The Mechanical Properties of Copper-Aluminium-Nickel-Iron Quaternary Cast Alloys*

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The microstructures of copper-aluminium-nickel-iron quaternary alloys, especially the cause of κ-phase precipitation, is greatly influenced by percentages of nickel and iron. And because these alloys are regarded as precipitation hardening alloys, the relationship between their type of precipitates and their mechanical properties is important. Therefore the relationship between microstructure and mechanical properties were investigated using quaternary alloys containing aluminium 9 to 10%, nickel 1 to 6% and iron 1 to 6%.

The effect of adding nickel and iron to copper-aluminium alloys is more remarkable in increasing the mechanical strength by κ-phase precipitation than in increasing the strength of the α matrix by dissolving into a solid solution. Nickel rich κ precipitates are a predominant factor for mechanical properties, and the effect of adding iron influences them by changing the type of the κ phase precipitates and the mean free path between particles.

A favorable mechanical properties were obtained when the Ni% + Fe% makes about 10% and the [Fe%]/[Ni%] ratio is about 1.1, and this is explained by the type of the κ phase precipitates and their distribution.

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1. Introduction

In the authors previous reports, the microstructures of copper-aluminium-nickel-iron quaternary alloys were discussed. In this report, the relationship between their microstructures and their mechanical properties has been investigated. The copper-aluminium-nickel-iron alloys containing aluminium from 8 to 11%, nickel 1 to 6% and iron 1 to 6% can be, from the point of microstructure, classified into the

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$(\alpha+\kappa)$ phase and $[\alpha+\kappa+\delta(\text{or } \beta')]$ phase field in general sand castings cooled at the rate of less than 5°C/min. And the $(\alpha+\kappa)$ phase field can be further classified into the iron rich κ phase coagulation and nickel rich κ phase coagulation field when the type of precipitates is taken into consideration. Judging from the κ phase constituent, the alloy which has been established as the $(\alpha+\kappa)$ phase is considered to be the precipitation hardening alloy, so the relationship between the type of precipitates and the mechanical properties is very important(1) and the effect of the κ phase precipitation on the mechanical properties will be thoroughly discussed.

2. Specimens and Experimental Procedure

The specimens used in these experiments are chiefly those of the same composition which were used in previous reports, but besides the above alloy specimens alloys containing 4.7% nickel and 5.3% iron were used also. Static tensile test specimens were of two sizes—one of 7 mm diameter and 25mm gauge length and the other of 14 mm diameter and 50 mm gauge length. For the fatigue test, a Wöhler testing machine was used.

Plastic strain properties of homologous series of alloys with a discontinuous hard phase randomly distributed in the ductile matrix is empirically deduced in the following formula(2) as a function of A and n:

$$\sigma = A\,\varepsilon^{n} \tag{1}$$

[Fe]/[Ni]

0.45 Lamellar precipitation of the Ni rich κ phase.

1.1 Finely precipitated κ phase.

4.2 Dendritic precipitation of the Fe rich κ phase.

×2,000

Fig. 1 The typical relationship between the [Fe%]/[Ni%] ratio and the form of the κ phase.

where, σ = the true deformation stress
ε = true plastic strain
A = the deformation stress at unit strain
n = the strain hardening index

For a given class of alloys, the relationship between the structure and the mechanical properties can be easily investigated if n is a singlevalued function of A, for example, the relationship between n and A depends only on the mean path between the hard constituents in the matrix. As for copper-aluminium-nickel-iron quaternary alloys, however, their types of structure are vary greatly according to their composition as shown in the authors previous reports and Fig. 1, and this makes it complicated to study the relationship between their composition and their mechanical properties. So it was necessary to know the results of all the specimens.

3. Experimental Results and Discussion

(1) The effect of nickel and iron together

The diagrams between the composition and the ultimate tensile strength, the hardness and the elongation on the alloys containing about 9.3% aluminium and alloys containing about 10.3% aluminium using the specimens in a as cast state cooled at 5°C/min. are shown in Fig. 2, 3, 4, 5, 6 and 7.

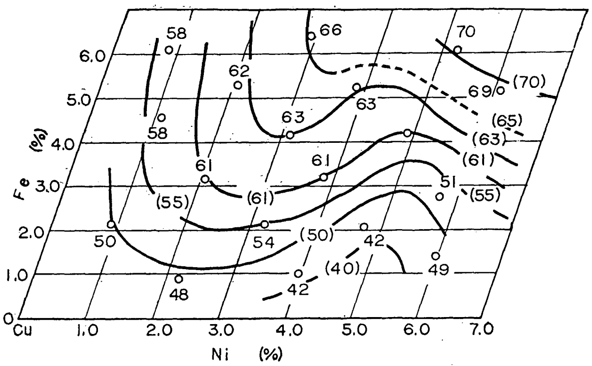

Fig. 2 The relationship between composition and the ultimate tensile*strength in Cu-Al-Ni-Fe alloys. Each figure is represented in kg/mm². (Al≃9.3% base and rate of cooling, 5°C/min.)
Key to Fig. 1~Fig. 12
* Fracture showed defective specimen.

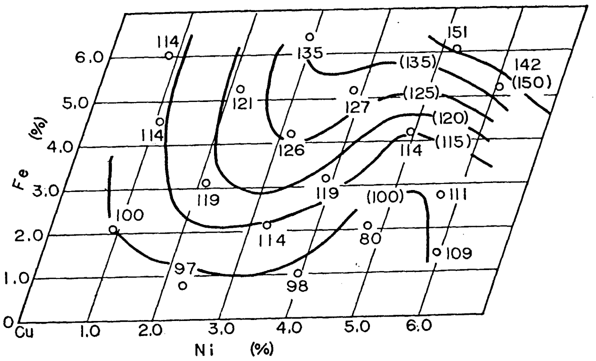

Fig. 3 The relationship between composition and hardness in Cu-Al-Ni-Fe alloys. Each figure is represented in HB Number, load 1.5 ton. (Al≃9.3% base and rate of cooling, 5°C/min.)

The diagrams between the composition and the ultimate tensile strength, the hardness and the elongation, where the specimens are slowly cooled at

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(1) J. E. Dorn, C. D. Starr: *Relation of Properties to Microstructure*, ASM (1954), 71.
(2) ibid, 84.

0.5°C/min from 750°C, are shown in Fig. 8, 9, 10, 11, 12 and 13.

In the diagram between composition and ultimate tensile strength of alloys cooled at 5°C/min., the iso-strength curve shapes ∽ (horizontal S). From the shape of this curve, it is known that the effect of iron on ultimate tensile strength is smaller in the lower nickel side and, approaching the higher nickel side, it increases accordingly. Observing the effect of nickel, it is comparatively small in the lower iron side and increases towards the higher iron side; but, when the amount of nickel increases to 4% or over, no striking effect can be noticed as far as the tensile strength is concerned.

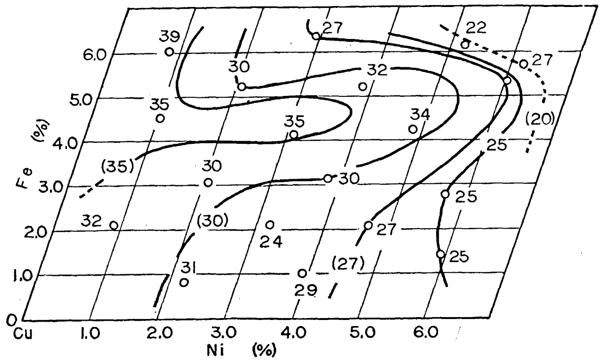

Fig. 4 The relationship between composition and elongation in Cu-Al-Ni-Fe alloys. Each figure is represented in %, gauge length 25 mm. (Al≃9.3% base and rate of cooling, 5°C/min)

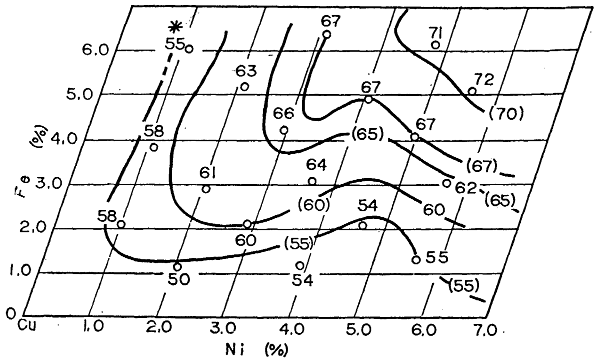

Fig. 5 The relationship between composition and the ultimate tensile strength in Cu-Al-Ni-Fe alloys. Each figure is represented in kg/mm². (Al≃10.3% base and rate of cooling, 5°C/min)

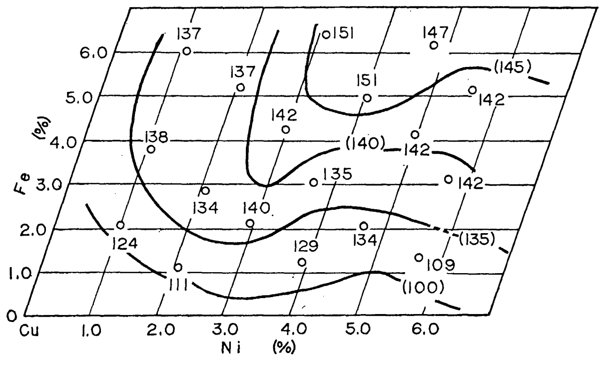

Fig. 6 The relationship between composition and hardness in Cu-Al-Ni-Fe alloys. Each figure is represented in Hb Number, load 1.5 ton. (Al≃10.3% base and rate of cooling, 5°C/min)

The diagram showing composition and the ultimate tensile strength on slowly cooled alloys changes into a C-curve; and the same relationship can be seen in the diagram between composition and hardness and the change from the "∽" to the C-curve is significant, the curve becoming almost straight; thus, the effect of nickel has been clearly revealed.

The diagram showing composition and elongation of the slowly cooled alloys in the higher aluminium side, shows the decrease of elongation in the $(\alpha+\kappa+\delta)$ phase field and in the higher percentage nickel and lower percentage iron side.

Observing the above mentioned relationship from the view-point of the microstructure, it is thought

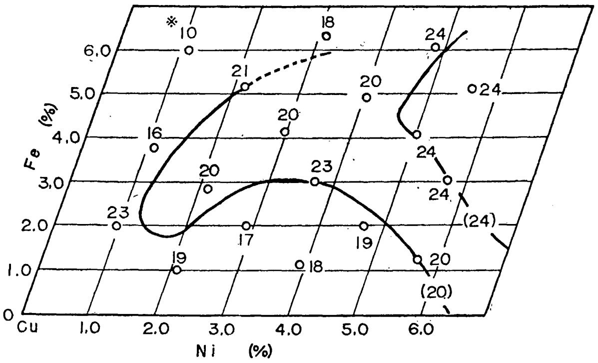

Fig. 7 The relationship between composition and elongation in Cu-Al-Ni-Fe alloys. Each figure is represented in %, gauge length 25 mm. (Al≃10.3% base and rate of cooling, 5°C/min)

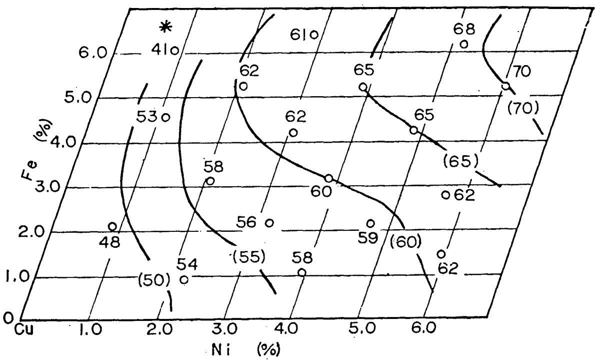

Fig. 8 The relationship between composition and the ultimate tensile strength in Cu-Al-Ni-Fe alloys. Each figure is represented in kg/mm². (Al≃9.3% base, Slowly cooled at 10°C/hr from 700°C)

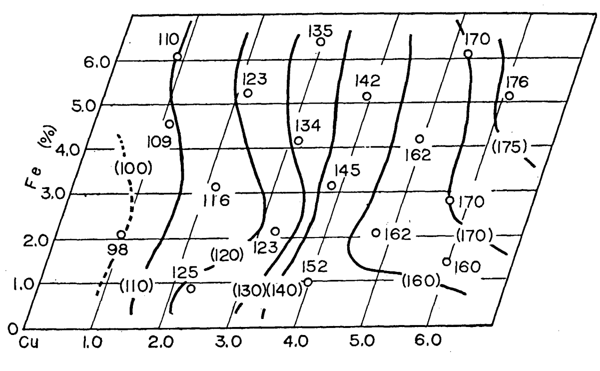

Fig. 9 The relationship between composition and hardness in Cu-Al-Ni-Fe alloys. Each figure is represented in Hb Number, load 1.5 ton. (Al≃9.3% base, Slowly cooled at 10°C/hr from 700°C)

that mechanical properties of the copper-aluminium-nickel-iron quaternary alloys are mainly governed by the shape and distribution of the κ-phase precipitation, especially by the lamellar precipitates of nickel rich κ and their dispersion accompanied on increase in percentage of iron. The change of tensile strength by increasing the percentage of iron is not so significant in the lower nickel side where the tendency of the nickel rich κ phase lamellar coagulation is comparatively small, but on the higher nickel side, where the nickel rich κ phase lamellar coagulation is found, change of the method of precipitation by the increase of iron percentage increases the tensile strength very clearly. When the lamellar coagulation in the higher nickel side tends to predominate, and especially, in the case of the κ phase it forms a continuous brittle band around the α phase, the elongation decreases remarkably.

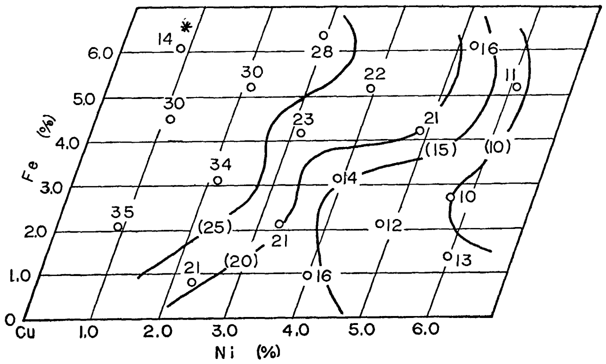

Fig. 10 The relationship between composition and elongation in Cu-Al-Ni-Fe alloys. Each figure is represented in %, gauge length 25 mm. (Al≃9.3% base, Slowly cooled at 10°C/hr from 700°C)

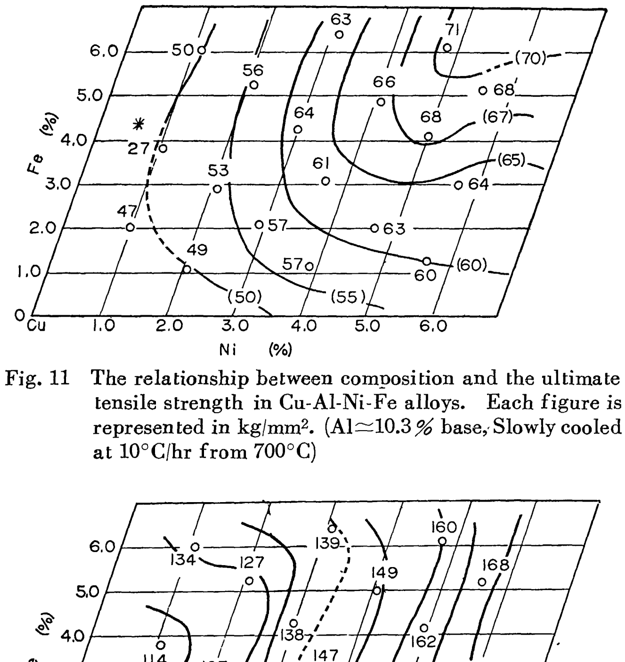

Fig. 11 The relationship between composition and the ultimate tensile strength in Cu-Al-Ni-Fe alloys. Each figure is represented in kg/mm². (Al≃10.3% base, Slowly cooled at 10°C/hr from 700°C)

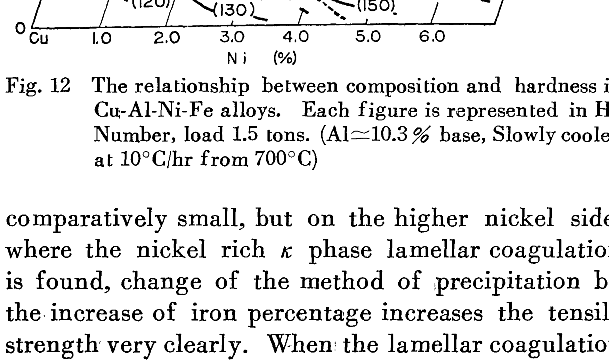

Fig. 12 The relationship between composition and hardness in Cu-Al-Ni-Fe alloys. Each figure is represented in HB Number, load 1.5 tons. (Al≃10.3% base, Slowly cooled at 10°C/hr from 700°C)

Because of the decrease of strength in the lamellar precipitates, it is considered the motion of the dislocation line is more quickly checked against the lamellar precipitates, than the particle precipitates, besides, stress concentration caused by such a condition as above becomes more important in comparison with particle precipitates.

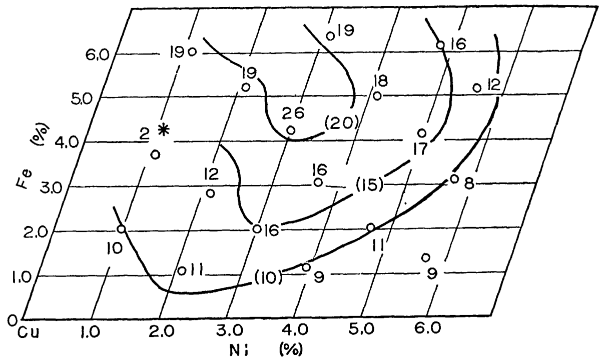

Fig. 13 The relationship between composition and elongation in Cu-Al-Ni-Fe alloys. Each figure is represented in %, gauge length 25 mm. (Al≃10.3% base, Slowly cooled at 10°C/hr from 700°C)

Difference of mechanical properties caused by the different types of precipitates is shown in Fig. 13; which clearly indicates the change of strength caused by the different types of precipitates on specimens of the same hardness.

Considering these results, it can be said that the addition of nickel and iron to copper-aluminium cast alloy systems affects their mechanical properties more remarkably as a function which causes κ phase precipitation hardening than as a function which increases the strength dissolving in the α solid solution; and that the type of nickel rich κ phase precipitates influences their mechanical properties as a predominant factor, and the adding of iron affects them by changing the type of κ precipitates and the degree of dispersions.

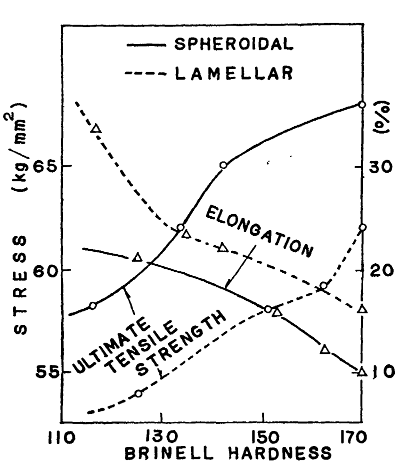

Fig. 14 The influence of structure on the tensile properties in Cu-Al-Ni-Fe alloys.

(2) The effect of aluminium

The authors studied the results obtained in the preceeding section, and found that the mechanical properties of copper-aluminium-nickel-iron quaternary alloys indicate a preferable value when Ni% + Fe % is about 10% and the [Fe%]/[Ni%] ratio is about 1.1, we shall discuss here the effect on the alloys containing nickel 4.7% and iron 5.3% by changing the quantity of aluminium. This is shown in Fig. 15, where they are cooled at 5°C/min. The distribution of the κ phase precipitates is influenced, more or less, by the amount of aluminium, however it is considered that, in case the [Fe%]/[Ni%] ratio is about 1.1 and aluminium is 9 to 10%, there is no remarkable change. The change of the mechanical properties shown in Fig. 15 is considered to be mainly effected by the change of strength of the α solid solution.

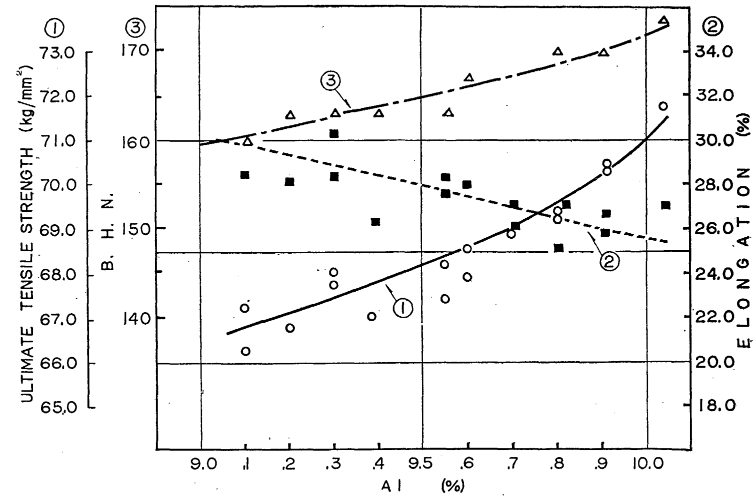

Fig. 15 The effect of Al content on the tensile properties of 4.7% Ni, 5.3% Fe alloy. (rate of cooling, 5°C/min and gauge length, 50 mm)

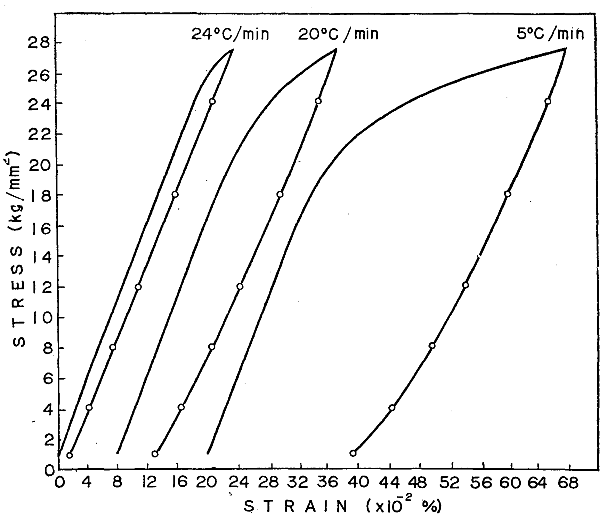

Fig. 16 The relationship between the rate of cooling, the stress-strain curve and the elasticity after effect in 9.75/4.7/5.3 alloy.

3. Proof Stress and Fatigue Strength

One of the important problems of alloys used for propeller is permanent set. The stress-strain curve of alloys containing nickel 4.7% and iron 5.3% is shown in Fig. 16. When alloys are aged beyond the maximum hardness state, spacing of the precipitate particles is considered to be the factor which determine the deformation strength of precipitation hardening alloys.(2)(3) This is shown by the following formula:

$$r = Gb/\Lambda \qquad (2)$$

where, r = yield stress

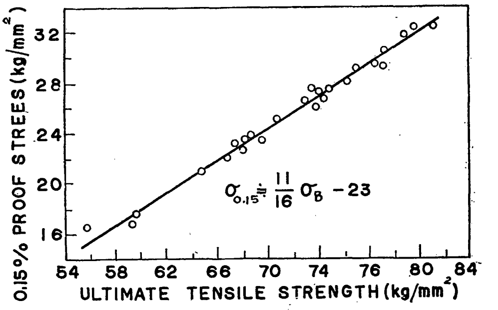

Fig. 17 The relationship between ultimate tensile strength and 0.15% proof stress in 9.75/4.7/5.3 alloy.

G = rigidity modulus

b = Burgers vector

Λ = mean spacing of the precipitate particles

Therefore, as the cooling rate decreases and spacing of the precipitate particles increases with κ phase coagulation, proof stress decreases accordingly. And, as shown in Fig. 16, the elasticity after-effect of the alloys is large and the permanent set value measured by the off set method differs about 30% from the true value. Where the type of κ phase precipitates is changed by the rate of cooling, the relationship between proof stress and ultimate tensile strength is a linear function as shown in Fig. 17. Therefore, conditions where only the spacing of the precipitate particles has been changed, the mechanical properties are also expected by the method of the κ phase coagulation.

Copper-aluminium alloys are valuable for casting

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(3) E. Orowan: *Symposium on Internal Stresses in Metals and Alloys*, Inst. Metals, (1948), 451.

propellers because the specific gravity is small, erosion resistance is excellent and, the fatigue strength is especially high. The S-N curve of the alloy containing 4.7% nickel and 5.3% iron is shown in Fig. 18, and it can be seen that the fatigue strength is very high. The relationship between fracture and microstructure in air is shown in Fig. 19 and that of corrosion fatigue is shown in Fig. 20. As for corrosion fatigue, cracks occur mostly at the α phase boundary where the κ phase precipitate is of the highest density. The corrosion fatigue resistance of whose alloys is more influenced by the distribution of precipitate density than by the mean spacing of the precipitate particles.*

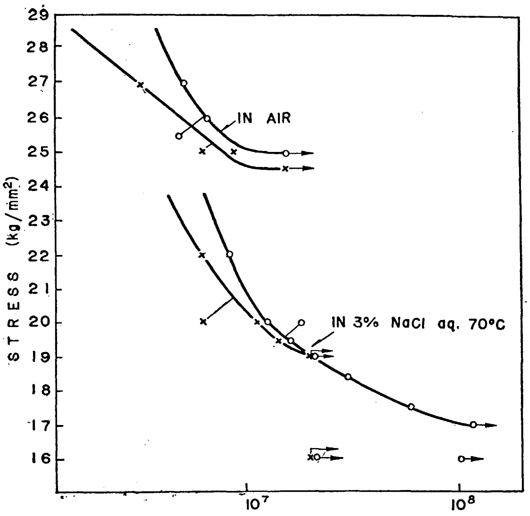

Fig. 18 Typical S-N curves of 4.7/5.3 alloys.
(—⊙— Al 9.63%)
(—×— Al 10.10%)

4. Summary

The relationship between microstructure and the mechanical properties of copper-aluminium-nickel-iron quaternary cast alloys has been investigated.

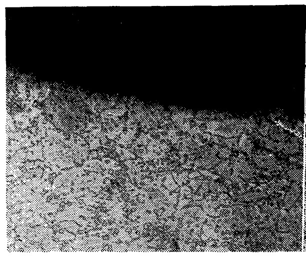

Fig. 19 Crack and microstructure in dry fatigue rupture.

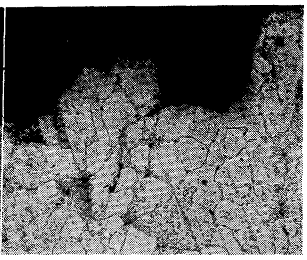

Fig. 20 Crack and microstructure in corrosion fatigue rupture.

The effect of adding nickel and iron to copper-aluminium alloy systems is more remarkable in increasing mechanical strength by κ phase precipitation rather than in advancing the strength of the α matrix dissolving the solid solution. In the case of the mechanical properties, the type of nickel rich κ phase precipitates are a predominant influence factor and the adding of iron affects them by changing the type of the κ phase precipitates and mean free path between particles.

The mechanical properties indicate a preferable value when Ni% + Fe% is about 10% and the [Fe%]/[Ni%] ratio is about 1.1, and this is explained by the type of κ phase precipitates and their distribution.

As far as the alloys having uniformly distributed κ phase precipitate particles, the relationship between proof stress and ultimate tensile strength by difference of the κ phase coagulation is a linear function.

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* In some cases, the corrosion fatigue resistance of the alloy slowly cooled at 0.1°C/min. (where mean spacing of the κ phase precipitate particles is large, however distribution of precipitates is comparatively uniform) is sometimes higher than that of the alloy quickly cooled at 24°C/min. (where mean spacing of the κ phase precipitate particles is small, but precipitate density is high at the α phase boundary).