Study of microstructure of chill cast aluminium bronzes (Cu-Al-Fe-Mn)

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SYNOPSIS

Based on the exhaustive study on the production and mechanical properties of the high tensile aluminium-bronzes in the range of aluminium 8·8–10·8%, iron 2–6% and manganese 0·1–3·5%, typical microstructures of a few compositions have been compared with regard to different etching reagents and their mechanical properties.

SUBSTANTIAL information is available on the microstructures of high tensile aluminium-bronzes but most of the literature is pertaining to the alloys containing nickel. Exhaustive amount of work was carried out by Gupta et al. at the National Metallurgical Laboratory to study the mechanical properties of aluminium-bronze alloys in the chill-cast condition without nickel addition, the results of which have already been reported in an earlier paper.[1] The present paper relates to the study of microstructures of these chill-cast aluminium-bronze alloys. A few microstructures of Cu-Al-Fe system have been given by Copper Development Association in their recent publication on aluminium-bronzes.[2]

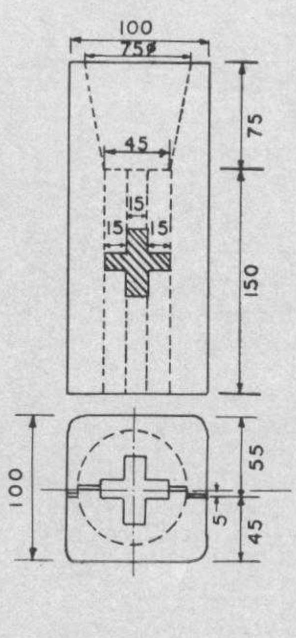
The microstructures studied earlier were at low magnification and did not appear to have any effect on the proof stress values of these alloys. In the present work an exhaustive study was undertaken on the microstructures of more than hundred alloys, to find out whether there is any relation of the microstructure to the proof stress and elongation values of the alloys. Different etching reagents have been used to have a proper evaluation of the structures. The bronzes which are under study contain 8·8 to 10·8% aluminium, with additions of 2 to 6·0 per cent iron, 0·01 to 3·4 per cent manganese and balance copper. All these alloys exhibited minimum ultimate tensile strength of 60 kg/mm², proof stress between 20 and 24 kg/mm² and elongation from 10 to 50 per cent.

Experimental

The alloys were melted in different types of furnaces viz. gas and oil-fired crucible furnaces of 10-lb capacity, indirect electric arc and direct electric arc furnaces of 10-lb and 50-lb capacity respectively. All the alloys were cast in a specially shaped cast iron mould shown in Fig. 1 preheated to about 150°C, in the temperature range of 1080°C to 1180°C. The castings were immediately stripped as soon as the hot tops had solidified. The process hardly took two minutes. The hot tops were as heavy as the castings. During this period the cast ingot's flanges were expected to have reached to a temperature of the order of 400°C to 500°C.

Effect of etching reagents

During preparation of the specimens for metallographic examination it was observed that when different



1 *Split cast iron mould design for crucified small ingot test piece (dimensions in mm)*

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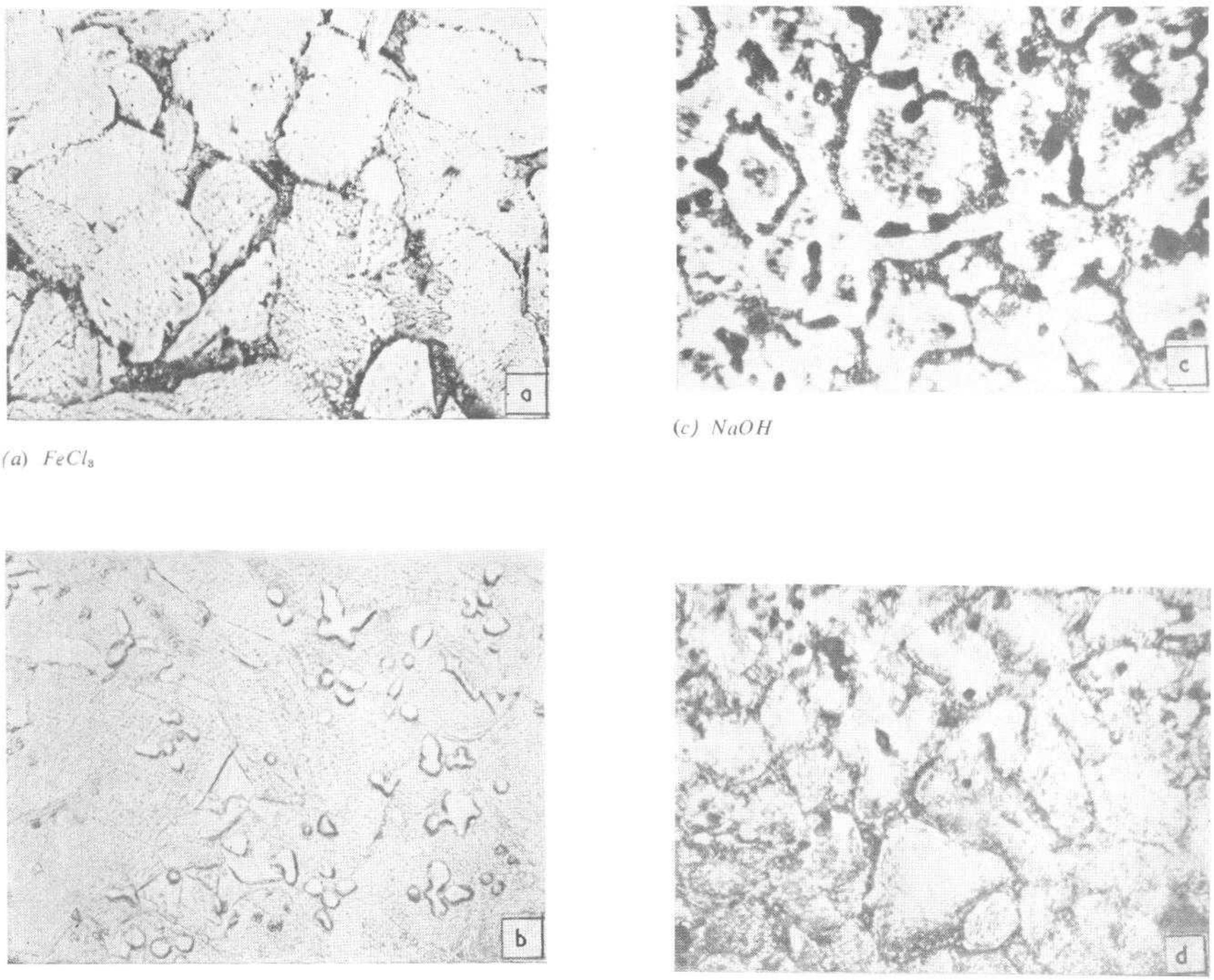


(a) $FeCl_3$

(c) $NaOH$

(b) $NH_4\ CH/H_2O_2$

(d) H_3PO_4

2 *Effect of etching reagents*

etching reagents were used for the same alloys the structure appeared to be altogether different in each case. The effect of the following etchants is shown in Fig. 2.

1. Ferric chloride.
2. Ammonium hydroxide and hydrogen peroxide.
3. Sodium hydroxide (electrolytic etching).
4. Orthophosforic acid (electrolytic etching)

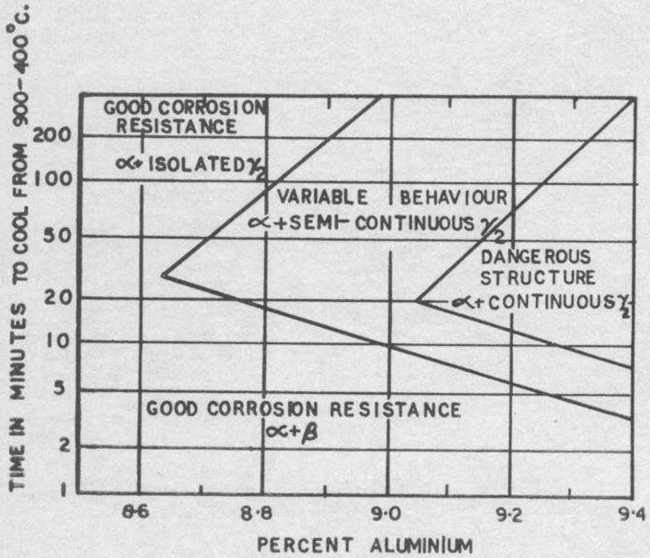
However, the specimens which were etched with ferric chloride after electrolytic polishing gave very clear structures.

For a systematic study the Cu-Al-Fe-Mn alloys which are represented in the paper along with their microstructures, have been grouped under the following three categories :

Category 'A' (Aluminium as variable) deals with different sets of alloys, each set having the same iron and manganese percentage but different aluminium contents.

Category 'B' (Iron as variable) deals with different sets of alloys each set having the same aluminium and manganese percentage but different iron contents.

Category 'C' (Manganese as variable) deals with different sets of alloys, having the same aluminium and iron percentage but different manganese contents.



3 *Influence of aluminium content and cooling rate on the corrosion resistance of binary copper-aluminium alloys*

TABLE I Category A-Alloys with variable aluminium

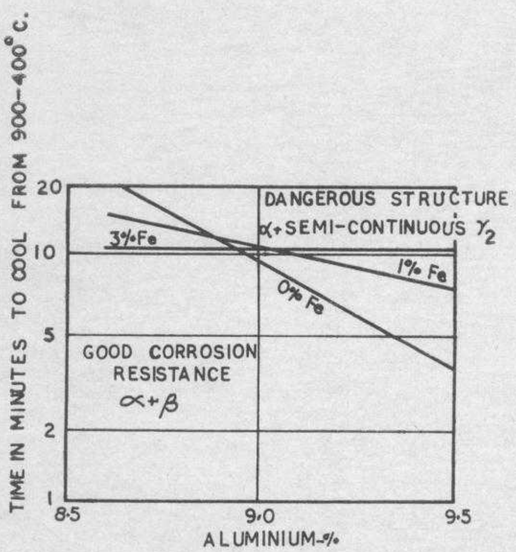
Alloy no.	Chemical composition wt % Al	Fe	Mn	Mechanical properties 0·2% proof stress kg/mm²	Elongation %
113	9·46	2·06	0·37	18·8	40
72	10·05	2·1	0·59	24	26
58	10·50	1·9	0·54	21·68	24
130	10·50	2·11	0·25	23	24
73	10·70	1·85	0·63	23·68	12
100	8·8	2·7	0·45	24	40
135	9·45	2·94	0·38	22·8	37
120	9·6	4·29	0·42	23	40
129	10·20	4.22	0·24	20·5	34

RESULTS and DISCUSSION

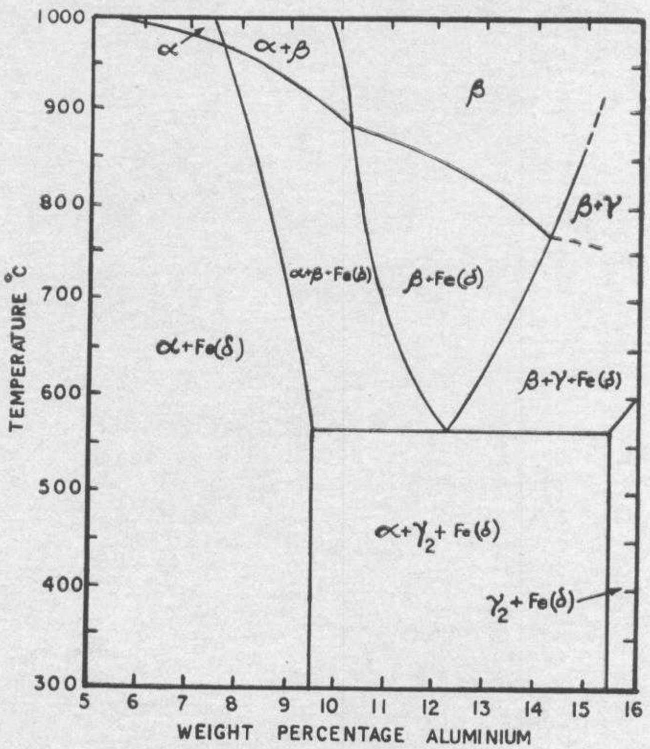
Mechanical properties vs composition

Aluminium variable

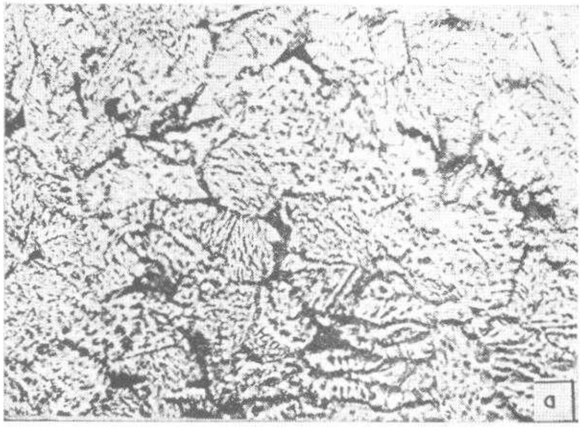
Alloys pertaining to category A are given in Table I with their chemical composition and mechanical properties (0·2% proof stress and elongation). From the table it can be seen that elongation decreases with increase in aluminium content of the alloy while in case of the proof stress no correlation can be made with the aluminium content of the alloy.



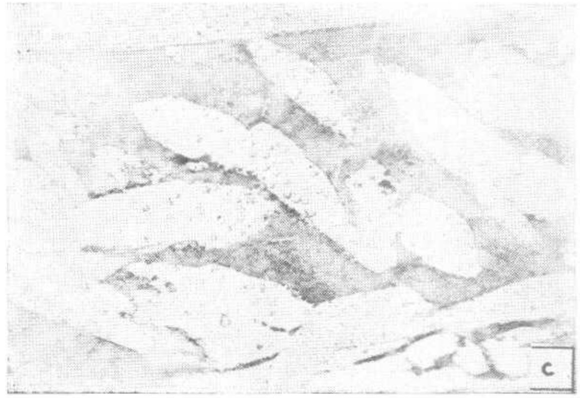
4 *Effect of iron and aluminium content and cooling rate on the corrosion resistance of ternary Cu-Al-Fe alloys*



5 *Vertical section of the Cu-Al-Fe system at 3 % Fe*

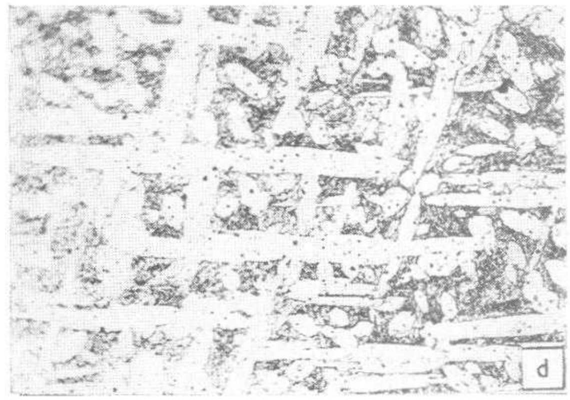


(a) 8·8%Al, 2·7% Fe, 0.5% Mn



(c) 10·5%, 1·9% Fe, 0·5% Mn

(b) 10·0% Al, 2·1% Fe, 0·6% Mn



(d) 10·7%, Al, 2·0% Fe, 0·6%Mn

6 *Effect of aluminium on microstructure* ×760

Iron variable

Alloys belonging to category B with variable iron content are given in Table II with their chemical compositions and mechanical properties. The study of elongation values of different sets of alloys given in the above table shows that elongation does not have a direct bearing on the iron content of these aluminium-bronzes of the quaternary system of Cu-Al-Fe-Mn. Proof stress also does not appear to be influenced by iron content of the alloy when varied between 2 and 6 per cent.

Manganese variable

Alloys belonging to category C with variable manganese and constant aluminium and iron contents have been grouped with different aluminium and iron contents in Table III along with their chemical composi-

TABLE II Category B-Alloys with variable iron

Alloy no.	Chemical composition wt %			Mechanical properties	
	Fe	Al	Mn	0·2% proof stress kg/mm²	Elongation %
72	2·10	10·5	0·59	24	26
75	3·13	10·00	0·35	24	19
101	3·30	10·00	0·53	23	30
104	2·1	9·5	1·6	21·8	40
83	4·3	9·4	1·8	23·7	28
73	2·0	10·7	0·63	23·68	12
32	4·5	10·8	0·72	—	6
132	2·85	9·58	0·17	21·24	40
111	5·15	9 50	0·15	21·5	40
108	5·47	9·4	0·18	21·15	24

TABLE III Category B-Alloys with variable manganese

Alloy no.	Chemical composition wt %			Mechanical properties	
	Mn	Al	Fe	0·2% proof stress kg/mm²	Elongation %
93	0·01	10·43	2·63	21·60	50
130	0·25	10·51	2·11	23·00	24
106	1·75	10·22	2·05	21·00	27
138	2·79	10·45	2·05	21·40	32
133	0·36	9·46	2·06	18·8	40
104	1·57	9·5	2·10	21·8	40
137	3·4	9·46	2·08	—	—
132	0·17	9·58	2·85	21·4	40
136	1·14	9·50	2·87	22·8	40
125	0·29	9·58	4·42	21·4	35
119	3·15	9·50	3·92	23·1	28
108	0·18	9·40	5·42	21·15	24
83	1·83	9·40	4·30	23·7	28

tions and mechanical properties. From the table it can be observed that in alloys containing less than 10 per cent aluminium when the manganese content is increased the proof stress values were found to improve with no systematic change in elongation ; however, with higher aluminium above 10 per cent the effect of manganese was found to have an opposite effect i.e. when manganese is increased from 0·25 to 2·79 the proof stress values decreased from 23·00 to 21 kg/mm² and elongation increased from 24 to 32.

In this study of mechanical properties with respect to composition it may be mentioned that the observations made by Crofts[3] on 3–7 per cent nickel bearing aluminium bronze with respect to elongation with varying aluminium and manganese percentages conform to the present work. Proof stress in alloys with less than 10 per cent aluminium with varying manganese contents showed similar trend as observed by Crofts.

Microstructure vs composition

The cooling rate in all the experimental heats had been of the same order. This critical cooling rate has been reported by Upton[4] to be sufficient to prevent the transformation of β to $\alpha+\gamma_2$ as this is evident from Figs. 3 and 4. Hence it has been taken for granted that the phases that will be dealt in our investigation are limited to α, β and the iron-rich constituent precipitating out on cooling in the entire matrix as shown in Fig. 5.[5] The addition of manganese is not likely to produce any new phase because of its high solubility in copper except that it retards[6] the breakdown of β to $\alpha+\gamma_2$, and even prevents this transformation when present in more than 6 per cent in the sand-cast alloys.

Aluminium variable

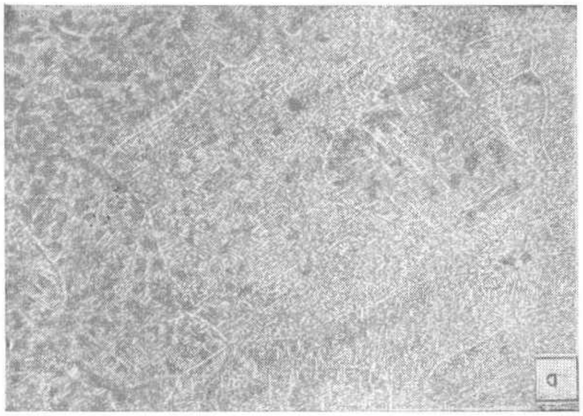
With increase in aluminium content the α phase decreased in amount and became finer. In case of 10·7 per cent aluminium it was in the form of needles as shown in Fig. 6 (d). The iron-rich phase became finer with increase in aluminium content except in the case 8·8 per cent aluminium (Fig. 6a) where it was in the lamellar shape which may be due to a little high iron content compared to other alloys.

Iron variable

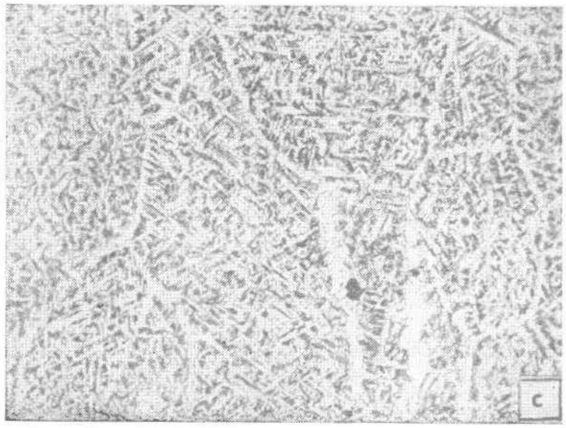
In the alloys having high aluminium content above 10·5 per cent with increase in the iron content from 2 to 4·5 per cent, it was observed from Figs. 7a and 7b that the overall grain size was reduced considerably with increase in iron content. When aluminium content was about 10 per cent, increase in iron from 2 to 3·1 per cent was having a marked effect on the structure as shown in Figs. 7c and 7d. The coarse overall grain boundary shown in alloy 72 (Fig. 7c) was completely absent in alloy 75 (Fig. 7d). The precipitation shown in alloy 72 is both as needle and globular and is coarse in nature ; however, with increase in iron content the precipitation became finer with the needle shaped completely disappearing as in alloy 75. In alloys with less than 10 per cent aluminium similar observations were made as above in the structure when the iron content varied from 2 to 5 per cent (Figs. 8a, 8d).

Manganese variable

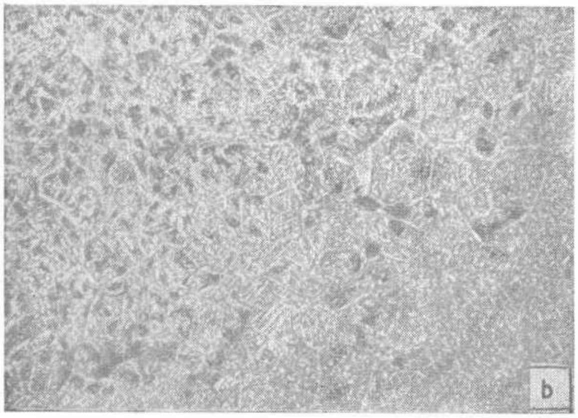
With aluminium below 10 per cent and iron percentage constant at about 2 per cent, increase in manganese content from 0·35 to 3·5 per cent influenced the structure markedly as shown in Fig. 8. It can be seen that the α constituent which was elongated and was of very coarse nature (Fig. 8a) changed to fine when the manganese content increased (Fig. 8c). The effect of manganese on the structure was further influenced by the iron content in the alloy. When the iron content of the alloys was increased to above 4 per cent, change in the manganese content from 0·18 to 1·8 per cent changed the structure from uniform coarse to uniform fine distribution of α and β as shown in Figs. 8d, 8e. It may also be pointed out that the α phase distribution changed from coarse elongated needle type at low iron content to uniform fine distribution at high iron content in the alloys at constant manganese and aluminium contents (Figs. 8a, 8d).



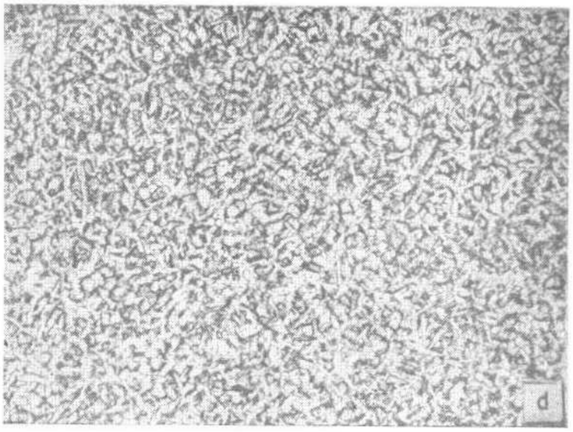
(a) 10·7% Al, 2·0% Fe, 0·6% Mn



(c) 10·0% Al, 2·1% Fe, 0·6% Mn



(b) 10·8% Al, 4·5% Fe, 0·3% Mn



(d) 10·0% Al, 3·1% Fe, 0·3% Mn

7 *Effect of iron on microstructure* ×55

Alloys having more than 10 per cent aluminium and 2 per cent iron with increase in manganese showed that needles got slightly coarser (Figs. 9a and 9b) which is contradictory to the effect of manganese mentioned in the earlier paragraph in case of bronzes containing less than 10 per cent aluminium.

Distribution of iron-rich phase

It may be interesting to note the shape and distribution of iron in the alloys with different compositions. It has been observed that in low aluminium alloys with high iron content the iron-rich phase separates out with coarse globular and irregular shape as shown in Fig. 10.

Microhardness

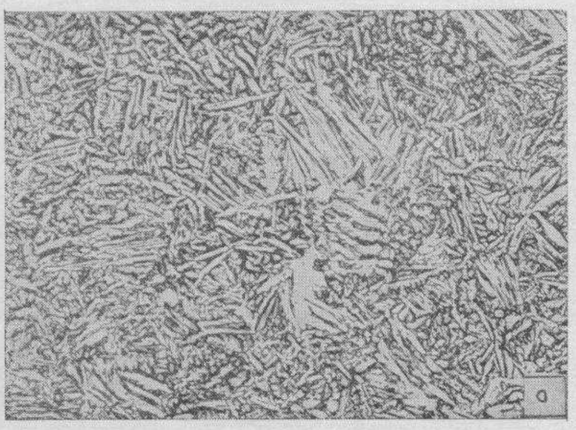
Microhardness was attempted in different phases in the alloy and in this context two alloys were selected with the following composition :

Alloy No.	A	Fe	Mn
82	9·32	4·64	1·88
108	9·4	5·42	0·178

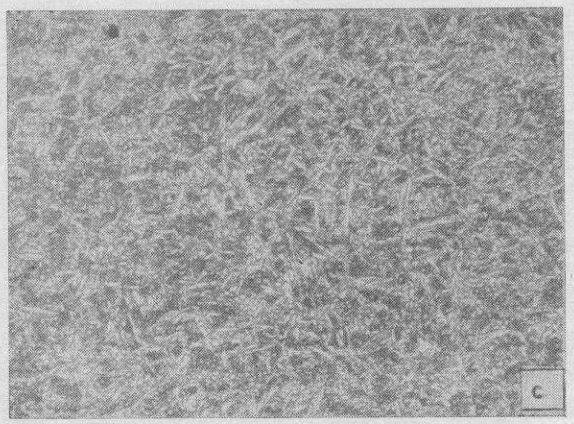
and their hardness was found as follows :

Position	Hardness value *V.P.N. (10 gm)	
	Alloy 82	Alloy 108
Matrix	113	106
Globular iron-rich phase	—	186
Rosette iron-rich phase	276	—
Irregular iron-rich phase	359	358

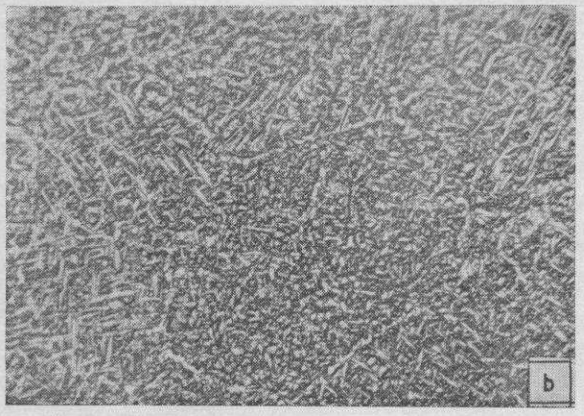
*average of three readings.



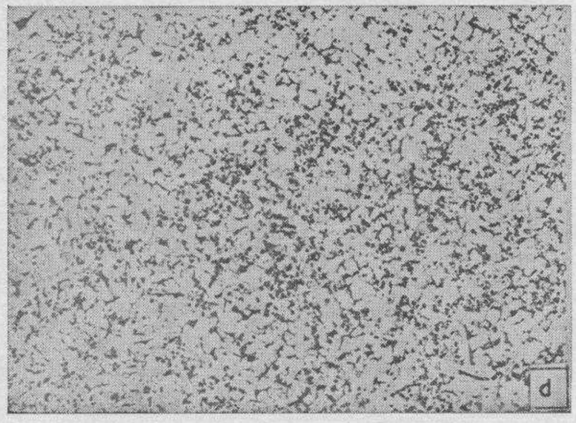
(a) 9·5% Al, 2·1% Fe, 0·4 Mn



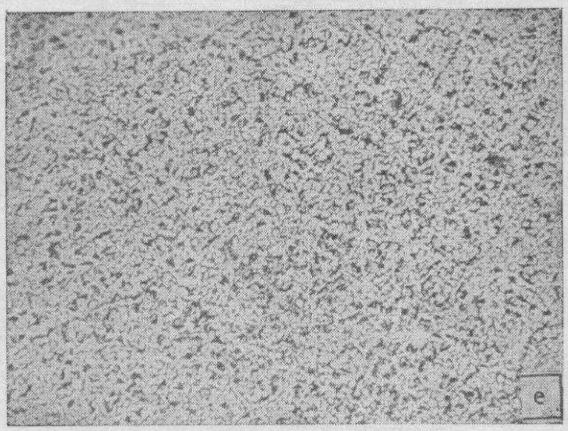
(c) 9·5% Al, 2·1% Fe, 3·4% Mn



(b) 9·5% Al, 2·1% Fe, 1·6% Mn

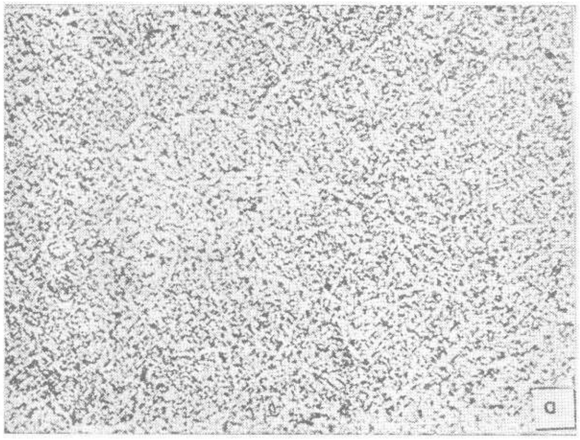


(d) 9·5% Al, 5·1% Fe, 0·2% Mn

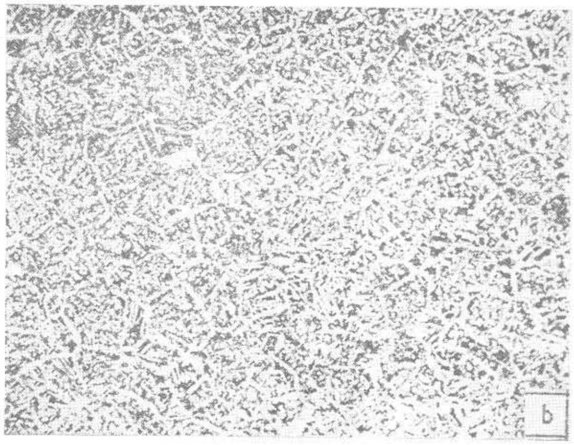


(e) 9·4% Al, 4·3% Fe, 1·8 Mn

8 *Effect of manganese on microstructure with <10% Al* ×55



(a) 10·5% Al, 2·1% Fe, 0·25%



(b) 10·5% Al, 2·1% Fe, 2·8% Mn

9 *Effect of manganese on microstructure with >10% Al* ×55

There is some difference in the hardness of the matrix and that of the globular and rosette iron-rich phase of the two alloys ; this may be attributed to the effect of manganese which is the major differing constant in the alloys. Some more work is needed in this line regarding the composition of these phases and their possible effect on the mechanical properties particularly the proof stress.

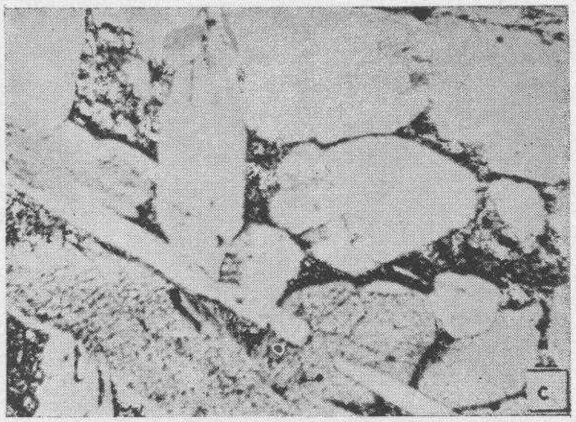
Microstructure vs mechanical properties in relation to compositional limits

A comparison of the microstructure with the mechanical properties has been made and it is observed that the microstructures can be classified into two distinct groups : (a) *needle type* where the α gets precipitated in the form of needles in the matrix as shown in Figs. 7a and 8a and (b) *needle free* where needles are completely absent in the matrix and α is uniformly distributed as in Fig. 7d. These two types of structures are formed depending on the compositional limits primarily of aluminium and iron as shown in Table IV. Based on the above data it can be said that structures containing needles of α are formed where (1) aluminium is less than 10 per cent with iron approximately 2 per cent and (2) aluminium above 10 per cent with iron above 2 per cent. On the otherhand structures free from α shaped needles are formed where aluminium content of the alloy is less than 10 per cent in combination with iron more than 2 per cent. It may be interesting to note that the structures free from needle shaped α exhibit proof stress above 21 kg/mm^2 whereas the structures containing needle shaped α give proof stress in the range of 19 to 24 kg/mm^2 depending upon the aluminium content of the alloy with higher aluminium percentage (more than 10 per cent) giving higher values. It is felt that the type and distribution of the needles affect the mechanical properties.

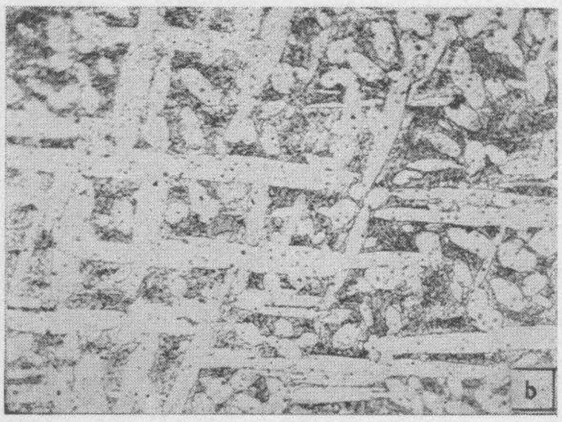
TABLE IV Alloys with their chemical composition and mechanical properties for study of microstructure vs proof stress

Alloy no.	Chemical composition wt % Al	Fe	Mn	Mechanical properties 0·2% proof stress kg/mm^2	Elongation %
Needle shaped α					
113	9·46	2·06	0·36	18·8	40
104	9·50	2·10	1·57	21·8	40
137	9·46	2·08	3·4	—	—
72	10·05	2·13	0·59	24	26
58	10·50	1·90	0·54	21·68	—
129	10·22	4·22	0·24	23·5	30
73	10·74	2·00	0·60	23·6	12
32	10·80	4·5	0·72	—	6
130	10·51	2·11	0·25	23·00	24
Needle free α					
75	10·0	3·10	0·35	24	19
83	9·40	4·30	1·8	23·7	28
108	9·40	5·47	0·18	21·15	24
100	8·81	2·70	0·45	24	40

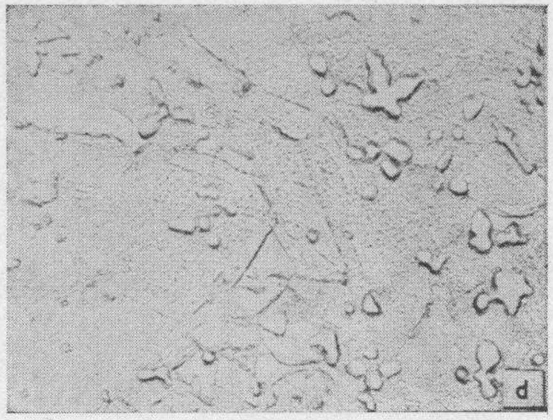
(a) 10·0% Al, 3·1% Fe, 0·3% Mn



(c) 9·5% Al, 2·1% Fe, 0·4% Mn



(b) 10·7% Al, 2·0% Fe, 0·6% Mn



(d 9·5% Al, 5·2% Fe, 0·2% Mn

10 *Shape and distribution of iron with chemical composition* ×760

Conclusion

The structures obtained in the chill-cast nickel-free aluminium-bronze alloys can be broadly classified into two types (a) Needle shaped α in the matrix and (b) Structure free from α needles.

Structure with needle shaped α is formed (a) when aluminium is less than 10 per cent with iron approximately 2 per cent and (b) when aluminium is above 10 per cent with iron 2 per cent and above. Structure free from α needles are formed when aluminium content of the alloy is less than 10 per cent in combination with iron more than 2 per cent.

Needle shaped α gave high proof stress values in alloys containing more than 10 per cent aluminium.

Alloys with needle free α also showed improvement in proof stress.

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Discussions

Mr **A. K. Banerji** (Chittaranjan Locomotive Works, Chittaranjan) : Were the test pieces casting variables taken into consideration while studying the relationship between mechanical properties and composition?

I would also like to know the type of test pieces used, whether they were of the same composition and how many of them were used to obtain the results reported in the paper.

Dr **S. S. Bhatnagar** (N M L): Did you come across martensite while examining the microstructure?

Mr **R. D. Gupta** (Author) : In all the cases the mould temperature was kept at about 150°C prior to pouring as indicated in the paper.

The test pieces were machined from the flanges of the castings, as shown in Fig. 1, in accordance with Indian Standard Specification No. 497–1853. The results given in the paper are the average of 3 to 4 heats of the same composition.

In answer to Dr Bhatnagar, in our range of composition we did not notice any martensite during the investigation.