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Fabrication of automotive heat exchanger using kinetic spraying process

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Abstract

The conventional manufacturing process of the automotive brazed heat exchanger includes complex preparation processes before brazing: aluminum brazing filler alloy is pre-claded on both sides of a fin by an extrusion method, and holed aluminum tubes are coated on both sides with Zn for corrosion protection by a wire arc spraying process.

The intent of this study is to simplify the preparation process by kinetic spraying using all of the components, including Al–12%Si (for the brazing filler metal), Zn (for corrosion protection), and KAlF4 (flux powder). Four kinds of blended powders were evaluated with and without flux. The bond properties and composition distribution of composition at the braze joint area were evaluated by scanning electron microscope (SEM) and electron probe micro analyzer (EPMA).

In this study, kinetic spray condition was optimized, in order to fabricate the heat exchanger. It was observed that the joints of the brazed specimens at each side were sounder than that achieved by the conventional methods. It is necessary to control the Zn content to get the high corrosion resistance and good brazeability of the aluminum heat exchanger. Further, the kinetic sprayed heat exchanger showed acceptable corrosion protection.

Keywords: Brazed aluminum heat exchanger; Kinetic spraying; Electron probe micro analyzer; Corrosion

1. Introduction

In recent years, brazed aluminum heat exchangers have been increasingly introduced in air conditioning equipments for all types of vehicles [1,2]. The conventional manufacturing process of an automotive brazed heat exchanger includes complex preparation processes before brazing [2]: aluminum brazing filler alloy is pre-claded on both sides of a fin by an extrusion method, holed aluminum tubes are coated on both sides with Zn for corrosion protection by wire arc spraying process, and flux is used for assembling an Al tube with a claded fin by dipping and painting before brazing.

The kinetic spraying process is an emerging low temperature solid state particle impacting deposition technology. Deposition efficiency mainly depends on the velocity (kinetic energy) of in-flight particles rather than thermal energy, spray materials experience little microstructure change, oxidation, or decomposition. Furthermore, dense and thick coatings can be formed at a very high deposition rate by kinetic spraying [3–7]. Hence, novel kinetic spraying process is a promising candidate for simplifying the brazing process.

In this study, Al–Si–Zn coatings were deposited by kinetic spraying from Al–12%Si (for the brazing filler metal), Zn (for corrosion protection), and KAlF4 (flux powder) mixture feedstock. The aluminum heat exchanger manufacturing process is schematically shown in Fig. 1. As the Zn content plays an important role for improving the corrosion resistance and brazeability [8], four kinds of coatings with different Zn content were prepared and characterized. In addition, the effect of flux on the properties of the coatings was evaluated in order to realize the deposition without flux.

2. Experimental

In this study, a commercially available CGT kinetic spraying system was used. The equipments and the coating process are

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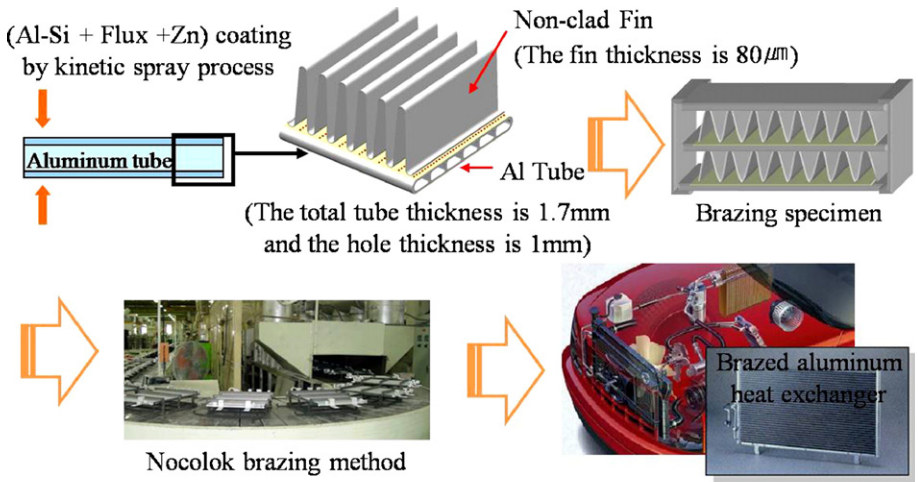

Fig. 1. Schematic process of the brazed aluminum heat exchanger manufacturing using kinetic spraying process.

described elsewhere [3–7]. A de Laval WC MOC type nozzle with a round exit was used. Nitrogen and helium were used as the process gases for the process. The detailed spray parameters are listed in Table 1. The feedstocks were Al–12%Si, Zn, and KAlF4 powders. An aluminum tube of a heat exchanger was used as the substrate. In order to investigate the effect of the flux and the Zn content on the brazing properties, four kinds of blended powder (with different Zn content) with and without flux were used. After coating, a scanning electron microscope (SEM) with back-scattered electrons and an energy dispersion X-ray spectroscope (EDS) were utilized to analyze the microstructure and composition of the coatings. An aluminum heat exchanger was assembled with an as-sprayed aluminum tube and a non-clad fin and subsequently brazed by the Nocolok brazing method [9] at 620 °C for 20 min. After brazing, the bond soundness and composition distribution at the brazing joint area were evaluated by SEM and electron probe micro analyzer (EPMA). In addition, the effect of Zn on the erosion of the aluminum tube after brazing was evaluated by SEM and image analysis methods. The corrosion resistance is tested by the on-site field test—SWAAT (Seawater Acetic Acid Test).

Table 1
The parameters of kinetic spraying process

Desig.	Al–12Si:Zn: flux [wt.%]	Process gas type	Process temperature (K)	Process pressure (bar)	Invariables
K1	70:30:0	Nitrogen	673/773	21/25/29	– Spray distance: 30 mm
K2	80:13:7				– Gun travel speed: 10 mm s^{-1}
K3	70:25:5				– Powder feed rate: 8 g min^{-1}
K4	60:34:6				
K5	70:30:0	Helium			
K6	80:13:7				
K7	70:25:5				
K8	60:34:6				

3. Results and discussion

3.1. Feedstock characteristics

One of the feedstocks used was Al–12Si filler powder with a size, ranging from 10 to 45 μm. The physical density and the melting point of the powder are 2.67 g/cm^3 and 850 K respectively. The detailed characteristics of the feedstock are listed in Table 2. The morphologies and the size distribution of Al–Si, Zn, and the flux powder particles are shown in Fig. 2. It is seen that the Al–Si and Zn powder feedstock are spherical in shape, and the flux powder is irregular in shape.

3.2. As-sprayed coating characteristics

The process parameters were optimized in order to get the high deposition efficiency (DE), as the coating thickness should be 50 μm for the high quality brazing and corrosion resistance. The deposition efficiency (DE), which is the weight fraction of the deposited coating to the total feed, was calculated for different deposition conditions, by changing the process gas pressure and temperature for optimizing the process. As shown in Table 3, the DE of the as-sprayed coatings prepared from nitrogen as the process gas is increased with the gas temperature and pressure.

The surface morphologies of as-sprayed coatings for different process gases at the same gas pressure and temperature are compared in Fig. 3. The Al tube substrate was crushed due to erosion, as shown in Fig. 3b, when helium

Table 2
Characteristics of the feedstock

Powder	Size (μm)	Morphology	Density (g/cm^3)	Melting point (K)
Al–Si	+10–45	Spherical	2.67	850
Zn	+1–7	Irregular	7.13	692
Flux	+6–12	Spherical	2.88	843

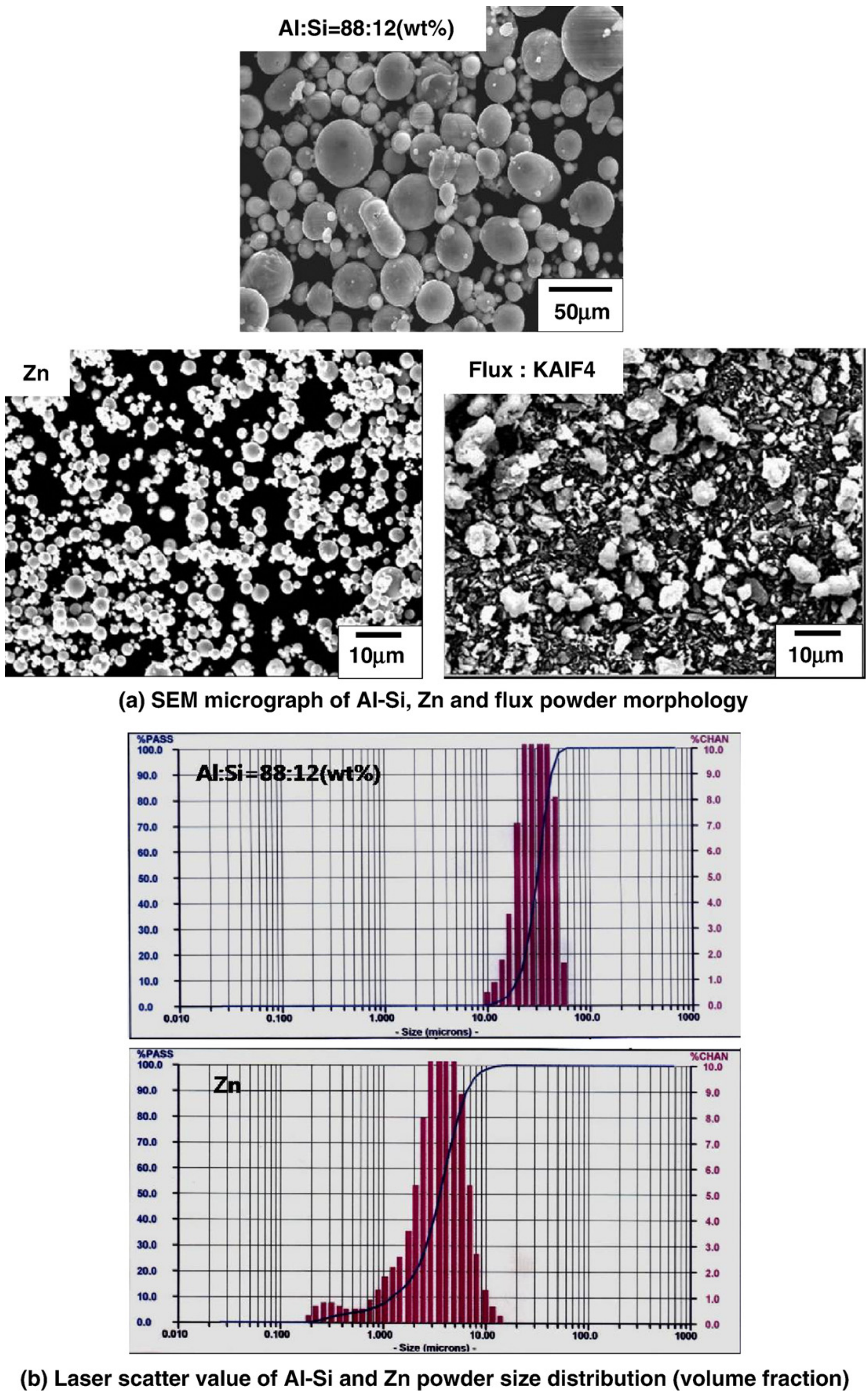

Fig. 2. The morphologies and size distribution of the feedstock.

Table 3
The deposition efficiency of as-sprayed coating for nitrogen process gas

Desig.	Al–12Si: Zn:flux [wt.%]	Process temperature (K)	Process pressure(bar)		
			21	25	29
			Deposition efficiency (%)		
K1	70:30:0	673	15	28	39
		773	27	41	55
K2	80:13:7	673	9	13	18
		773	18	20	26
K3	70:25:5	673	11	15	22
		773	15	19	30
K4	60:34:6	673	10	14	20
		773	16	22	32

was used as the process gas. This is possibly due to the excessive impact velocity and stress delivered by the powders on the thin walled aluminum tube, as the wall thickness is only 350 μm and the inner diameter is 1 mm. Hence, it was decided that the high impact particle velocity is unnecessary and the same was harmful, for the deposition on the aluminum substrate in this study.

The cross-sectional microstructures of the as-sprayed coatings are shown in Fig. 4. The as-sprayed K1 (no flux) coating is thicker than others (flux addition) as the flux is a salt with low ductility. The critical velocity of the same is higher than that of other soft components. The coating consists of three obvious phases as the dark grey contrast is Al–Si particles, the bright white contrast is Zn particles, and the dark white contrast is flux particles.

The composition of individual phases was measured by EDS after coating is given in Table 4. The zinc fraction in the as-sprayed coatings is higher than that of the initial feedstock, as it is known that the Al–Si powder has higher critical velocity than Zn powder during the deposition onto the substrate under the same spray conditions [10]. Thus the coating with proper Zn fraction could be achieved by the initial feedstock with low Zn fraction.

3.3. Effect of the flux on the soundness of brazed joint

After coating, an aluminum heat exchanger was assembled with the as-sprayed aluminum tube and a non-claded fin and was the same subsequently brazed by the Nocolok brazing method at 620 °C for 20 min. Generally, flux performs a number of important functions, such as displacement of the oxide layer from the surface, promotion of base metal wetting characteristics, and filler fluidity simultaneously during the brazing process [11,12]. Nevertheless, there are also disadvantages in using the flux. The post-braze removal of the flux is difficult, and the susceptibility to aqueous corrosion of parts is notable.

The cross-sectional microstructures of a brazed joint are shown in Fig. 5. It is seen that the K2, K3, and K4 brazed joints show good bonding which can be compared with the conventional one (Fig. 5e). Even though the K1 coating contains no flux, the brazed joint area shows a similar bonding property as the above three joints. No significant cracks or pores are found at the interface between the joint and the filler after brazing (Fig. 5a–d). Apparently, the flux is not indispensable for brazing the kinetic sprayed coatings. This is due to pre-wetting effect of the substrate surfaces by the pre-sprayed filler material.

In addition, in order to estimate the bonding property at the brazed joint, the joint length was measured (from "A" to "B" marked in Fig. 5a) in this study. The results (Table 5) show that the K1, K2, K3, and K4 brazed joint lengths are longer than that of the conventional products. Thus it is expected that the new heat exchanger joints have better thermal cycle (fatigue) resistance than the conventional one. As a result, the lifetime of the aluminum heat exchanger can be extended.

The composition distributions at the brazed joint area measured by EPMA are shown in Fig. 6. During the brazing process, silicon and Zn in the molten filler material diffuse into the grain boundaries of the fin and Al tube which is to be enriched, as shown in Fig. 6 [13]. Thus it can be expected that the brazing time and the temperature were enough to diffuse the fin and Al tube during the brazing process.

3.4. Effect of the Zn content on the brazeability

The fraction of Zn in the as-sprayed coating plays an important role in the brazeability and corrosion resistance of the

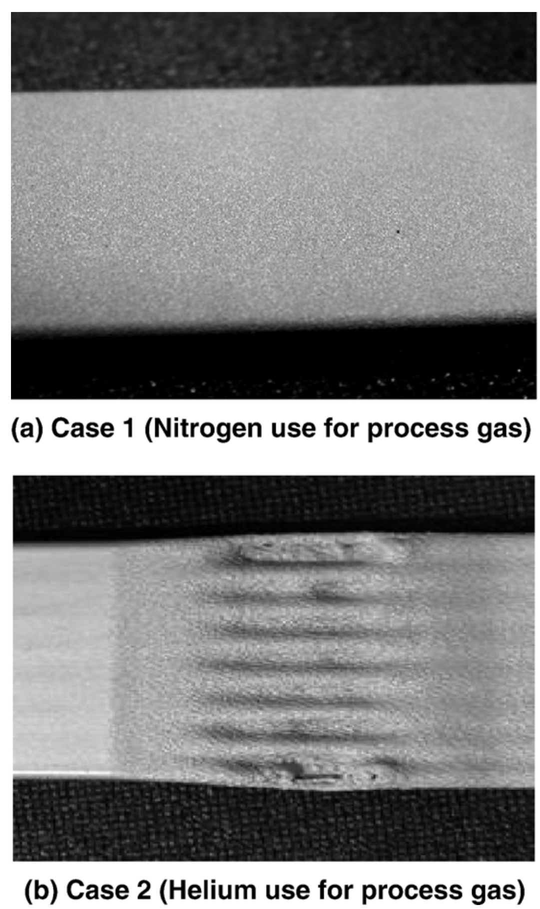

Fig. 3. The surface morphology of as-sprayed coating according to process gas type.

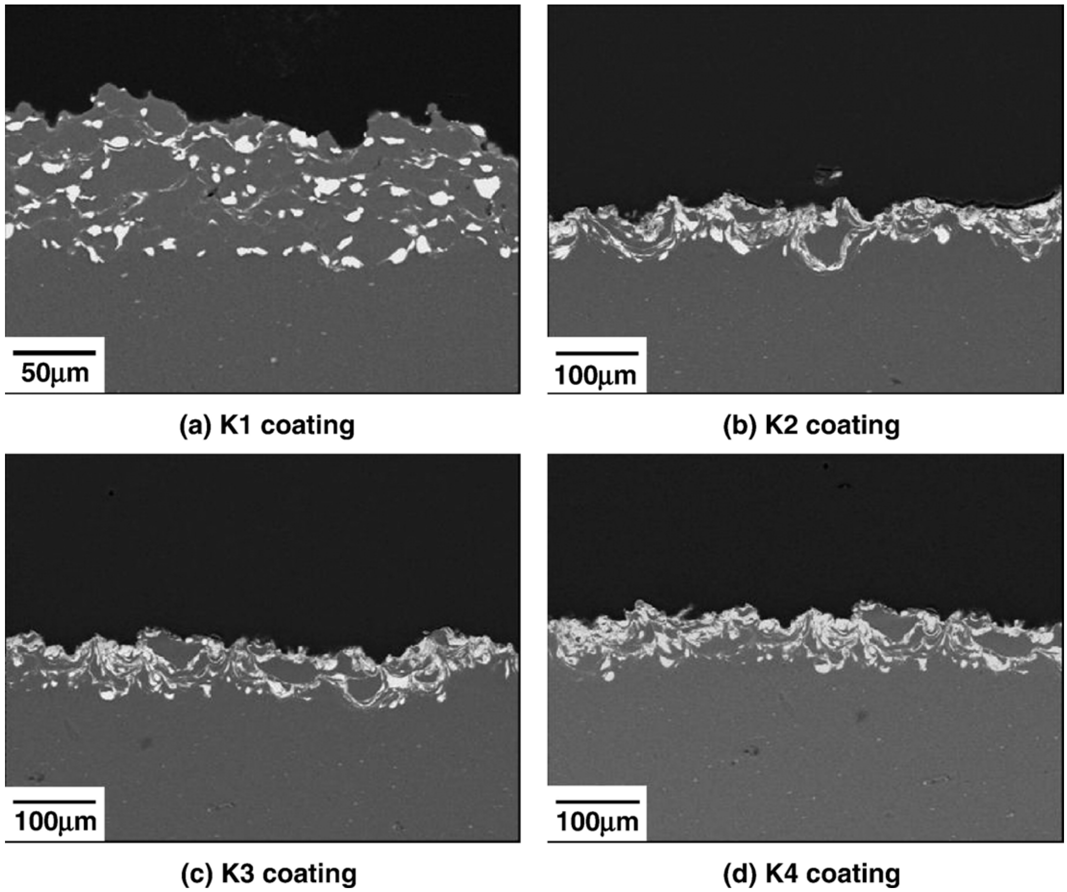

Fig. 4. The cross-sectional microstructures of the as-sprayed coating.

heat exchanger by lowering both the solidus and liquidus temperature and as a sacrifice anode, respectively. The corrosion resistance and the lifetime of the heat exchanger are improved with the increase of Zn content in the coating.

However, high Zn content reduces Al tube thickness and induces the formation of holes between fin and tube due to surface tension of melted Al tube, as shown in Fig. 7a. The formation of the holes decreases the brazeability of the coated Al tube as the number of holes during brazing depends on the Al tube thickness change, the Al tube thickness after brazing could be used to evaluate its brazeability.

The original Al tube thickness is decreased, by liquid erosion, with the increase of the content of Zn in the as-sprayed coating. The Zn and Al–Si are melted at the brazing temperature (900 K) and Zn and Si are diffused into the Al base metal. Suzuki et al. [14] found that by increasing the Zn addition to the Al–12Si filler metal from 0 to 50 wt.%, the eutectic points of such ternary Al–Si–Zn alloys decreased linearly from 850 to 798 K. The liquid metal re-solidifies after a dwell, during which Zn diffusion within the joint and into the Al base metal continues. This is associated with base metal dissolution, liquid penetration, and ultimately with Al tube erosion. In the molten phase, the melt has a different phase composition as the solid Zn melts earlier. From the Al–Zn binary phase diagram (Fig. 7b) at a brazing temperature of 900 K, the equilibrium state of Zn content is 25 wt.%. If the content of Zn in the coating is above 25%, such as 45 wt.% in K4 case, the Zn melts faster than Al to keep the equilibrium state at 900 K. Therefore, if additional melting of the Al tube occurs, constitutional liquidation occurs. The reduction of the Al tube thickness in the case of K4 is much higher than that of K2, due to the formation of the rich Zn phase (shown in Fig. 7c). Then at a local point near the joint, holes are formed in that walled tube, due to the reduction of the Al tube thickness surface tension of melted Al tube. Therefore, it is necessary to control the Zn content, in order to balance the corrosion resistance and brazeability of the aluminum heat exchanger.

3.5. Leak and corrosion tests

In general, the flux is always used to remove the surface oxides in order to get a dense joint during brazing. In the present paper,

Table 4
Chemical compositions of initial feedstock and as-sprayed coating

Desig.	Composition of initial feedstock (Al:Si:Zn [wt.%])	Composition of as-sprayed coating (Al:Si:Zn [wt.%])
K1	64.5:8.8:26.7	61.7:7.3:31.0
K2	74.5:10.1:15.4	69.6:9.1:21.3
K3	64.5:8.8:26.7	57.1:6.7:36.2
K4	56.9:7.8:35.3	48.3:6.2:45.5

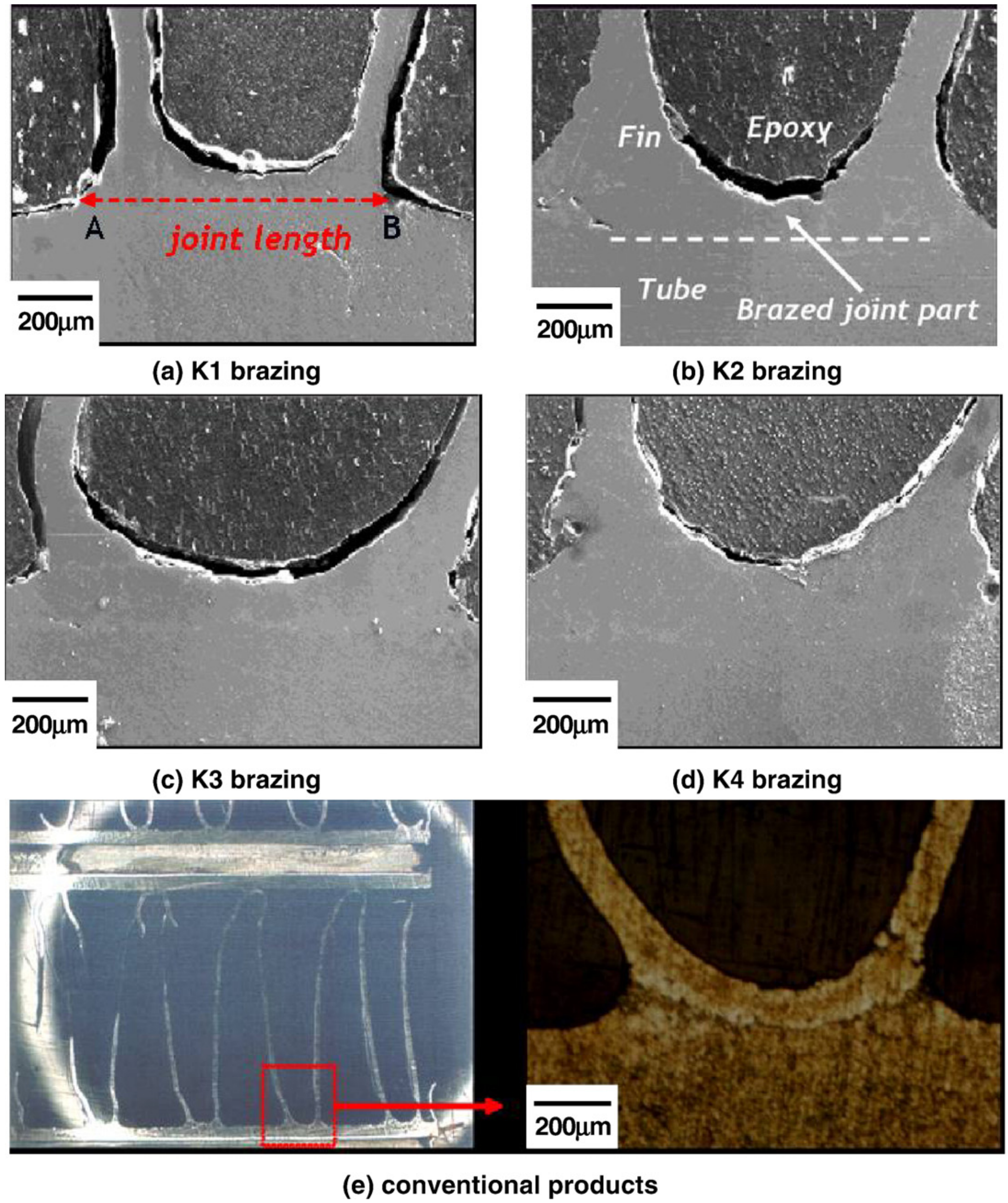

Fig. 5. Cross-sectional microstructures of the joint after brazing.

coating without flux by kinetic spray technology was proposed to improve the simplified brazing process. Then, it is necessary to test the leak and corrosion resistance for the joint prepared by kinetic spray coating. An automobile heat exchanger was fabricated for K1 without flux addition by using the kinetic process as shown in Fig. 8a. In order to find the occurrence of holes during brazing, a leak test was conducted with water pressure. There was no evidence for any detectable leak, which is shown in Fig. 8a. In addition, a corrosion test was conducted in saltwater acetic acid (SWAAT TEST) environment to evaluate the lifetime of the novel heat exchanger. No leak was occurred after corrosion for 500 h (Fig. 8b). Hence, assembly of the brazed heat exchanger manufactured by the kinetically sprayed components revealed good brazing and corrosion resistance. This realizes simplification of the manufacturing process.

Table 5
The average length at the brazed joint area

Desig.	Average length (μm)
K1	710
K2	888
K3	912
K4	918
Conventional products	687

4. Conclusions

(1) The kinetic spraying technique is a simple and healthful way to manufacture the automotive Al-tube heat exchanger.

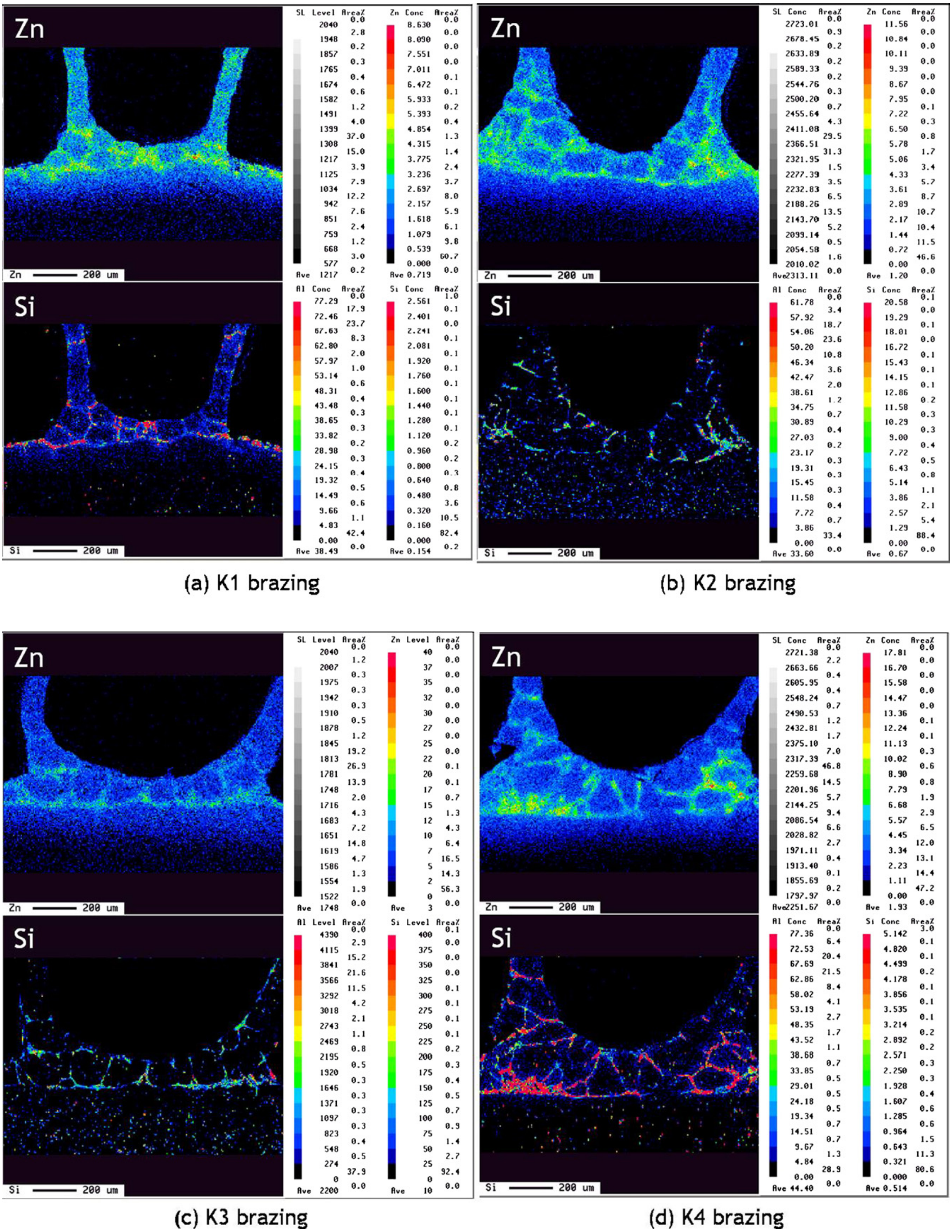

Fig. 6. Electron probe X-ray micro analyzer of the joint after brazing.

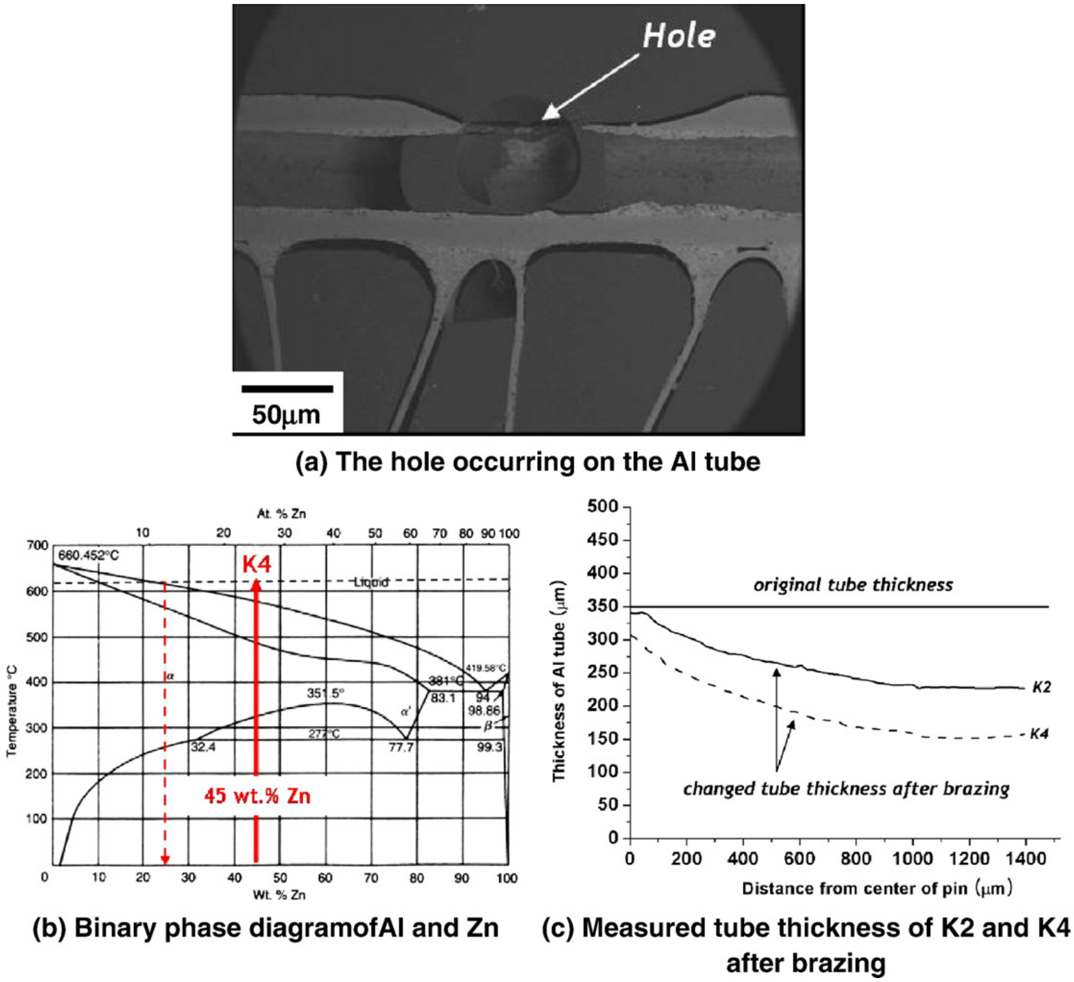

Fig. 7. The effect of zinc content on aluminum tube thickness after brazing.

In addition, the high quality coating without flux onto thin Al tube could be achieved using nitrogen as process gas.

(2) The zinc powder fraction in the as-sprayed coatings was higher than that of the initial feedstock. The high quality coating, which has high corrosion resistance with good brazeability, could be obtained by using the initial feedstock with lower zinc fraction. It is beneficial to decrease the coating manufacturing cost.

(3) The brazed joint between kinetic sprayed coating and the fin shows good bonding and high compactness regardless of the flux addition. Thus, no flux brazing could be realized by the predeposition of kinetic sprayed coatings.

(4) Fabricated heat exchanger using kinetic spray process has shown acceptable corrosion protection.

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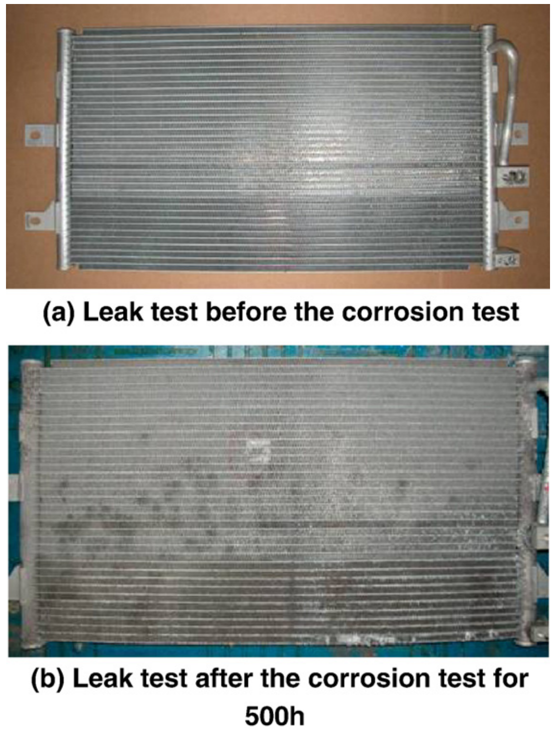

Fig. 8. The morphologies of the fabricated automobile heat exchanger before and after corrosion test.