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Effects of In and Ga on Spreading Performance of Ag10CuZnSn Brazing Filler Metal and Mechanical Properties of the Brazed Joints

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Abstract: Ag-based brazing filler metals are preferred in many industries, but the high price of Ag restricts their wider application. Therefore, developing novel low-Ag brazing filler metals has aroused extensive interest. In this study, the effects of the In and Ga elements on the melting behavior and spreading property of Ag10CuZnSn filler metal and the microstructure and strength of the brazed joints were investigated. The results show that both In and Ga can significantly decrease the solidus and liquidus temperatures of the filler metal. The In element can dissolve into the liquid filler metal and the Ga element can decrease the surface tension of the melted filler metal, which, in turn, improves the spreading area. The In element prefers to dissolve into the Ag-rich phase, and the Ga element prefers to dissolve into the Cu-rich phase; both improve the strength of the filler metal through solid-solution strengthening. The shear strength of the 304 stainless-steel brazed joint reached a peak value of 396 MPa when the Ag10CuZnSn-1.5In-2Ga (wt%) filler metal was used. However, the excessive addition of In and Ga forms brittle intermetallic compounds (IMCs) in the brazing seam, which decreases the strength of the brazed joint.

Keywords: low-Ag filler metal; melting temperature; spreading performance; microstructure; mechanical properties

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1. Introduction

Ag-based brazing filler metals have moderate melting points, excellent wetting and spreading properties as well as good thermal conductivity, electric conductivity and corrosion resistance, which make them the most suitable brazing filler metals for the joining of metals such as copper, iron, stainless steel and hard alloys [1–3]. Among them, the AgCuZnCd-series filler metals were the most widely used in the past [4–6], but the application of Cd-containing filler metals has been restricted due to the toxicity of Cd [7,8]. Moreover, the price of Ag is high, resulting in serious cost pressure on the Ag brazing filler metal industry. Therefore, developing Cd-free low-Ag brazing filler metals has significant social significance and application value.

Compared with the brazing filler metals with high Ag, the low-Ag brazing filler metals have significant cost advantages, but the decrease in the content of Ag directly results in problems such as high melting points and poor flowability, which limit the application of low-Ag brazing filler metals in industries such as air conditioning, refrigerators, motors and instruments [9–11]. Some previous studies have revealed that any element that can decrease the melting temperature of the main element in the brazing filler metal can also decrease the melting point of the filler metal alloy [12–14]. The main elements in low-Ag brazing filler metal are Ag, Cu and Zn, with melting temperatures of 961.78 °C, 1083.4 °C and 419.53 °C, respectively. The melting points of Ag and Cu are much higher than that of Zn. Therefore, the microalloying of low-Ag brazing filler for decreasing the melting temperature can be designed by studying Ag- or Cu-related phase diagrams.

According to the Ag-In, Cu-In, Ag-Ga and Cu-Ga phase diagrams [15], In and Ga can significantly decrease the melting points of Ag and Cu, and the prices of In and Ga are much lower than that of Ag. It has been shown that the solidus temperature and liquidus temperature of 30Ag-Cu-Zn brazing filler metal decrease from 690 °C and 770 °C to 652 °C and 710 °C, respectively, with the addition of the In and Ga elements. Moreover, the wettability, microstructure and mechanical properties of the filler metal are also remarkable [16], but the silver content is as high as 30 wt.%, which is expensive.

In this study, the Ag10CuZnSn low-Ag brazing filler metal was selected as the basic alloy, different contents of In and Ga were added to it and the influences of the two elements on the solidus and liquidus temperatures and spreading performance of the low-Ag brazing alloy were investigated. Moreover, the influences of In and Ga on the microstructure of the filler metal and the mechanical properties of the joint brazed with these filler metals were also studied in order to obtain a Cd-free low-Ag brazing filler metal with an obvious Ag saving effect and excellent brazing performance.

2. Materials and Methods

The raw materials used to prepare the filler metals were Ag, Zn and Sn ingots, In blocks and Ga blocks with a purity of 99.99% and electrolytic Cu plates with a purity of 99.9%. The smelting was carried out under laboratory conditions using an intermediate-frequency induction furnace (frequency: 600 Hz; power: 50 KW). The weighed Cu plate and Ag ingot were first put into a crucible and then covered with a covering agent and induction-heated. After the Cu and Ag were melted, the Zn ingots were added, and the power of the furnace was turned to 5 KW. Then, the Sn, In and Ga were added. The liquid alloy was stirred, skimmed to remove the slag, kept for a while and then poured into the steel molds to obtain ingots. The ingots were peeled, mechanically polished, extruded into a wire embryo with a 2.5 mm diameter and then prepared into a wire with a diameter of 2.0 mm through drawing, straightening and pickling. The designed compositions of the novel low-Ag brazing filler metals used in this study are listed in Table 1.

Table 1. Chemical compositions of the Ag10CuZnSn-xIn-yGa low-Ag brazing filler metals.

Number	Contents of Alloy Elements (wt%)					
	Ag	**Zn**	**Sn**	**In**	**Ga**	**Cu**
1	10	40.16	1.5	0	0	Bal.
2	10	39.34	1.5	1.5	0	Bal.
3	10	38.76	1.5	1.5	1	Bal.
4	10	38.21	1.5	1.5	2	Bal.
5	10	37.67	1.5	1.5	3	Bal.
6	10	36.83	1.5	3	3	Bal.

A differential thermal analyzer (DTA) (type: HCR-1) was used to measure the melting behaviors of the low-Ag filler metals. The weight of each specimen was controlled to be 20 ± 1 mg, the test temperature range was selected to be 25~900 °C and the heating rate was 10 °C/min. During the test, N_2 was introduced for protection, and the gas flow rate was 200 mL/min.

The wettability tests of the filler metals were conducted according to the Chinese national standard GB/T 11364-2008 "Test Method for Wettability of Brazing Filler Metals" [17]. The base materials were the commercial T2 Cu plate and 304 stainless-steel plate with a size of 40 mm × 40 mm × 2 mm. Before the test, the surfaces of the plates were polished with sandpaper, followed by chemical cleaning and air drying to remove the oil stains and oxide films. The samples controlled to be 200 ± 5 mg in weight were placed at the center of the test plates and covered with some FB102 brazing flux. The samples were put into a box-type resistance furnace with a temperature of 860 °C, kept for 1 min and then taken out. After that, the spreading areas of the filler metals were calculated using Image-Pro Plus software. Five parallel specimens were tested for each group of filler metals to ensure the accuracy of the test results.

Shear strength tests of the flame-brazed T2 Cu/304 stainless-steel and 304 stainless-steel/304 stainless-steel lap joints were conducted according to the Chinese national standard GB/T 11363-2008 "Test Methods for Strength of Brazed Joints" [18], and the FB102 brazing flux was used. The size of the lap-joint specimen was 80 mm × 25 mm × 2 mm, and the test was carried out via an electronic universal tensile testing machine (type: SANS-CMT5105) under a cross-beam speed of 5 mm/min. Five specimens were tested for each group of specimens to obtain the average value.

The cross-section specimens of the filler metal alloys and brazed joints were prepared via spark wire cutting. After embedding, grinding and polishing, the specimens were corroded with a corrosion agent of ammonium persulfate (15 g) + ammonia water (2 mL) + distilled water (100 mL) for 8 s. Microstructures of the brazing filler metals and the brazing seams were observed using a field-emission Scanning Electron Microscope (SEM) (type: ZEISS Σ IGMA 500, Oberkochen, Germany), and the compositions at different locations were analyzed using an Energy-Dispersive Spectrometer (EDS) (type: Bruker Nano XF Lash Detector 5010, Bruker, Massachusetts, MA, USA) equipped on the SEM. In addition, the phase compositions of the brazing alloys were ascertained using an X-ray diffractometer (XRD) (Bruker D8 Advance, Billerica, MA, USA) with Cu Kα radiance.

3. Results and Discussion

3.1. Effects of In and Ga on Melting Behaviors of Ag10CuZnSn Filler Metal

The solidus and liquidus temperatures of the Ag10CuZnSn-xIn-yGa brazing filler metals are shown in Figure 1. It was found that with the continuous increase in the In and Ga contents, the solidus and liquidus temperatures of the Ag10CuZnSn-xIn-yGa filler metal decrease. Compared with the Ag10CuZnSn basic alloy, the solidus temperature and liquidus temperature decrease by 16 °C and 19 °C when the content of the In element is 1.5 wt%, respectively, and the melting temperature range also decreases. This is because the melting temperature of In is only 156.61 °C, and a trace amount of the In element can dissolve into the Ag-rich phase and the Cu-rich phase in the Ag10CuZnSn filler metal and significantly decrease the melting temperature [19], whereas when the addition amount of In is 3 wt%, the decreasing trend of the liquidus temperature begins to slow down (see filler metal No. 6 shown in Figure 1). As the content of Ag in the Ag10CuZnSn-xIn-yGa filler metals is only 10 wt%, just a small amount of In can be dissolved in the Ag-rich phase. The solid solubility of In in the Cu-rich phase decreases sharply with decreasing temperature, and it is very low at room temperature; therefore, when the addition of In reaches 3 wt%, the excessive In cannot dissolve in the Ag-rich phase or Cu-rich phase but exists in the form of Ag-In and Cu-In intermetallic compounds (IMCs) [20]. As a result, the effect of In on decreasing the liquidus temperature of the Ag10CuZnSn-xIn-yGa filler metal is weakened.

When the In content in the Ag10CuZnSn-xIn-yGa filler metal is 1.5 wt.%, both the solidus and liquidus temperatures of the filler metal decrease with the increasing Ga content, and the decreasing trend of the solidus temperature is greater, making the melting temperature range increase (see filler metal Nos. 3–5 in Figure 1). During the brazing process, a larger melting-temperature range can more easily lead to the formation of segregation and residual oxide slag and will decrease the fluidity, and, in turn, deteriorate the spreading performance of the filler metal and the mechanical properties of the brazed joints [21]. The melting point of Ga is only 29.8 °C, and its influence mechanism on the melting temperature of the Ag10CuZnSn-xIn-yGa filler metal is similar to that of the In element, mainly via solid solutions and the formation of low-melting-point IMCs. Unlike the In element, the solid solubility of the Ga element in the Cu-rich phase is quite high. As the content of Cu in the Ag10CuZnSn-xIn-yGa filler metals is the highest, the Ga element can give full play to its effect on decreasing the melting temperature. Therefore, when the content of Ga is 1~3 wt%, the solidus and liquidus temperatures of the filler metal continue to decrease with the increasing Ga content.

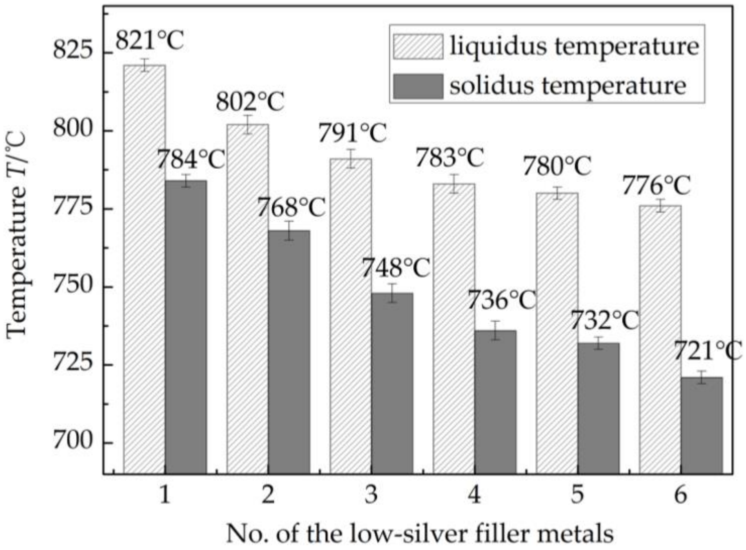

Figure 1. The solidus and liquidus temperatures of the Ag10CuZnSn-xIn-yGa low-Ag brazing filler metals. Sample numbers 1–6 are the same as in Table 1.

3.2. *Effects of In and Ga on Spreading Performance of Ag10CuZnSn Filler Metal*

The spreading areas of the Ag10CuZnSn-xIn-yGa filler metals on the T2 Cu and 304 stainless-steel plates are presented in Figure 2. It can be seen that when the addition amount of In is 1.5 wt%, the spreading areas of the filler metal on the T2 Cu plate and 304 stainless-steel plate increase by 18.1% and 23.7%, respectively, indicating that the spreading performance of the filler metal is significantly improved. With the composite addition of In and Ga, the spreading areas of the filler metals on the T2 Cu and 304 stainless-steel test plates increase continuously.

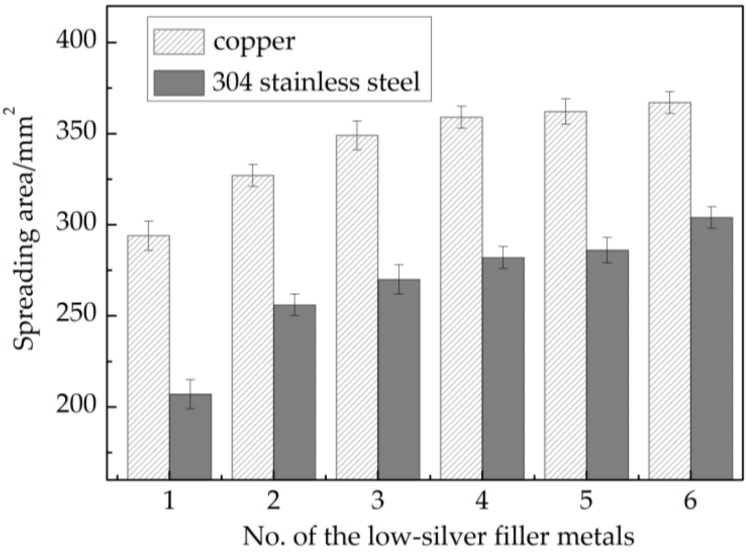

Figure 2. Spreading areas of the Ag10CuZnSn-xIn-yGa low-Ag filler metals on the T2 Cu and 304 stainless-steel plates. Sample numbers 1–6 are the same as in Table 1.

Compared with the main elements of Ag, Cu and Zn in the low-Ag filler metals, the surface tensions of liquid In and Ga are lower, as shown in Table 2. During the spreading test, In and Ga tend to accumulate at the surface of the filler metals to form positive adsorption, which decreases the surface free energy of the liquid filler metal and significantly improves the spreading area on the test plates [22,23]. Moreover, the superheat degree of the filler metal with a lower melting temperature is greater at the same brazing temperature. As the In and Ga decrease the melting temperature of the filler metal, the force of the internal atoms of the filler metal to the surface atoms will be weakened; therefore, the viscosity of the liquid filler metal will decrease, and the fluidity will be improved [24].

Table 2. Surface tensions of components in the Ag10CuZnSn-xIn-yGa brazing filler metals.

Element	Temperature (°C)	Surface Tension (10^{-5} N/cm)
Ag	960.8	930
Cu	1200	1300
Zn	419.5	824
Sn	231.9	566
In	157	559
Ga	29.8	735

It should be noted that the addition of In and Ga results in the formation of wetting rings during the spreading tests. Figure 3 shows the high-magnification backscattered electron image of the wetting ring around the Ag10CuZnSn-1.5In-2Ga filler metal on the T2 Cu plate, and the EDS analysis results of different areas in the wetting ring are shown in Table 3. From the image, it can be seen that the wetting ring is mainly composed of a white river-like area (Area A) and a gray island-like area (Area B). The content of Cu in Area B is 96.73 wt%. Thus, it can be determined that the gray island-like area is the T2 Cu plate rather than the Cu-rich phase because the contents of alloy elements in it are very low. In contrast, Area A contains the Ag, In, Cu and Sn elements, and the contents of Ag, In and Sn are 79.23 wt%, 9.74 wt% and 2.41 wt%, respectively, which are significantly higher than their contents in the filler metal. Therefore, it can be assumed that the white river-like structure is an Ag-based solid solution rich in the In and Sn elements.

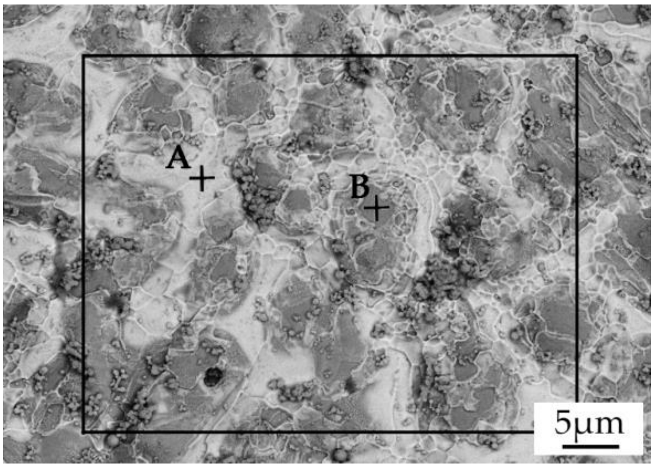

Figure 3. SEM image of the wetting ring around the Ag10CuZnSn-1.5In-2Ga filler metal. Area A: white river-like; Area B: gray island-like.

Table 3. Compositions at Areas A and B in Figure 3 characterized via EDS.

Location	Ag	Cu	Zn	Sn	In	Ga
A	79.23	7.06	0.94	2.41	9.74	0.62
B	0.81	96.73	1.14	0.27	0.49	0.56

To reveal the distribution of elements in the wetting ring, an area scanning analysis was performed on the wetting ring shown in Figure 3, and the obtained results are shown in Figure 4. It can be clearly seen that the Ag, In and Sn elements overlap with the white river-like area, while the Cu element overlaps with the gray island-like area, and the distributions of Ga and Zn are relatively uniform, with no significant enrichment. The analysis results above indicate that the formation of the wetting rings is mainly related to the Ag, In and Sn elements, while the Ga element does not participate in the formation of the wetting rings (i.e., the influence mechanisms of the Ga element on the spreading performance of the filler metals are different from those of the In element). It has been revealed that the formation of a wetting ring is positive for the wetting and spreading of the filler metals on the base material [25]. During the spreading test process of the Ag10CuZnSn-1.5In-2Ga filler metal, the Ag, In and Sn elements can expand more rapidly along the grain boundaries or the capillary wear marks of the base metal in a solid-state atomic diffusion manner [26], which decreases the interfacial tension between the liquid filler metals and the base metals. Therefore, adding 1.5 wt% of In can significantly increase the spreading area of the Ag10CuZnSn filler metal on T2 Cu and 304 stainless-steel plates.

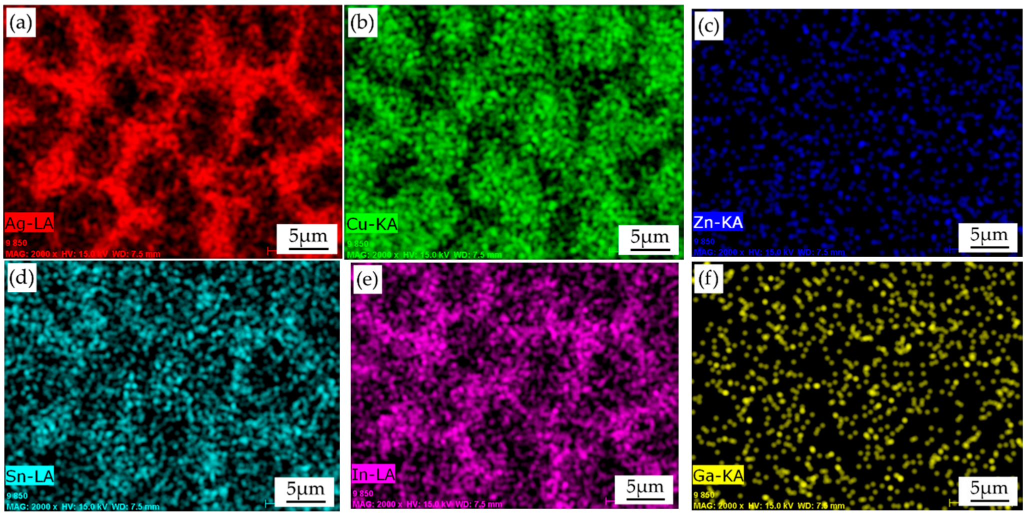

Figure 4. Elemental distribution images of wetting rings around the Ag10CuZnSn-1.5In-2Ga filler metal: (**a**) Ag, (**b**) Cu, (**c**) Zn, (**d**) Sn, (**e**) In, (**f**) Ga.

3.3. *Effects of In and Ga on Microstructure of Ag10CuZnSn Filler Metal*

Figure 5 shows the microstructures of the Ag10CuZnSn-xIn-yGa filler metals, and Table 4 shows the EDS analysis results of points A~D in Figure 5. It has been revealed that AgCuZnSn brazing alloys with low Ag contents are composed mainly of needle-shaped Ag-based solid solutions, bulk Cu-based solid solutions and the CuZn compound [9]. Based on this and the results in Table 4, it can be inferred that the white needle-shaped structure is the Ag-based solid solution, and that the In and Sn contents in the Ag-based solid solution are relatively high. The gray matrix structure is a mixed phase of the Cu-based solid solution and CuZn compound, and its content of Ga is relatively high.

Table 4. Compositions of points A~D in Figure 5 characterized via EDS.

Location	**Contents of Alloy Elements (wt%)**					
	Ag	**Cu**	**Zn**	**Sn**	**In**	**Ga**
A	42.60	30.41	20.66	2.53	3.06	0.74
B	4.08	58.14	34.80	0.55	0.62	1.81
C	5.21	55.93	32.98	0.67	1.02	4.19
D	14.62	42.73	30.19	2.91	8.29	1.26

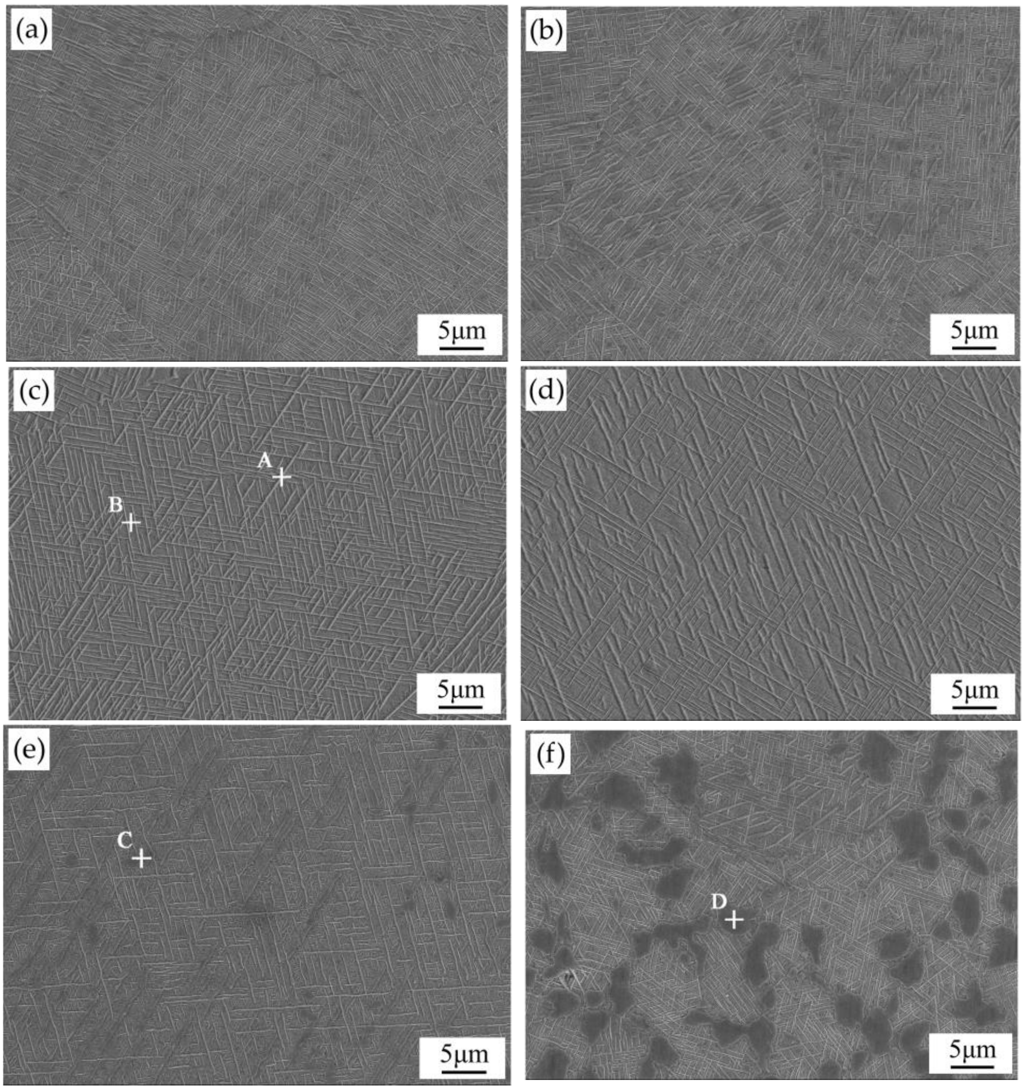

Figure 5. Microstructures of the Ag10CuZnSn-xIn-yGa brazing filler metals: (**a**) Ag10CuZnSn, (**b**) Ag10CuZnSn-1.5In, (**c**) Ag10CuZnSn-1.5In-1Ga, (**d**) Ag10CuZnSn-1.5In-2Ga, (**e**) Ag10CuZnSn-1.5In-3Ga, (**f**) Ag10CuZnSn-3In-3Ga.

When the addition amount of In is 1.5 wt%, the microstructure and morphology of the low-Ag filler metal are similar to those of the Ag10CuZnSn, both of which have a network structure. With the further addition of 1 wt% of Ga based on this, the needle-like Ag-based solid solution becomes more obvious, and the structure is coarser. When the Ga content increases to 3 wt%, the Ag-based solid solution gradually becomes wormlike, whereas when the contents of In and Ga both increase to 3 wt%, blocky new phases appear in the filler metal, which distribute randomly in the matrix structure. The EDS analysis results presented in Table 4 show that the In content in Region D is 8.29 wt%, much higher than the proportion of In in the filler metal, indicating that the In element is enriched in the block phase. Figure 6 shows the XRD pattern of the Ag10CuZnSn-3In-3Ga filler metal, in which a diffraction peak of Cu_4In can be seen. Therefore, it can be inferred that the In-rich phase is a Cu_4In IMC. A previous study has shown that the brittle Cu_4In IMC particles can generate significant stress concentrations around themselves and decrease the mechanical properties of the brazing filler metal [27].

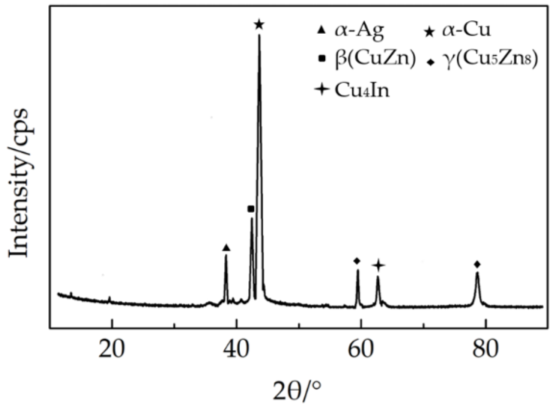

Figure 6. XRD pattern of the Ag10CuZnSn-3In-3Ga filler metal.

3.4. Effects of In and Ga on Microstructure of Ag10CuZnSn/304 Stainless-Steel Brazed Joints

The microstructures of the Ag10CuZnSn-xIn-yGa filler metals/304 stainless-steel brazing interface are shown in Figure 7, and the EDS analysis results of some areas are presented in Table 5. It can be seen that the microstructures of the brazed joints change obviously with the addition of In and Ga. Because the AgCuZnSn filler metals with low Ag contents are composed mainly of Cu-based solid solutions (α-Cu), Ag-based solid solutions (α-Ag) and secondary solid solutions based on CuZn compounds (β-CuZn) [28], it can be inferred from the results in Table 5 that the gray block-like structure in the brazed joints is the α-Cu phase, the white network structure is the eutectic structure of the α-Ag and α-Cu phases and the content of the CuZn phase is relatively low.

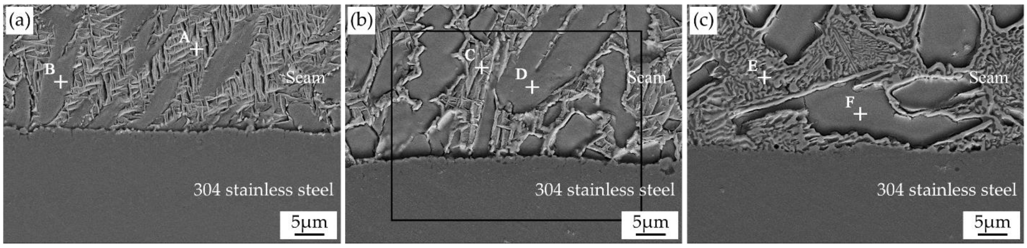

Figure 7. Microstructures of the Ag10CuZnSn-xIn-yGa filler metals/304 stainless-steel brazing interface: (**a**) Ag10CuZnSn, (**b**) Ag10CuZnSn-1.5In-2Ga, (**c**) Ag10CuZnSn-3In-3Ga. Points A and B are in Figure (**a**); Points C and D are in Figure (**b**); Points E and F are in Figure (**c**).

Table 5. Compositions of points A~D in Figure 7 characterized via EDS.

Location	Content of Alloy Elements (wt%)					
	Ag	**Cu**	**Zn**	**Sn**	**In**	**Ga**
A	44.82	30.43	21.27	3.48	-	-
B	5.74	59.38	34.31	0.57	-	-
C	43.69	27.08	19.84	3.55	4.68	1.16
D	4.36	55.75	35.67	0.61	0.77	2.84
E	46.81	24.59	15.75	3.42	7.71	1.72
F	4.58	55.84	33.04	0.87	1.14	4.53

From the analysis results of points C~F in Table 5, it can be found that there is a relatively high content of the In element in the Ag-based solid solution, and the content of Ga in the bulk Cu-based solid solution is also relatively high. The atomic radii of the In, Ga, Ag and Cu elements are 2.00 Å, 1.35 Å, 1.44 Å and 1.27 Å, respectively. As their difference in atomic radii is not so serious, trace amounts of In and Ga mainly dissolve into the Ag-rich phase and Cu-rich phase under a substitutional mode and may form a "Cottrell atmosphere", which improves the strengths of the filler metals and brazed joints [29,30].

To reveal the element distribution in the brazing joint, area scanning analysis was performed on the black box in Figure 7b, and the results are shown in Figure 8. It is obvious that the Ag, In and Sn elements overlap with the network eutectic structure in the brazing seam, and the Cu element is more concentrative in the gray-block Cu-based solid solution. The alloy elements in the filler metal diffuse significantly into the 304 stainless-steel base material, and the diffusion of the In and Sn elements is more pronounced at the brazing-seam/304 stainless-steel interface. Moreover, a few Fe, Cr and Ni elements in the stainless steel also dissolve in the brazing seam. These results indicate that when the addition amounts of Ga and In are 2 wt% and 1.5 wt%, respectively, fine metallurgical bonding is formed between the 304 stainless-steel base material and the filler metal. However, when both the contents of In and Ga increase to 3 wt%, the In content in the eutectic structure of the brazed joint reaches 7.71 wt%. Combined with the XRD results of the Ag10CuZnSn-3In-3Ga filler metal, it can be inferred that there are Cu_4In IMCs in this eutectic structure, which will become crack sources and decrease the mechanical properties of the brazed joint [31].

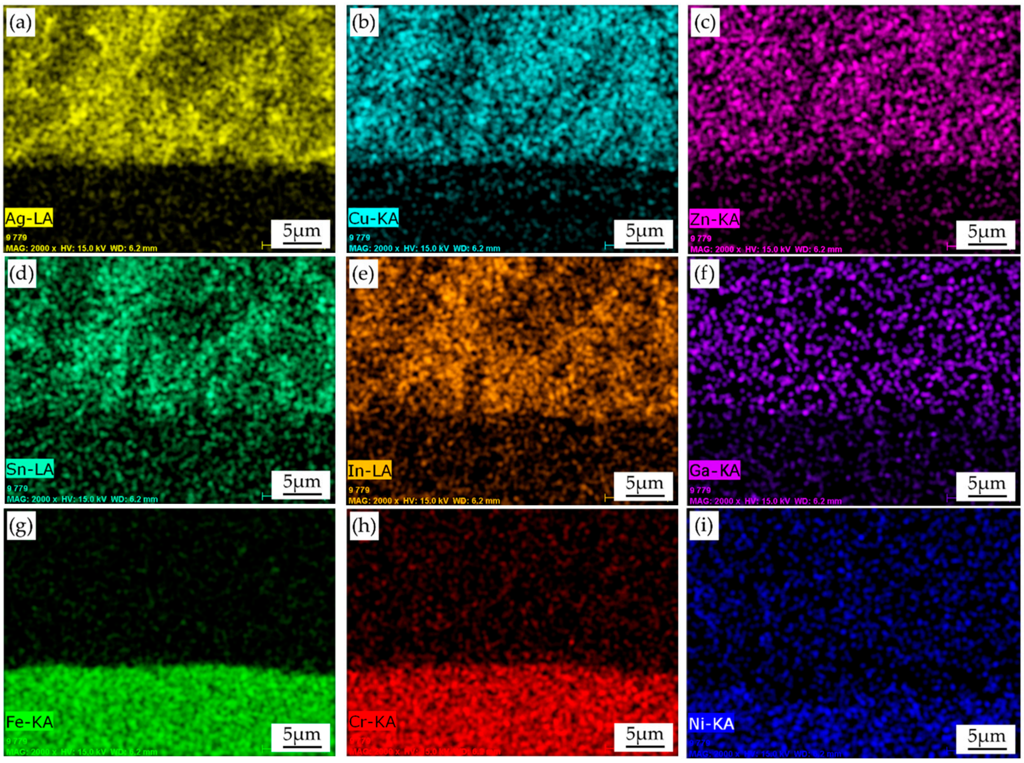

Figure 8. Elemental distribution images of the joint brazed with Ag10CuZnSn-1.5In-2Ga filler metal: (**a**) Ag, (**b**) Cu, (**c**) Zn, (**d**) Sn, (**e**) In, (**f**) Ga, (**g**) Fe, (**h**) Cr, (**i**) Ni.

3.5. Effects of In and Ga on Shear Performance of Ag10CuZnSn/304 Stainless-Steel Brazed Joint

The T2 Cu/304 stainless-steel and 304 stainless-steel/304 stainless-steel lap joints were flame-brazed using the Ag10CuZnSn-xIn-yGa filler metals. The shear test results of the brazed joints show that the fracture of the 304 stainless-steel/304 stainless-steel joints occurs in the brazing seam, while the T2 Cu/304 stainless-steel brazed joints fracture on the Cu side (as shown in Table 6), indicating that the strength of the joint is higher than that of the T2 Cu plate itself, and that T2 Cu/304 stainless-steel joints with excellent mechanical properties are achieved. Figure 9 shows the effect of the In and Ga addition on the shear strength of the 304 stainless-steel/304 stainless-steel joints. Compared with the Ag10CuZnSn basic alloy, the shear strength of the joint brazed with the No.1 filler metal containing 1.5 wt% of In increases significantly. The shear strength of the brazed joint first increases and then decreases with the continuous increase in the Ga content when the In content is 1.5 wt%, and it reaches a maximum value of 396 MPa when the content of Ga is

2 wt%. With higher contents of Ga or In, the shear strengths of the joints decrease, but they are still higher than that brazed with the basic alloy. Based on this, it can be concluded that T2 Cu and 304 stainless-steel brazed joints with excellent shear strength can be obtained using Ag10CuZnSn low-Ag filler metals with trace amounts of In and Ga.

Table 6. Shear strengths and fracture locations of Cu/304 stainless-steel joints brazed using different Ag10CuZnSn-xIn-yGa filler metals. Sample numbers 1–6 are the same as in Table 1.

Filler Metal Number	Shear Strength (MPa)	Fracture Location
1	288	Cu plate
2	289	Cu plate
3	287	Cu plate
4	289	Cu plate
5	290	Cu plate
6	289	Cu plate

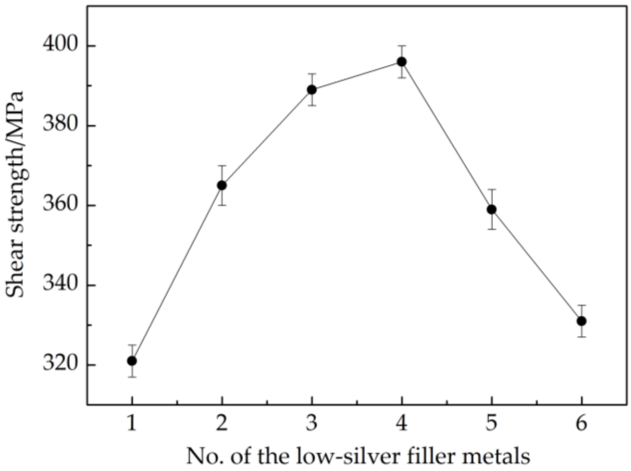

Figure 9. Shear strengths of the 304 stainless-steel/304 stainless-steel joints brazed using different Ag10CuZnSn-xIn-yGa low-Ag filler metals.

Figure 10 shows the shear fracture morphologies of the joints brazed with different Ag10CuZnSn-xIn-yGa filler metals. There are a large number of ductile dimples in the fracture surface of the joint brazed using the Ag10CuZnSn basic alloy, as presented in Figure 10a, which demonstrates obvious ductile-fracture characteristics. With the addition of 1.5 wt% In and 2 wt% Ga elements, the width and depth of the dimples in the fracture surface increase (see Figure 10b), and there are no defects, such as pores or inclusions. However, when the contents of the In and Ga elements both increase to 3 wt%, smooth blocky phases appear in the fracture surface, as shown in Figure 10c.

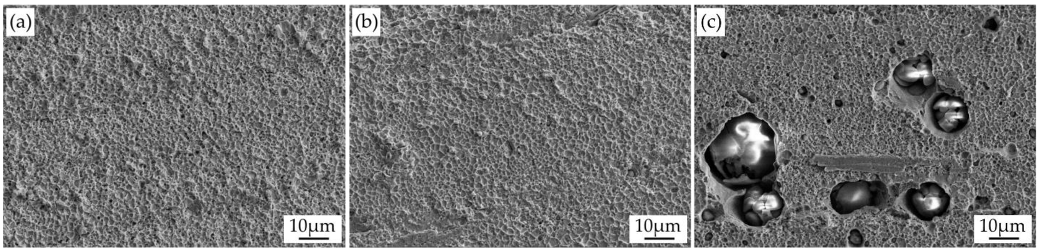

Figure 10. Shear fracture morphologies of the 304 stainless-steel joints brazed using Ag10CuZnSn-xIn-yGa filler metals: (**a**) Ag10CuZnSn, (**b**) Ag10CuZnSn-1.5In-2Ga, (**c**) Ag10CuZnSn-3In-3Ga.

The distributions of the elements in Figure 10c characterized via EDS are shown in Figure 11, from which it can be seen that the smooth block phase overlaps with the In element, while some of the Cr element dissolves in the block phase, demonstrating that the block phase is an IMC rich in In and Cr elements. Under the action of shear force, stress concentration can easily generate around the IMC-phase particle, making it become the crack source and decreasing the shear strength. Therefore, the addition amounts of In and Ga in the Ag10CuZnSn low-Ag brazing filler metal should not be too high, and the optimal addition amounts are 1.5 wt% and 2 wt%, respectively.

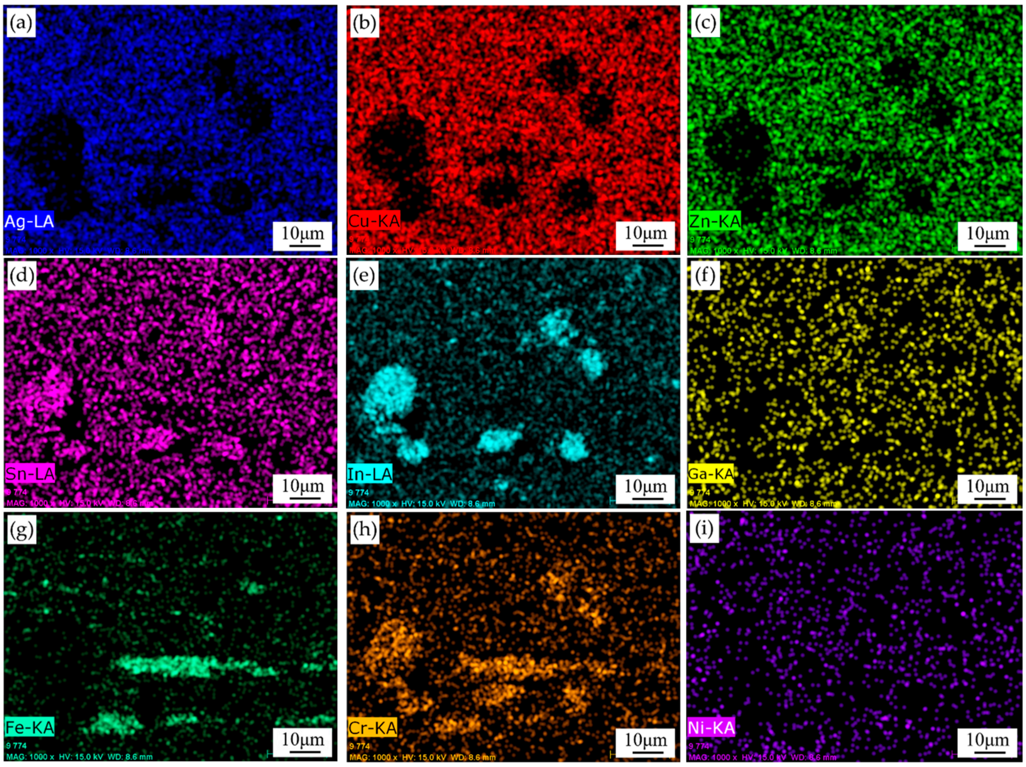

Figure 11. Elemental distribution on shear fracture surface of the 304 stainless-steel/304 stainless-steel lap joint brazed using Ag10CuZnSn-3In-3Ga filler metals: (**a**) Ag, (**b**) Cu, (**c**) Zn, (**d**) Sn, (**e**) In, (**f**) Ga, (**g**) Fe, (**h**) Cr, (**i**) Ni.

4. Conclusions

(1) The In added to the Ag10CuZnSn low-Ag brazing filler metal mainly dissolved in the Ag-based solid solution, and the Ga mainly dissolved in the Cu-based solid solution, which obviously decreased the solidus and liquidus temperatures of the filler metals. When the contents of In and Ga were both 3 wt%, blocky Cu_4In IMCs appeared in the filler metal;

(2) The addition of In and Ga significantly increased the spreading area of the Ag10CuZnSn filler metal on the T2 Cu and 304 stainless-steel plates. The In element improved the spreading performance through dissolution in a large amount into the wetting ring and expanded more rapidly than the liquid filler metal, while the Ga increased the spreading area mainly by decreasing the surface free energy of the liquid filler metal;

(3) The Ag, In and Sn elements in the brazing seam mainly distributed in a network eutectic structure of α-Ag and α-Cu, and the In and Sn elements diffused obviously into the 304 stainless-steel base material. When the addition amounts of In and Ga were 1.5 wt% and 2 wt%, respectively, fine metallurgical bonding was formed between the filler metal and the 304 stainless-steel base material;

(4) The addition of In and Ga into the Ag10CuZnSn filler metal obviously improved the shear strength of the brazed joint, and the shear strength of the 304 stainless-steel/304 stainless-steel joint brazed with the Ag10CuZnSn-1.5In-2Ga filler metal reached the maximum value of 396 MPa. When the In and Ga contents were both

3 wt%, IMCs rich in In and Cr appeared around the brazed joint interface, and the shear strength decreased.

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