₆₀Sn₄₀ alloy



Figure 2b:- SEM of Bi₅₀Sn₄₀Sb₇Zn₃ alloy



Figure 2c:- SEM of Bi₅₀Sn₄₀Sb₇Ag₃ alloy



Figure 2d:- SEM of Bi₅₀Sn₄₀Al₅Cd₅ alloy



Figure 2e:- SEM of Bi₅₀Sn₄₀Al₈Cu₂ alloy

B. Wetting Behavior

Wetting is the ability of a liquid to maintain contact with a solid surface, resulting

from intermolecular interactions when the two are brought together. The contact angle is determined by the resultant between adhesive and cohesive forces. As the tendency of a drop to spread out over a flat, solid surface increases, the contact angle decreases. Thus, the contact angle provides an inverse measure of wettability. The spreading of $Bi_{60}Sn_{40}$, Bi50Sn40Sb7Zn3, $Bi_{50}Sn_{40}Sb_7Ag_3$, $Bi_{50}Sn_{40}Al_5Cd_5$ and $Bi_{50}Sn_{40}Al_8Cu_2$ molten alloys on copper surface in air is shown in Figure 3. The measured contact angles of used alloys listed in Table 2. Contact angle of Bi₆₀Sn₄₀ alloy increased after adding Sb-Zn or Sb-Ag or Al-Cd or Al-Cu and a significant increased (28%) occurred after adding Al-Cd.









Figure 3:-spreading of used alloys on copper in air

Table 2:-measured	contact angles	of used alloys on
	copper in air	

Alloys	Contact angle°
$Bi_{60}Sn_{40}$	48.75
$Bi_{50}Sn_{40}Sb_7Zn_3$	57.75
$Bi_{50}Sn_{40}Sb_7Ag_3$	57.5
$Bi_{50}Sn_{40}Al_5Cd_5$	62.5
$Bi_{50}Sn_{40}Al_8Cu_2$	56.25

C. Thermal performance

Melting temperature is very important for industrial and medicine applications. Thermo-graphs of $Bi_{60}Sn_{40}$, $Bi_{50}Sn_{40}Sb_7Zn_3$, $Bi_{50}Sn_{40}Sb_7Ag_3$, $Bi_{50}Sn_{40}Al_5Cd_5$ and $Bi_{50}Sn_{40}Al_8Cu_2$ alloys are shown in Figure 4. The melting point of used alloys is listed in Table (3). The melting temperature of $Bi_{60}Sn_{40}Al_5Cd_5$ alloy has lowest melting temperature.

The pasty range is the difference between solidus and liquidus points. The pasty range of $Bi_{60}Sn_{40}$, $Bi_{50}Sn_{40}Sb_7Zn_3$, $Bi_{50}Sn_{40}Sb_7Ag_3$, $Bi_{50}Sn_{40}Al_5Cd_5$ and $Bi_{50}Sn_{40}Al_8Cu_2$ alloys are listed in Table 3. The $Bi_{50}Sn_{40}Al_8Cu_2$ alloy has low pasty range value.





Figure 4:- DSC thermographs of used alloys

 Table 3:- Melting Point And Pasty Range Of

 Used Alloys

Alloys	Melting	Pasty range
	point °C	°C
$\mathrm{Bi}_{60}\mathrm{Sn}_{40}$	140.3	1.3
$Bi_{50}Sn_{40}Sb_7Zn_3$	139.8	4
$Bi_{50}Sn_{40}Sb_7Ag_3$	142	1.5
$Bi_{50}Sn_{40}Al_5Cd_5$	128.4	-
$Bi_{50}Sn_{40}Al_8Cu_2$	139.7	1.2

D. Electrochemical corrosion behavior

 $Bi_{60}Sn_{40}$, Electrochemical polarization curves of $Bi_{50}Sn_{40}Sb_7Zn_3$, $Bi_{50}Sn_{40}Sb_7Ag_3$, $Bi_{50}Sn_{40}Al_5Cd_5$ and Bi₅₀Sn₄₀Al₈Cu₂ alloys in 0.5M HCl are shown in Figure 5. From this figure, the corrosion potential of used alloys exhibited a negative potential. Also the cathodic and the anodic polarization curves showed similar corrosion trends. The corrosion potential (E_{Corr}) , corrosion current (I_{Corr}) and corrosion rate (C.R) of $Bi_{60}Sn_{40}$, Bi₅₀Sn₄₀Sb₇Zn₃, $Bi_{50}Sn_{40}Sb_7Ag_3$, Bi₅₀Sn₄₀Al₅Cd₅ and Bi₅₀Sn₄₀Al₈Cu₂ alloys in 0.5M HCl are listed in Table 4a. Corrosion rate of Bi₆₀Sn₄₀ alloy decreased after adding Sb-Zn or Sb-Ag but it increased after adding Al-Cd or Al-Cu. That is because adding Sb-Zn or Sb-Ag or Al-Cd or Al-Cu to Bi₆₀Sn₄₀ alloy caused microstructure changed and its affected microsegregation and reactivity of formed phases and other atoms with HCl solution. The Bi₅₀Sn₄₀Sb₇Zn₃ alloy has lowest corrosion current and corrosion rate values.

EFM is a non-destructive corrosion measurement technique. In which current responses due to a potential perturbation by one or more sine waves are measured at more frequencies than the frequency of the applied signal. The results of EFM experiments are a spectrum of current response as a function of frequency. The intermodulation spectrum of $Bi_{60}Sn_{40}$, $Bi_{50}Sn_{40}Sb_7Zn_3$, $Bi_{50}Sn_{40}Sb_7Ag_3$, $Bi_{50}Sn_{40}Al_5Cd_5$ and $Bi_{50}Sn_{40}Al_8Cu_2$ alloys in 0.5M HCl solution are shown in Figure 6. The larger peaks were used to calculate the corrosion current density (i_{corr}) and the corrosion rate and then listed in Table 4b. The corrosion current density (i_{corr}) of $Bi_{60}Sn_{40}$ alloy varied after adding alloying elements.









Table 4a:- corrosion potential (E_{Corr}), corrosion current (I_{Corr}), and corrosion rate (C. R) of used alloys

Alloys	E	$I_{Corr}\mu A$	C. R
	mV		mpy
Bi ₆₀ Sn ₄₀	-557	36	49.01
$Bi_{50}Sn_{40}Sb_7Zn_3$	-437	2.24	3.05
$Bi_{50}Sn_{40}Sb_7Ag_3$	-558	28.1	38.26
Bi50Sn40Al5Cd5	-940	273	371
$Bi_{50}Sn_{40}Al_8Cu_2$	-1.04	321	4377





Figure 6:-intermodulation spectrum obtained by EFM technique for used alloys

Table 4a:- the corrosion current density $(i_{\mbox{\scriptsize corr}})$ and	
the corrosion rate (C. R) of used alloys	

Alloys	i _{Corr} μa	C. R x 10^{3}
		mpy
$\mathrm{Bi}_{60}\mathrm{Sn}_{40}$	1.202	1.638
$Bi_{50}Sn_{40}Sb_7Zn_3$	1.007	1.372
$Bi_{50}Sn_{40}Sb_7Ag_3$	1.086	1.480
$Bi_{50}Sn_{40}Al_5Cd_5$	1.347	1.836
$Bi_{50}Sn_{40}Al_8Cu_2$	14.79	20.16

IV. CONCLUSION

X-ray diffraction and scanning electron microscope analysis show that, the microstructure of Bi₆₀Sn₄₀ alloy changed after adding alloying elements. Contact angle of Bi₆₀Sn₄₀ alloy increased after adding Sb-Zn or Sb-Ag or Al-Cd or Al-Cu and a significant increased (28%) occurred after adding Al-Cd. The melting temperature of Bi₆₀Sn₄₀ alloy varied after adding alloying elements. The Bi₅₀Sn₄₀Al₅Cd₅ alloy melting has lowest temperature. Corrosion rate of Bi₆₀Sn₄₀ alloy decreased after adding Sb-Zn or Sb-Ag but it increased after adding Al-Cd or Al-Cu. The corrosion current density (icorr) of Bi60Sn40 alloy varied after adding alloying elements.

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