Electrical conductivity of some aluminium alloys

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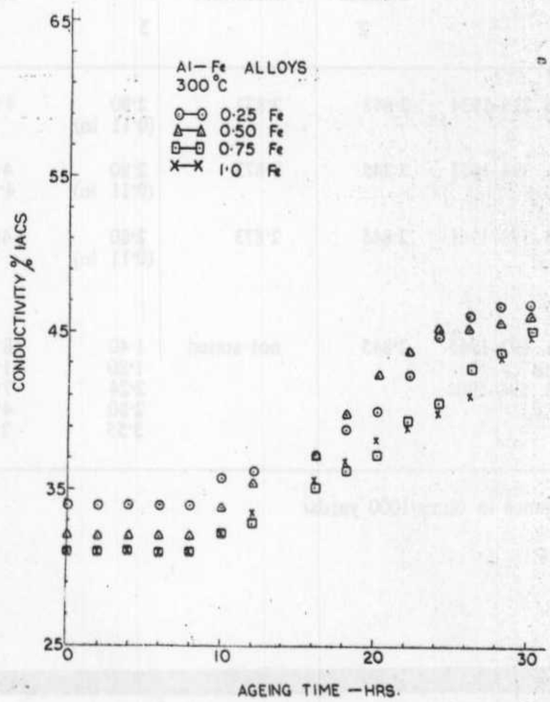
As INDIGENOUS resources of copper are not sufficient to meet the mounting engineering demands for the transmission of electricity, it is being increasingly replaced by aluminium as electrical conductivity of aluminium is second only to that of copper amongst engineering conductor materials. Whereas copper conductors employ copper of highest purity to obtain maximum conductivity, aluminium conductors cannot be made from super-pure aluminium inspite of its superior electrical conductivity as it is soft and of inferior strength. The substitution of copper by aluminium for electrical transmission by overhead ACSR conductors, power cables, etc. has almost become a national policy with the Government for a balanced economic growth of the country although transmission of electricity by ACSR conductors has been in vogue for over twenty years in India. Even in countries where import of copper is not a problem, transmission of electricity by aluminium conductors is proving economical and its use is advocated not as a substitute but as serious competitor of copper on its own merits. The use of aluminium in electrical transmission calls for the development of an aluminium conductor with high conductivity and adequate strength. These are diverse metallurgical objectives since conductivity decreases as alloying elements are added to the lattice of aluminium to raise its strength. It is estimated that almost 50% of the estimated production of 70 000 tons[1,2] of aluminium in 1965–66 will be used to transmit electricity and is likely to increase several folds in subsequent development plan periods. However, there is an acute shortage in the supply of electric grade aluminium (electrical volume conductivity 62% International Annealed Copper Standard in the annealed conditions and 61% IACS in the hard drawn condition).[3] In India the position is further complicated as many of the aluminium producers are not producing aluminium of requisite grade. The problem is so serious that it seems to have forced the Indian Standard Institute to relax in a subtle manner the minimum requirements of conductivity as summarized in calculations of Table I. For example, the I.S.: 398–1953 stipulated a maximum acceptable resistance of 4·64 ohm/km (4·285 ohm/1000 yds) for the 0·110 in. dia. hard-drawn aluminium wire but the value was raised to 4·759 ohm/km in I.S.: 694 (Part II) 1964. The situation can be substantially improved if aluminium could be upgraded by alloy additions.

Electrical properties of aluminium and its alloys

An aluminium conductor can normally transmit 78% of the load that can be carried by a copper conductor



1a *Variation of electrical conductivity of Al-Fe binary alloys with ageing time at 300°C*

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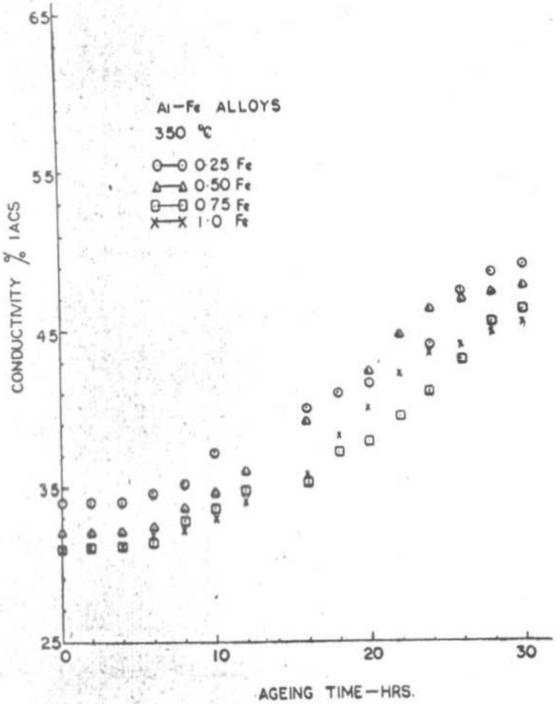
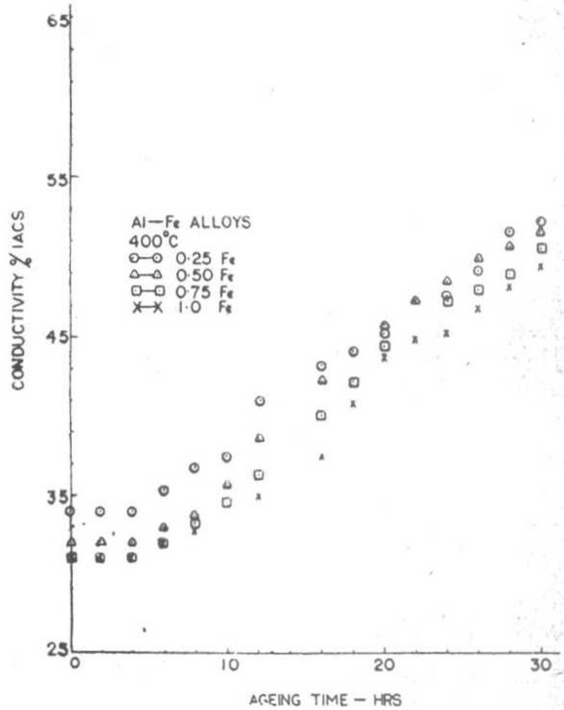


1b *Variation of electrical conductivity of Al-Fe binary alloys with ageing time at 350°C*

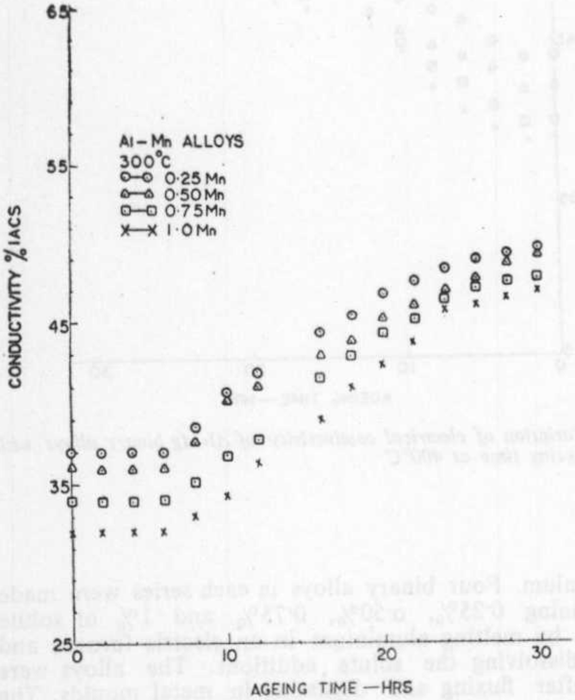


1c *Variation of electrical conductivity of Al-Fe binary alloys with ageing time at 400°C*

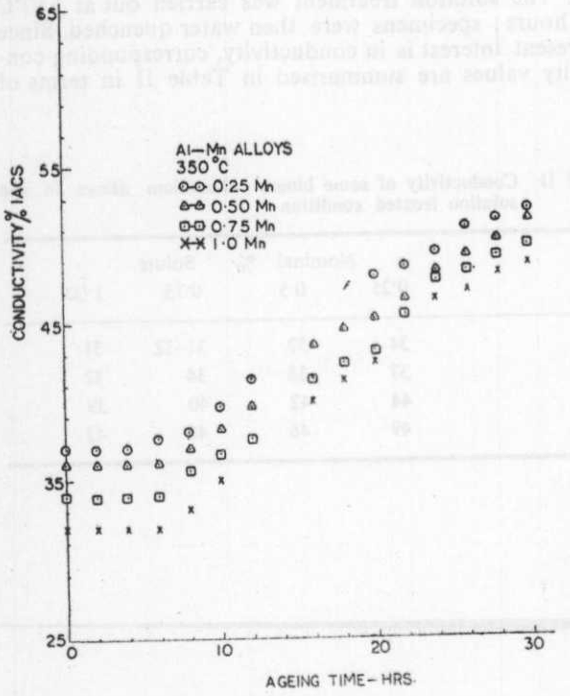
TABLE I Relaxation of Indian standards for minimum requirements of conductivity of different aluminium conductors

	Standard	Resistivity microhms/cm cube		Size dia mm	Resistance ohm/km at 20°C.		Resistivity microhms/cm cube by calculation of date in column (4)		Remarks
		Standard	maximum		Standard	maximum			
	1	2		3	4		5		6
(1)	BS 215–1934	2·845	2·873	2·80 (0·11 in)	4·242*	4·285*	—	—	
(2)	IS 398–1953	2·845	2·873	2·80 (0·11 in)	4·242* 4·620	4·285* 4·640	—	—	No difference between (1) and (2).
(3)	IS 398–1961	2·845	2·873	2·80 (0·11 in)	4·654	4·700	2·891	2·895	Resistivity of columns (2) and (5) are incompatible which suggests relaxation of Indian standards.
(4)	IS 692–1965 and IS 694–1964	2·845	not stated	1·40 1·80 2·24 2·80 3·55	18·48 11·18 7·219 4·620 2·874	19·03 11·5 7·436 4·759 2·960	2·845 2·8452 2·845 2·845 2·845	2·931 2·931 2·932 2·932 2·931	Suggests relaxation of the maximum acceptable resistance of the conductor.

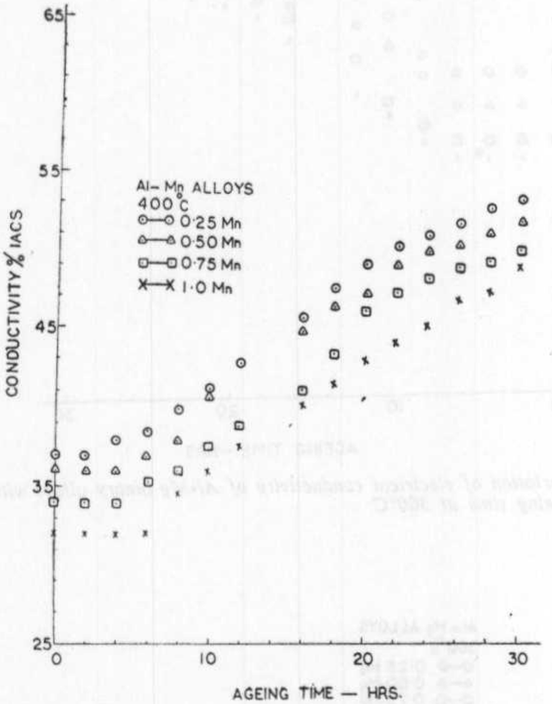
*Resistance in ohms/1000 yards.



2a *Variation of electrical conductivity of Al-Mn binary alloys with ageing time at 300°C*



2b *Variation of electrical conductivity of Al-Mn binary alloys with ageing time at 350°C*

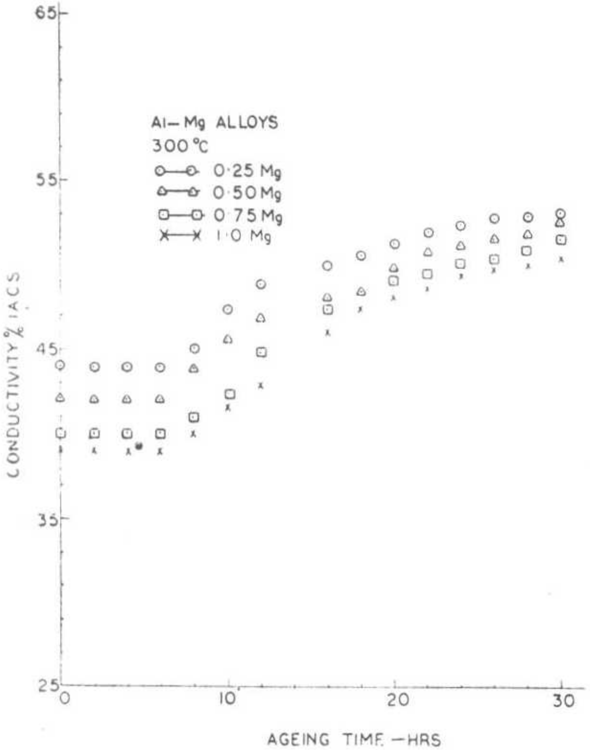


2c *Variation of electrical conductivity of Al-Mn binary alloys with ageing time at 400°C*

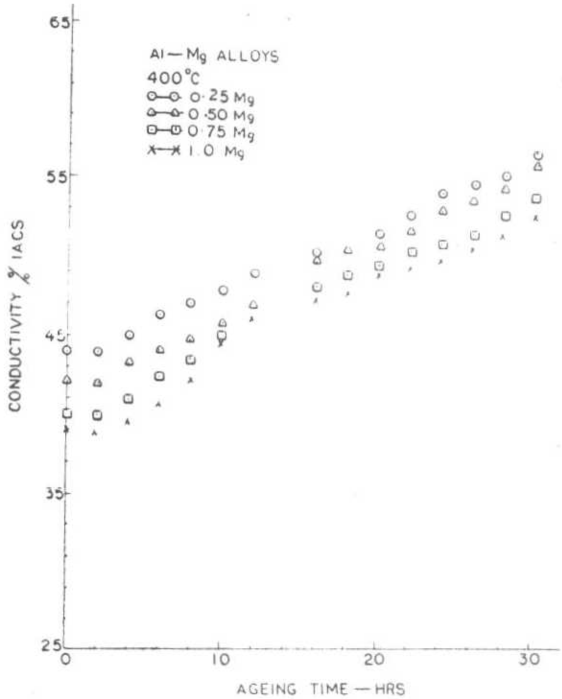
of equal cross sectional area for the same rise of temperature. For equal electrical resistance an aluminium conductor has 1½ times the cross sectional area of copper but weighs only half as much, and as such a ton of aluminium is the equivalent of two tons of copper. Besides, in international market the cost of copper conductor is 3·7 times more than for equivalent aluminium conductor. In India, the imbalance in the market price of aluminium and copper is very much more than in the international market due to severe import restrictions. By virtue of its naturally formed oxide film, aluminium resists corrosion in atmosphere and in chemical environments.[4] It is also easy to fabricate. It offers good potentialities for use in rotating electrical machinery such as field windings in generators driven by high speed turbines as it is light in weight. On this score, machine builders would welcome the development of high strength high conductivity aluminium alloys.

Experimental research

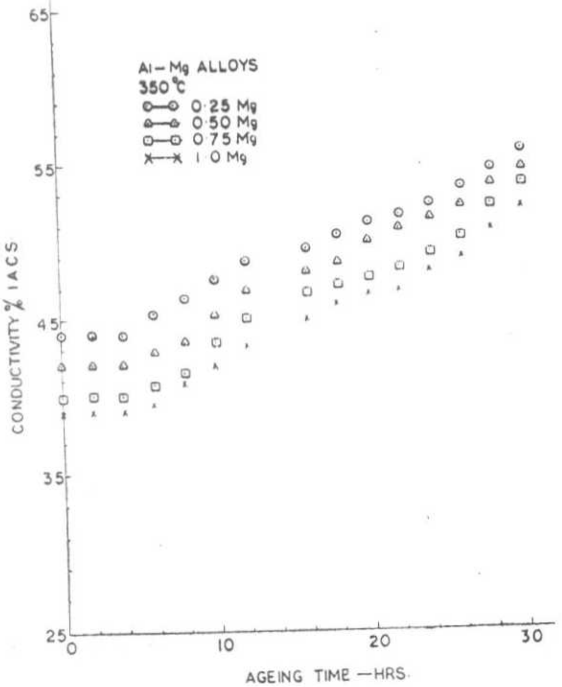
To develop an aluminium alloy of higher conductivity from electric grade aluminium it was necessary to undertake a basic programme of research to determine the effect of binary solute additions of silicon, iron, manganese and magnesium, each up to 1·0% on the electrical conductivity and tensile properties of electric grade



3a *Variation of electrical conductivity of Al-Mg binary alloys with ageing time at 300°C*



3c *Variation of electrical conductivity of Al-Mg binary alloys with ageing time at 400°C*



3b *Variation of electrical conductivity of Al-Mg binary alloys with ageing time at 350°C*

aluminium. Four binary alloys in each series were made containing 0·25%, 0·50%, 0·75% and 1% of solute atoms by melting aluminium in an electric furnace and then dissolving the solute additions. The alloys were cast after fluxing and degassing in metal moulds. The cast ingots (3·5 cm sq × 20 cm) were homogenised and hot forged at 450°C and cold rolled into 0·3 cm thick sheets. Specimens for the measurement of electrical resistivity were made from the rolled sheets and the resistivity was determined in the solution treated condition. The solution treatment was carried out at 550°C for 8 hours; specimens were then water quenched. Since the present interest is in conductivity, corresponding conductivity values are summarised in Table II in terms of

TABLE II Conductivity of some binary aluminium alloys in the solution treated condition

Alloy	Nominal % Solute			
	0·25	0·5	0·75	1·00
Al-Fe	34	32	31–32	31
Al-Mn	37	36	34	32
Al-Mg	44	42	40	39
Al-Si	49	46	45	45

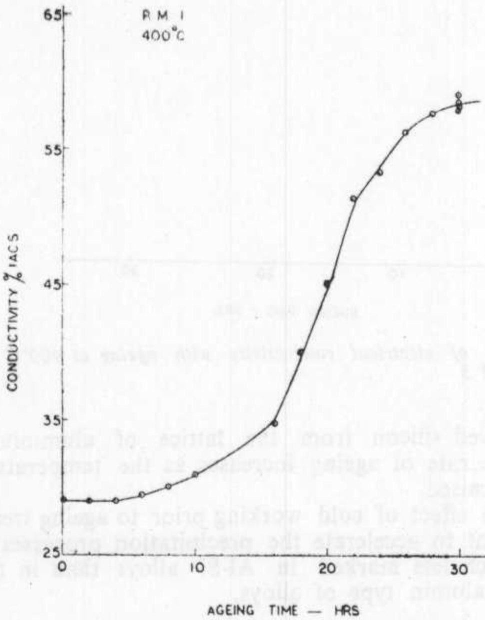
TABLE III Ultimate tensile strength in kg/sq. mm of binary aluminium alloys in the solution treated condition

Alloy	Nominal % Solute 0·25	0·5	0·75	1·00
Al-Fe	7·3	8·6	8·5	9·5
Al-Mn	7·1	7·5	8·7	7·8
Al-Mg	8·6	9·9	9·3	9·8
Al-Si	9·8	10·2	10·5	11·7

the International Annealed Copper Standard in the solution treated condition ; Table III shows the values for the ultimate tensile strength. From the published values[5] for the effect of titanium on the electrical conductivity of aluminium and from Table II, it is concluded that amongst the chief impurities present in aluminium, titanium, gallium, iron, silicon and probably vanadium are largely responsible for the decrease in its conductivity when present as substitutional solutes. Its conductivity may be improved by removing these soluble impurities by (i) heat-treatment (ii) suitable alloying additions or (iii) by both through precipitation of their intermetallic compounds. The effect of the removal of silicon as Mg_2Si from the lattice of aluminium in its electrical conductivity was investigated earlier.[6] Fig. 1, 2 and 3 summarise the variation of electrical conductivity with ageing time and temperature for the Al-Fe, Al-Mn and Al-Mg alloys respectively. It will be noted that substantial improvements in the conductivity of aluminium alloys are obtained only after prolonged ageing up to 30 hours and more between 350–400°C. Since the tensile strength of aluminium conductors is also an equally important factor, it was determined for all specimens in correspondingly heat treated condition but Table IV incorporates data for the specimens aged at 350°C and 400°C for 30 hours. The following experimental conclusions are drawn from the present work and that of Singh and Kumar.[6]

TABLE IV Tensile strength in kg/sq. mm of binary aluminium alloys aged at 350°C and 400°C for 30 hours

Alloy	Temp. °C	Nominal % Solute 0·25	0·5	0·75	1·00
Al-Fe	350	7·4	8·7	7·6	8·1
	400	7·0	8·3	7·3	7·9
Al-Mn	350	7·1	7·4	7·1	7·6
	400	7·2	7·3	8·0	7·7
Al-Mg	350	8·5	8·4	8·9	9·6
	400	8·2	8·5	9·2	9·4
Al-Si	350	8·3	8·4	8·5	8·1
	400	8·8	9·0	9·8	10·3

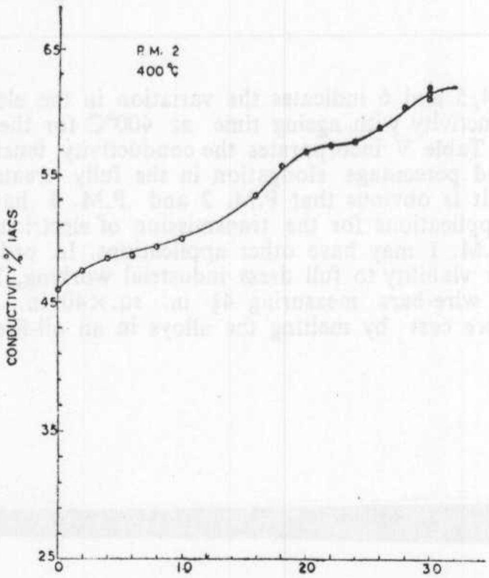


4 *Variation of electrical conductivity with ageing time at 400°C for alloy PM 1*

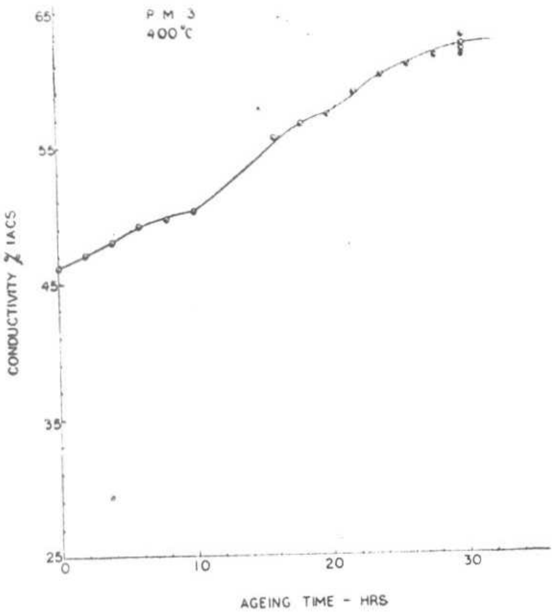
(a) Aluminium after optimum solution treatment and quenching resists the removal of solutes from its lattice during ageing.

(b) The rate of removal of solute atoms is fastest in Al-Si alloys and decreases in aluminium alloys with Mg, Mn, and Fe in that order.

(c) The addition of magnesium to Al-Si alloys substantially increases the rate of removal of dis-



5 *Variation of electrical conductivity with ageing time at 400°C for alloy PM 2*



6 *Variation of electrical conductivity with ageing at 400°C for alloy PM 3*

solved silicon from the lattice of aluminium. The rate of ageing increases as the temperature is raised.

(d) The effect of cold working prior to ageing treatment to accelerate the precipitation processes is much less marked in Al-Si alloys than in the duralumin type of alloys.

Based on the experience gained with the binary alloys, the following three alloys were made using aluminium of different purities on laboratory scale.

Alloy			% purity
P. M. 1	...	...	98·5
P. M. 2	...	...	electric grade
P. M. 3	...	...	electric grade

Figures 4, 5 and 6 indicates the variation in the electrical conductivity with ageing time at 400°C for these alloys and Table V incorporates the conductivity, tensile strength and percentage elongation in the fully treated condition. It is obvious that P.M. 2 and P.M. 3 have potential applications for the transmission of electricity, although P.M. 1 may have other applications. In order to test their viability to full dress industrial working, 30 kg tapered wire-bars measuring $4\frac{1}{2}$ in. sq. × 40 in. at the top were cast by melting the alloys in an oil-fired furnace using the usual Foseco Fluxes and degassers, but without observing the usual precautions in the casting of oxide free aluminium alloys. These wire-bars were handed over to M/s. Indian Cable Co. Ltd., Jamshedpur, for favour of rolling and drawing to the size (0·110' dia.) used in the ACSR conductors. P.M. 2 was successfully rolled and drawn without altering either the rolling or drawing sequences and stood all the tests* specified in the Indian Standard for hard-drawn conductors and Table VI gives its electrical and mechanical properties. But P.M. 3 failed in the first rolling operation presumably due to improper grain structure. P.M. 2 is economically and financially important and its salient features are :

TABLE V Conductivity and tensile strength of three aluminium alloys after ageing at 400°C for 30 hours

		Conductivity % IACS	Ultimate tensile strength kg/sq. mm	% Elongation on 50 mm gauge length
P·M.	1	58–59	12·5	30
P.M.	2	61–62	8·9	39
P.M.	3	61–63	12·4	27

TABLE VI Electrical and mechanical properties of P.M. 2

Resistance ohms/km	...	4·585
Resistivity at 20°C microhm/cm³	...	2·810
Conductivity % IACS	...	61·4
Minimum ultimate tensile strength Psi		28 400
Improvement in tensile strength as compared to IS. 398	...	17%
Elongation on 10″ gauge length %	...	3·5

1. that it is based on electric grade aluminium ;
2. that improvement in conductivity is accompanied by more than 15% increase in ultimate tensile strength coupled with better ductility.
3. that no heat treatment is required after drawing.

Although P.M. 2 has been successfully industrially drawn for ACSR conductors, it can also be used for insulated cables as it satisfies the requirements of their strength.

*These tests were kindly performed by the Metallurgical and Testing Laboratory of M/s. Indian Cable Co. Ltd., Jamshedpur.

PVC insulated cables (I.S. : 694 Part II-1964)	14·80–19·00 kg/sq. mm
Paper insulated lead sheathed cables (I.S. : 692–1965)	not less than 15·00 kg/sq. mm

It can also be used for the manufacture of belted or sector cables since its ductility in the hard-drawn condition as shown by percentage elongation is considerably above the value specified in the IS : 398.

Acknowledgements

The authors wish to acknowledge their thanks to Dr B. R. Nijhawan for his keen interest in this investigation. It is a pleasure for them to acknowledge their gratitude for the hearty cooperation received from Mr R. Bowyer, Resident Director, Dr A. J. P. Sabharwal, Works Manager and Mr K. P. Ganapathi, Production Manager, at M/s. Indian Cable Co. Ltd., Jamshedpur. Thanks are also due to the staff of Mechanical Metallurgy Division of National Metallurgical Laboratory for carrying out the mechanical test on the specimens.

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Discussions

Mr **L. J. Balasundaram** (NML) : I would like to compliment Dr Rajendra Kumar on the useful work he has reported in improving the electrical conductivity of Indian aluminium. When he mentioned his results to me, we fell to talking the mechanism of the process, he said that the unwanted metal is made to come out of the lattice of aluminium when it is fixed up with alloy additions and therefore does not hinder electrical conduction. But this raises the fundamental question as to the nature of electrical conduction in metals and the point that needs clarification is even though the interfering metal after being fixed up with alloy addition comes out of the lattice of aluminium, it is still in the block of metal and is providing an obstacle to the flow of current. Is the increase in conductivity due to less strain in the lattice of aluminium due to the alloying element coming out ?

Dr **Rajendra Kumar** (Author) : The resistivity of a solid solution is greater than that of pure metal as the mean free path of the electron decreases because (i) the solute atoms, of atomic size different than that of the solvent, increase the number of local scattering centres and (ii) the electron/atom ratio may be different in the alloy. Therefore any factors which affect the periodicity of the lattice exercise corresponding effect on the resistivity. The periodicity of the lattice of aluminium is improved by the removal through precipitation of the soluble impurities. The contribution of any second phase to the resistivity of a metal is, however, proportional to its volume fraction. The detrimental effect of precipitated impurities on the conductivity is thus much less than the effect of equivalent number of dissolved atoms.

Dr **Dharmendra Kumar** (Hindustan Aluminium Corpn. Renukoot) : The authors have attempted a very interesting line of investigation for the improvement of electrical conductivity. As suggested by Dr Nijhawan similar kind of work has been attempted in Hungary where additions of small amounts of copper have been made to improve the electrical conductivity of aluminium.

In the paper the purity of the electrical grade aluminium has been mentioned as 99·7–99·8% whereas as per Indian specification EC grade aluminium is 99·5% with an electrical conductivity of 61% IACS minimum. The effect of different alloying elements on the electrical conductivity of aluminium is approximately as follows :

	Percentage decrease per 0·01% of element
Titanium	0·75%
Manganese	0·79%
Vanadium	0·9%
Chromium	0·96%
Silicon	0·2% (for 0·11–0·3% silicon)

The approach of the investigation is very interesting and should be pursued keeping in view that with every additional heat treatment operation the cost increases by Rs 350-500 per tonne.