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NEW HIGH RESISTIVITY ALUMINUM CAST ALLOY "FR-Al"

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I. INTRODUCTION

The traditional method of manufacturing the cage rotor of a squirrel cage induction motor is to make a slot in the circumference of the rotor core, pass through a copper or copper alloy rod and braze end rings to both ends. However, because of problems concerning manufacturing costs and joint reliability, the aluminum alloy die cast method is becoming more popular. In addition to pure aluminum, the casting materials include Al–12% Si alloy, Al–11% Si–2.5% Cu alloy, Al–10% Mg alloy, etc.

Because of the increasing demands for squirrel cage induction motors and the widening range of applications, the manufacturing methods are becoming more rational and in order to improve the starting torque characteristics, materials with a higher specific electric resistance than the former aluminum alloy castings are needed. If such an aluminum casting can be obtained, it is possible to manufacture induction motors with various torque characteristics by using the material properly so that the core solt shape is constant. Another important advantage is that an aluminum casting can be used in place of the former high resistance copper bar.

Under such conditions, Fuji Electric has developed, on the basis of long years of experience, an Al–Mn system new aluminum cast alloy (Fuji Resistivity Aluminum Alloy—patent applied for) which a high resistance of less than 15% IACS conductivity and also features good castability, corrosion resistance and elongation properties. These alloys are now being applied in actual machines. This article will introduce the development process of these new "FR–Al" alloys and their characteristics.

II. GENERAL OUTLINE AND REASONS FOR DEVELOPMENT

Aluminum cage rotor are mainly manufactured by die casting or gravity casting in the case of large rotors. The shape of the slot is rather narrow and excellent castability, especially die castability, is required. Mechanical elongation is also a very important factor since there is a danger of cracking or failure occurring in alloys which will not elongate fully during cooling after the die casting, pulling away from the mold or subsequent handling. It is also necessary to consider corrosion due to the atmosphere in which the rotor is used.

It is therefore necessary to fulfill these requirements and also use a material with the required resistance value (conductivity) but the formerly used alloys all have both good and bad points and the maximum resistance value is 21% IACS conductivity. In addition to pure aluminum (50% IACS conductivity when die cast), the well known cast alloys used for cage rotors are Al–12% Si alloy (30% IACS), Al–12% Si–2.5% Cu alloy (23% IACS) and Al–10% Mg alloy (21% IACS). Although the maximum resistance is found with the Al–Mg alloy and corrosion characteristics are better than in other cases, the castability is very bad and this alloy is not used at present. In the case of the Al–Si alloy and the Al–Si–Cu alloy, the castability is good but the mechanical elongation is small and the corrosion characteristics are less than those of the Al–Mg alloy.

Under those conditions, there was a strong incentive for the development of an aluminum alloy which would conform with the above mentioned requirements and also be freely adjustable within the range of 30～15% IACS.

III. PRINCIPLES USED IN THE DEVELOPMENT OF THE "FR-Al" ALLOY

Generally, the conductivity of a metal decreases as the amount of impurities and alloying elements increase and the greater the amount in the solid solution state. For example, there have been many reports in the literature concerning the influence of alloying elements on the conductivity of aluminum. Considering these in order to obtain a high resistance, it appears easy for the conductivity to decrease in the case of Al–Si or Al–Si–Cu alloy by adding the minute amounts of Mn, Ti, V, Cr and Zr. However, actually there is a saturation of about 20% IACS whenever any alloying element is added and when larger amounts are added, the conductivity will increase and the elongation will decrease remarkably. The influence on the conductivity of the Al–Si alloy due to the addition of various elements is shown in *Fig. 1*. In this case, the casting was made by the gravity method but the same tendencies have been found in the die cast method. Therefore, it can be considered that the base metal will contain more elements in the solid solution state and the conductivity will be lower in the case when these elements are added to the pure aluminum than in the case when they are added to the alloys.

Manganese, one of the alloying elements for which the conductivity becomes extremely low, is known to have the advantage of raising the corrosion resistance in a wrought alloy when added up to about 1.5% in usual cases. According to the equilibrium phase diagram, manganese exists as a solid solution only in 1.4 wt % at 658.5°C but when the cooling is very rapid, it is super soluted up to 9 wt % and it is easy to form a super saturated solid solution[1),(2)]. *Fig. 2* shows an aluminum rich side diagram for an Al–Mn binary alloy, as well as the super saturated solid solution curves. In the case of the alloy which contains 3～4% Mn of hyper-eutectic composition, it is known the castability is excellent. The first report was published by Marc van Lancker[(3)] of Belgium considering the applicability in cases such as die casting where the cooling rate is very rapid, and various types of recearch have also recently been performed in Japan[(1),(4)]. There have also been recent reports of the actual application of this Al–Mn system alloy[(5)].

Fig. 3 shows the results of a test of the influence on the conductivity when up to 5% of manganese was added to 99.0% aluminum. Even in the case of gravity casting, the conductivity decreased when about 4.5% of manganese was added, and further when other various elements were added in minute amounts, the conductivity can be decreased up to about 16% IACS. As is evident from *Fig. 3*, the super-saturating tendency increases and the conductivity decieases when the permanent mold size is small and the cooling rate is high. However, the conductivity decreases even more when die casting is used and up to 13% IACS can be achieved. Under those conditions, it seems possible to obtain alloys for which the range of conductivity can be freely controlled in accordance with the amount of manganese added. *Fig. 4* shows the micro-structure and Mn X-ray image in accordance with the amounts of manganese added. After manganese is present in amounts of 3%, acicular type precipitates (probably an intermetallic compound of Al_6Mn or Al_4Mn) appear and increase as the amount of manganese addition increases. However, as will be described later, such an acicular type precipitates have not been confirmed in the super soluted state in die casting. According to the crack susceptibility test by the ring cast method[(6)], a crack initiation tendency was found at manganese contents of 1～2% but this was prevented when other elements were added.

The results of various other practical experiments have shown the excellence of the FR–Al Nos. 1～4 high resistivity aluminum cast alloys with four types of conductivity. As will be described in the following sections, these alloys also have excellent castability, elongation, corrosion characteristics etc.

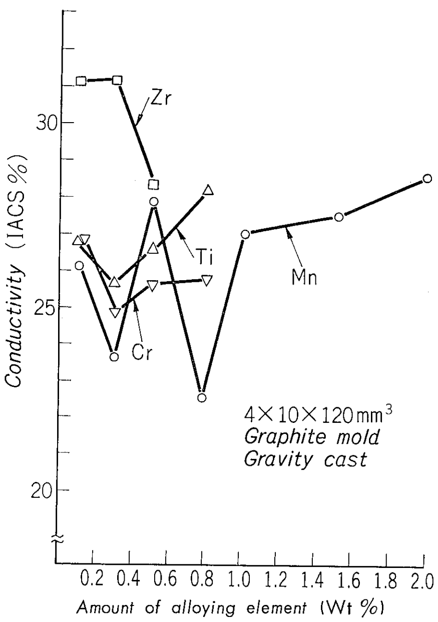


Fig. 1 **Effect of various alloyimg elements on the electrical conductivity of Al–Si alloy**

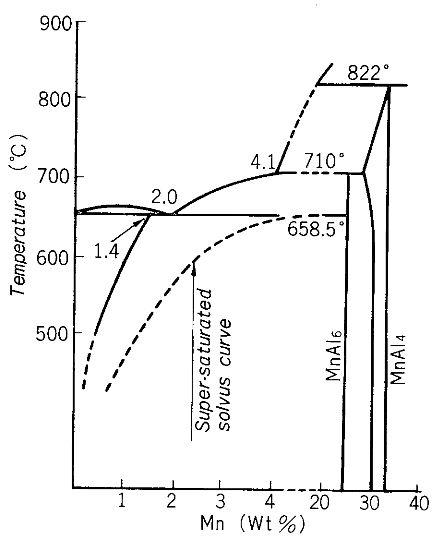


Fig. 2 **Al–Mn binary equilibrium diagram**

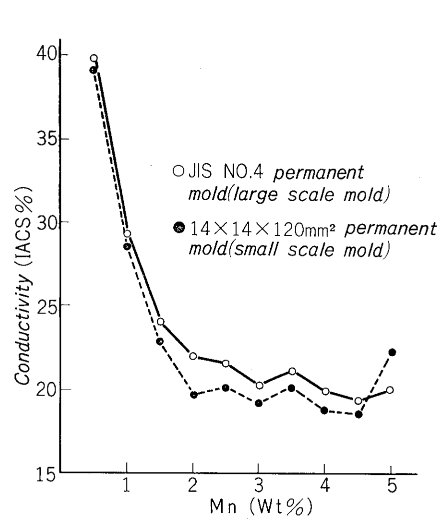


Fig. 3 **Effect of manganese content on the electrical conductivity of Al–Mn alloy**

IV. OUTLINE OF "FR-Al" ALLOYS

1. Electrical Resistance of "FR-Al"

As will be described below, the "FR–Al" alloys can have higher resistances than usual alloys (FR3 and FR4) but there are also types with lower resistance values (FR1 and FR2). For details refer to *Table 2.*

2. Castability of "FR-Al"

The conditions when "FR–Al" alloys are die cast in the rotors are excellent and the castability can be considered the same as that with the former Al–Si–Cu alloy. *Fig. 5* shows a typical example of results of a crack susceptibility test using "FR–Al" alloys Nos. 1∼4 and former alloys cast by the ring cast method. The results are good in all cases. *Fig. 6* shows the micro-structure of gravity cast "FR–Al" No. 4 (JIS No. 4 permanet mold) and the same Alloy die cast for the rotor. As was mentioned previously, considerable precipitation has been confirmed with manganese compounds in gravity cast material but the die cast material can form a uniform

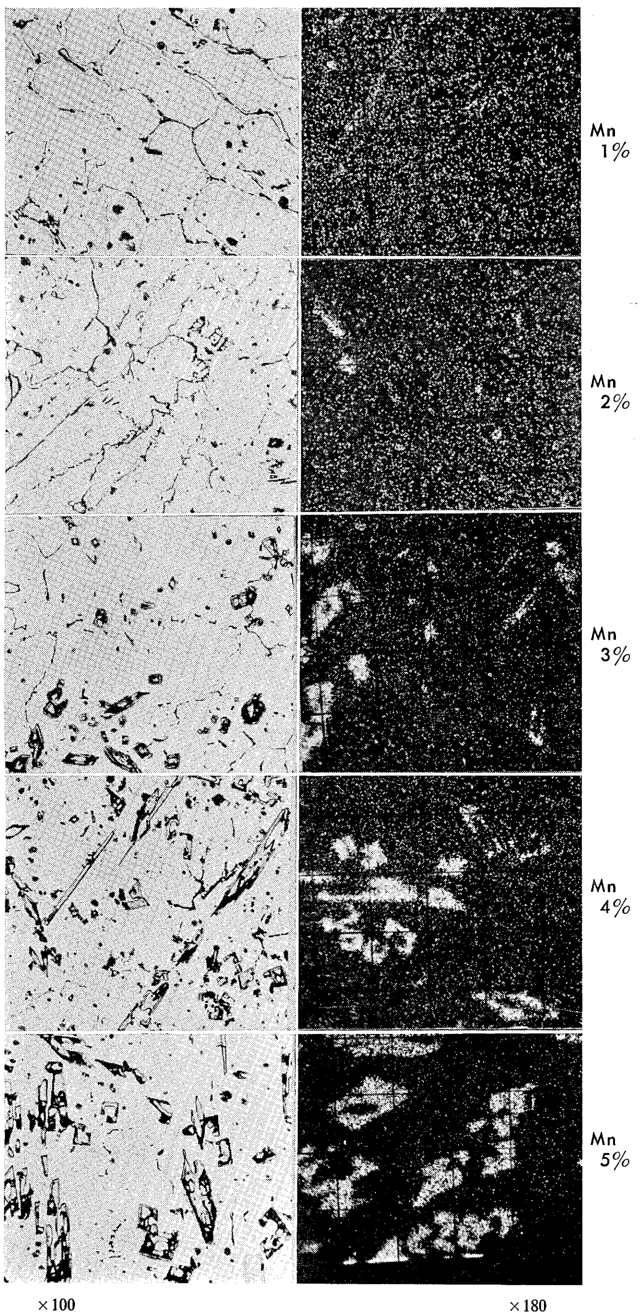


Fig. 4 Effect of manganese content on the microstructure (left) and X-ray image of manganese (right) in Al–Mn alloy

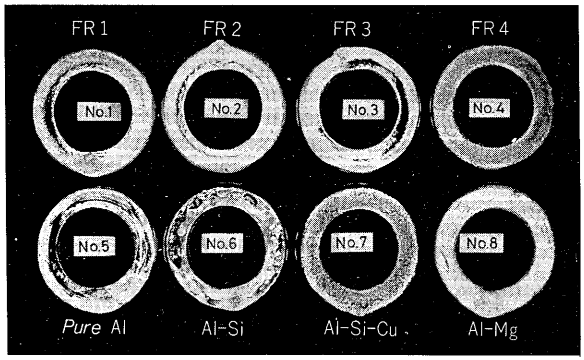


Fig. 5 Appearance of crack susceptibility test by ring casting method

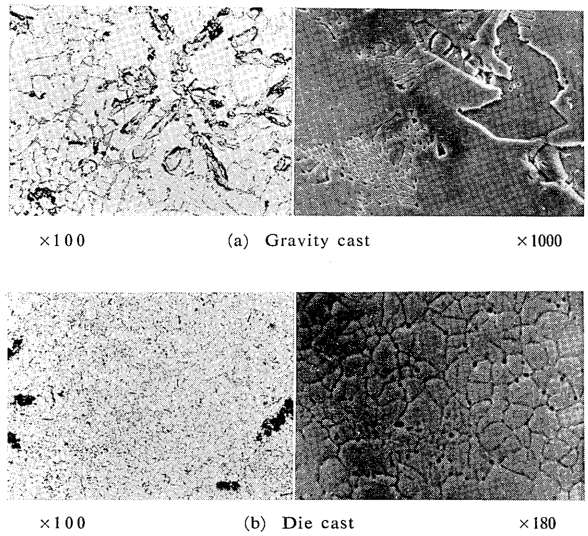


Fig. 6 Effect of casting methods on the microstructure of "FR-Al" No. 4

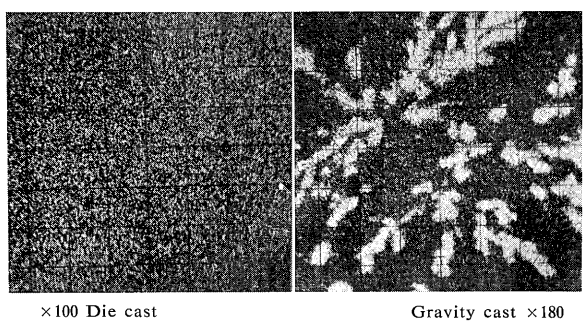
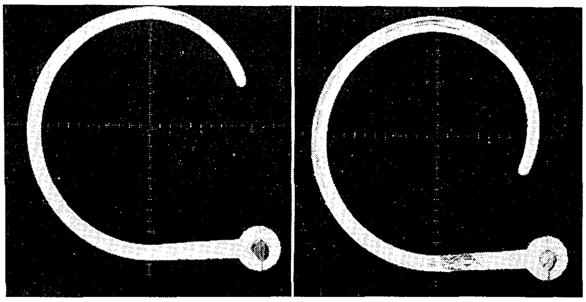


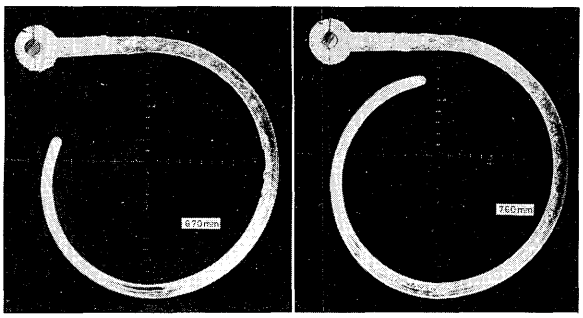
Fig. 7 X-ray image of manganese in "FR-Al" No. 4



Al-Mg 21% IACS
Casting temperature 700°C
(m. p. +100°C)

"FR-Al" No. 4 16% IACS
Casting temperature 800°C
(m. p. +100°C)

Fig. 8 Comparison of casting fluidity between "FR-Al" No. 4 and Al-10% Mg alloy



No Zr is added

Zr is added

Fig. 9 Effect of zirconium addition on the casting fluidity of "FR-Al" No. 3

solid solution and its micro-structure is remarkably different. This clear from the Mn X-ray image in *Fig. 7*. It is evident that this alloy is excellent particularly when used with die casting.

Concerning the casting fluidity, one of the criteria for judging castability, *Fig. 8* shows the results of a test using a spiral graphite mold[7]. When the casting is performed at 100°C above the melting point, the "FR-Al" No. 4 alloy shows better casting fluidity than the Al-Mg alloy which had the highest electric resistance of all the former alloys. *Fig. 9* shows the results of an investigation concerning the influence on the casting fluidity of the addition of a small amount of Zr to the "FR-Al" No. 3 alloy. As can be seen from the figure, the casting fluidity of the alloy is improved by the addition of the Zr. This is one of the features of these alloys. All of the above results indicate that the "FR-Al" alloys have sufficient castability.

3. Mechanical Properties of "FR-Al"

When aluminum alloys are used in cage rotors, there is almost no problem of strength but there is a demand of the large amount of elongation. In the case of Al-Mn binary alloys, the effects of including the manganese on the mechanical properties are shown in *Fig. 10*. The strength is raised by the addition of Mn but not very much. The elongation decreases as the amount of Mn added is increased but the absolute value is rather large in this case.

The rotor is subjected to various heat affects during manufacture and during motor operation, so that stability at high temperatures is required. As a reference, the JIS No. 4 tensile test piece which had been gravity cast was subjected to various types of heat treatment and the results of the test which indicate the effects on the mechanical properties and the conductivity are shown in *Table 1*. As is evident from these results, the "FR-Al" alloys are stable in respect to thermal cycles.

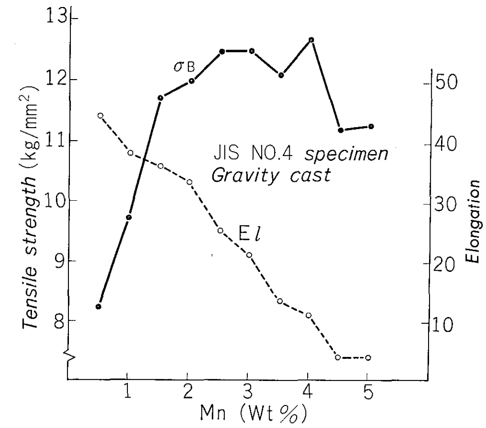


Fig. 10 Effect of manganese content on the mechanical properties of Al-Mn alloy

Table 1 **Effect of heat treatment on the properties of "FR-Al" No. 4**

Heat treatments	Conductivity IACS%	Tensile test	
		σ_B (kg/mm²)	*El* (%)
Virgin	16. 1	11. 9	5. 6
400°C×3h+ Water quench	15. 9	12. 0	5. 6
400°C×3h+Air cool	16. 4	11. 9	4. 6
250°C×100h+Air cool	17. 0	10. 7	4. 0

4. Corrosion Resistance of "FR-Al"

Corrosion resistance must be considered in accordance with the environment in which the motor is to be operated. Manganese is known to give good corrosion resistance and from this it can be expected that the "FR-Al" alloys will also have excellent corrosion resistance.

According to the results of a salt water spray test, (refer to *Fig. 11*), the "FR-Al" alloys have better corrosion resistance than the Al-Mg alloy which was previously considered to be the best in this respect. Therefore, the "FR-Al" alloys can be utilized as corrosion resistant alloy castings.

5. Application of "FR-Al" Alloys

The above features confirm that the "FR-Al"

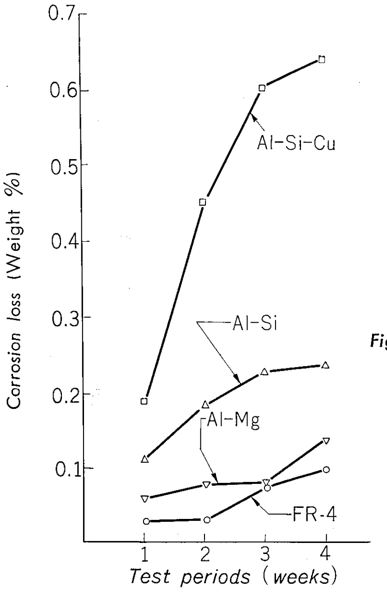


Fig. 11 An example of salt spray test results with 5% NaCl solution

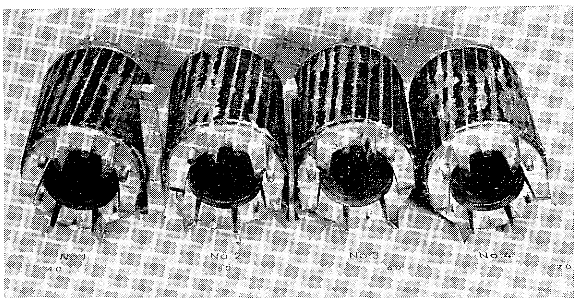


Fig. 12 Rotor die cast with "FR-Al" No. 1~4

alloys can be used in cage rotors. *Table 2* shows all of the various characteristics of the "FR-Al" alloys based mainly on the test results described previously. *Fig. 12* shows an outerview of the alloys when die cast in an actual cage rotor.

In addition to cage rotors, the high resistance characteristics of the "FR-Al" alloys can be utilized in other electrical machinery. For example, it can be used in place of the former Al-Si alloy in the cast vessels for current transformer cores to prevent eddy current loss. In such cases, a sand cast with a thickness of 5 mm is employed and the anticipated resistance can be obtained even in such a slow cooling rate condition. "FR-Al" alloys may be used in place of Al-Mg alloys employed in parts requiring high corrosion resistance, and also as various types of structural materials.

V. CONCLUSION

The percentage of material costs is very high in the overall costs of producing electrical equipment, and therefore, it is very important to carefully investigate manufacturing systems and substitute materials from this standpoint. The high electrical conductivity aluminum "FS-Al" alloy was formerly developed[8] and are being used in place of copper, but now the "FR-Al" alloys with even lower conductivity and high resistance have been developed and are introduced here.

All of the "FR-Al" alloys, Nos. 1~4, can be supplied as alloy ingots and they are expected to become popular with users.

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Table 2 Various properties of some aluminum cast alloys and "FR-Al"

Alloy \ Item	Castability**	Corrosion resistance**	Tensile test σ_B (kg/mm²)	Tensile test *El* (%)	Conductivity (IACS %) Gravity cast*	Conductivity (IACS %) Die cast	Specific resistance (Die cast) (℧ m/mm²)	Melting point (°C)	Recommended casting temp. (°C)
Pure Al (99.0)	○	○	9.0	48.2	58.0	50.0	29	660	700~720
AC 3 A (Al-12 Si)	◎	△	14.7	3.2	33.2	30.0	17.4	580	620~640
AD C 12 (Al-11 Si-2.5 Cu)	○	×	21.1	2.2	24.6	22.7	13.2	580	620~640
AC 7 B (Al-10 Mg)	×	○	23.8	5.4	22.8	20.6	12	600	640~660
F R - 1	○	◎	10.5	48.0	33.6	30.0	17.4	660	700~740
F R - 2	○	◎	10.9	25.6	42.4	21.0	12.2	660	700~740
F R - 3	○	◎	13.2	36.0	21.3	17.5	10.2	660	700~740
F R - 4	○	◎	11.9	6.0	16.1	13.0	7.6	700	740~760

* JIS No. 4 permanent mold test piece ** ◎ Very good ○ Good △ General × Bad