Development of Aluminum Alloy Fin Stock for Heat Exchangers Using Twin-Roll Continuous Casting Method

by *Akira Kawahara* [*], *Akio Niikura* [*] and *Takeyoshi Doko* [*]

ABSTRACT The authors have developed and put into practical use an aluminum alloy fin stock for automobile heat exchangers that satisfies the requirements for high strength and high thermal conductivity. This fin stock is an Al-Fe-Ni-Si alloy manufactured by the twin-roll continuous casting method, whereby the mechanical strength is increased by finely and densely enhancing dispersion of intermetallic compounds.

The fin stock developed here with a thickness of 0.06 mm has, after brazing process at 600 °C for 3 min, a tensile strength of 130 MPa and an electrical conductivity of 50 % IACS. For comparison, 3000-series alloys widely used for automobile heat exchangers have, under the same conditions, approximately a tensile strength of 110 MPa and an electrical conductivity of 40 % IACS. Thus the new fin stock has achieved a strength increase while maintaining an electrical conductivity equivalent to that of 1000-series alloys, enabling thickness reduction of fin stocks for heat exchangers.

1. INTRODUCTION

There has been a requirement to improve fuel economy of automobiles aimed at preventing global warming and so on, raising a strong demand for weight reduction of heat exchangers --one of the major automobile components. Aluminum alloys are commonly used as a material for heat exchangers, since they have high thermal conductivity and their specific strength is superior to other metal materials such as copper. Recently, much research and development work is going on to lessen the thickness of aluminum alloy members in order to further reduce the weight of heat exchangers.

Figure 1 shows the schematic of a radiator, one of the automobile heat exchangers made of aluminum alloy. Fin stock is one of the main members of heat exchangers, and it is necessary to improve its mechanical strength and thermal conductivity so as to reduce its thickness. Usually heat exchangers of aluminum alloy are manufactured using the brazing method, whereby aluminum alloy members are heated up to approximately 600°C, which is close to their melting point. This process makes it difficult to improve the mechanical strength and thermal conductivity of the fin stock, because of the fact that the heating for brazing is equivalent to annealing for the aluminum alloy leading to mechanical strength reduction and that the heating also acts as a solution treatment thus reducing thermal conductivity.

Addressing such tasks, we have gained, through previous research work, a technological knowledge of adding nickel to Al-Fe-Si alloys thereby improving the mechanical strength without decreasing the thermal conductivity. It is thought that, in this alloy system, the mechanical strength is increased due to the dispersion enhancement of intermetallic compounds in the Al-Fe-Ni-Si system, while the thermal conductivity does not decrease because of the small solid solubility of the added element into the aluminum matrix [1]. The Al-Fe-Ni-Si alloy thus developed has superior mechanical strength and thermal conductivity after brazing, and is in production as a fin stock material for radiators [2].

Since then, heat exchanger manufacturers continued

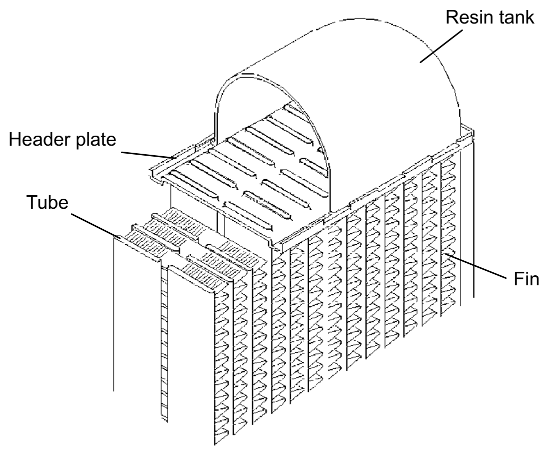

Figure 1 Schematic view of heat exchanger.

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to study the issue of thinning fin stocks, creating a requirement for a new fin stock having a thermal conductivity equivalent to, and a mechanical strength higher than, the fin stock in production. To meet this requirement, we pursued the study of mechanical strength improvement based on dispersion enhancement. This paper reports on the development of an Al-Fe-Ni-Si alloy fin stock whereby the twin-roll continuous casting method was applied.

2. REQUIREMENTS FOR FIN STOCK CHARACTERISTICS

Figure 2 illustrates the manufacturing process of a radiator made of aluminum alloy [2]. The fin stock is corrugated, assembled with other members such as the tube stock, and subsequently brazed at temperatures near 600°C. The heating temperature of 600°C is close to the melting point of the aluminum alloy, so that various influences are exerted on its characteristics. Those that are most strongly influenced will be described below.

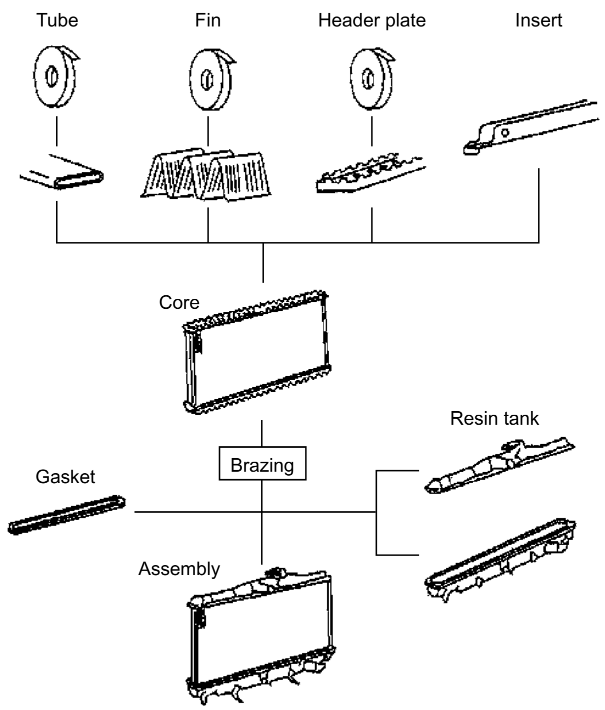

Figure 2 Manufacturing process of heat exchanger made of aluminum alloy [2].

2.1 Tensile Strength

During the use of a heat exchanger, the pressure of cooling water swells the tube. If the mechanical strength of the fin withstanding the swell is insufficient, the fin would buckle, resulting in breakage of the tube. Consequently, the tensile strength of the fin stock should desirably be high. But commonplace methods of strengthening aluminum alloys are difficult to be applied effectively because of the heating for brazing. The method of enhancing the tensile strength will be described in detail in Section 3.

2.2 Thermal Conductivity

To improve the thermal efficiency of heat exchangers, it is desirable that the thermal conductivity of constituting materials be high. But elements added to aluminum alloys degrade the thermal conductivity, when they dissolve into the aluminum matrix at brazing.

2.3 Brazeability

Fin stocks are required not to be eroded by filler metal during brazing process. If the molten filler metal erodes the fin stock as shown in the right-hand photo of Figure 3, the mechanical strength of fin-tube joints would be degraded, resulting in deformation or buckling of the fin stock during the brazing process, or insufficiency of supporting the swelling of the heat exchanger tubes during the use.

As fin stocks become thinner, it is more likely that they are severed by the filler metal due to erosion [3]. Moreover, at the brazing process of volume production lines, heat exchangers of various sizes are heated all together, so that the temperatures of small heat exchangers tend to rise higher than 600°C, readily resulting in defects due to erosion.

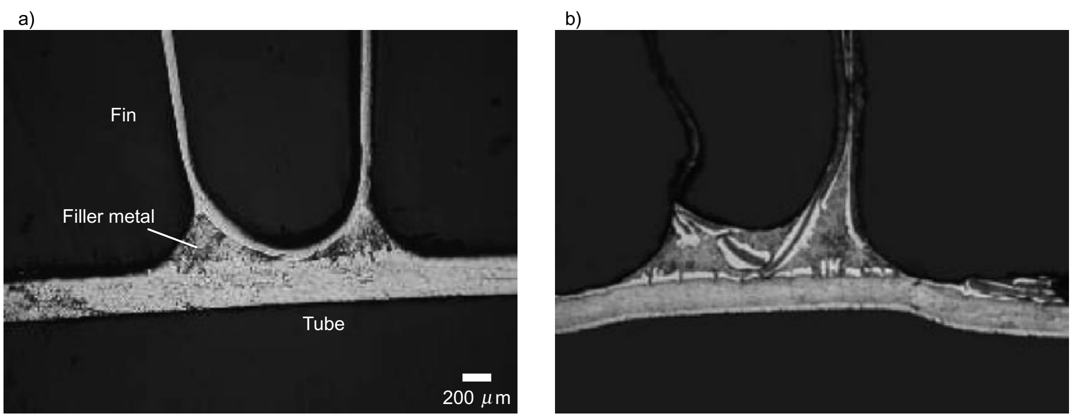

Figure 3 Microphotographs of fin-tube joint. Left: Good joint. Right: Erosion by filler metal causing buckling of the fin stock can be seen.

2.4 Sag Resistance

At the brazing process, heat exchangers are fastened using steel wires and the like to keep their geometrical shape, so that they are firmly squeezed due to the difference of thermal expansion between steel and aluminum at 600°C. Consequently, fin stocks must have superior sag resistance (buckling resistance) in order to protect the heat exchangers from deformation due to buckling in spite of the fastening by steel wire at temperatures near 600°C.

3. INVESTIGATION OF IMPROVING MECHANICAL STRENGTH

We investigated performance requirements for fin stocks focusing primarily on the improvement of tensile strength, considering this is the most important factor for thickness reduction of fin stocks. Below will be described the techniques for improving the tensile strength together with its effects on other characteristics.

Solid-solution hardening is known as one of the mechanical strength improving methods for aluminum alloys. For example, 5000-series alloys take advantage of the solid-solution hardening by magnesium. However, it is impossible to use magnesium as an adding element to fin stock alloys, because the element reacts with fluorine, a component of brazing flux, during heating for brazing thus ruling out jointing. Although silicon and copper also improve the mechanical strength by dissolving into aluminum, they lower the melting point of the alloy simultaneously. When the melting temperature of a fin stock alloy is lowered approaching the brazing temperature, the erosion by filler metal mentioned in Section 2.3 can occur more readily. Therefore, silicon and copper cannot be added into heat exchanger members in large amounts.

On the other hand, as crystallized grain structures are made finer, the proof strength and tensile strength increase in general. However, finer recrystallization grain structure of fin stocks for heat exchangers corresponds to an increase in the grain boundaries that constitute the path for fast diffusion of the molten filler metal, leading to easy erosion. In addition, slippage deformation along grain boundaries is considered to dominate the deformation of aluminum alloys at elevated temperatures. Thus finer recrystallization grain structure of fin stocks, in effect, results in a reduction of sag resistance mentioned in Section 2.4.

What is more, work hardening cannot be used to improve the mechanical strength of heat exchanger members, because the fin stock is annealed by the heating for brazing.

For the reasons mentioned above, it is thought that dispersion enhancement is the most effective technique of improving the mechanical strength of fin stocks without degrading their thermal conductivity, brazeability, and other characteristics.

The 3000-series alloys comprise manganese-added aluminum alloys whereby Al-Mn intermetallic compounds are precipitated to improve the mechanical strength. But manganese has a large solid solubility with aluminum alloys at 600°C, and because of this, the thermal conductivities of 3000-series alloys after brazing are considerably lower than 1000-series alloys and the Al-Fe alloys, making it unfavorable to apply these alloys to fin stocks for heat exchangers where much emphasis is placed on thermal conduction efficiency.

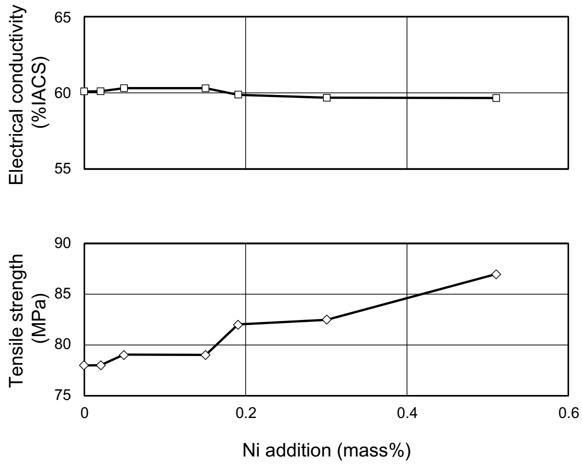

Figure 4 **Changes in tensile strength and electrical conductivity after brazing of Al-0.1 wt%Si-0.5 wt%Fe alloy when nickel is added [2].**

We paid attention to the fact that the maximum solid solubility of iron in the Al-Fe alloys is as small as 0.05 wt% [5], and that that of nickel in the Al-Ni alloys is also small as comparable to iron [6]. Figure 4 shows changes in the tensile strength and electrical conductivity of an Al-0.1 wt%Si-0.5 wt%Fe alloy when nickel is added [2]. Meanwhile, this paper uses electrical conductivity as an index to represent thermal conductivity, because, as is known, the two are in a proportionality relation and the former is easier to measure experimentally. It was found, as shown in Figure 4, the mechanical strength of an Al-Fe-Ni-Si alloy after brazing can be improved without degrading the thermal conductivity by increasing the addition of nickel. Thus an Al-Fe-Ni-Si alloy with superior thermal conductivity and mechanical strength was developed, and was put to practical use in 1995.

Table 1 shows the changes in fin stock characteristics when various improvement methods for mechanical strength are applied to.

4. INVESTIGATION OF TWIN-ROLL CONTINUOUS CASTING METHOD

We found that, as a result of our investigations later than 1995 to improve the mechanical strength of fin stock, the addition of iron and nickel above a certain extent did not improve the mechanical strength but reduced the size of recrystallization grain structure after heating for brazing. Thus it was concluded that development of a fin stock

Table 1 Strengthening methods of aluminum alloys and associated problems when applied to fin stock.

Strengthening method	Technique	Problem
Solid-solution hardening	Addition of magnesium	Incapable of being brazed
	Addition of copper or silicon	Thermal conductivity decreases Erosion resistance against filler-metal decreases
Dispersion hardening	Addition of manganese	Thermal conductivity decreases significantly after brazing
	Addition of iron and nickel	None
Work hardening	Impartment of strain	Imparted strain is annealed by heating for brazing After brazing, strain cannot be imparted because fin is jointed with tube
Grain size reduction	Increase of cold rolling reduction ratio	Erosion resistance against filler-metal decreases Buckling resistance decreases

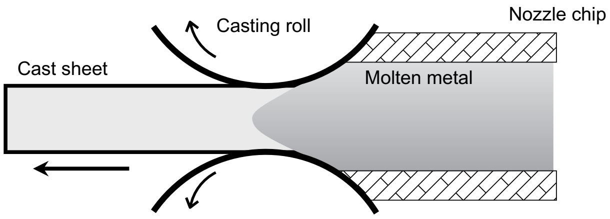

Figure 5 Schematics of solidification area of molten metal in CC method.

suitable for thickness reduction could not be achieved solely by changing alloy composition.

We paid attention to the fact that higher speeds at molten alloy casting reduce the grain size of precipitation phase [7)], and proceeded to investigate the manufacturing of fin stock for heat exchangers using twin-roll continuous casting method (hereafter called “CC method”) whereby a higher chilling speed at casting was expected to be obtained.

Figure 5 is a schematic diagram of the solidification area of molten metal in the CC method. In this method, molten metal of aluminum alloy is continuously supplied between the casting rolls to be cast into a sheet a few millimeters thick, and is directly wound into a coil. Because the molten metal is directly chilled with the water-cooled casting roll, the chilling speed at casting is higher than the direct chill method (hereafter called “DC method”) commonly used in industrial casting. Figure 6 shows the result of SEM observation of a sheet cast by a CC casting machine, whereby it was confirmed that coarse intermetallic compounds larger than 10 μm were not present in the whole area.

The SEM image of Figure 6 was used to estimate the chilling speed at casting. It has been experimentally confirmed, and a theoretical explanation is provided, that in many alloy systems a relationship given below exists between dendrite arm spacing (DAS) d and chilling speed c at casting [7)]:

$$d=A\times c^{-n}$$

where, A and n are constants specific to the alloy system

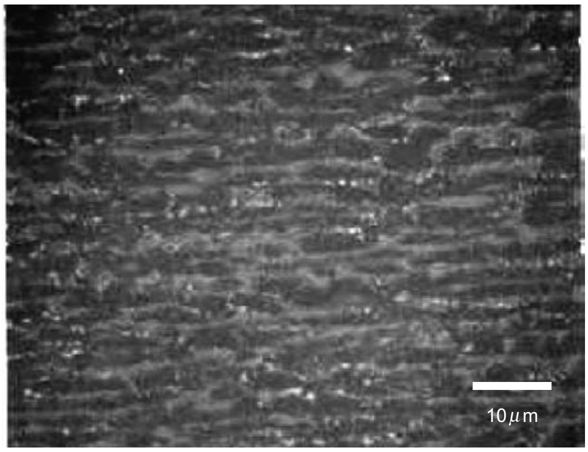

Figure 6 SEM image of cast sheet.

The values of A and n are identified as 33.4 and 0.33, respectively [8)], in an Al-Fe-Si alloy which resembles the alloy system developed here. Since d is seen to be about 4 μm from the SEM image in Figure 6, the chilling speed at casting is calculated, using the equation above, as 600~700°C/sec. This is almost 100 to 1000 times the chilling speed in the DC method of 0.5~5.0°C/sec.

Figure 7 gives the tensile strength of fin stocks manufactured by adding varied amounts of iron plus nickel to an Al-Si alloy. The fin stocks were prepared by casting Al-0.5 wt%Si alloys added with varied amounts of iron plus nickel using the DC and CC methods, respectively, hot-rolling only the ingot cast by the DC method, and cold-rolling down to 0.06 mm through intermediate annealing. The fin stocks were heated at 600°C for 3 min, tensile tested using JIS Standard specimens, and their tensile strengths were plotted with respect to the total addition of iron plus nickel. It can be seen that the fin stock by DC method does not significantly increase in strength when the total addition of iron plus nickel exceeds 2.0 wt%. In contrast, the fin stock by CC method increases in the tensile strength as the total addition of iron plus nickel increases. Furthermore, the fin stock cast by the CC method has higher tensile strengths than the fin stock by DC method, when their total addition of iron plus nickel is almost equivalent.

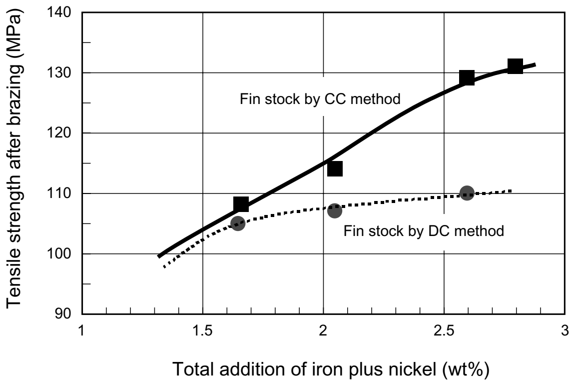

Figure 7 Relationship between tensile strength after brazing and total addition of iron plus nickel in Al-0.5 wt%Si alloy.

5. CHARACTERISTICS OF THE DEVELOPED FIN STOCK

Thus the application of the CC method was confirmed to improve the tensile strength. To improve other characteristics such as electrical conductivity, we further investigated the alloy composition, casting conditions, and cold-rolling conditions after casting, thereby succeeded in developing an aluminum fin stock for heat exchangers that is effective in thickness reduction. Table 2 shows a typical chemical composition of the new alloy developed here.

Table 2 Typical chemical composition of fin stock alloy developed here.

Si	Fe	Ni	Zn	Al
0.5	1.7	1.1	0.6	Balance

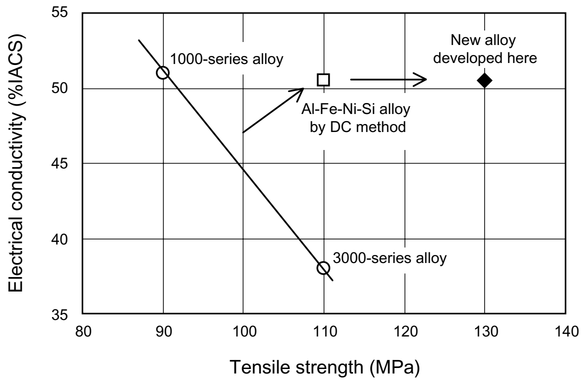

Figure 8 Relationship between tensile strength and electrical conductivity after heating for brazing.

5.1 Thermal Conductivity and Tensile Strength

Figure 8 shows the tensile strength and electrical conductivity after heating for brazing of the developed fin stock, in comparison with those of 3000-series alloy (A3003 alloy added with 1.5 wt% zinc), 1000-series alloy (A1050), and Al-Fe-Ni-Si alloy developed by the authors previously, all manufactured by the DC method. The fin stocks are unified into a thickness of 0.06 mm.

The developed fin stock has a tensile strength of about 130 MPa, which is higher than that of the previously developed Al-Fe-Ni-Si alloy by about 20 MPa, and an electrical conductivity of 50 %IACS equivalent to 1000-series alloys.

Figure 9 and Figure 10 show the results of SEM and TEM observations of the fin stocks after heating at 600°C, respectively. In Figure 9, while intermetallic compounds are hardly seen to exist in the 3000-series alloy (Figure 9-c), they do exist in the Al-Fe-Ni-Si alloy (Figure 9-b) and abundantly exist, with a fine and dense distribution, in the developed fin stock (Figure 9-a) using the CC method. In Figure 10, some intermetallic compounds in the Al-Fe-Ni-Si fin stock manufactured by the DC method are seen to be more than 5 μm in size, suggesting that the mechanical strength by the DC method did not improve despite the increased addition of iron and nickel, because the intermetallic compounds coarsened instead of growing in number. In contrast, most of the intermetallic compounds in the developed fin stock are not larger than 1 μm. It is thus supposed that, because the CC method has a high chilling speed at casting, the intermetallic compounds did not coarsen despite the addition of iron plus nickel to a high concentration, thereby achieving a dispersion enhancement in number to result in strength improvement.

5.2 Brazeability

Figure 11 shows the macrostructures of the developed fin stock, Al-Fe-Ni-Si fin stock by DC method, and 3000-series alloy fin stock. These observations were carried out by dipping the specimens, after they were heated corresponding to brazing, into aqua regia. The recrystallized grain size of the fin stock by DC method is seen to be around 0.2~1 mm, while that of the developed fin stock is coarsened to more than 5 mm.

As was stated in Section 3, the recrystallized grain size of fin stocks for heat exchangers should desirably be large, as is the case in the developed fin stock. Dispersed precipitates larger than about 5 μm in size readily accumulate strain around themselves, often turning into a nucleus generating site for recrystallization. In view of the fact that the developed fin stock has few intermetallic compounds larger than 5 μm in size, this fin stock is supposed to have fewer recrystallization generation sites in comparison with the fin stocks manufactured by the DC method. On the other hand, the developed fin stock has many intermetallic compounds smaller than 1 μm, which is considered to impede moving of subgrains or grain boundaries at recrystallization of aluminum alloys. Therefore, because the developed fin stock has fewer recrystallization generation sites and also the move of grain boundaries is impeded, recrystallization is retarded up to high temperatures, and as a result, the recrystallized grain size becomes larger after heating for brazing.

Figure 12 shows the cross-sectional microphotographs of fin-tube joints brazed at 610°C for 3 min. The thicknesses for the developed fin stock and other fin stocks are 0.06 mm and 0.07 mm, respectively. Whereas

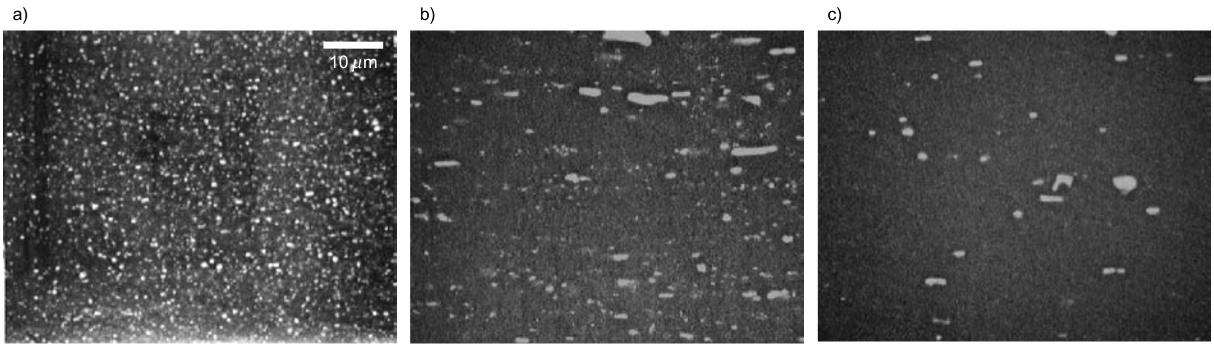

Figure 9 SEM images of fin stocks after heating for brazing.
a) Fin stock developed here, b) Al-Fe-Ni-Si fin stock by DC method, c) 3000-series alloy

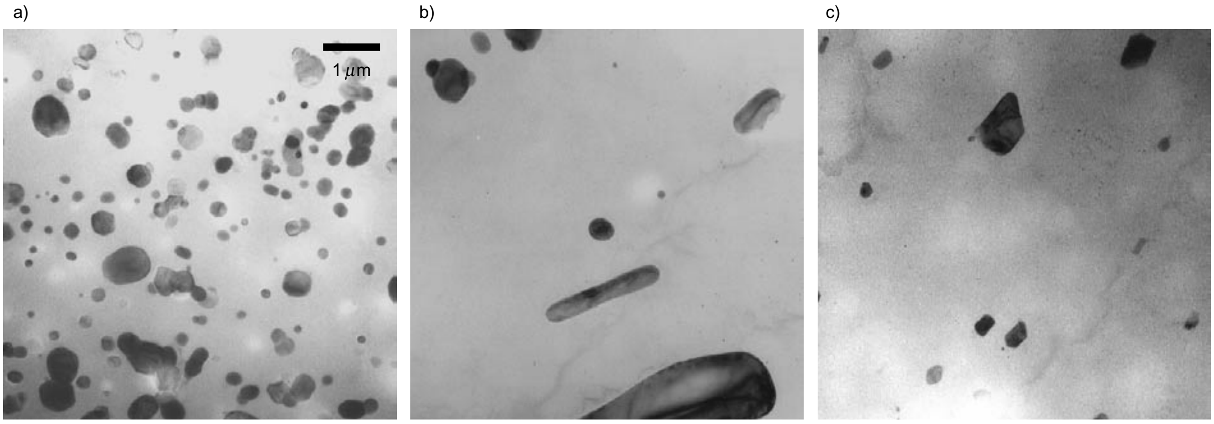

Figure 10 TEM images of fin stocks after heating for brazing.
a) Fin stock developed here, b) Al-Fe-Ni-Si fin stock by DC method, c) 3000-series alloy

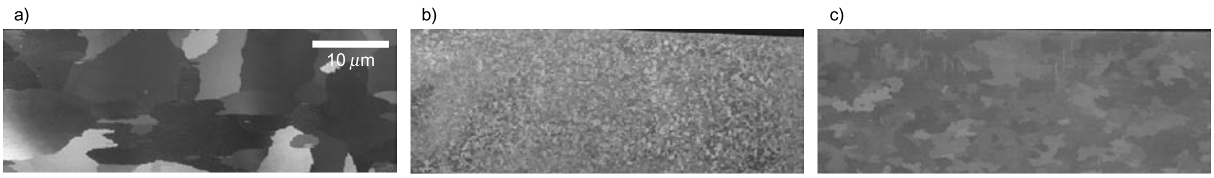

Figure 11 Macrostructures of fin stocks after heating for brazing.
a) Fin stock developed here, b) Al-Fe-Ni-Si fin stock by DC method, c) 3000-series alloy

in the joint using the fin stock by DC method the filler metal erodes the fin stock thus severing it, the developed fin stock has, in spite of its smaller thickness, a sound joint without being eroded by the filler metal. Thus the developed fin stock has superior resistance against filler metal erosion at brazing.

5.3 Sag Resistance

Because slippage deformation along grain boundaries is considered to dominate the deformation of aluminum alloys at elevated temperatures over 500°C, it would be effective to make recrystallization grain structure coarsen in order to prevent the deformation of fin stock at elevated temperatures. As mentioned earlier, the fin stock developed here has a coarse recrystallization grain structure, and it is thought to have high sag resistance, accordingly.

Sag resistance of a fin stock can be evaluated by measuring fin pendency [9], which becomes smaller, the thicker the fin stock is, and the larger the recrystallized grain size becomes. The fin pendency was measured using the method shown in Figure 13, whereby a cantilever specimen with an arm length of 50 mm was heated up to 600°C at a speed of 50°C/min, kept for 5 min, and cooled down to room temperature to make a measurement. The specimens used were 0.06 mm and 0.07 mm in thickness for the developed fin stock and the others, respectively.

The sag value of each specimen is shown in Figure 14, in which the developed fin stock is seen to have superior sag resistance than those by DC method despite its reduced thickness.

5.4 Corrosion Resistance

The potential of fin stock is designed to be less noble than that of tube so that the former corrodes faster than the latter. Corrosion resistance, (i.e., penetration lifetime of the tube) of heat exchangers are designed based on this

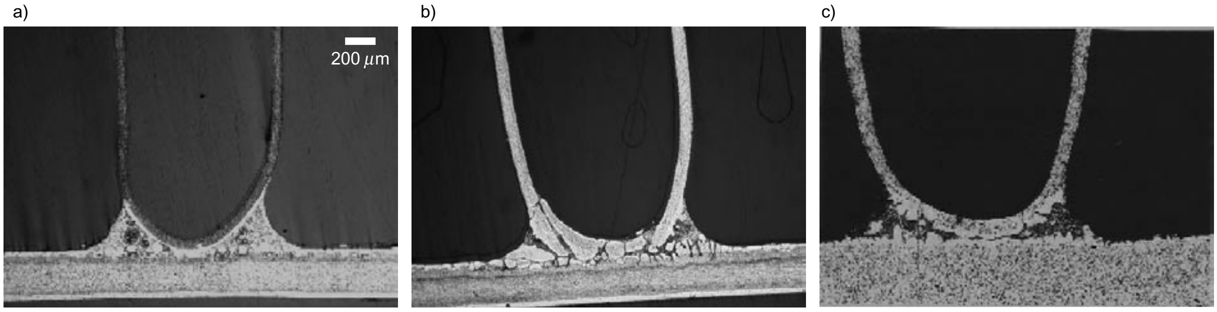

Figure 12 Cross-sectional microphotographs of brazed fin-tube joints.
a) Fin stock developed here, b) Al-Fe-Ni-Si fin stock by DC method, c) 3000-series alloy

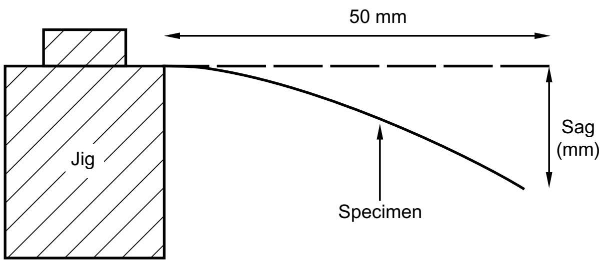

Figure 13 Sag measuring apparatus.

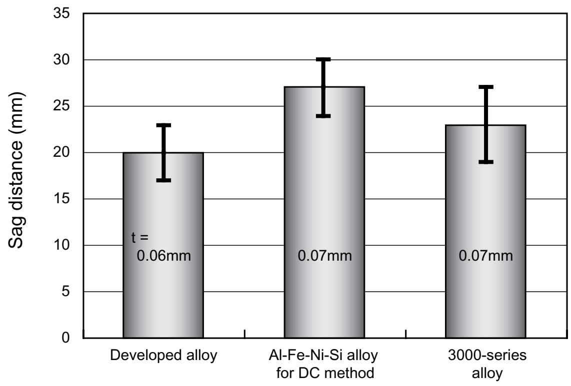

Figure 14 Sag value of fin stocks kept at 600°C for 5 min.

sacrificial corrosion prevention by fin stock over tube, and usually zinc is added to the fin stock for heat exchangers to make the potential of the material less noble. In the developed fin stock also, the needed addition of zinc is calculated for a tube material to be incorporated, and 0.6 wt% of zinc is added accordingly.

The fin stock cold-rolled down to 0.06 mm was corrugated, brazed with the tube material, and thus a simulation sample of mini cores with three tubes was prepared. The sample was subjected to the salt spray (SS) test and the copper accelerated acetic acid salt spray test (CASS) test to evaluate the penetration lifetime of the tube material. As a result, it was shown that the sacrificial lifetime of the developed fin stock was equivalent to that of fin stocks by DC method, resulting in an equivalent penetration lifetime of the tubes.

6. IN CONCLUSION

An aluminum alloy fin stock for automobile heat exchangers has been developed. The fin stock developed here has, since twin-roll continuous casting method is applied for its casting, a metallurgical structure in which intermetallic compounds are distributed finely and densely. Due to the dispersion enhancement by intermetallic compounds, the developed fin stock has a tensile strength of 130 MPa after heating for brazing and, simultaneously, an electrical conductivity of 50 %IACS after heating for brazing that is equivalent to 1000-series alloys. These characteristics have been achieved by thorough investigations of the casting method and alloy composition, whereby added elements scarcely dissolve into the aluminum matrix and precipitation of intermetallic compounds are prevented to grow in size. Also the developed fin stock has superior characteristics such as filler metal erosion resistance and sag resistance, because of the coarse recrystallization grain structure after brazing in comparison to the fin stock by DC method.

The developed fin stock shows superiority in terms of important characteristics for thickness reduction, as was stated above, and has been in practical application for automobile radiators. Application of this material to heat exchangers other than radiators is also expected to enable weight reduction and miniaturization of these heat exchangers.

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