UDC 621. 71. 018: 621. 315, 53

"FS-AL" NEW ALUMINUM ALLOY FOR ELECTRICAL CONDUCTORS

Toshiro Kobayashi

Kenzo Miyagawa

Kazuo Tazaki

Central Research Laboratory

I. FOREWORD

The vast majority of electrical conductors are made of copper, but copper is now being replaced by aluminum due to the rapid depletion of copper resources and its fluctuating price. This of course is related to advances being made in aluminum connecting methods and refining technology, but the major influence is considered to be from the standpoint of price. In addition, the opportunity to shift to the use of aluminum is also when the price of copper is at its highest.

Under these conditions, Fuji has successfully developed a new aluminum alloy wire having the electrical conductivity of pure electrical conductor grade aluminum (EC aluminum) plus excellent mechanical characteristics (strength and ductility) and thermal resistance. This alloy has already been patented in Japan and abroad and a quantity production system has been established with the cooperation of related companies. Its ideal characteristics as the winding material of electric machines has been confirmed by its adoption in our transformer windings and motor windings and its use in areas where EC aluminum alloy is indispensable in the near future is though to be possible. This new alloy has been given the trade name " FS-AL ".

II. ALUMINUM AND ALMINUM ALLOYS FOR ELECTRICAL CONDUCTOR

Although electrical conductivity of aluminum is 62 per-cent of the copper, the weight of aluminum necessary for the same electrical current capacity is saved only half of copper. Generally, the conductivities of metals are influenced by impurities; i.e., high purity metal has a good electrical conductivity. In aluminum for electrical purpose, the impurities such as Mn, Ti, V that decrease the electrical conductivity remarkably are limited, and such aluminum is called Electrical Conductor Grade Aluminum (EC-AL).

EC-AL has a good electrical conductivity for its high purity, but mechanical properties, thermoresistance are rather inferior to those of copper. To improve such inferiorities, various aluminum alloys have been developed mainly by electric wire makers. Such aspects are summarized in *Fig. 1*. Heat-treating type alloys are generally high in cost, for such reasons as solution heat treatment and aging during manufacturing are needed. However, work-hardening type alloys are not necessary such treatments, and high mechanical strength is obtained only by working. But in this case, the electrical conductivity is generally decreased remarkably. Generally, aluminum alloys for electrical conductor are classified into two types, that is, high-strength type and thermoresistance type. However, it is considered that the final purpose in the development of aluminum conductor alloys is to combine such properties as strength, thermo-resistance and electrical conductivity.

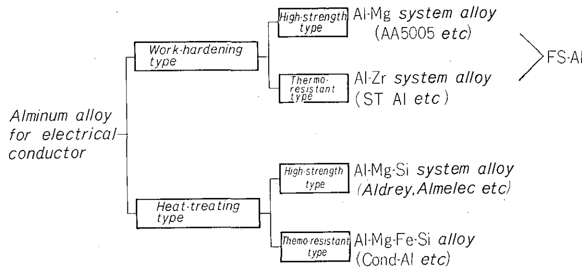


Fig. 1 Classification of various aluminum alloys for electrical conductor

These properties are contradictory and it is very difficult to combine with each other. However, it is considered that FS-AL is rather succeeded in this respect, that is, high mechanical strength, high thermoresistance and electrical conductivity comparable with EC-AL are combined in FS-AL. Further, FS-AL is work-hardening type alloy and the manufacturing process is easy. That is, it is considered that various property needs for aluminum alloy conductor are combined in FS-AL.

III. GENERAL ASPECTS OF FS-AL

1. Features and Various Characteristics of FS-AL

FS-AL is consisted of basic alloying emements, such as magnesium and iron; and further the fourth alloying element is added specially. FS-AL is a work-hardening type and it has good mechanical strength, high electrical conductivity and thermo-resistance. Furthermore, flexibility, corrosion-resistance and fatigue strength, these properties are specially demanded for aluminum alloy conductor, are all satisfied in FS-AL.

Special feature of FS-AL is based on the newly discovered phenomenon that the fourth alloying element improves electrical conductivity and thermo-resistance at the same time. This fact is shown in

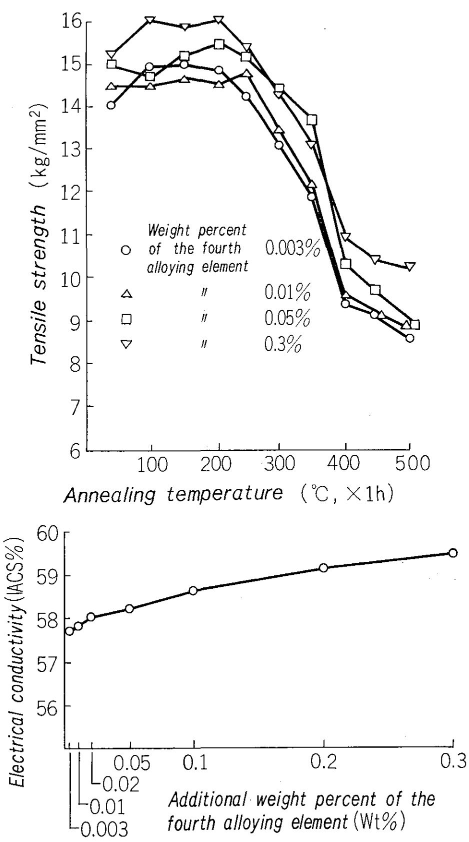


Fig. 2 **Effect of the fourth alloying element addition on the recrystallization characteristic and conductivity of FS-AL**

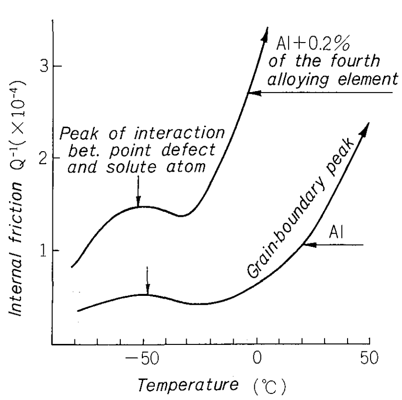


Fig. 3 **Effect of the fourth alloying element addition on the internal friction properties of aluminum**

Fig. 2. This is because the fourth alloying element combines with vacancies in the metal crystals which are made during solidification and working and then lowers the electrical conductivity. Furthermore, the decrease of the free vacancies makes the alloying element such as iron difficult to diffuse in aluminum matrix at a high temperature and suppress recovery and recrystallization.

This is suggested from the fact shown in *Fig. 3*. *Fig. 3* shows the result of internal friction test on pure aluminum and aluminum which was added the fourth alloying element; this test measures the behaviour of lattice defects in matal crystals sensitively. It is observed the peak about −50°C, and this peak is generally said due to the internal reaction between the vacancies and solute impurity elements. It is observed in *Fig. 3* that this peak is increased by addition of the fourth alloying element. This fact suggests the reaction between the vacancies and the alloying element and explains the phenomenon mentioned above.

Fatigue and creep rupture test results on the specimens which were taken from EC-AL and FS-AL manufactured in the laboratory are shown in *Table 1*. Corrosion test results are also shown in *Table 2*. From these results, it is found FS-AL is excellent not only in mechanical strength, thermo-resistance and conductivity, but also in the corrosion resistance and fatigue strength.

Table 1 **An example of the fatigue and creep-rupture tests results (50% cold worked specimen**

Items / Materials	Rotating bending fatigue test (room temp.)		Creep rupture test (200°C)	
	σ=8kg/mm²	σ= 10kg/mm²	σ= 7.5 kg/mm²	σ= 10kg/mm²
FS-AL	N= 5.156×10^6	N= 7.52×10^4	21 hrs.	5 hrs.
EC-AL	—	—	50 min.	2 min.
Other alloy	N= 1.292×10^5	N= 7.0×10^4	2 min.	—

Table 2 **An example of the corrosion test results**

Test results / Materials	Weight loss after immersion in 2.4N HCl solution (%) (30 min)	Weight loss after immersion in 2.4N NaOH solution (%) (30 min)
FS-AL	0.740	1.261
EC-AL	0.004	1.474
Other alloy	0.964	1.354

2. Manufacture of FS-AL

When FS-AL is used as magnet wires or transmission and distribution lines, wire rod (9.5∼12 mm ϕ) is manufactured at first and then the wires which have various shapes and characteristics are worked. As manufacturing methods until wire rods, extrusion and usual hot-rolling processes are well known.

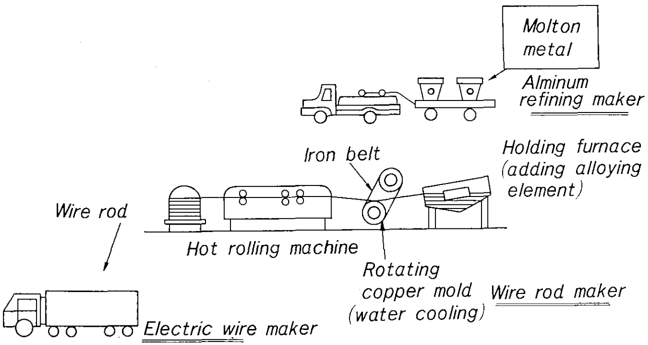
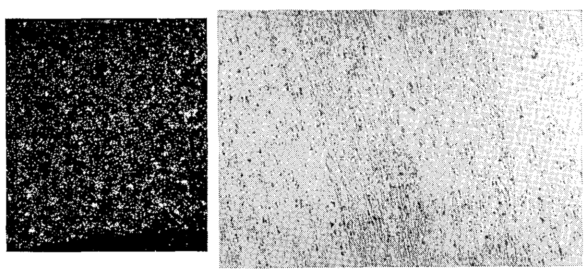


Fig. 4 Manufacturing process of alminum wire rod

However, recently, continuous casting and rolling processes such as Properzi and Speedem ones are popularily used. Manufacturing process of wire rods from this Properzi process is shown schematic ally in *Fig 4*.

In continuous casting and rolling process, the metal is usually solidified rapidly and then hot-rolled by utilizing the heat of casting. Therefore, the alloying element is apt to exist in the metal matrix as a solid solution. This tendency is favorable to increase the thermo-resistance of FS-AL. *Fig. 5* shows the microstructure and X-ray micro-analysis image at the section of FS-AL wire rod. It is observed homogeneous working state and distribution of iron: remarkable precipitation of iron is hardly observed.



(1) Fe X-ray micro-analysis image of FS-AL wire rod ×250 (2) Microstructure at the mid-section of the wire rod ×200

Fig. 5 Microstructure and X-ray micro-analysis image of FS-AL wire rod

IV. APPLICATION OF FS-AL TO TRANSFORMER WINDINGS

In our company, application of aluminum as transformer windings has been performed successfully until now. But only EC-AL has been used. To increase the power capacity of the transformer which is able to be made from aluminum windings, the development of a new aluminum alloy was demanded. The operating temperature of the transformer is usually 95°C, and further various heat cycles and dynamic mechanical stresses are considered during short. From these reasons, heat-softening has been worried in the case of aluminum and the design stress has been suppressed rather low. Although it is difficult to reappear these heat and mechanical behaviour in the laboratory test, we assume the heat-softening behaviour during life can be reappeared by the next heat treatment, 200°C × 100 hrs.; and then the mechanical stress during short is reappeared by giving the load cycles at high temperature (150°C). After from these tests, the total elongation is measured and the design stress is decided. The design stress in the case of copper, 0.2 percent proof stress ($\sigma_{0.2}$) is generally adapted. But, in the case of aluminum, the lower stress than 0.2 percent proof stress has been considered.

Fig. 6 shows the result of such test as mentioned above, which was conducted on FS-AL. According to the load-elongation curve, copper has a remarkable elongation and tensile strength in comparison with aluminum. However, no difference is observed in 0.2 percent proof stress. And it is observed the elongation after heat and load cycles is rather lower in FS-AL. From this, FS-AL is considered to be excellent as the transformer windings. Naturally, this is due to the fact that the rate of work hardening in FS-AL is large against copper, but FS-AL has a good flexibility and windability as described in the next.

Various properties on 4×10 mm size transformer windings (½ hard) of EC-AL, other aluminum conductor alloy, and FS-AL are summarized in *Table 3*. And recrystallization characteristics, which is a measure of thermo-resistance, are shown in *Fig. 7*. On regarding to the strength, from the view of winding operation, it is proper to be 13~15 kg/mm^2. However, high strength offers high design stress. And any strength level is easily obtained in FS-AL by controlling the manufacturing process. And also, electrical conductivity of FS-AL is about 62% IACS: this corresponds to one of EC-AL. On regarding to the thermoresistance, it is observed that FS-AL is superior to EC-AL and other aluminum alloy and it is considered FS-AL can be used continuously even at 180°C.

Further, it is assured the flexibility which is specially demanded for windings is very excellent. In *Fig. 8~10*, flat-wise bend test, edge-wise bend

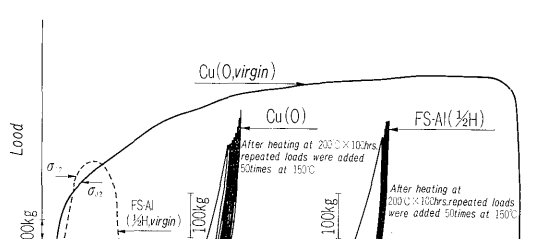


Fig. 6 Comparison of mechanical properties between FS-AL and copper for transformer windings (4×10 mm)

Table 3 **Typical characteristics of FS-AL windings (4×10 mm) for transformer**

Items \ Materials	FS-AL No. 1	EC-AL
Tensile strength (kg/mm²)	14.7	13.5
0·2% proof stress (kg/mm²)	11.9	10.8
Elongation (%, G.L.=250mm)	5.0	2.8
Electrical conductivity (IACS %)	62.0	62.1
Young's modulus (kg/mm²)	6725	7600
Edge-wise bend test (numbers to fracture, r/t=3)	9~11	6~7
Flat-wise bend test (numbers to fracture, r=30)	7~11	5~6
Flat-wise bend test in the welds (numbers to fracture, r/t=3)	2~11	2~8
Winding operation	OK	OK
Tensile strength after heating at 200°C×100 hrs. (kg/mm²)	13.8	11.5

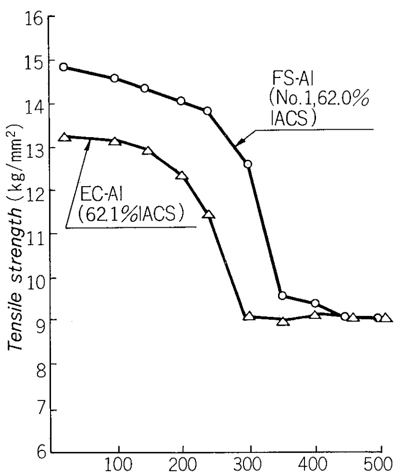


Fig. 7 Recrystallization characteristics of FS-AL windings (4×10 mm) for transformer

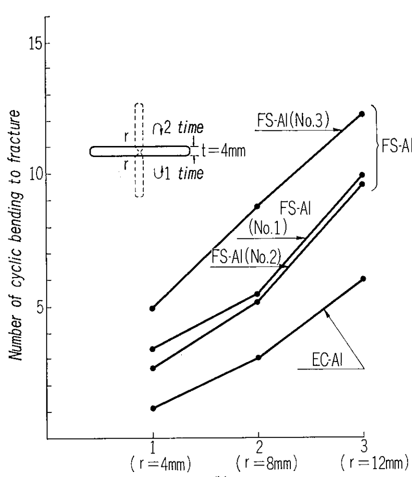


Fig. 8 90° flat-wise bend test of FS-AL (4×10 mm, ½H) for transformer

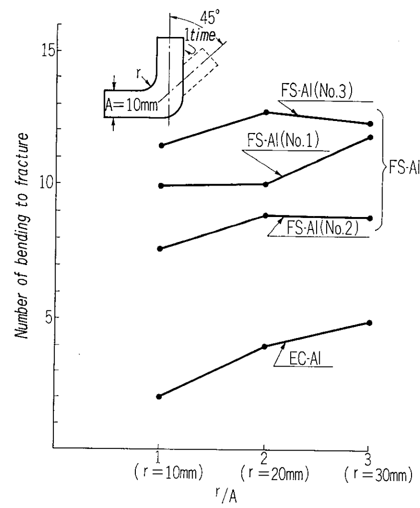


Fig. 9 45° edge-wise bend test of FS-AL (4×10 mm, ½H) for transformer

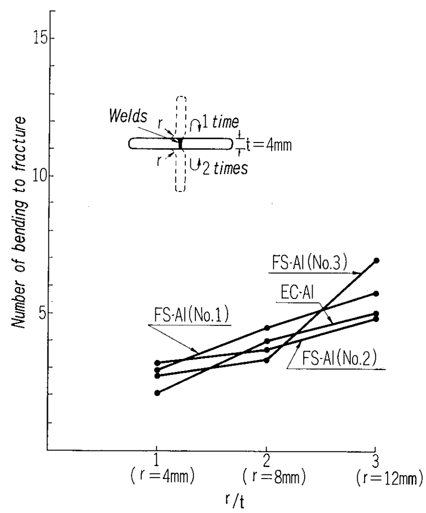


Fig. 10 90° flat-wise bend test of the welds of FS-AL (4×10 mm, ½H) for transformer

test and flat-wise bend test in the welds on various materials are shown. It is obvious from these results that FS-AL is superior to EC-AL and other aluminum alloy in flexibility, and FS-AL endures about two times against the repeated bending cycles. From these, it is obvious FS-AL has very excellent properties as transformer windings.

V. APPLICATION TO MOTOR WINDINGS

It is obvious FS-AL has most suitable properties as a magnet wire as already mentioned. Here, it is mentioned about the polyester wires for motor windings. FS-AL has already been popularized as windings for various electric components in our company.

Various characteristics as a polyester wire (0.95 mm ϕ) are shown in *Table 4*. In EC-AL, tensile strength is low because of the heat affect at the time of final polyester depositing process. However, certain strength is needed to operate by automatic winding machine. In this respect, as FS-AL is superior in strength and thermo-resistance, appropriate strength level is obtained by controlling the manufacturing process. And it has been assured that the wires

***Table 4* Typical characteristics of FS-AL (0.95 mm ϕ polyester wire) windings for motors**

Items \ Materials	FS-AL No. 1	FS-AL No. 2	FS-AL No. 3	EC-AL
Tensile strength (kg/mm^2)	15.0	13.0	13.1	10.5
0.2% proof stress (kg/mm^2)	11.2	8.0	10.5	6.0
Elongation (%, G.L.= 250 mm)	13.0	20.5	15.0	21.0
Electrical conductivity (IACS%)	60.0	60.8	62.5	61.9
Spring back (degrees)	—	60	—	—
Winding operation	OK	OK	OK	It is difficult to wind by machine
Tensile strength after heating at 200°C × 100 hrs (kg/mm^2)	14.8	13.1	12.7	7.4

could be inserted fully and the change of diameter after winding operation was hardly observed.

Test results on recrystallization are shown in *Fig. 11* and it is observed FS-AL has a good thermoresistant property. Test result on changes of tensile strength by long time heating at 120°C and 150°C are shown in *Fig. 12* and *13*, together with in the case of transformer windings. No obvious decrease in tensile strength is observed. From this result and the same result at the heat treatment of 200°C × 100 hrs. shown in *Table 4*, it is considered FS-AL can be used as F and H insulation grade windings. Moreover, even on the problem of winding connection, it has been assured that FS-AL could be treated in the same manner with EC-AL. Appearance of induction motor wound by FS-AL is shown in *Fig. 14*.

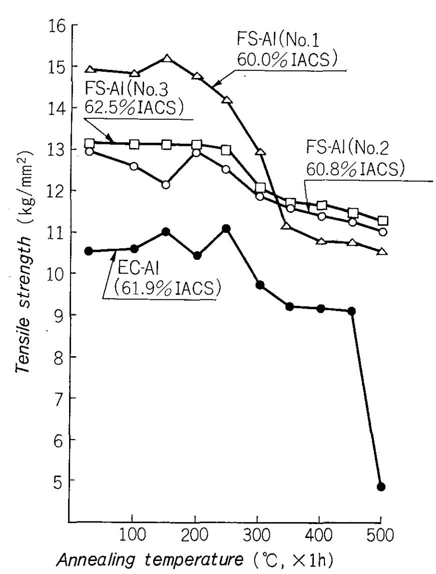


Fig. 11 Recrystallization characteristics of 0.95ϕ polyester wire

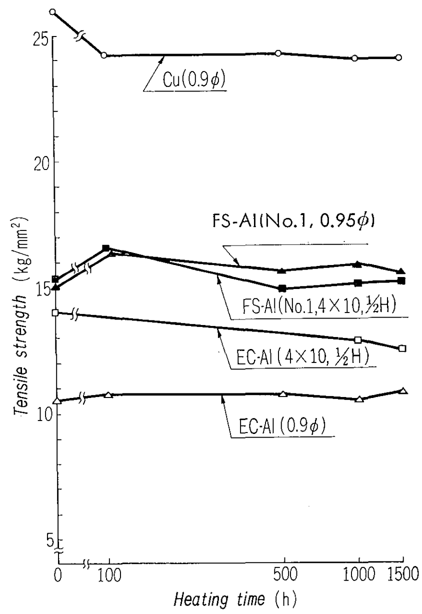


Fig. 12 Changes of tensile strength by long time heating (120°C)

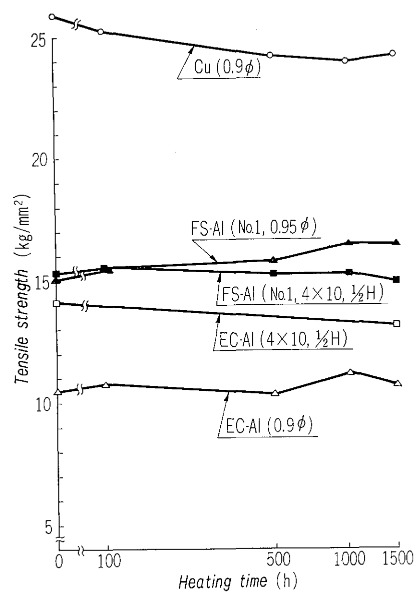


Fig. 13 Changes of tensile strength by long time heating (150°C)

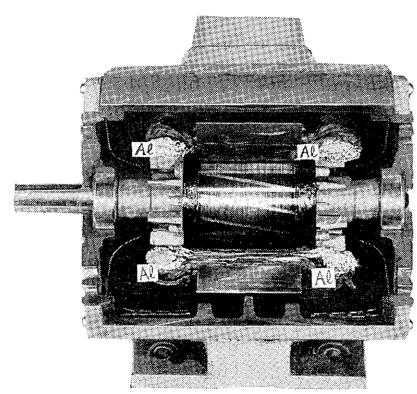


Fig. 14 FS-AL used for the windings of the induction motor

VI. APPLICATION OF FS-AL TO VARIOUS ELECTRICAL CONDUCTORS

FS-AL has ideal characteristics as the winding material of electric machines and its applications in this field are increasing. Also its use as an electrical conductor in various other application is expected to increase due to its high conductivity and high mechanical strength. One example is its application to bus bars. Test products have been produced and studies on problem points encountered in actual application are progressing.

Developement A*l*-Zr system alloys having superb thermal resistance characteristics are flourishing. The strength of this type of alloy is about the same as that of EC aluminum, but there is a small drop in conductivity. However, since its heat softening during use is small, it is superior to EC aluminum when the creep property of the material is considered. For example, the permissible continuous operating temperature of this alloy when used as transmission or distribution lines can be increased from 90°C EC-AL to 150～180°C. However, in this case, steel reinforcement is required to obtain sufficient strength, and this arouses the problem of contact corrosion are easily produced.

Table 5 **Typical characteristics for transmission and distribution lines (2.0～5.0 mm ϕ)**

Items \ Materials	FS-AL	EC-AL	A*l*-Zr system alloy
Tensile strength (kg/mm²)	22.0～29.0	17.0～19.0	18.0～20.0
Elongation (%, G.L.=250mm)	3.0～4.0	1.5～2.5	2.0～3.0
Electrical conductivity (IACS %)	58.5～61.0	61.0～62.0	58.0～60.0
Tensile strength after heating at 200°C× 100 hrs. (kg/mm²)	17.0～20.0	11.0～13.0	15.0～17.0
Tensile strength after heating at 250°C×1 hr. (kg/mm²)	18.0～22.0	13.0～15.0	16.0～19.0

The advantages of FS-AL lie in the fact that its mechanical strength is superior to that of EC aluminum and that the drop in electrical conductivity is extremely small. For example, a tensile strength of 25～30 kg/mm² and a conductivity of over 59% IACS can be obtained when made into hard drawn wire of about 3 mm ϕ. Since the driving energy with respect to recovery and recryztallisation generally increases when the strength of a work hardening type alloy such as FS-AL is increased by increasing the degree of working it tends to become soft easily. However, since the inherent strength of FS-AL is high, the priority of unheated materials can also be maintained. The superior thermal resistance of FS-AL compared with EC aluminum has also been confirmed through tests. From this, the adoption of FS-AL to ACAR (Aluminum Conductor Alloy Reinforced) and AAAC (All Aluminum Alloy Conductor) which requires no steel reinforcing in plaec of ACSR (Aluminum Conductor Steel Reinforced) is anticipated in the future.

With further experiments and testing, its use even as a lower tensile strength drop, higher thermal resistance alloy (the drop in tensile strength due to softening which is general permissible from the standpoint of material quality is set at about 10% during its life) even at high temperatures will be possible by sacrificing a little strength by adjusting the additional amount of alloying element. The results of strength, conductivity, and heating tests for FS-AL, EC aluminum, and zirconium alloy as typical hard materials are given in *Table 5*.

VII. CONCLUSION

The super characteristics of the new FS aluminum alloy for electrical conductors developed by Fuji Electric has been confirmed and its adoption as a winding material is gradually increasing. At the present time, copper prices are fairly low, but there is the possibility that they will again reach a new high in the future and shift to aluminum can still be recommended at this time.

FS-AL also possesses ideal characteristics as hard drawn wire and its increasing use in a wide range of applications from bus bars to transmission and distribution lines in the future can be anticipated. Fuji Electric, a user of electric wire, obtained the cooperation of related companies in the developement of this alloy and a gradual increase in the popularity of FS-AL in a wide range of electrical conductors is anticipated in the future.