技術論文

A High-Strength Aluminum Alloy Fin Stock for CAB Produced Using a Twin-Roll Strip Caster

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Abstract： We developed a new fin stock of an Al-Si-Fe-Mn-Zn alloy for automotive heat exchangers. The new stock has good properties suitable for making thinner fins than the ones used at present. It shows an ultimate tensile strength of about 130 MPa at a thickness of 0.05 mm after brazing and electrical conductivity of about 50% IACS. In contrast, conventional Al-Mn (3000-series) alloy fin stocks show the strength of about 110 MPa and electrical conductivity below 40% IACS. Therefore, the strength of the new alloy fin stock is much higher than that of typical 3000-series alloy fin stocks, while the thermal conductivity of the former is comparable to that of commercial pure aluminum stocks. In addition, corrosion resistance of the new alloy fin stock is the same as that of the 3000-series alloy fin stocks. These properties are attributable to constituent particles dispersed finely and densely in the new alloy fin stocks. This alloy is manufactured by using a twin-roll continuous caster.

1. INTRODUCTION

Since aluminum alloys have high specific strength and good thermal conductivity, they are used extensively in heat exchangers for automobiles. Recently, the demand for making aluminum alloy heat exchangers small and light has been strong because it will improve the fuel efficiency and performance of automobiles. To meet the demand, it is essential to make components of heat exchangers thinner.

To make thinner fins which are the main component of heat exchangers, several properties of fins must be improved. The first is mechanical strength. When heat exchangers are used, tubes expand as a result of internal pressure. If the fin stocks have insufficient mechanical strength, the fin will buckle and break, leading to breaking of tubes. The second is thermal conductivity. To maintain enough performance of smaller and lighter heat exchangers, it is necessary to increase the cooling efficiency per unit of volume of the exchangers. Thus, the thermal conductivity of the fin stock must be increased. The third is the corrosion resistance. When tubes are corroded to the point that holes occur, the heat exchanger breaks down. Thus, the fin stock is designed to have a sacrificial effect so that the fins corrode first. However, corroded fins lower the cooling efficiency of the heat exchanger and excessively corroded fins lead to the break down of heat exchangers, because excessive corrosion lower the mechanical strength of the fins. Therefore, fin stocks themselves must have good corrosion resistance. The fourth is brazeability. The majority of heat exchangers are manufactured using the controlled atmosphere brazing (CAB) process. The above-mentioned are related to post-brazing properties. But in-process properties, such as sag resistance and erosion resistance against molten filler metals, are important too. Because parts of heat exchangers are tied strongly by wires during the brazing process, poor sag resistance leads to the buckle of fins. Poor erosion resistance causes diffusion of the filler metals inside the fins, and the diffusion degrades the mechanical strength of the fin stock. Generally, these in-process properties are degraded clearly when fin stocks are made thinner.

This paper explains the development concept and properties of the new fin stock of which above properties are good.

2. GENERAL FIN STOCKS

Generally, commercial pure aluminum and 3000-series alloys are used in the bare fins of automotive heat exchangers. In thinner fin stocks, however, commercial pure aluminum is not mechanically strong enough, and a 3000-series alloy show insufficient thermal conductivity (**Table 1**).

Alloys that have both high mechanical strength and high thermal conductivity are not extensively used as fin stocks. This is because many heat exchangers are produced using CAB process. In this brazing process, heat exchangers are heated up to about 600 degrees C and materials with a melting temperature lower than 600 degrees C are unusable. Materials with high magnesium contents are also unusable, because magnesium decreases the effect of the non-corrosive flux which plays an important role in CAB. Therefore, materials for fin stocks are limited. Since the brazing temperature is high as above, properties of fin stocks are affected during brazing process in several ways. First, the dissolution of alloy elements such as manganese in the aluminum matrix takes place and it lower thermal conductivity. Second, the strength of work-hardened fins is decreased by recovery and recrystallization during the brazing process. Third, penetration of the molten filler alloy along grain boundaries decreases the brazeability of fine grained fin stocks. Thus, it is rather difficult to obtain fin stocks having high mechanical strength together with high thermal conductivity.

3. FIN STOCK PRODUCTION USING A CONTINUOUS CASTER

We deduced that dispersion strengthening using constituent particles and precipitates is the most effective method for giving both high mechanical strength and high thermal conductivity to the fin stocks. Moreover, adding alloy elements of which maximum solid solubility in the aluminum matrix at 600 degrees C is small may contribute to alleviate the lowering of thermal conductivity during the brazing process: it is because thermal conductivity of 3000-series alloys decrease during the brazing process due to dissolution of manganese of which the maximum solid solubility is rather high. We noted that the maximum solubility of iron in binary Al-Fe alloys is less than 0.05%[1)] and the solubility of nickel in binary Al-Ni alloys is also small[2)]. Therefore, we first selected an Al-Si-Fe-Ni-Zn alloy and investigated its properties[3), 4)].

However, when we used conventional direct chill (DC) casting, addition of a certain amount of alloying elements such as iron and nickel brought about a sparse distribution of coarse constituent particles unexpectedly. These coarse dispersoids hardly contribute to dispersion strengthening, but they deteriorate the workability and sometimes cause breaking of fin stocks, and this problem becomes more serious as fin stocks become thinner.

For this reason, we adopted a twin-roll continuous (TRC) casting. The cooling rate of DC casting is from 0.5 to 10 degrees C/sec, and that of TRC casting, from 100 to 700 degrees C/sec. Since the cooling rate of TRC casting is higher than that of DC casting, constituent particles becomes much finer and denser when used TRC casting. **Fig.1** shows schematic views of the direct chill casting machine- (a) and twin-roll continuous casting machine- (b), respectively. Using TRC casting, we developed an Al-Si-Fe-Ni-Zn alloy fin stock that has both high mechanical strength and high thermal conductivity[5)]. The mechanical strength of this fin stock is much higher than that of conventional 3000-series alloy fin stocks, while the thermal conductivity of the former is comparable to that of

Table 1 Comparison of chemical compositions and properties of fin stocks. Here, Al-Si-Fe-Ni-Zn alloy was previously developed and the new alloy was developed later.

Alloy	Chemical composition (wt.%)						Properties		
	Si	Fe	Cu	Mn	Ni	Zn	Mechanical strength	Thermal conductivity	Corrosion resistance
AA1050	<0.25	<0.4	<0.05	<0.05	–	<0.05	Not good	Good	Good
AA3003+Zn	<0.6	<0.7	0.05 –0.2	1.0 –1.5	–	1.0 –2.5	Good	Not good	Good
Al-Si-Fe-Ni-Zn	0.5	1.7	–	–	1.2	0.55	Good	Good	Not good
The new alloy	0.9	1.5	–	0.8	–	0.55	Good	Good	Good

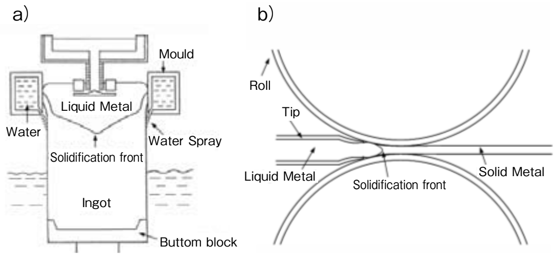

Fig.1 Schematic view of
(a) the direct chill casting machine and
(b) the twin-roll continuous casting machine.

commercial pure Al fin stocks. The Al-Si-Fe-Ni-Zn fin stock with a thickness of 0.06 mm, has been used in radiators since 1999 in Japan. As far as we know, this fin stock is the first one manufactured by using TRC casting and applied for radiators in the world.

Unfortunately, the corrosion resistance of the Al-Si-Fe-Ni alloy is inferior to that of Al-Mn alloys. This lowered corrosion resistance is due to the constituent particles which are dispersed densely and finely in the Al-Si-Fe-Ni alloy. Based upon the noble corrosion potentials of Al-Fe, Al-Ni and Si compounds [6], the particles in Al-Si-Fe-Ni alloy are supposed to have much nobler corrosion potential than the aluminum matrix. The surfaces of the noble compounds should act as strong cathode for the matrix surface around them and the anodic dissolution of the matrix should be accelerated. Thinning of this fin stock further degrades the reliability of radiator cores. In addition, nickel is hardly recyclable. Therefore, a new alloy which does not contain nickel is desirable, though Al-Si-Fe-Ni-Zn alloy fin stock has high mechanical strength and high thermal conductivity.

4. DESIGN OF A NEW ALLOY FIN STOCK

We investigated the effects of alloying elements having small maximum solubility on the corrosion resistance. In contrast to the compounds of Al-Si-Fe-Ni alloy, the compounds of Al-Mn alloys have less noble corrosion potentials than the aluminum matrix [7] and don't accelerate the corrosion. Moreover, manganese addition is reported to suppress the corrosion acceleration by the iron content [8]. Therefore, we focused on the simultaneous addition of iron and manganese. The maximum solubility of manganese in the binary Al-Mn alloy is nearly 1.0 % at 600 degrees C, but the maximum solubility of manganese in ternary Al-Fe-Mn alloys is reduced when the iron content is increased [9]. We therefore investigated Al-Si-Fe-Mn-Zn alloys with high iron contents. As a result, we successfully developed a new alloy fin stock in 2000 [10]. Other fin stock manufactured by using TRC casting has been reported in 2001 [11]. Constituent particles are dispersed finely and densely in the new alloy when manufactured by using TRC casting, and they improved both the mechanical strength and the thermal conductivity. Furthermore, the fin stock showed good corrosion resistance.

5. PROPERTIES OF THE NEW ALLOY FIN STOCK

We developed this new alloy fin stock by investigating the effect of the chemical composition, casting and process conditions on properties of the alloy fin stocks. Since the developed fin stock manufactured by using TRC casting has good properties, we used it to make a thinner fin stock. An example of chemical composition of the new alloy fin stock is shown in **Table 2**. We will describe the properties of this fin stock in the following sections.

5.1 Mechanical Strength and Thermal Conductivity

Fig.2 shows an ultimate tensile strength (UTS) and electrical conductivity of the new alloy fin stock after brazing process in comparison with those of fin stocks of 3000-series alloy (AA3003+1.5Zn), commercial pure aluminum (AA1050) and Al-Si-Fe-Mn-Zn alloy manufactured by using DC casting, of which chemical

Table 2 Example of chemical composition of the new alloy fin stock (wt.%).

Si	Fe	Mn	Zn	Al
0.9	1.5	0.8	0.55	Rem.

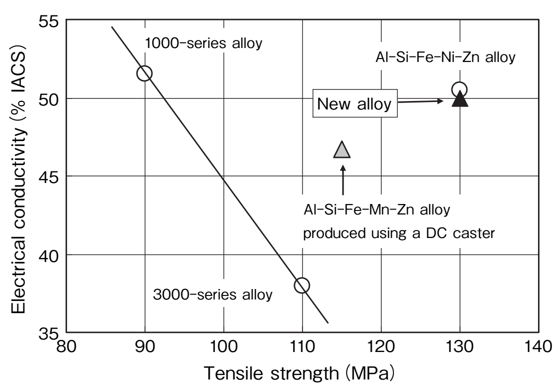

Fig.2 Relationship between ultimate tensile strength and electrical conductivity after brazing.

composition is the same as the new alloy. In this figure, we used electrical conductivity as an index of thermal conductivity, because the two values are proportional. The thickness of the new alloy fin stock is 0.05 mm and that of the other fin stock is 0.06 mm.

UTS of the new alloy fin stock manufactured by using TRC casting is about 130 MPa, and is superior to that of 3000-series alloy fin stock and Al-Si-Fe-Mn-Zn alloy fin stock manufactured by using DC casting. In addition, the electrical conductivity of the new alloy fin stock is about 50 % IACS and nearly equivalent to that of the commercial pure aluminum fin stock. The new alloy fin stock has equivalent properties to the Al-Si-Fe-Ni-Zn alloy fin stock that we developed previously.

The reason why the new alloy fin stock has both high tensile strength and high electrical conductivity is shown in the SEM images (**Fig.3**) and TEM images (**Fig.4**) of fin stocks after brazing. Fine and dense constituent particles are observed in the new alloy fin stock and Al-Si-Fe-Ni-Zn alloy fin stock. Dispersion strengthening is increased as constituent particles become finer and denser. Thus, the level of dispersion strengthening in these fin stocks is higher than those of 3000-series alloy fin stock and of the same alloy produced by DC casting. In addition, the degradation of electrical conductivity is smaller, because the majority of the alloy elements are contained in constituent particles and the amount of elements dissolved in the aluminum matrix is rather small.

In the 3000-series alloy fin stock, smaller amounts of constituent particles are observed in Fig.3 (d) and Fig.4 (c) : this means that the effect of dispersion strengthening is small and manganese atoms which are not contained in constituent particles are dissolved in aluminum matrix, leading to reduction of electrical conductivity of the alloy. In the Al-Si-Fe-Mn-Zn alloy fin stock manufactured by using DC casting, coarse and sparse constituent particles are observed because the cooling rate of DC casting is slower than that of TRC casting. When the effect of dispersion strengthening is smaller and dissolved amounts of manganese and silicon increase, both UTS and electrical conductivity decrease.

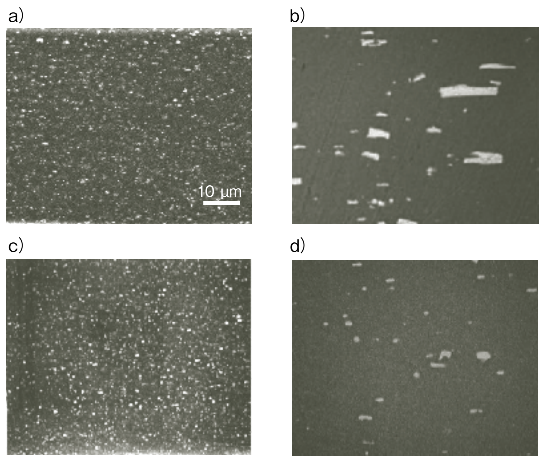

Fig.3 SEM images of fin stocks after brazing.
a) the new alloy fin stock.
b) the Al-Si-Fe-Mn-Zn alloy fin stock made using DC casting.
c) the Al-Si-Fe-Ni-Zn alloy fin stock.
d) the 3000-series alloy fin stock.

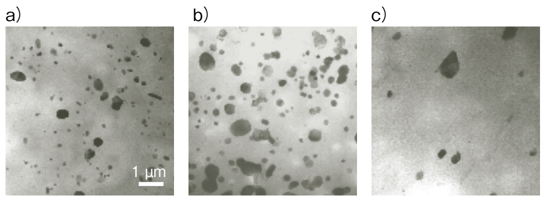

Fig.4 TEM images of fin stocks after brazing.
a) the new alloy fin stock.
b) the Al-Si-Fe-Ni-Zn alloy fin stock.
c) the 3000-series alloy fin stock.

5.2 Corrosion Resistance

Fig.5 shows the results of a copper accelerated acetic acid salt spray (CASS) test for aluminum sheet specimens after 3 days or 7 days. In the CASS test, high weight loss means low corrosion resistance of fin stocks. Corrosion resistance of the new alloy fin stock is approximately the same as that of the 3000-series alloy fin stock. On the other hand, corrosion resistance of Al-Si-Fe-Ni-Zn alloy fin stock, whose tensile strength and electrical conductivity is the same as that of the new alloy fin stock, is much less than other fin stocks. Only the new alloy fin stock can be used in the mass-production of fin stocks with a thickness of 0.05

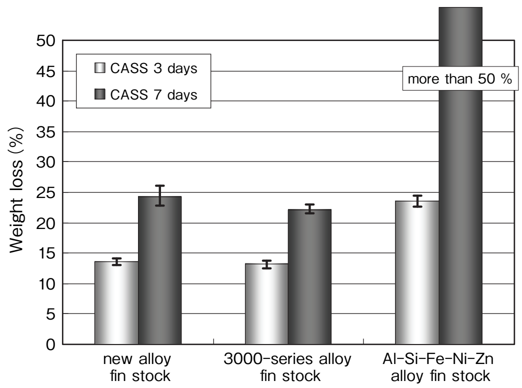

Fig.5 Weight loss of fin stocks after CASS test.

mm and still maintain the reliability of radiator cores.

Zinc has been added to the new alloy fin stock to create a sacrificial anode effect. The additional amount of zinc was determined by the corrosion potential of the tubes and plates that were brazed with the fin stock. The corrosion resistance of heat exchangers is thought to be high based on the result of the CASS test.

5.3 Brazeability

Fig.6 shows macro structures of fin stocks of the new alloy- (a), the Al-Si-Fe-Ni-Zn alloy- (b), and of the 3000-series alloy- (c) after brazing. The new alloy fin stock has recrystallized grains of which size ranges from 0.3 to 2 mm in diameter. **Fig.7** shows the cross section of a fin-tube joint after brazing at 610 degrees C for three minutes. The condition of the fin-tube joints remained good in every fin stock. During the brazing process of aluminum alloy fin stocks, filler metal erodes the fin stock along the grain boundaries and the fin stocks are segmented at the fin-tube joints. This phenomenon is explained by the diffusion of molten filler alloys along grain boundaries, and this degrades the strength of heat exchangers. If the recrystallized grains are too small, area fraction of grain boundary increases: as a result grain boundaries act as diffusion paths of the filler alloys and erosion occurs easily. If a fin stock is thin, molten filler alloy may penetrate the fin stock easily. Though the thickness of the new alloy fin stock is only 0.05 mm, the erosion of the fin stock was not observed. This means the recrystallized grains of the new alloy fin stock are sufficiently larger for preventing the erosion of molten metal.

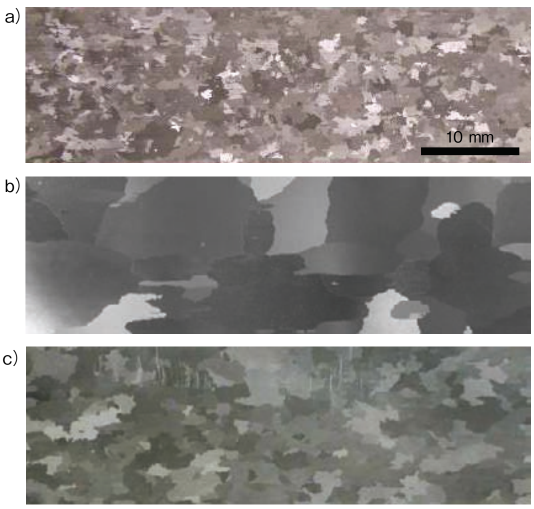

Fig.6 Macro structure of fin stocks after brazing.
a) new alloy fin stock.
b) Al-Si-Fe-Ni-Zn alloy fin stock.
c) 3000-series alloy fin stock.

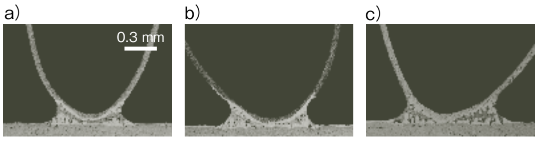

Fig.7 Cross section of a fin-tube joint.
a) the new alloy fin stock.
b) the Al-Si-Fe-Ni-Zn alloy fin stock.
c) the 3000-series alloy fin stock.

We then evaluated the sag resistance of the fin stocks by measuring sag distance. To perform such measurements, fin stocks were overhung by 50 mm as shown in **Fig.8** (a), heated to 600 degrees C and held at that temperature for 5 minutes. A small sag distance of a fin stock means that the fin stock has a favorable sag resistance. Evaluated sag distances of every fin stock are shown in Fig.8 (b). Generally, sag resistance degrades as the thickness decreases and the recrystallized grain becomes smaller [12]. However, sag resistance of the new alloy fin stock is comparable to that of the other fin stocks, though the new alloy fin stock is thinner than the other fin stocks.

In conclusion, the brazeability of the new alloy fin stock is good, though the thickness of the fin stock is only 0.05 mm.

6. CONCLUSIONS

We developed a new fin stock of an Al-Si-Fe-Mn-Zn alloy for automotive heat exchangers. The new alloy is manufactured by using a twin-roll continuous caster. This produced alloys having fine and dense constituent particles. Using this caster enabled us to produce a new alloy fin stock that has both high tensile strength and high electrical conductivity. The new alloy fin stock shows an ultimate tensile strength of about 130 MPa at a thickness of 0.05 mm after the brazing process , and its electrical conductivity is about 50% IACS. The strength of the new alloy fin stock is much higher than that of conventional 3000-series alloy fin stocks, while the thermal conductivity of the new alloy fin stock is comparable to that of commercial pure Al fin stocks. Corrosion resistance of the new alloy fin stock is approximately the same as that of 3000-series alloy fin stocks. The new alloy fin stock also exhibits good in-process properties such as sag resistance and erosion resistance against molten filler metals.

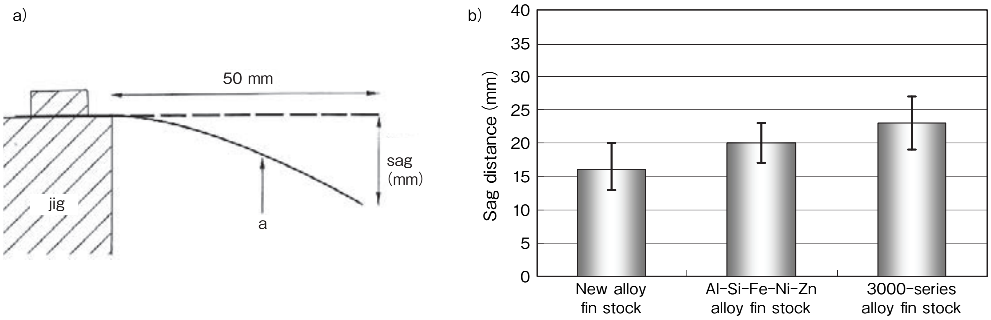

Fig.8 a) Sag test apparatus (arrow a indicates a specimen)
b) Sag distance of the fin stocks.

The above properties make it very suitable for manufacturing thinner fin stocks than the one used at present. The new alloy fin stock with a thickness of 0.05 mm has been used for fins of radiators. The fin stock can be used to produce lighter and smaller aluminum heat exchangers. The casting of the new alloy is performed by Choil Aluminum Co., LTD and ELVAL S. A. (Hellenic Aluminium Industry S. A.).

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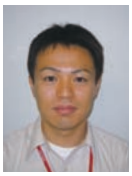

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