CONSTITUTION AND METALLOGRAPHY OF ALUMINUM AND ITS LIGHT ALLOYS WITH COPPER AND WITH MAGNESIUM

By P. D. Merica, R. G. Waltenberg, and J. R. Freeman, jr.

CONTENTS

I. INTRODUCTION

Aluminum and its alloys have been the subject of much investigation [1] during recent years, in the course of which the principal features of the constitution of most of the binary alloy systems with aluminum have been determined.

Except in the case of a few metals—silicon, bismuth, cadmium, lead, zinc, and tin—an aluminum-rich compound is formed in each binary system, which forms a eutectic with the aluminum or its solid solution with this compound. Thus, such compounds as $FeAl_3$, $CuAl_2$, Mg_4Al_3, and $NiAl_3$ are formed, which are found in aluminum-rich alloys of their respective series as eutectics with the aluminum solid solution. These compounds are in all cases hard and brittle and their presence affects profoundly the physical properties of the alloys in which they occur. Within the zinc-aluminum system a compound, Al_2Zn_3, is formed which decomposes at lower temperatures.

Silicon and tin each form a simple eutectiferous series with aluminum. Bismuth, lead, and cadmium are only partially miscible in the liquid state with aluminum.

[1] Discussion and bibliography of the literature dealing with aluminum and its alloys will be found in Circular of the Bureau of Standards, No. 76; 1919.

The extent of the solubility in aluminum in solid solution of these compounds or of the elements themselves in the case of those series in which compounds are not formed is of the greatest importance in considering the effect of these compounds or elements upon the physical properties of aluminum-rich alloys. Whether the compound, $CuAl_2$, is dissolved in the aluminum in an aluminum-rich alloy or is in the form of a hard and brittle constituent distributed throughout the mass must be a question of primary importance in a consideration of the mechanical properties of the alloy.

Reference to the equilibrium diagrams of the binary aluminum alloys as they are established to-day shows that with a few exceptions the solubilities of these compounds either have not been determined with any exactness or not at all. Only the solubility of zinc and that of $CuAl_2$ in aluminum have received any attention, the former at two, the latter at only one temperature; reference is made to these determinations below. In many other cases an estimate, at best unsatisfactory, has been made from thermal analysis of the position of the end of the eutectic horizontal line or arrest.

The authors have undertaken to determine the solubilities of a number of these compounds at different temperatures and thus to establish the missing solubility-temperature curve of these compounds in the equilibrium diagram. This paper deals with the solubility-temperature curves of $CuAl_3$ and of Mg_4Al_3, and incidentally with the solubility of $FeAl_3$ and the condition and solubility of silicon in aluminum; later determinations will be reported on the curves for $MnAl_3$ and $NiAl_3$.

II. CONSTITUTION OF COMMERCIAL ALUMINUM

Commercial ingot aluminum contains from 0.2 to 0.5 per cent each of iron and of silicon as impurities, which are at least partially visible under the microscope. Figs. 1 and 2 show the microstructures of two compositions of aluminum ingot at a low magnification; the grains of aluminum are partly surrounded by particles of other constituents, the amount of which is greater in a composition having higher content of total impurities. In Figs. 3, 4, and 5 are shown microstructures of the same materials at higher magnification.

The microstructure of aluminum and of its light alloys is best developed by careful grinding and polishing, followed by etching with a dilute solution of sodium hydroxide; the authors prefer one

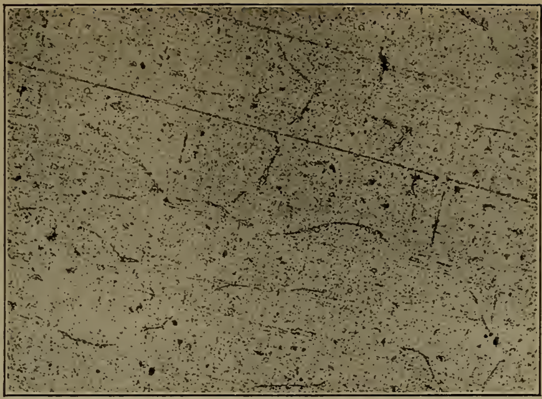

FIG. 1.—*Pure aluminum (Al–5) containing Fe, 0.24 per cent; Si, 0.14 per cent (etched with 0.1 per cent NaOH). ×100*

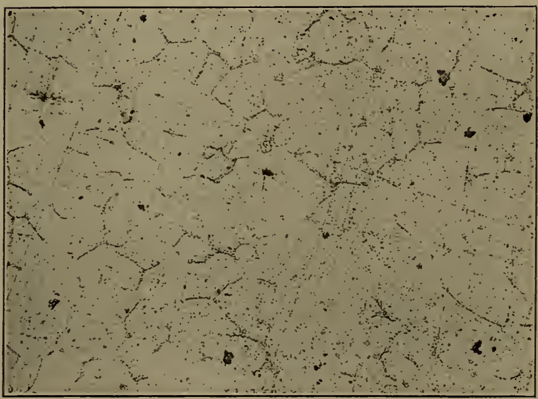

FIG. 2.—*Commercial ingot aluminum (Al–2) containing Fe, 0.5 per cent; Si, 0.2 per cent (etched with 0.1 per cent NaOH). ×100*

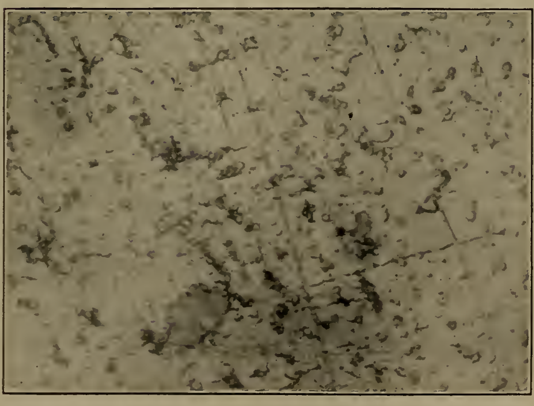

FIG. 3.—*Pure aluminum ingot containing Fe, 0.15 per cent; Si, 0.12 per cent, showing fine particles, probably of constituent X. ×1500*

of 0.1 per cent, with the addition of approximately 10 per cent alcohol. Such a solution does not etch deeply enough to develop the grain boundaries but it does bring out quite well the various other constituents found in aluminum and its light alloys which are often in such fine distribution that they are obliterated by heavier etching with more concentrated solutions of sodium hydroxide or of hydrofluoric acid which are more commonly used. As much care must be used in the grinding and polishing of the metal as in its etching in order to secure the best results, the grinding with the finer grades of emery paper must be done with the aid of some lubricant such as paraffin, oil, or simply alcohol, and best results are obtained by polishing with alumina on suitable cloth moistened with alcohol. The subject of the preparation of aluminum for microscopic examination is discussed in two papers by R. J. Anderson.[2]

The constitution of the binary alloys of iron with aluminum has been investigated by Gwyer.[3] The compound $FeAl_3$ forms a eutectic with aluminum at 649° C; its composition is unknown, but it contains undoubtedly a low percentage of iron—1 to 2 per cent. Gwyer did not determine the solubility of $FeAl_3$ in aluminum, but noted that it was very slight.

The most complete investigations of the equilibrium of binary alloys of silicon and aluminum were made by Fränkel[4] and Roberts;[5] the latter investigation confirming the first one in practically all respects. According to these investigations no compound is formed in this series; the two elements form a eutectic at about 15 per cent silicon and 576° C; the solubility of silicon in aluminum is given as less than 0.5 per cent.

It was necessary for the authors' work on the solubility of $CuAl_2$ and Mg_4Al_3 that they first be able to identify the various constituents which would be present in alloys of aluminum with these metals. On comparing the microstructures, therefore, of several different compositions of aluminum in the light of these investigations of the equilibrium between aluminum and iron and aluminum and silicon it was possible to identify a light bluish constituent occurring in all compositions as $FeAl_3$; this is shown in Fig. 4. In compositions having less than about 0.2 per cent

[2] R. J. Anderson, The Metallography of Aluminum, Chem. and Met. Engineering, 18, p. 172, 1918; and Journal of the Franklin Institute, 187, p. 1, 1919.

[3] A. Gwyer, Constitution of Binary Alloys of Aluminum with Iron, Copper, Nickel, Cobalt, Lead, and Cadmium, Zeit. anorg. Chem., 57, p. 113; 1908.

[4] W. Fränkel, Silicon-Aluminum Alloys, Zeit. anorg. Chem., 58, p. 154; 1908.

[5] C. E. Roberts, Silicon-Aluminum Alloys, Trans. Chem. Soc., 105, p. 1383; 1914.

of silicon no other constituent was noticed in the eutectic islands; in those having this amount or more of silicon a second constituent, slightly darker than the $FeAl_3$, was noticed. This is shown, together with the $FeAl_3$, in Fig. 5. In order to be more certain of the identity of these two constituents of the eutectic islands, samples were prepared from a relatively pure aluminum, called Al–1, containing:

	Per cent
Iron	c. 15
Silicon	.12
Copper	.02

With the addition of more silicon and of more iron the microstructure of these samples showed that as the silicon was increased the darker constituent increased in amount, whereas as the iron increased the amount of the lighter one increased in amount. Fig. 6 shows the two constituents in a sample containing 2 per cent each of iron and silicon. It was at first assumed that this darker constituent was crystallized silicon, in accordance with the equilibrium diagram. However, the results of thermal analyses made on 30 g samples of different compositions of aluminum did not bear this conception out.

Cooling curves of the inverse-rate type on four different compositions of aluminum are shown in Fig. 7. The temperature of the $FeAl_3$-aluminum eutectic arrest is indicated clearly on each; it is lower with increasing silicon content. The sample Al–1, containing only 0.12 per cent of silicon, showed no other arrest between this temperature and ordinary temperature; this specimen contained only the one eutectic; that is, that with the constituent identified as $FeAl_3$. The other compositions of higher silicon content show a lower arrest at 610° C, quite constant in temperature; the intensity of the arrest increases with the increase in silicon content. None of these compositions showed an arrest at 576° C. The appearance of the arrest at 610° C corresponds with the appearance of the darker constituent in the eutectic in small amounts. With higher amounts of silicon, therefore, a thermal arrest is found at about 576° C, corresponding to the silicon-aluminum eutectic (and this was confirmed by the authors), which is not found in aluminum of low silicon content; in place of the 576° C arrest is found one at 610° C.

The evidence seems to point to the fact that the second and darker constituent found in the eutectic islands in aluminum is not silicon, but a compound of unknown composition, either of

FIG. 4.—*Commercial aluminum (Al–2), showing eutectics of $FeAl_3$ and of constituent X.* ×1000

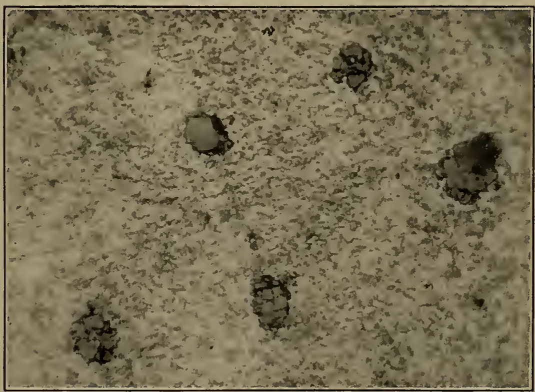

FIG. 5.—*Commercial aluminum (Al–2), showing eutectics of $FeAl_3$ and of constitutent X.* ×1000

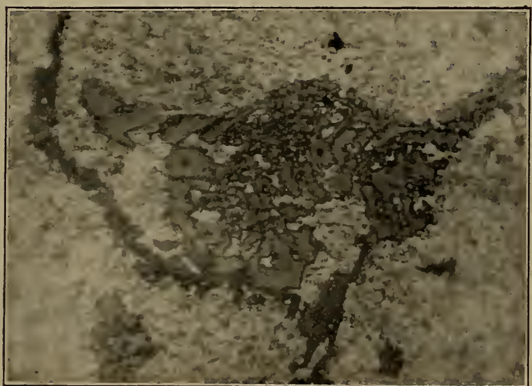

FIG. 6.—*Alloy containing 2 per cent each of iron and silicon. The two constituents, Si (dark) and the FeAl (light) are readily distinguished.* ×1000

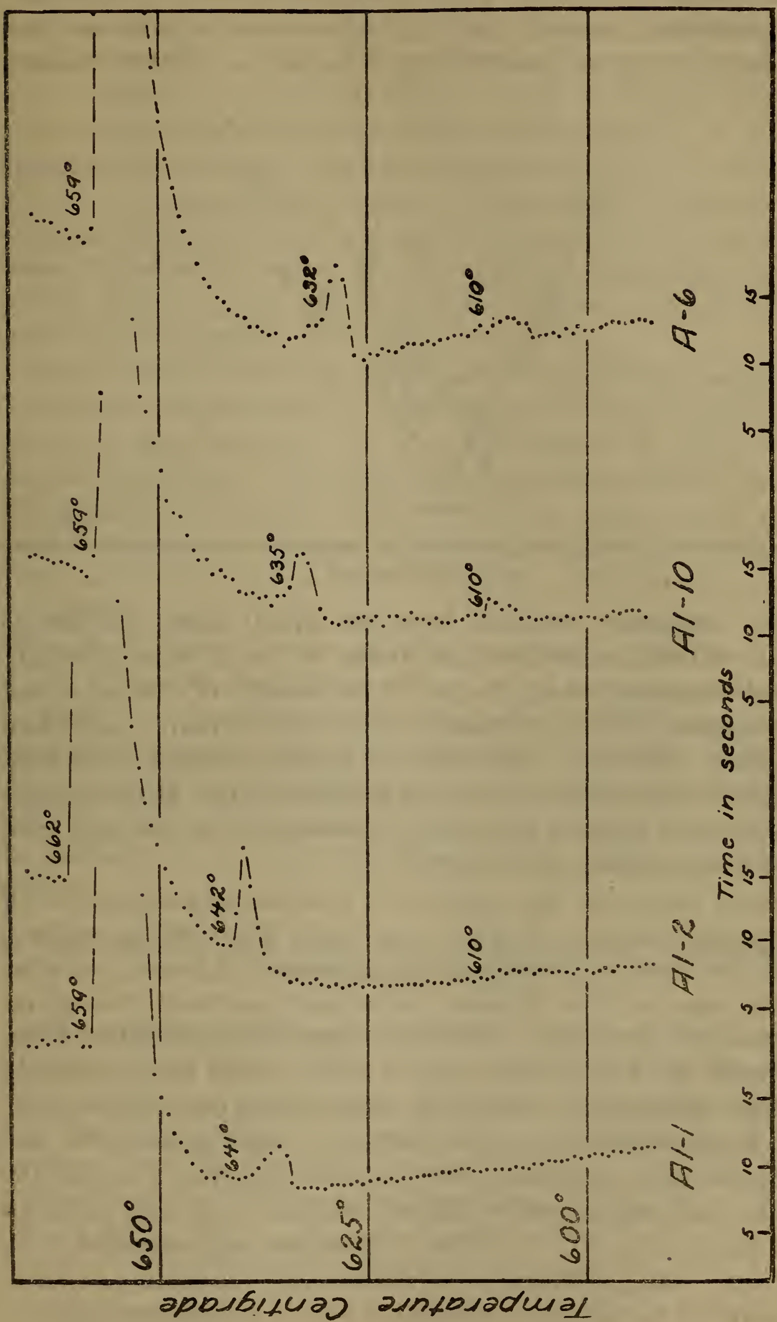

Fig. 7.—*Inverse rate cooling curves of aluminum with different amounts of silicon; Al–1, 0.12 per cent Si; Al–2, 0.2 per cent Si; Al–10, 0.24 per cent Si; A–6, 0.3 per cent Si*

iron and silicon alone, or of these with aluminum; it will henceforth be referred to as *X* (AlFeSi). The ternary liquidus surfaces must have somewhat the form shown in Fig. 8. Within the area

FIG. 8.—*Suggested form of liquidus surfaces of ternary system aluminum-iron-silicon near aluminum end*

Al–abcd aluminum separates from the liquid; along the line *ab* eutectic of $FeAl_3$ and aluminum; along the line *dc* eutectic of silicon and aluminum; along the line *bc* the eutectic of aluminum and the compound *X;* at the points *b* and *c* of invariant equilibrium two binary eutectics. This view, of course, remains to be confirmed by a necessarily much more extensive study of the ternary equilibrium; it appears at present, however, to be the only consistent interpretation of the facts.

Another feature of the structure of commercial aluminum is of the greatest interest. In Figs. 3, 4, and 5 there will be noticed, besides the grains of aluminum and the eutectic islands, a number of quite fine particles of some constituent scattered throughout the grains of aluminum. These are apparently particles of the constituent *X*, and possibly also of $FeAl_3$, which have separated from solid solution in aluminum at temperatures below the eutectic one. It was noted above that there is a slight solubility of the constituent *X* in aluminum, since it is not found as a part of the eutectic when the amount of silicon is only 0.12 per cent, nor is an arrest found at 610° C. At 610° C, therefore, approximately 0.12 to 0.20 per cent of silicon as *X* dissolves in aluminum; at lower temperatures its solubility diminishes and it precipitates again in much finer particles.

Little can be said as yet about the solubility of $FeAl_3$ in aluminum, as in the purest aluminum yet prepared and examined, $FeAl_3$ has been found in quite appreciable quantities; this sample, Al–1, contained 0.15 per cent of iron. Iron, as $FeAl_3$, is therefore not completely soluble in aluminum in this amount. It may be mentioned also that although no attempts were made to discover whether by annealing this amount of iron could be made to dissolve in commercial aluminum, in the course of the work described below it was noted that in alloys containing besides this amount of iron about 0.5 per cent copper, no solution of the $FeAl_3$ occurred upon annealing for 20 hours at 500° C.

In the course of the examination and investigation of aluminum no evidence has been found of any transformation of silicon from one form into another, nor of the existence of the so-called graphitoidal silicon. This latter term originated with the analyst of aluminum and its light alloys, who finds under certain conditions that there is a residue left from the action of the concentrated acids used in dissolving the sample, which is insoluble in hydrofluoric acid. It is suggested that the occurrence of the silicon in the various forms, (1) of eutectic particles of constituent *X*, (2) of eutectic particles of silicon, (3) of segregate particles of *X*, and (4) of a solid solution in aluminum, possibly explains the phenomena experienced in the analysis of the metal. Thus, the silicon existing in solid solution in aluminum would undoubtedly dissolve readily in the concentrated acids to give SiO_2, whereas the particles of *X* or of crystallized silicon would be much less soluble.

III. SOLUBILITY OF $CuAl_2$ IN ALUMINUM AT DIFFERENT TEMPERATURES

The equilibrium of copper-aluminum alloys has been investigated by Gwyer (see footnote 3, p. 107), Carpenter and Edwards[6], Curry[7], Guillet[8], Campbell and Matthews,[9] and others. Gwyer finds that 4 per cent of copper dissolves in aluminum as $CuAl_2$. Carpenter and Edwards place the solubility at 4 per cent, Curry at 11 per cent, and Campbell and Matthews at 2 per cent. These values hold for the eutectic temperature 540° C.

[6] Proc. Inst. Mech. Eng., p. 57; 1907.

[7] Journ. Phys. Chem., 11, p. 425; 1907.

[8] C. R 141, p. 464; 1905.

[9] Journ. Am. Chem. Soc., 24, p. 253; 1902.

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Annealing experiments were undertaken to ascertain the course of the solubility temperature curve. For these determinations 100 g melts of different compositions of copper-aluminum alloys, varying from 0.5 to 5 per cent of copper, were made in a small gas furnace; the purest aluminum available was used, namely, Al–1, of which the composition is given on page 108. The resulting alloys were cast in chill molds, one-half inch in diameter. Figs. 9 and 10 show the typical structures of these alloys as chill cast in this form. Free $CuAl_2$ was observed even in the cast specimen C–20 containing 0.5 per cent copper.

The $CuAl_2$ can readily be distinguished from the $FeAl_3$ particles by the fact that they are much whiter in natural color and that they do not turn brown upon etching for several minutes with 0.1 per cent NaOH as does $FeAl_3$.

The compositions of the cast alloys are given in Table 1.

Specimens of these alloys were annealed for 20 hours at 525, 500, 400, and 300° C, quenched in water from these temperatures and examined microscopically for the presence of free $CuAl_2$. The results of these examinations are also given in Table 1. A series of photomicrographs, Figs. 11 to 14, show the microstructures of alloys C24–B to C27–B after annealing at 500° C and quenching. $CuAl_2$ is found in C27–B (3.8 per cent Cu) and C26–B (3.6 per cent Cu) but not in C25–B (3.1 per cent Cu) and C24–B (2.5 per cent Cu).

TABLE 1.—The Microscopic Examination for the Presence of Free $CuAl_2$ in Annealed Chill Cast Copper-Aluminum Alloys

[All specimens were quenched in water after annealing]

Number of alloy	Per cent of copper	Results of microscopic examination to determine whether free $CuAl_2$ was present after annealing			
		Annealed at 525° C, marked G	Annealed at 500° C, marked B	Annealed at 400° C, marked A	Annealed at 300° C, marked C
	Per cent				
C-20	0.5	No $CuAl_2$	No $CuAl_2$	No $CuAl_2$	No $CuAl_2$
C-21	1.1	do	do	do	Do.
C-22	1.6	do	do	do	Small amount
C-23	2.1	do	do	Small amount	Much $CuAl_2$
C-24	2.5	do	do	Much $CuAl_2$	Do.
C-25	3.1	do	do	do	Do.
C-26	3.6	do	Small amount	do	Do.
C-27	3.8	One or two particles only.	Much $CuAl_2$	do	Do.
C-28	4.5	Small amount	do	do	Do.
C-29	5.1	Much $CuAl_2$	do	do	Do.

FIG. 9.—*Alloy C20 as cast, showing eutectic of $CuAl_2$—aluminum; Cu, 0.5 per cent.* ×100

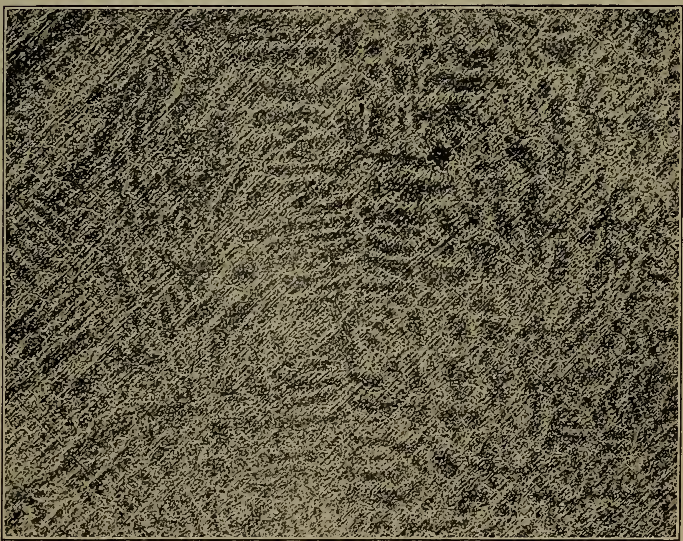

FIG. 10.—*Alloy C29 as cast, showing eutectic of $CuAl_2$—aluminum; Cu, 5.1 per cent.* ×100

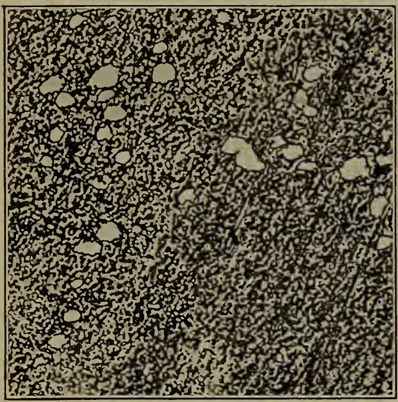

FIG. 11.—*Alloy C27B; Cu, 3.8 per cent.* ×300

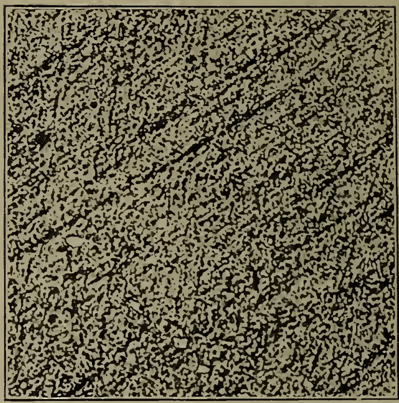

FIG. 12.—*Alloy C26B; Cu, 3.6 per cent.* ×300

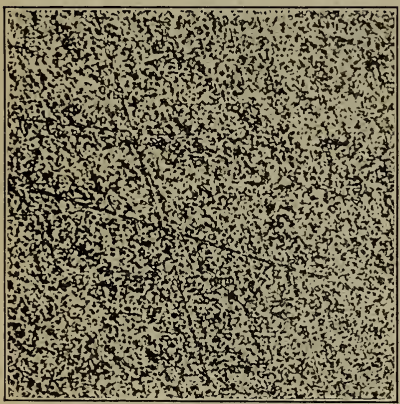

FIG. 13.—*Alloy C25B; Cu, 3.1 per cent.* ×300

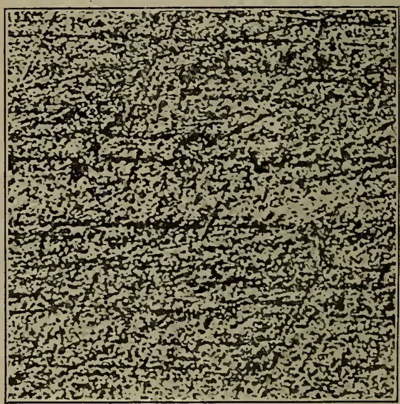

FIG. 14.—*Alloy C24B; Cu, 2.5 per cent.* ×300

The structure of alloys C24 to 27B, annealed and quenched from 500° C

To observe whether 20 hours' annealing was really sufficient to bring about equilibrium within these alloys, specimens of C20 to C25 (and marked H) were annealed 10 days at 400° C and quenched. The results of examination showed that C23–H contained a small amount of $CuAl_2$, C22–H, none, in exact agreement with observations after 20 hours' annealing at the same temperature.

A curious fact was noticed in the annealing of these alloys Once the $CuAl_2$ has dissolved in the aluminum it precipitates again from supersaturated solutions only with difficulty; or, perhaps more accurately stated, it apparently precipitates from such solutions, but in particles of very high dispersion or small size, and these particles coalesce into larger ones only with difficulty. Specimens of the C20 to C29–B series, which had been annealed 20 hours at 500° C and quenched, were reannealed and quenched from lower temperatures as follows: C20 to C29–B–1, at 320° C for 45 hours; C20 to C29–B–2, at 400° C for 20 hours. Reannealing caused apparently no change in the structure of any of the alloys; at least no particles of $CuAl_2$ of a size comparable with the original eutectic generation reappeared in those samples to correspond with the diminution of solubility at the lower temperatures. Fig. 15 shows the structure of C25–B–1, which may be compared with Figs. 11 to 14.

Only upon very slow cooling through the temperature range 500 to 300° C do segregate or precipitated particles of $CuAl_2$ coalesce to such an extent that they may readily be identified as such. Specimens of C25–B and of E13–B which had been annealed at 500° C were reheated to 500° C and cooled from that temperature very slowly to room temperature. The furnace cooled from 500 to 345° C in 15 hours. Areas were marked off on both specimens before this final treatment and examined before and after heating and cooling. As annealed and quenched no $CuAl_2$, corresponding to the equilibrium solubility, was found in either of the specimens; after heating to 500° C and cooling at this slow rate $CuAl_2$ particles of fairly large size were found in both specimens in profusion. Figs. 16 and 17 show an area of C25–B before and after heating and slow cooling, respectively.

Samples of alloys E9 to E11 were annealed for various periods of time at 400° C to determine what period was necessary to produce equilibrium between the $CuAl_2$ and solid solution. The results of these experiments are given in Table 2. At 400° C equilibrium was attained in these small chill-cast specimens after 30 minutes; after that period no further change took place.

TABLE 2.—Microscopic Examination for the Presence of Free $CuAl_2$ in Samples of Chill-Cast Copper-Aluminum Alloys Annealed at 400° C and Quenched

Number of sample	Per cent copper	Period of annealing	Temperature of annealing	Examination for the presence of free $CuAl_2$
		Hours	°C	
E9–A	1.0	¼	400	Small amount of $CuAl_2$.
E10–A	1.5	¼	400	Considerable $CuAl_2$.
E9–B	1.0	½	400	No $CuAl_2$.
E10–B	1.5	½	400	Very small amount of $CuAl_2$.
E11–B	1.9	½	400	Much $CuAl_2$.
E10–C	1.5	1	400	No $CuAl_2$.
E11–C	1.9	1	400	Small amount of $CuAl_2$.
E10–E	1.5	13	400	No $CuAl_2$.
E11–E	1.9	13	400	Small amount of $CuAl_2$.

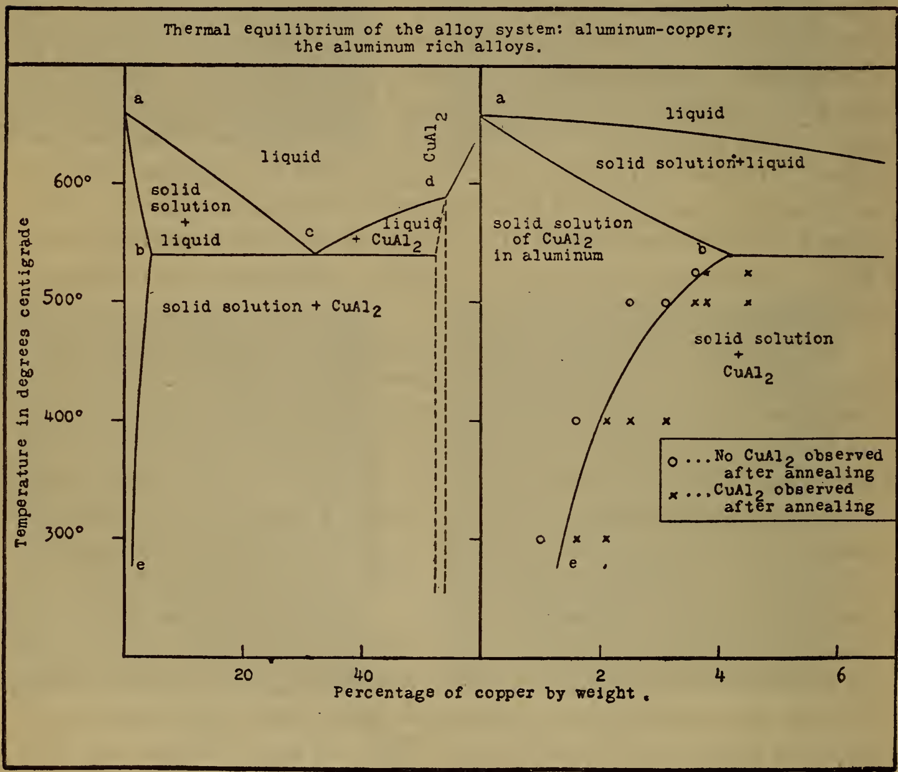

FIG. 18

In Fig. 18 are shown the results of these solubility determinations. There is given the aluminum side of the equilibrium diagram of copper and aluminum, of which the portion, *be*, has been determined by the above experiments; the remainder is taken

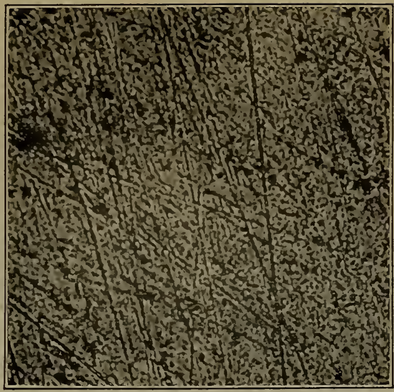

FIG. 15.—*Alloy C25B–1, annealed 20 hours at 500° C, quenched, reannealed 45 hours at 320° C, and quenched. No particles of $CuAl_2$ are visible at this magnification; Cu, 3.1 per cent.* ×300

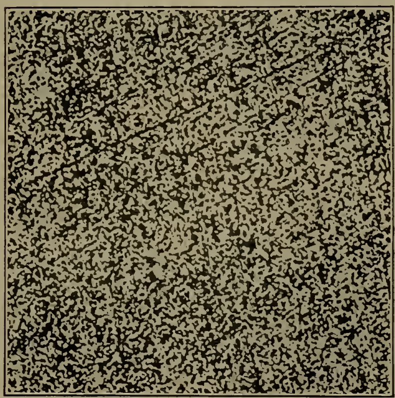

FIG. 16.—*Specimen C25B, annealed at 500° C and quenched; Cu, 3.1 per cent.* ×300

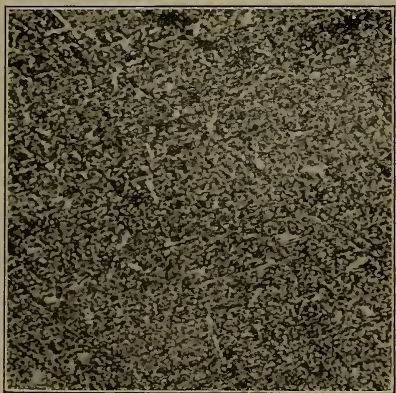

FIG. 17.—*Same area of C25B as shown in Fig. 16 but after reheating to 500° C and slowly cooling. $CuAl_2$ has precipitated and coalesced.* ×300

FIG. 19.—*Magnesium-aluminum alloy A38, as chill cast; Mg, 17.8 per cent (etched with 5 per cent NaOH).* ×300

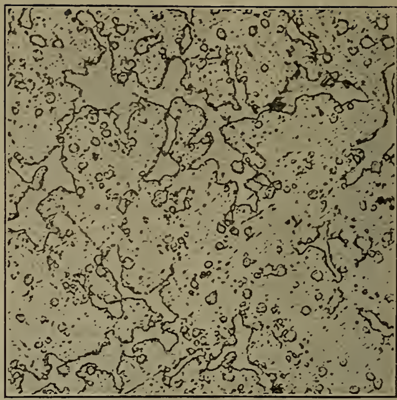

FIG. 20.—*A37–400; Mg, 17.1 per cent.* ×300

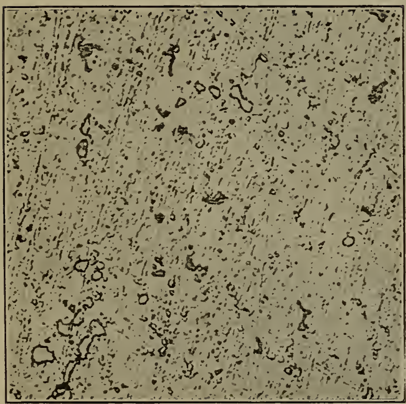

FIG. 21.—*A27–400; Mg, 13.2 per cent.* ×300

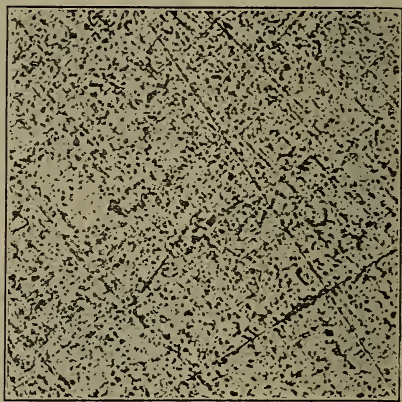

FIG. 22.—*A36–400; Mg, 11.7 per cent.* ×300

Figs. 20, 21, and 22 show structure of magnesium-aluminum alloys, annealed 20 hours at 400° C and quenched (etched with 5 per cent NaOH) from the results of previous investigations. The solubility of $CuAl_2$ decreases with decreasing temperature from about 4 per cent at 525° C to about 1 per cent at 300° C, and is apparently still diminishing at lower temperatures.

EFFECT OF MAGNESIUM UPON THE SOLUBILITY OF $CuAl_2$ IN ALUMINUM

In seeking an explanation for the effect of magnesium upon the physical properties of heat-treated duralumin (see footnote 14, p. 118) the question presented itself whether the solubility-temperature curve of $CuAl_2$ in aluminum was displaced by the presence of the usual small amounts of magnesium.

Specimens were chill cast containing the following constituents:

	Copper	Magnesium
	Per cent	Per cent
C30	1	0.5
C31	2	.5
C32	3	.5
C33	4	.5
C34	1	1.0
C35	2	1.0
C36	3	1.0
C37	4	1.0

These were examined after annealing 20 hours at 500° C, followed by quenching. Specimens C32 and C36 contained after this annealing no free $CuAl_2$, whereas specimens C33 and C37 did. Apparently as much as 1 per cent of magnesium does not affect appreciably the temperature-solubility curve of $CuAl_2$ in aluminum.

IV. SOLUBILITY OF Mg_4Al_3 IN ALUMINUM AT DIFFERENT TEMPERATURES

The equilibrium of magnesium-aluminum alloys has been studied by Schirmeister,[10] Wilm,[11] and Grube.[12] Schirmeister finds no eutectic arrest for the eutectic of Mg_4Al_3 aluminum at 1 per cent magnesium; Grube makes no comment on the amount of Mg_4Al_3 which may be soluble in aluminum.

For the authors' determinations, samples of magnesium-aluminum alloys were prepared in the same manner as were those for the previous series. Table 3 gives the compositions of the alloys so prepared and Fig. 19 shows the typical duplex structure of one of the chill cast alloys, No. A–38.

[10] Metall u. Erz., 2, p. 522; 1914.
[11] Metallurgie, 8, p. 225; 1911.
[12] Zeit anorg. Chem., 45, p. 225; 1905.

Specimens of the alloys were annealed for 20 hours at 450, 400, and 300° C and then quenched. The microstructure was developed by etching with 5 per cent NaOH solution and the specimens were examined for the presence of free Mg_4Al_3. Table 3 also gives the results of these determinations. Figs. 20 to 22 show typical microstructures for a series annealed at 400° C.

TABLE 3.—Microscopic Examination for the Presence of Free Mg_4Al_3 in Annealed Chill-Cast Magnesium-Aluminum Alloys

[All specimens were quenched in water after annealing]

Number of alloy	Per cent of magnesium	Results of microscopic examination whether free Mg_4Al_3 was present after annealing		
		Annealed at 450° C, marked—45	Annealed at 400° C, marked—4	Annealed at 300° C, marked —3
A-31	5.9	No Mg_4Al_3	No Mg_4Al_3	Small amount Mg_4Al_3
A-32	6.9	do	do	Much Mg_4Al_3
A-34	9.1	do	do	Do.
A-36	11.7	do	do	Do.
A-35	12.2	do	do	Do.
A-27	13.2	Small amount Mg_4Al_3	Small amount Mg_4Al_3	Do.
A-37	17.1	Much Mg_4Al_3	Much Mg_4Al_3	Do.
A-38	17.8	do	do	

The solubility of Mg_4Al_3 in aluminum decreases with lowering of the temperature exactly as in the case of $CuAl_2$. Specimens of A35–450 and of A36–450 annealed 20 hours at 450° C and quenched were reheated to 420° C and allowed to cool very slowly in the furnace. The furnace cooled from 420° to 260° C in 24 hours. In these specimens, previously free from Mg_4Al_3, this second heat treatment caused a copious precipitate of this constituent. Figs. 23 and 24 show the structure of A35–450 before and after slow cooling, respectively.

The results of these determinations are shown in Fig. 27, in which is reproduced a portion of the equilibrium diagram as determined by Grube for the magnesium-aluminum alloys, and in which is inserted the portion, *be*, determined by the above experiments.

In aluminum-rich alloys of magnesium with commercial aluminum besides the two constituents, or phases, aluminum solid solution and Mg_4Al_3, another constituent is invariably found, the amount of which seems to increase slowly, if at all, with increase of magnesium content beyond about 1 per cent. It has a deep blue color and is easily distinguished from the other two constituents mentioned, and from the $FeAl_3$, which is also present. It is

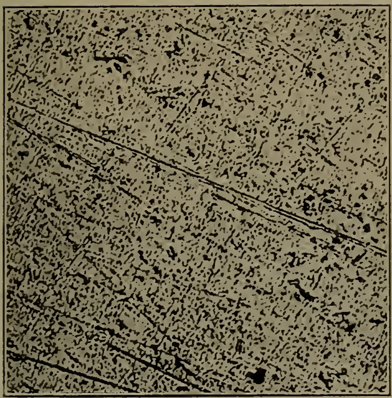

FIG. 23.—*A35–450; Mg, 12.2 per cent (quenched).* ×*300*

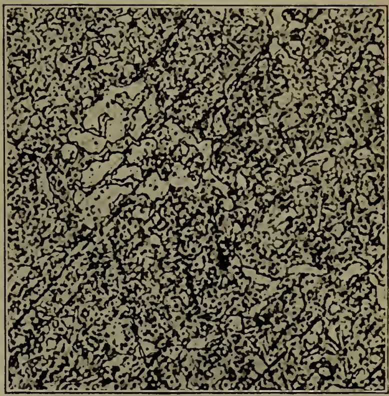

FIG. 24.—*A35–450A; Mg, 12.2 per cent (slowly cooled).* ×*300*

Magnesium-aluminum alloy A35–450, which contains no Mg_4Al_3 *after annealing at 450° C and quenching (Fig. 23), but in which* Mg_4Al_3 *precipitates upon reheating to 420° C and slowly cooling (Fig. 24)*

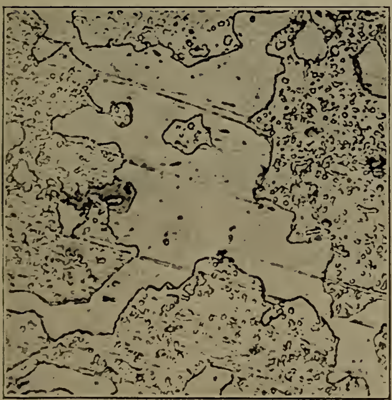

FIG. 25.—*A35–300; Mg, 12.2 per cent.* ×*500*

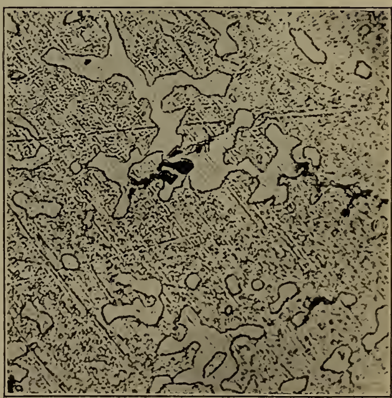

FIG. 26.—*A37–300; Mg, 17.1 per cent.* ×*500*

Magnesium-aluminum alloys annealed at 300° C, showing the deep-blue constituent (dark in the photograph)

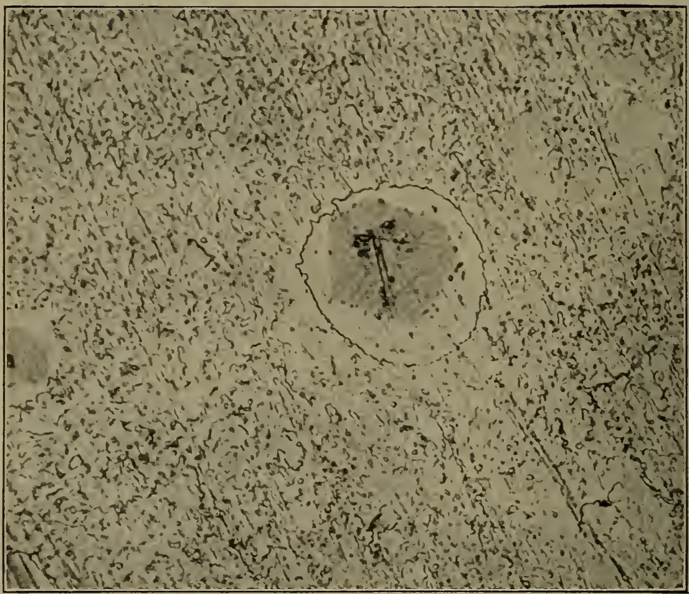

FIG. 28.—*Alloy N28, containing: Cu, 4.98 per cent; Mg, 2.41 per cent; Fe, 0.62 per cent; and Si, 0.32 per cent, and showing deep-blue constituent characteristic of aluminum-rich alloys containing magnesium* ×*1000*

shown in Figs. 25 and 26. This constituent occurs in alloys also containing both copper and magnesium. Fig. 28 shows an island of $CuAl_2$ in such an alloy in which is embedded a particle of this blue constituent.

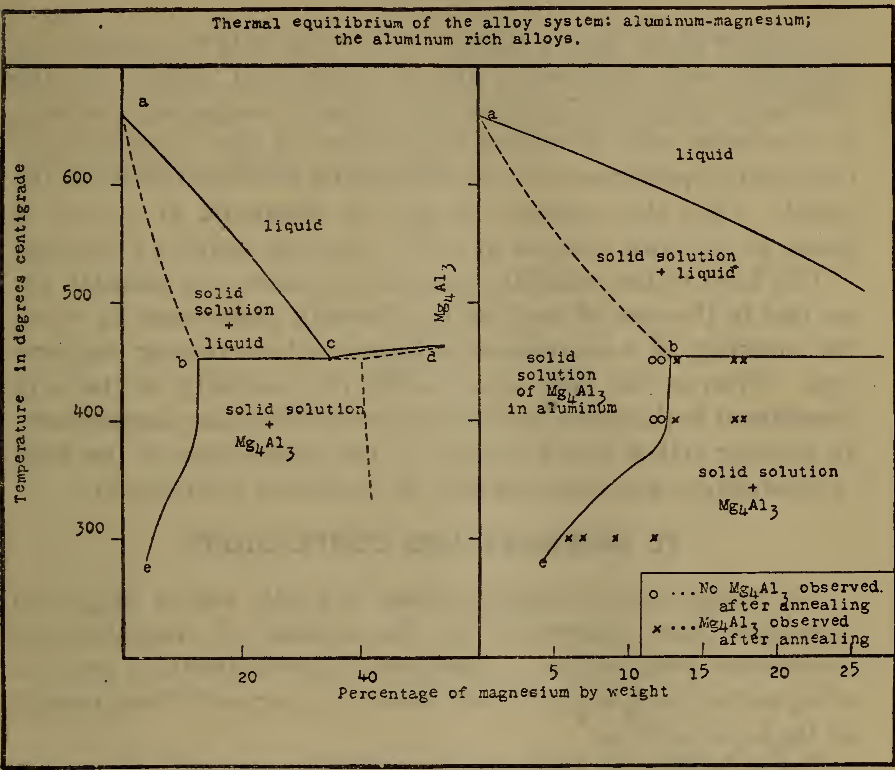

FIG. 27

This is believed to be Mg_2Si, although the authors have no direct evidence for this belief. Vogel[13] found a very marked and definite compound, Mg_2Si, in his study of the binary series, magnesium-silicon, which was of a deep blue color, much resembling the constituent described above. It is unlikely that this constituent is a compound of iron and magnesium since these two metals unite only with much difficulty and probably do not form a compound. The only other possibility therefore is that the constituent is a silicate or a ternary or quaternary compound containing magnesium, silicon, iron, or aluminum.

The occurrence of this constituent in light alloys of aluminum containing magnesium is believed to be of the greatest significance in connection with the effect of magnesium upon the mechanical

[13] Vogel, Magnesium-silicon alloys, Zeit., anorg. Chem., 61, p. 46; 1909.

and other physical properties of these alloys. This question is, however, discussed at greater length in another article.[14]

V. SOLUBILITY OF METALS AND METAL COMPOUNDS IN ALUMINUM

A review of the results obtained above and of those obtained by Rosenhain and Archbutt [15] and of Bauer and Vogel [16] on the solubility of zinc in aluminum shows that a decreasing solubility in aluminum with decreasing temperature of that constituent in immediate equilibrium with the aluminum is characteristic of the metal. Thus the solubility of zinc in aluminum at 443° C is about 40 per cent, whereas at 256° C it is only about 25 per cent.

This form of the solubility curve is, of course, not unusual, yet we find in the case of equilibrium of metals many cases in which the solubility of a constituent increases with decreasing temperature. Thus in the zinc-copper series the solubility of the beta constituent in the alpha one decreases with increasing temperature. In another article (see footnote 14) the significance of the form of solubility curve characteristic of aluminum is discussed.

VI. SUMMARY AND CONCLUSIONS

The temperature-solubility curves of $CuAl_2$ and of Mg_4Al_3 in aluminum were determined by the method of annealing and microscopic examination. Aluminum dissolves about 4.2 per cent of copper as $CuAl_2$ at 525° C and about 12.5 per cent of magnesium as Mg_4Al_3 at 450° C.

The solubility of both compounds decreases with decreasing temperature. At 300° C aluminum dissolves only 1 per cent of copper as $CuAl_2$ and slightly less than 5.9 per cent of magnesium as Mg_4Al_3.

The structural identification of the various constituents, $FeAl_3$, $CuAl_2$, Mg_4Al_3, found in alloys with magnesium and with copper is described, and a constituent is noted in all light aluminum alloys containing magnesium which is believed to be Mg_2Si.

The solubility of iron as $FeAl_3$ in aluminum is at all temperatures less than 0.15 per cent.

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[14] Merica, Waltenberg and Scott, Heat-treatment of Duralumin, this Bulletin, 15, 1919.

[15] Phil. Trans., 211, p. 315; 1911.

[16] Int. Zeit. Metallographie, 8, p. 101; 1916.

Small amounts of silicon up to from 0.12 to 0.20 per cent are dissolved by aluminum at the eutectic temperature, but are reprecipitated upon cooling corresponding to the diminished solubility for silicon of aluminum at lower temperatures.

Silicon in the usual commercial amounts is probably present as a compound of iron and silicon, together with some aluminum. The composition of this compound is not known but it separates out with aluminum and $FeAl_3$ at an invariant point at 610° C.

WASHINGTON, February 2, 1919.