DEPARTMENT OF COMMERCE

CIRCULAR
OF THE
BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 76

ALUMINUM AND ITS LIGHT ALLOYS

ISSUED APRIL 21, 1919

PRICE, 20 CENTS
Sold only by the Superintendent of Documents, Government Printing Office
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PREFACE

The Bureau is continually in receipt of requests for information concerning the properties, statistics, and manufacture of metals and of alloys, coming from other departments of the Government, technical or purchasing agents of manufacturing firms, or from persons engaged in special investigative work in universities and private technical institutes. Such information is rarely to be found in systematic form; usually the sources of such information are difficult of access, and their accuracy not always certain. Often quoted information of this sort is valueless, either for the reason that the data upon which it is based are actually incorrect or that they have not been properly interpreted.

There are therefore being issued from time to time in response to these demands circulars on individual metals or alloys, with the idea of grouping in these circulars all of the best information which the Bureau has as a result of its tests and investigations, together with that available in all records of published tests and investigations of such material.

The circulars deal primarily with the physical properties of the metal or alloy. All other features, except a few statistics of production and such as methods of manufacture, presence of impurities, etc., are discussed only in their relation to these physical properties. It must be realized that the physical properties of metals and alloys are often in great degree dependent upon such factors, so that the statement of values for such properties should include accompanying information regarding these factors by which the properties are affected.

The endeavor, therefore, in the circulars is to reproduce only such data as have passed critical scrutiny and to suitably qualify in the sense outlined above all statements, numerical or otherwise, made relative to the characteristics of the metal. The data and information have been put in the form of tables and curves, the curves being reproduced in such dimensions that accurate interpolation of values on them is possible by the use of a rule graduated in decimal parts of a centimeter. The probable degree of accuracy of data is indicated or implied by the number of significant figures in the values given.

ALUMINUM AND ITS LIGHT ALLOYS[1]

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[1] Of this series, Circular No. 58, relating to invar and similar nickel steel, and Circular No. 73, on copper, have already been issued. There is in preparation a similar circular on iron.

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A. ALUMINUM

I. COMMERCIAL ALUMINUM

1. SOURCES, METALLURGY

Although the element aluminum constitutes approximately 7 per cent of the earth's crust in the form mainly of clay, feldspar, and other double or complex silicates, it is from two relatively rarely occurring minerals or ores that commercial aluminum is manufactured. These are bauxite ($Al_2O_3.3H_2O.xFe_2O_3$) and cryolite (Na_3AlF_6). The former occurs near Baux, France, in Hessen-Nassau, Germany, in Ireland, and in the State of Arkansas. Cryolite is found at Ivitut, Greenland.

The manufacture of metallic aluminum consists properly of two operations: (1) The preparation of pure raw materials, aluminum oxide (Al_2O_3) and cryolite ($AlNa_3F_6$), and (2) the electrolysis of the aluminum oxide in a fused mixture of oxide, cryolite, and often other halide additions.

Bauxite as mined contains from 1 to 30 per cent of both iron oxide (Fe_2O_3) and silica, from which it must be freed before its addition to the electrolytic bath, since otherwise these metals would pass into the cathode metal in large quantities, being more readily separated from their oxides than aluminum. Two processes for doing this are in use. The older process, due to Le Chatelier and Morin, consisted in roasting the powdered bauxite with soda, whereby sodium aluminate ($NaAlO_2$), silica (SiO_2), and iron oxide (Fe_2O_3) are formed. The sodium aluminate is then dissolved out by water, leaving undissolved iron oxide and silica. From this solution aluminum hydroxide ($Al(OH)_3$) is obtained by passing carbon dioxide (CO_2) through it, by which aluminum hydrate is precipitated, forming soda (Na_2CO_3) anew. The aluminum hydrate is calcined to oxide. The von Bayer method produces the sodium aluminate by treatment of bauxite with sodium hydroxide solution under pressure (five atmospheres of steam pressure). From this solution the greater part of the aluminum hydrate is precipitated by stirring with pure aluminum hydrate.

The natural cryolite is generally used in this country, but some artificial salt is produced, particularly abroad.

The electrolysis is carried out in carbon-lined pots about 3 by 3 by 6 feet long, using a bath of oxide and cryolite (with other halide additions, such as aluminum fluoride and chloride, potassium and sodium chlorides) containing not more than 20 per cent of oxide. The carbon lining may serve as the cathode and carbon blocks as anodes. The electrolysis is usually carried out at a temperature of from 900 to 1000° C, using a current density of about 700 amperes per square foot and an electrode potential of 7.5 to 8.5 volts. The heating is accomplished by this current, the theoretical decomposition voltage being about 2.8 volts. Approximately 30 kilowatt-hours are required for the production of 1 kg of metal.

As the electrolysis proceeds oxide is added and the cryolite is regenerated. The molten aluminum is tapped from these reduction pots every 24 hours into small ladles, and from this into a large ladle. From this mixing ladle it is poured into ingot molds, furnishing commercial aluminum.

Since a material is required, free from ash, iron, and silicon, the anodes and lining are made of retort or petroleum carbon. These anodes are rapidly worn away, usually at the rate of 1 pound of anode for 1 pound of aluminum produced.

The details of the construction of the reduction pots, composition of bath, etc., vary largely in different plants. Those who were mainly instrumental in developing the present type of electrochemical reduction process for aluminum were Bunsen (1854), St. Claire Deville (1854), Heroult (1886), Minet (1887), and Hall (1886).

2. COMMERCIAL GRADES, USES

In this country two commercial grades of aluminum are produced: (1) Grade A, containing 99 per cent or more aluminum, and (2) Grade B, containing from 98 to 99 per cent aluminum. The first grade is largely used for wrought aluminum ware and for the preparation of light alloys for rolling and castings. The second grade is used in the steel industry, and sometimes for casting alloys.

The impurities in commercial aluminum are chiefly iron and silicon, although traces of copper and sodium are sometimes found. In the A grade the aluminum content will normally average about 99.3 per cent, with silicon varying from 0.15 to 0.40 per cent and iron varying from 0.25 to 0.70 per cent. The iron content is usually greater than the silicon content. Copper will vary from a trace only to perhaps 0.05 per cent, whereas sodium is in recent years found only in traces. The B grade is characterized by the presence of more iron and a somewhat greater silicon content.

In Table I are given the results of the analysis by Withey (30)[2] of four samples of "the purest commercial aluminum." These were presumably furnished by the British Aluminum Co. Echevarri (54) states that the product of the British Aluminum Co. (Ltd.) now contains close upon 99.5 per cent aluminum. Aluminum of greater than commercial purity has, of course, been prepared. It is only necessary to use care in the preparation of raw materials in order to eliminate the iron; silicon is more difficult to eliminate. Such samples of pure aluminum will be referred to under the paragraphs dealing with the physical properties of the metal.

Aluminum comes on the market in several forms:

Ingots for Remelting.—Either "waffle" ingots, consisting of series of square plaques 3 by 3 by ¾ inches, connected by a thin web, or notched-bar ingots about 14 inches long by 1¼ inches wide.

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[2] These figures relate to the numbered references in the "Bibliography" at the conclusion of this Circular.

Rolling Ingots of Different Sizes.—3½ by 12 by 24 inches; 3 by 12 by 32 inches; 2 by 12 by 20 inches; 1⅜ by 12 by 18 inches.

Rolling Slabs.—Ingots broken down to about three-eighths inch thickness.

The story of the uses and applications of aluminum is quite a long one. As might be expected, it has made a place for itself everywhere where lightness, malleability, high electrical conductivity, and moderate resistance to corrosion are service features.

TABLE 1.—Analyses by Withey (30) of Samples of Purest Commercial Aluminum

Impurity	Sample A	Sample B	Sample C	Sample D
Copper	0.0265	0.0800	0.0463	Trace
Iron	.1829	.4077	.1972	0.1522
Zinc	.0060	.0120	.0075	.0024
Silicon	Trace	.232	Trace	Trace
Silica	.333	.340	.290	.459
Nitrogen	.040	.006	.042	.092
Sodium	Trace	Trace	Trace	Trace
Sulphur	Nil	Nil	Nil	Nil
Phosphorus	Nil	Nil	Nil	Nil

About one-third of the production is consumed in the automobile industry (Richards, 38), where it is used in the form of castings and of sheets for chassis and paneling. Other major uses of this metal are for cooking utensils and vessels of all kinds, for electrical conductors to replace copper, for lightning arresters, and in the form of alloy castings. It is also used as a deoxidizing agent in the manufacture of iron and steel, in the Goldschmidt thermit process, as a substitute for stone in lithographic work, as wrapping foil, as paint powder, as a constituent of the explosive ammonal, as the anode in electrolytic rectification cells. It is manufactured in every commercial form—bars, tubes, sheets, powder, foil, sections, and ingots. Richards (44) lists about 200 commercial and technical uses of aluminum.

It may be worth while to point out that aluminum may be used as a substitute in many cases for metals which are either more expensive or are difficult or impossible to obtain. During the present shortage of tin, aluminum foil can be used to replace tin and tin-lead alloy foil. It can be used at least for many cases as a constituent of bronze castings to replace tin. The greater cost per pound of aluminum than metals such as lead and zinc should not be allowed to give a false impression of its cost. In many cases, such as that of foil, of small manufactured articles, and of many castings, the size and shape of the article is determined by its use, so that it is the cost per unit of volume of the material, not that per unit of weight, which must be considered. Aluminum compares quite favorably in this respect with other metals, as the following table indicates:

Metal	Cost per unit of weight (pounds)	Cost per unit of volume (cubic inches)
Copper	$0.15	$0.048
Tin	38	100
Lead	4	16
Zinc	5½	14
Aluminum	23	22

3. PRODUCTION, PRICE

Table 2 gives a general idea of the world's production and consumption of aluminum. Both production and consumption have increased within the past 15 years at a remarkable rate. The United States leads the world in production.

Table 3 gives the average yearly prices for ingot aluminum from the beginning of its manufacture on a commercial scale.

The production of aluminum is in the hands of comparatively few large firms. Ninety per cent of the aluminum was produced in 1914 by the following firms: Die Aluminium-Industrie A. G. in Neuhausen, Switzerland; Société Electro-Métallurgique Française in Froyes, France; Compagnie des Produites Chimiques, d'Alais et de la Camarque, in Salindres, France; the British Aluminium Co. (Ltd.), England, and the Aluminum Co. of America, Pittsburgh.

TABLE 2.—Aluminum Statistics

WORLD PRODUCTION IN TONS (2000 POUNDS)[a]

	1902	1903	1904	1905	1906	1907	1908
United States [b]	3650	....	....	....	....	....	....
United States and Canada	....	3750	4300	4960	6610	8820	6610
Germany	2700	2700	3300	3300	3850	4400	4400
Austria-Hungary							
Switzerland							
France	1500	1800	1900	3300	4400	6600	6600
England	650	760	760	1100	1100	1980	2200
Italy	....	....	....	....	....	....	660
Total	8500	9010	10 260	12 660	15 960	21 800	20 470
Value in $1000	4570	4820	5480	10 600	12 700	17 300	8150

[a] All of these values except those marked (*a*) are taken from an assembly of statistics by Krause (4) which he states are in many cases only estimates, and are from reports of the Metallhandelgesellschaft Frankfurt A. M., and from reports appearing in Zeit. f. Elektrochemie. Further import and export statistics are given there also.

[b] From Geological Survey data (8, 27).

TABLE 2—Continued

WORLD PRODUCTION IN TONS (2000 POUNDS)

	1909	1910	1911	1912	1913	1914	1915
United States and Canada	14 550	17 750	19 850	19 850	....	....	....
Germany	5500	8800	8800	13 200	....	....	....
Austria-Hungary							
Switzerland							
France	6600	10 500	11 000	14 300	....	....	....
England	3100	5500	5500	8300	....	....	....
Italy	880	880	880	880	....	....	....
Norway	660	990	990	1650	....	....	....
Total	31 290	44 120	47 020	58 180	....	....	....
Value in $1000	10 500	15 800	13 600	22 900	....	....	....

WORLD CONSUMPTION IN TONS (2000 POUNDS)[a]

	1909	1910	1911	1912	1913	1914	1915
United States[b]	....	....	4300	5673	7455	8606	5576
France	770	1100	1200	2300	2900	3300	3800
England	660	770	770	1100	1100	2000	2200
Italy	....	....	....	....	....	....	550
Germany	3300	3420	3970	4520	5840	5500	6600
Austria-Hungary							
Switzerland							
Russia							
Other countries							
Total	4730	5290	10 240	13 593	17 295	19 406	18 126

WORLD CONSUMPTION IN TONS (2000 POUNDS)

	1909	1910	1911	1912	1913	1914	1915
United States[b]	17 105	23 867	23 063	32 804	36 189	39 564	49 903
France	5500	6000	5500	6600	....	....	....
England	2200	3000	3300	4400	....	....	....
Italy	880	990	990	1100	....	....	....
Germany	13 200	14 900	18 800	24 300	....	....	....
Austria-Hungary							
Switzerland							
Russia							
Other countries							
Total	38 885	48 757	51 653	69 204	....	....	....

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[a] All of these values except those marked ([a]) are taken from an assembly of statistics by Krause (4) which he states are in many cases only estimates, and are from reports of the Metallhandelgesellschaft Frankfurt A. M., and from reports appearing in Zeit. f. Elektrochemie. Further import and export statistics are given there also.

[b] From Geological Survey data (8,27).

TABLE 3.—Price of Aluminum[a]

Year	Price per pound	Year	Price per pound	Year	Price per pound
1852	$545.00	1896	$0.295	1910	$0.164
1854	272.20	1897	.283	1911	.131
1855	113.30	1898	.249	1912	.198
1856	34.00	1899	.249	1913	[b] .236
1857	27.20	1900	.227	1914	[b] .186
1857–1886	11.33	1901	.227	1915	[b] .334
1886	7.94	1902	.269	1916	[b] .607
1888	5.39	1903	.269	Jan.–Mar., 1917	[b] .595
1890	2.38	1904	.269	Apr.–June, 1917	[b] .599
1891	.91	1905	.396	July–Sept., 1917	[b] .462
1892	.566	1906	.396	Oct.–Dec., 1917	[b] .373
1893	.566	1907	.412	Jan.–Feb., 1918	.370
1894	.453	1908	.181	March–May, 1918	.32
1895	.34	1909	.156	May–Dec., 1918	.33

[a] All figures but those marked ([b]) refer to general market price (Krause, 4).
[b] From Eng. and Min. Journ. (26). These apply to the United States only.

II. METALLOGRAPHY

Aluminum exists in but one solid phase or form as far as is known. Laschtschento (97), Cohen (96), and Le Verrier (177), it is true, have considered that the results of their calorimetric experiments proved the existence of a thermal transformation in the metal at about 560° C, but the absorption of heat at this temperature (about 5 calories per gram, according to Laschtschento) is due undoubtedly to the fusion of the aluminum-silicon eutectic at this temperature. Laschtschento's results are given in Fig. 7. Thermal analyses of 99.6 per cent aluminum made at the Bureau show the heat evolutions or absorptions corresponding to the solidification or fusion of both the aluminum, aluminum-iron compound ($FeAl_3$) eutectic at 639° C, and the aluminum-silicon eutectic at 560° C. No other thermal arrests are, however, found.

Very little work has been done on the microstructure of aluminum, largely, perhaps, for the reason that it is difficult to prepare and etch a sample satisfactorily for observation. Precautions must be taken—(1) that the surface shall not be distorted by the sawing, grinding, and polishing, (2) that emery particles shall not be forced into the surface, and (3) that the final polishing process shall not dull the surface. Light-bearing pressures and the use of fine saws will prevent the first difficulty. Anderson (95) prevents the second by using the French emery paper coated with paraffin. It has been found at this Bureau that the use of alcohol on this emery paper produces excellent results. Final polishing on kersey, broadcloth, or chamois skin with a small amount of

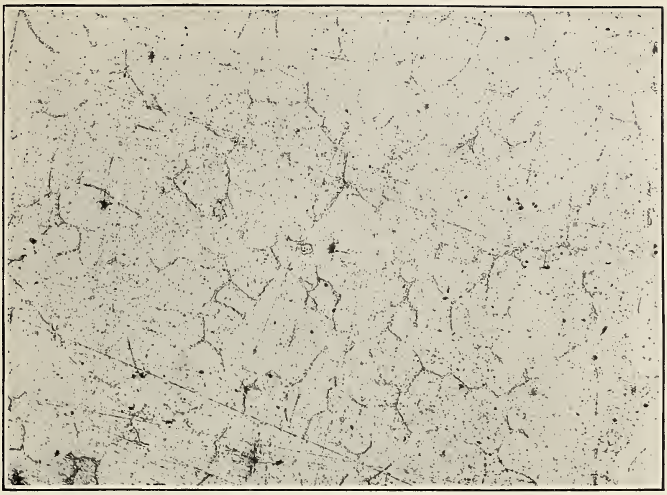

FIG. 1.—*99 per cent aluminum ingot; etched with 0.1 per cent NaOH.* ×100

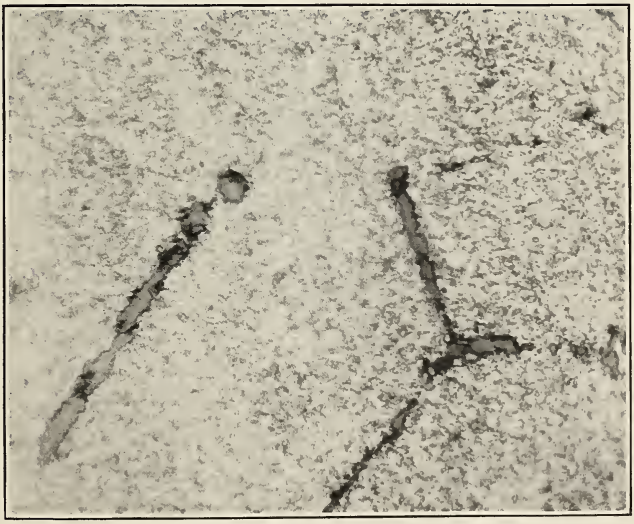

FIG. 2.—*99 per cent aluminum ingot; etched with 0.1 per cent NaOH.* ×1000

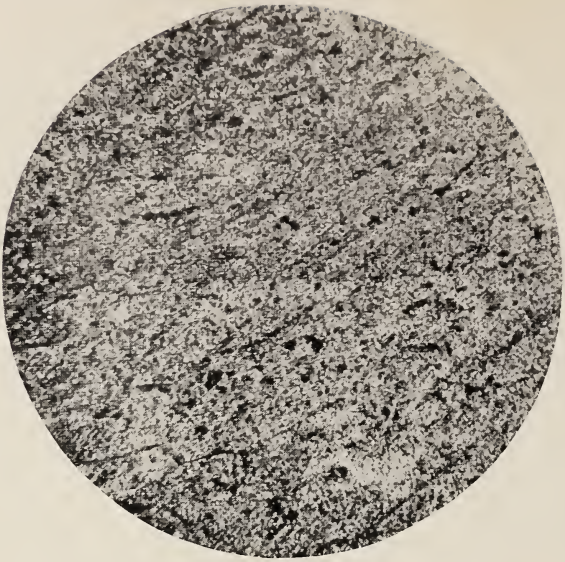

FIG. 3.—*Hard-rolled aluminum sheet (Anderson); etched with HF.* ×100

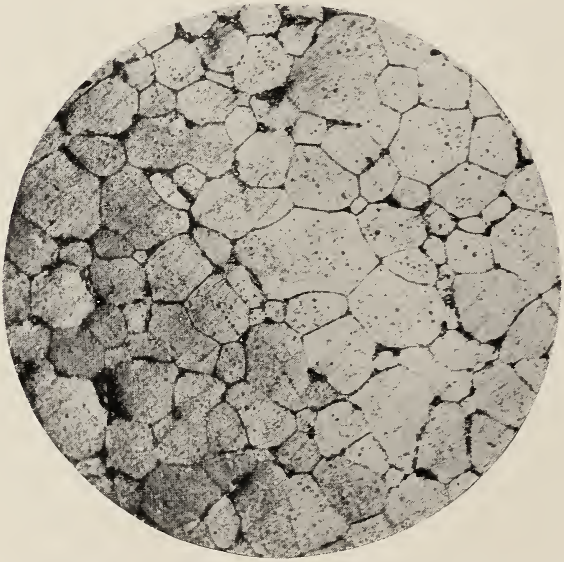

FIG. 4.—*Annealed aluminum sheet (Anderson); etched with HF.* ×50

levigated alumina moistened with alcohol will produce a well-polished surface.

The etching of aluminum may be done with 10 per cent sodium hydroxide (NaOH) in water, or with aqueous hydrofluoric acid (HF) (1 part in 8 parts of water) in order to develop the grain structures and for low magnification. For detail work, however, it is preferred at this Bureau to use a 0.10 per cent solution of sodium hydroxide in approximately 50 per cent alcohol. This solution does not develop the grain structure, but does show the impurities in much better manner than do the more concentrated reagents mentioned above.

Anderson (95) has given photomicrographs illustrative of the structure of commercial aluminum in different forms. These are shown in Figs. 1 to 3. The grains of aluminum can be seen only in cast or in wrought and annealed alloys. In cold-rolled sheet the grains can not be discerned.

All commercial aluminum, even the purest (99.6 per cent) shows in its microstructure a second constituent, the identity of which has never been definitely determined. In the unetched section it can be seen as a dull slate-gray mass illustrated in Fig. 4. This may be the iron-aluminum compound, $FeAl_3$, crystalline silicon, or a silicide of iron (with some aluminum) or a mixture of these. Alumina is seldom if ever noticed in the microstructure of commercial aluminum.

III. CHEMICAL PROPERTIES

Aluminum is a very active element and under proper conditions reacts readily with other elements and substances, such as chlorine, sulphur, oxygen. Its molecular heat or combustion is (for $Al_2O_3 = 102.2$ grams) 392 600 calories.

The ease, however, with which aluminum reacts with oxygen, water, etc., is very dependent upon the physical state of the metal. As a powder or in an amalgam, for example, it reacts quite readily with air, water, and other substances as one would expect from its high heat of reaction. As a solid mass, however, its rate of reaction with the same substances is very much slower, often almost unnoticeable. This in many cases, as, for example, its behavior toward oxidation, is undoubtedly due to its protection by a thin coating of reaction product, be it oxide, hydrate, or otherwise. An important corollary of this fact is that the rate of corrosion of aluminum and of its light alloys depends on whether this protective coating of oxide once formed remains in place, protecting the remainder of the metal, or whether it is removed as it is formed.

Thus the corrosion of the metal and its alloys is much more rapid in running water, and under conditions in which air and water erosion also play a part, than in still water.

Aluminum in the solid form is corroded slowly and superficially only by pure water. In the air, damp or dry, it is also only superficially oxidized. When heated to 400° C for 10 minutes in air a beginning oxidation is noticed which increases slowly up to 800° C and then increases rapidly. Very finely divided aluminum, wire, or foil will decompose water very slowly but noticeably at 100° C.

Ammonium hydroxide attacks aluminum slowly, forming aluminum hydrate. Sodium and potassium hydroxides (NaOH and KOH) attack it quite rapidly.

Sulphur, free or dissolved in carbon disulphide (CS_2), does not affect aluminum at ordinary temperatures.

A solution of a mercury salt attacks aluminum. The mercury liberated by the reduction of the salt amalgamates the aluminum. The aluminum in this amalgam is very active and from it aluminum oxide is very rapidly formed by the action of water. Aluminum articles must therefore be protected from the action of mercury salts.

Cold concentrated or dilute nitric acid (HNO_3) attack aluminum only very slowly. The metal becomes "passive" under the action of this acid. Dilute and concentrated sulphuric acid (H_2SO_4) attack aluminum but slowly when cold. When concentrated sulphuric acid is heated with aluminum, the latter is attacked with formation of sulphur dioxide (SO_2). Dilute and concentrated hydrochloric acid (HCl) readily dissolve aluminum, as well as other mineral acids in the presence of metal chlorides.

Seligman and Williams (98, 99, 101) have carried out extensive tests of the resistance of aluminum to corrosion by acids, particularly nitric, sulphuric, and acetic acids, the results of which are of the greatest practical value in view of the extensive use of aluminum for kitchen utensils and for acid vats and condensers. Their conclusions follow:

The rate of attack of aluminum by cold acetic acid is small; it increases with increasing dilution of the acid. Aluminum vessels can be used for containing concentrated nitric acid, when cold; with hot nitric acid of any concentration aluminum has but a limited life. Dilute cold nitric acid also can be handled in aluminum vessels, but the life of the latter is not as long as with the concentrated acid.

The corrosion of aluminum is greater in mixed sulphuric and nitric acids than in either alone (contrary to previously held opinion), and aluminum vessels should be used only with caution for handling such mixed acids.

The presence of impurities, iron, silicon, and copper is of little influence on the corrosion in acids. The presence of copper is much more injurious when the corrosion is by dilute than when by concentrated acid.

1. CORROSION

Our detailed knowledge of the corrosion of aluminum is perhaps largely due to Heyn and Bauer (128), who in a very thorough investigation described the characteristic variations in the behavior of aluminum to corrosion in water or air and studied the effect of different conditions upon this corrosion. Their investigation was made following an extensive epidemic of disintegration of aluminum cooking utensils which were then being put on the market. Upon storing, many of these became exfoliated, cracked, and blistered, undergoing in many cases an almost complete disintegration.

Heyn and Bauer found that aluminum undergoes two types of corrosion. It may corrode uniformly, a coating of oxide being formed over the whole surface; or it may be attacked locally, with formation of blisters and exfoliation. The latter type of corrosion is, of course, most dangerous and destructive. It appears to occur only when the aluminum is in the hard or cold worked condition and with certain types of tap water or salt solutions. Calcium salts seem to be accelerators of this type of corrosion. Tap water, for example, produces only slight uniform corrosion after several months on soft or annealed sheet; whereas it causes local corrosion, blistering, and disintegration with hard sheet. Distilled water and many other salt solutions, on the other hand, will not cause blistering even with hard sheet. Heyn and Bauer suggest that cooking utensils might well be annealed in order to eliminate entirely the danger of local corrosion.

This distinctive type of local corrosion is probably due (1) to the presence of initial stresses in the hard sheet which cause strains and buckling when released by corrosion and (2) the fact that, as Heyn has shown, hard aluminum is electropositive to soft or annealed aluminum (by about 0.03 volt in tap water).

An idea of the extent of corrosion undergone by aluminum may be gained from the following figures taken from Heyn and Bauer's results:

In distilled water, with access of air, the diminution in thickness of the sheets (from 0.8 to 1.2 mm thick) in 207 days was, for hard sheet, 0.0045 mm; medium sheet, 0.0048 mm; soft sheet, 0.0054 mm.

Samples of medium hard sheets showed the following losses in thickness after 61 days in sodium chloride (NaCl) solution of the following concentrations: 0.34 *N* NaCl, 0.0015 mm; 0.86 *N* NaCl, 0.0024 mm; 3.42 *N* NaCl, 0.0029 mm.

No effect of varying silicon content of the aluminum within the range 0.57 per cent to 0.86 per cent of silicon was noticed upon the type or amount of corrosion.

Aluminum is not attacked by water in the absence of air or oxygen.

The corrosion is much increased as the temperature rises. For example, a sample of medium hard sheet showed the following decrease in thickness after 48 days in tap water: At 20° C, 0.00039 mm; at 70° C, 0.0011 mm.

Bailey (120) finds that the presence of copper and sodium in it increases the corrosion of aluminum, and that, in general, the greater the purity of the metal the less the corrosion.

Guillet (121) finds that soda solutions attack aluminum and its alloys very rapidly. A sample of aluminum which lost only 2 mg weight after eight weeks in Seine water lost 3.95 g after the same time in a 1 per cent soda solution. Alloys containing copper are much more readily attacked than pure aluminum, and he corroborates Heyn's claim that in general cold-worked or hard aluminum resists attack less than the soft or annealed metal.

The Aluminum Co. of America (12) states that aluminum "withstands the action of sea water better than iron, steel, or copper. Strips of aluminum placed upon the sides of a wooden vessel were found to be corroded less than 0.005 inch after six months' exposure to sea water. Copper sheet treated similarly was corroded nearly twice as much."

(a) PROTECTION OF ALUMINUM AGAINST CORROSION

Both aluminum and its alloys are attacked by sea or salt water. The alloys of aluminum are attacked also by fresh water in which aluminum is much more stable. In order, therefore, to be able to utilize these alloys for construction purposes some method of protection against corrosion must be sought.

Of particular significance is the question of the protection of such alloys against corrosion in air-craft construction. Frames, beams, and struts for rigid dirigible construction have already been made entirely from aluminum alloys, and it is quite possible that similar construction will be tried for aeroplane construction to replace parts now fabricated of wood, since there is now no doubt of the mechanical superiority of the alloy duralumin, weight for weight, to wood or steel. An objection often raised against the use of these alloys is that they will corrode when exposed to the weather.

Although it is possible to electroplate aluminum, the effectiveness of such a coating is highly questionable. The coatings on aluminum do not adhere satisfactorily, and the metals used are all electronegative to the aluminum, such that if the coating were once punctured the corrosion at that point would be much accelerated.

The use of a paint, varnish, or enamel seems the most promising solution of the problem. Some experiments carried out by Sabin in 1896 (133) will indicate how far the protection of aluminum by such means is possible to-day.

Sabin carried out two series of tests, using in the first series 30 plates of aluminum and aluminum alloy and 25 plates in the second set. These were coated with various paints, enamels, and varnishes, and suspended in cages: (1) In the first series, from 5 to 6 feet below the water level in New York Navy Yard for six months; (2) in the second series, for two years in the water of the Norfolk Navy Yard, and about 13 months in the New York Navy Yard. The first series of tests showed that several coatings, namely, "Sabin process" pipe-coating enamel, baked; "Durable metal coating," both baked and unbaked; chromium oxide in kauri resin oil varnish, unbaked; spar varnish, baked and unbaked; and white zinc in kauri resin oil varnish gave practically perfect protection to the five-alloy series. In many cases blisters had formed in the coating, but no corrosion had set in. The same plates were again immersed in the water at the New York Navy Yard in 1897 for about 13 months. Some of them were lost, but those which were examined were still uncorroded.

The same may in general be said about the results of the second series of tests, although some of the coatings, notably those made with oil alone as a vehicle were destroyed by this exposure. Many remained absolutely intact, while during the same time heavy iron supporting chains were completely rusted away. The general conclusion from these tests is that aluminum and its alloys can be efficiently protected against corrosion under most severe conditions by the use of an enamel or varnish paint (the oil paints proved very inferior in these tests), and this fact, the result of extensive tests, is recommended to the attention of the aeronautical engineer.

2. ALUMINOTHERMY

Very extensive use is made of aluminum in the production of pure metals, such as chromium, vanadium, manganese, silicon, and ferroalloys by the Goldschmidt thermite process. This process depends on the reduction at high temperatures of the oxides of these metals by finely divided aluminum. The Goldschmidt Thermit Co. has published quite a bit of literature describing the alloys and metals which are thus produced.

The reaction between finely divided aluminum and the oxides of iron is also utilized as a welding process for steel and iron. In this process the crack or cavity is cleaned out and a sand mold built up around it. Into this mold the reaction mixture, finely divided aluminum with iron oxide, is placed, and, when ignited, forms molten iron which flows into the cavity and unites with the edges of the article to be welded. The aluminum oxide floats to the top of the weld mold. Welding by this method is very suitable for heavy repair work. The details are described in all books on welding. (See Hart 244.)

IV. PHYSICAL PROPERTIES

1. ELECTRICAL, MAGNETIC

(a) ELECTRICAL CONDUCTIVITY

The Aluminum Co. of America has given (147) values of the electrical resistivity and conductivity representing the mean of the values of its output for the years 1909 to 1914. These are:

Resistivity $(\rho)_{20}{}^\circ=2.828$ microhm-cm.
Resistivity $(\rho)_{20}{}^\circ=0.0764$ ohm (meter-gram).
Conductivity $=60.86$ per cent (international standard, by volume).
Conductivity $=200.46$ per cent (international standard, by mass).

The density corresponding to these values is 2.70. Seven exceptionally pure hard-drawn samples furnished by the same company and tested by the Bureau (149) showed a mean value of 2.806 microhms-cm (varying from 2.7845 to 2.8175) at 20° C for a mean aluminum content of 99.57 (varying from 0.26 to 0.34 per cent silicon, Si, 0.14 to 0.15 per cent iron, Fe). Other values have been given by Jaeger and Dieselhorst (151), Northrup (152), and by Richards and Thomson (153). Only the latter used (or at least described) purer aluminum and obtained consequently higher values for the conductivity than that tested at this Bureau. They found the following values:

Number	Chemical analysis				Specific resistance in centimeter-gram-seconds units at 0° C	
	Aluminum	Silicon	Iron	Sodium	Hard	Soft
1	99.66	0.16	0.10	0.008	2.4537	2.4322
2	99.58	.16	.25	.052	2.5840	2.5350

Using their value for the temperature coefficient the values of the resistivity for Nos. 1 and 2 hard, at 20° C, would be 2.6459 and 2.7890 microhm-cm, respectively.

The measurements of Richards and Thomson were apparently very carefully made. It is to be assumed that their lower values for the resistivity are actually to be referred to the greater purity of the material they used.

From previous investigations the value of 0.0039 may be accepted for the temperature coefficient of electrical resistivity of aluminum at 20° C.

This value holds well for temperatures between 0° and 100° C (Richards, Thomson, 153; Jaeger, Dieselhorst, 151).

The electrical conductivity of hard-drawn aluminum wire is increased by 1 per cent by annealing (Richards, 153).

(b) THERMO-ELECTROMOTIVE FORCE

The latest measurements of thermo-electromotive force on aluminum are by Northrup (154), who measured the value of the thermal emf to copper of a sample of aluminum containing 99.67 per cent aluminum at 100°, 232°, and 419° C. His results may be expressed by the following equation:

$$(\text{Al to Cu})\,10^6 E(\text{volts}) = 4.51t - {}^{0}.0122t^2 + {}^{0}.0000433t^3$$

$$(\text{Al to Cu})\,10^6 \frac{dE}{dt}(\text{volts}) = 4.51 - {}^{0}.0244t + {}^{0}.0001299t^2$$

Other measurements are by Wagner (155) and Jaeger and Dieselhorst (158), whose values for $\frac{dE}{dt}$ at temperatures between 0 and 100° C are lower than Northrup's. Since the samples of aluminum used by them were not as pure as that used by Northrup, the latter's results may be accepted as more nearly correct.

(c) ELECTROLYTIC SOLUTION POTENTIAL

The only measurements of electrode potentials of aluminum to solutions of its salts are by Neumann (158) and are rather unsatisfactory in view of the fact that no description of the aluminum used is given. He found the following values:

	Volts	Electrode potential [a]
$Al/nAl_2(SO_4)_3/nKCl/Hg$	+1.600	+1.040
$Al/nAlCl_3/nKCl/Hg$	+1.575	+1.015
$Al/nAl(NO_3)_3/nKCl/Hg$	+1.335	+ .775

[a] Calculated on basis of $\epsilon_h=0.560$ for the normal calomel electrode used.

Aluminum is thus markedly electropositive to most metals. Only magnesium, of the commoner metals, has a higher electrolytic solution potential.

Burgess and Hambuechen (144) give results of measurements of the electrolytic emf of aluminum to various solutions, including many acids.

(d) MAGNETIC SUSCEPTIBILITY

Aluminum is paramagnetic. For the susceptibility Honda (159) has furnished probably the most nearly correct value. He finds the following values for the susceptibility (κ) at 18° C:

Material	Susceptibility (κ)
Kahlbaum aluminum in rods (Fe=0.80 per cent)	$+0.695\times10^{-6}$
Siemens-Halske aluminum in wire (Fe=0.42 per cent)	$+ .685\times10^{-6}$
Neuhausen A. G. aluminum cast (Fe=0.08 to 0.24 per cent)	$+ .65\times10^{-6}$

The susceptibility diminished from $+0.695\times10^{-6}$ at 18° C to $+0.60\times10^{-6}$ at 657° C, and remained sensibly constant up to 1050° C.

Honda's values of κ are the lowest yet obtained. Other values are by Wills (160), Lombardi, and Koenigsberger.

2. THERMAL

(a) CHANGE OF STATE

The value of the melting or freezing temperature of aluminum is taken by this Bureau (161) as 658.7° C. This Bureau furnishes (see Circular No. 66) samples of aluminum (Fe=0.18, Si=0.15, Al=99.66 per cent) as one of its standard samples for thermometric fixed points and having the melting point given above (658.68).

There is a considerable discrepancy between the two values for the boiling point of aluminum given by V. Wartenberg (163) as over 2130° C and by Greenwood (162) as 1800° C. The latter value may be accepted probably as more nearly accurate, but it is very possibly only within ± 50° C of the correct value. The form of the vapor pressure curve is not known.

The heat of fusion of aluminum may be taken from measurements by Laschtschenko (97) as approximately 64 cal/g. The heat of vaporization has never been determined. Richards (14) calculates it to be 61 480 cal/g. (i. e., "about 23 times the temperature, absolute, at the boiling point").

(b) THERMAL CONDUCTIVITY

Values of the thermal conductivity of aluminum given by Lees (164) at 0° and 18° C as well as for lower temperatures (see Sec. VI) are probably the most accurate recorded. These are:

$$\lambda_{18}°\ \mathrm{C} = 0.504 \left(\frac{\mathrm{Cal}}{\mathrm{sec.} - \mathrm{cm}^3 - 1°\ \mathrm{C}}\right)$$

$$\lambda_{0}°\ \mathrm{C} = 0.502 \left(\frac{\mathrm{Cal}}{\mathrm{sec.} - \mathrm{cm}^3 - 1°\ \mathrm{C}}\right)$$

These values are determined on a "99 per cent aluminum", without other description. Other values, by Jaeger and Diesselhorst, are lower, due most probably to a high percentage of impurity (including copper, 0.36 per cent) in the sample tested.

(c) THERMAL EXPANSIVITY

Three important series of measurements of the linear thermal expansivity of aluminum have been made. Two of these at least by Dittenberger (171) and by this Bureau, were carried out with sufficient precision of measurement. That by Brislee (167) was carried out with the purest material. Their values are given below:

Dittenberger (A. E. G. pure aluminum):

between 0° and 610° C

$$\frac{\Delta l}{l_0} = (23.536\,t + 0.017071\,t^2)\ 10^{-6}$$

Brislee (Si = 0.25 per cent, Fe = 0.25 per cent):

between 0° C and 100° C

$$\frac{\Delta l}{l_0} = \begin{pmatrix} 24.50\,t, \text{ annealed} \\ 24.30\,t, \text{ hard} \end{pmatrix} 10^{-6}$$

Bureau of Standards (Si = 0.45 per cent, Fe = 0.35 per cent):

between 15° C and 295° C

$$\frac{\Delta l}{l_0} = (22.31\ t + 0.01115\ t^2)10^{-6}$$

In the absence of further measurements it is impossible to choose between these values. It is probable that small amounts of impurities have a considerable effect on the thermal expansivity, explaining the divergence of the results.

Henning (170) obtains the value, $-3.799\ \frac{mm}{m}$, of the quantity,

$$\frac{lt - l_0}{l_0} \text{ at} - 191° \text{ C}$$

for the same sample of aluminum used by Dittenberger. This value is much lower than that calculated from Dittenberger's formula $\left(4.882\ \frac{mm}{m}\right)$.

(d) SPECIFIC HEAT

The most accurate data on the specific heat of aluminum are given by Jaeger and Dieselhorst (151). They give two values for an aluminum containing 0.48 per cent Fe, 0.36 per cent Cu (Si not determined), of a mean specific heat over a very small temperature interval, practically the true specific heat, $\frac{dq}{dt}$, as follows:

$$\frac{dq}{dt}\ (18°\ \text{C}) = 0.2143\ \left(\frac{\text{Cal}}{\text{gram, degrees C}}\right)$$

$$\frac{dq}{dt}\ (100°\ \text{C}) = 0.2228\ \left(\frac{\text{Cal}}{\text{gram, degrees C}}\right)$$

Brislee (172) by calorimetric measurements determined the mean specific heat of 99.6 per cent aluminum to be:

From 300 to 20° C: $\sigma_m = 0.2354\ \left(\frac{\text{Cal}}{\text{gram, degrees C}}\right)$

From 200 to 20° C: $\sigma_m = 0.2240\ \left(\frac{\text{Cal}}{\text{gram, degrees C}}\right)$

From these results the equations are deduced:

$$\frac{dq}{dt}\ (\text{from } 18° \text{ to } 100° \text{C}) = 0.2124 + 0.000104\ t \text{ (Jaeger and Dieselhorst)}$$

$$\frac{dq}{dt}\ (\text{from } 0° \text{ to } 300° \text{ C}) = 0.2012 + 0.000228\ t \text{ (Brislee)}$$

The former value for the true specific heat is probably more accurate, at least at temperatures of from 0 to 100° C than the latter, although Brislee used a purer aluminum.

Laschtschenko's results on the mean specific heat of aluminum between higher and ordinary temperatures indicate that the total heat per gram of aluminum from 0 to 658° C, the melting point, is 187 calories.

3. OPTICAL

The absorption index and the refractive index for aluminum (no further description given) have been given by Drude (179).

$$N \text{ (for } \lambda = 0.589) = 1.44$$
$$K \text{ (for } \lambda = 0.589) = 5.32$$

The reflecting power of this metal is given by Drude (loc. cit.) as 83 per cent for $\lambda = 0.583$, and by Coblentz (178) as 68.5 per cent for $\lambda = 0.60$.

4. MECHANICAL

(a) ELASTICITY

The best values for E, the (Young's) modulus for elasticity are given by Brislee (181) for 99.3 per cent aluminum bars and wire. This mean value is: $E = 9\,810\,000$ pounds per square inch at 17° C; for bars, $E = 9\,840\,000$ pounds per square inch; for wire, $E = 9\,790\,000$ pounds per square inch.

Koch and Dannecker (180) give the following values for the modulus (F) of torsion ($E =$ (approximately) $2.72\ F$) at higher temperatures:

Temperature in degrees centigrade	Modulus of torsion in pounds per square inch
20	3 870 000
100	3 730 000
200	3 450 000
300	3 100 000
400	2 630 000
450	2 030 000
500	680 000

Poisson's ratio (μ) is given by Cardani (183) as 0.363 and by Schaefer as 0.359. A mean value of 0.36 may be accepted. (Katzenelsohn finds that μ increases 15.7 per cent between 0 and 100° C.)

(b) TENSILE TEST

Aluminum may best be "normalized" by mechanical working (rolling, drawing, forging) followed by annealing at about 400° C. In this soft state it possesses the mean tensile properties following.

	Pounds per square inch	Kilograms per square millimeter	Per cent
Tensile strength	12 500–15 000	8.78–10.54	
Yield point	8 000– 9 000	5.52– 6.32	
Elongation in 2 inches			10–40
Reduction of area			20–30

Table 4 will give an idea of the tensile properties of this metal in other forms.

TABLE 4.—Tensile Properties of Aluminum[a]

Form	Tensile strength	Yield point	Elongation in 2 inches	Reduction of area
	Lbs./in.^{2}	Lbs./in.^{2}	Per cent	Per cent
Sand cast	11 000–13 000	8 500	15–25	
Chill cast	12 000–14 000	9000	15–25	
Sheet:				
Annealed	12 000–15 000	8000– 9000	12–35	20–30
Half-hard	18 000–22 000	9000–12 000	5–12	20–30
Hard	22 000–35 000	12 000–25 000	1– 7	20–30
12-gage	25 000		7	
16-gage	28 000		5	
20-gage	30 000		3	
Bars (hard)	28 000–35 000	14 000–23 000		30–40
Wire (hard)	25 000–55 000	16 000–33 000		40–50
40-mil	31 000			
80-mil	28 000			
120-mil	25 000			
200-mil	22 000			

[a] These figures are by the Aluminum Co. of America (12), and others.

Gavey (194) has found that the duration of application of stress has a marked effect on the ultimate tensile stress. Hard-drawn aluminum wires which had been in service as electrical conductors for a few months and had become somewhat corroded showed the following ultimate tensile stress:

Time of application of ultimate breaking load	Breaking load	Tensile strength[a]
	Pounds	Lbs./in.^{2}
Ordinary tensile test	325	25 300
One-half hour	300	23 300
5 hours	280	21 800
118 hours	240	18 700
525 hours	220	17 100
1900 hours[b]		

[a] Wire weighed 75 pounds per mile and was apparently No. 10 British wire gage. The values in column 3 are calculated on this basis.

[b] Not broken but still stretching.

(c) COMPRESSION TEST

The behavior of aluminum in compression is described by the Aluminum Co. of America (12) as follows: Elastic limit 6000 to 25 000 lbs./in.^{2}; ultimate strength 16 000 to 100 000 lbs./in.^{2}

Elmendorf (187) finds an average value (11 tests) of 67 000 lbs./in.^{2} for the ultimate strength of cast aluminum.

(d) HARDNESS

The scleroscope hardness (magnifying hammer) of annealed or of cast aluminum varies from 4 to 6. The hardness of cold-rolled sheets is increased to from 13 to 15; the Brinell hardness (500 kg, 10 mm ball, 30 seconds) of cast aluminum varies from 23 to 28.

(e) DUCTILITY (ERICHSEN TEST)

The ductility of soft annealed aluminum sheets, such as are used for stamping and drawing, is well indicated by the Erichsen test. Average Erichsen values (185, 186) are given below for different gages of commercial aluminum sheets:

B. & S. gage	Thickness in inches	Erichsen value	B. & S. gage	Thickness in inches	Erichsen value
28	0.0126	5.5–7.5	18	0.0403	8.0– 9.5
26	.0159	7.0–8.0	16	.0508	9.0–10.5
24	.0201	7.0–8.0	14	.0640	10.0–11.5
22	.0253	7.0–8.5	12	.0808	10.5–12.0
20	.0319	7.5–9.0	10	.1018	11.0–12.5

(f) ALTERNATING STRESS TEST

The only tests of which results are published are those on the White-Souther machine by Elmendorf (187) on cast aluminum of tensile strength averaging 15 000 pounds per square inch. He finds the following relation:

$$S = 48\,000 R^{-0 \cdot 0113}.$$

where S = fiber stress.

R = number of reversals to rupture.

This gives for 10 000 pounds per square inch fiber stress one million reversals, for 7800 pounds per square inch, ten million reversals.

5. MISCELLANEOUS

(a) DENSITY

Seven samples of hard-drawn wire of from 99.52 to 99.60 per cent aluminum tested at this Bureau averaged 2.6991 in density, ranging from 2.6983 to 2.6996 (149). Brislee (141, 142) has shown that the density of aluminum depends upon the heat treatment and amount of mechanical working it has suffered. He found that the mean increase of seven samples of density of cold-worked metal upon annealing was 0.0017, or 0.063 per cent.

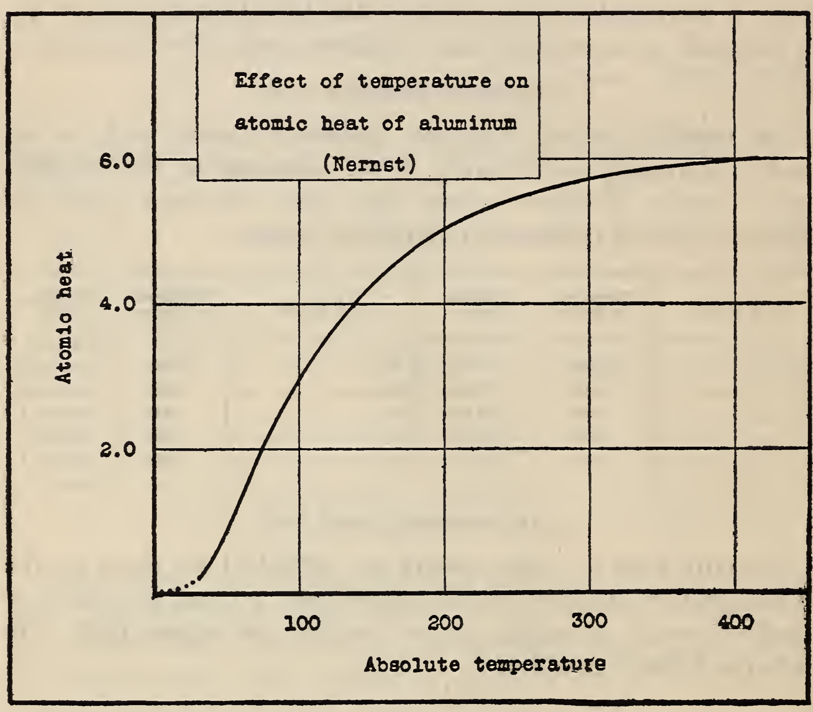

FIG. 5.—*Effect of temperature on the atomic heat of aluminum.* (Nernst, 197)

Annealed aluminum may be regarded as having a density of 2.702 and cold-worked or hard aluminum, one of 2.700.

V. PHYSICAL PROPERTIES AT HIGHER AND LOWER TEMPERATURES

Niccolai (203) has determined the specific electrical resistivity of aluminum at temperatures from −189 to 400° C. His values are given in Table 5 and plotted in Fig. 6. Lees (164) also gives similar values for the electrical resistivity at lower temperatures.

TABLE 5.—Effect of Temperature on the Electrical Resistivity of Kahlbaum Aluminum (Niccolai, 203)

Temperature in degrees Centigrade	Electrical resistivity in microhms per cubic centimeter	Temperature in degrees Centigrade	Electrical resistivity in microhms per cubic centimeter
−189	0.641	+125	4.192
−175	.795	+150	4.496
−150	1.038	+175	4.827
−125	1.282	+200	5.172
−100	1.535	+225	5.518
− 75	1.782	+250	5.850
− 50	2.067	+275	6.204
− 25	2.321	+300	6.559
± 0	2.618	+325	6.917
+ 25	2.925	+350	7.274
+ 50	3.237	+375	7.638
+ 75	3.562	+400	7.991
+100	3.858		

Lees (164) gives the following values for the thermal conductivity of 99.0 per cent aluminum:

Temperature in degrees Centigrade	Thermal conductivity in calories per second per cubic centimeter per 1° C	Temperature in degrees Centigrade	Thermal conductivity in calories per second per cubic centimeter per 1° C
−170	(0.524)	− 75	(0.493)
−160	.514	− 50	.496
−150	.508	− 25	.499
−125	.491	0	.502
−100	.492	+ 18	.504

The effect of low temperatures upon the atomic heat of aluminum is shown in the Fig. 5 from data by Nernst (200).

The total heat of aluminum at higher temperatures has been measured by Laschtschenko (97) from *t*° to 24° C. His results are plotted in Fig. 7.

Investigation has been made by Breuil (202), Baumann (199), and Bengough (198) of the effect of temperature on the tensile properties of aluminum. Their results are shown in the Tables 6, 7, and 8 and in Fig. 8. The variation in the results is due, in all probability, to the difference in the speed of testing, which has undoubtedly much effect on the results obtained.

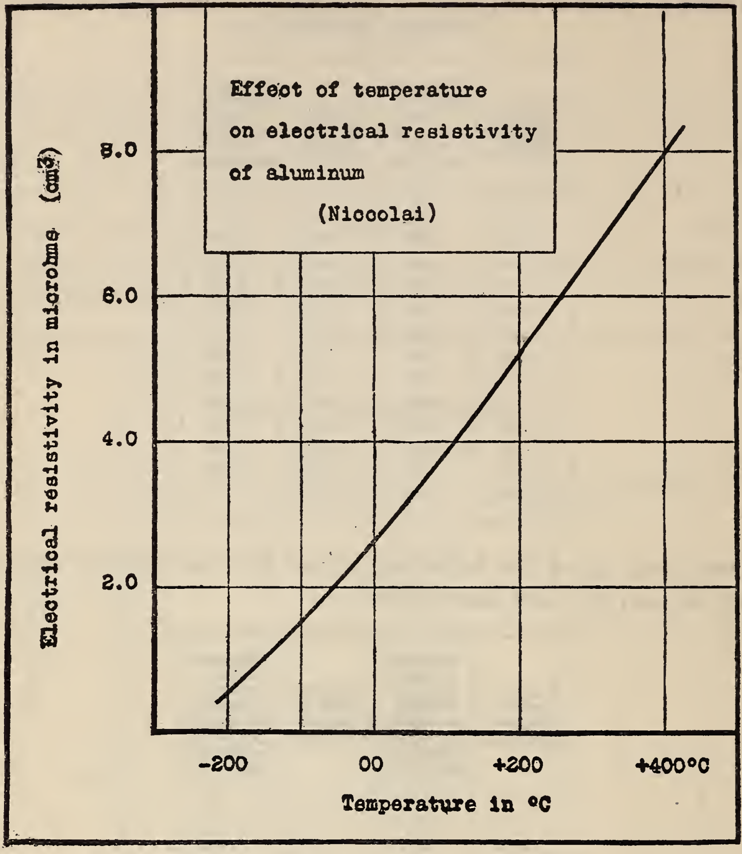

FIG. 6.—*Effect of temperature on electrical resistivity of aluminum.* (Niccolai, 203)

TABLE 6.—Tensile tests of Hard-drawn Aluminum Tubes, (Breuil 202)

EFFECT OF ANNEALING [a]

Temperature of anneal in degrees centigrade	Tensile properties			
	Tensile strength	Yield point	Elongation in 2.7 centimeters	Reduction of area
	Lbs./in.²	Lbs./in.²	Per cent	Per cent
Hard	31 600	30 900	4.0	18
100	35 800	31 600	6.6	15
200	31 600	18 100	5.6	31
300	21 600	15 000	22.2	42
EFFECT OF TEMPERATURE ON PROPERTIES				
20	31 600	30 800	4.0	18
100	29 900	29 900	9.6	24
200	20 800	15 800	22.2	41
300	10 100	10 100	31.4	35

[a] Tubes were annealed in oil (time not given) and tested.

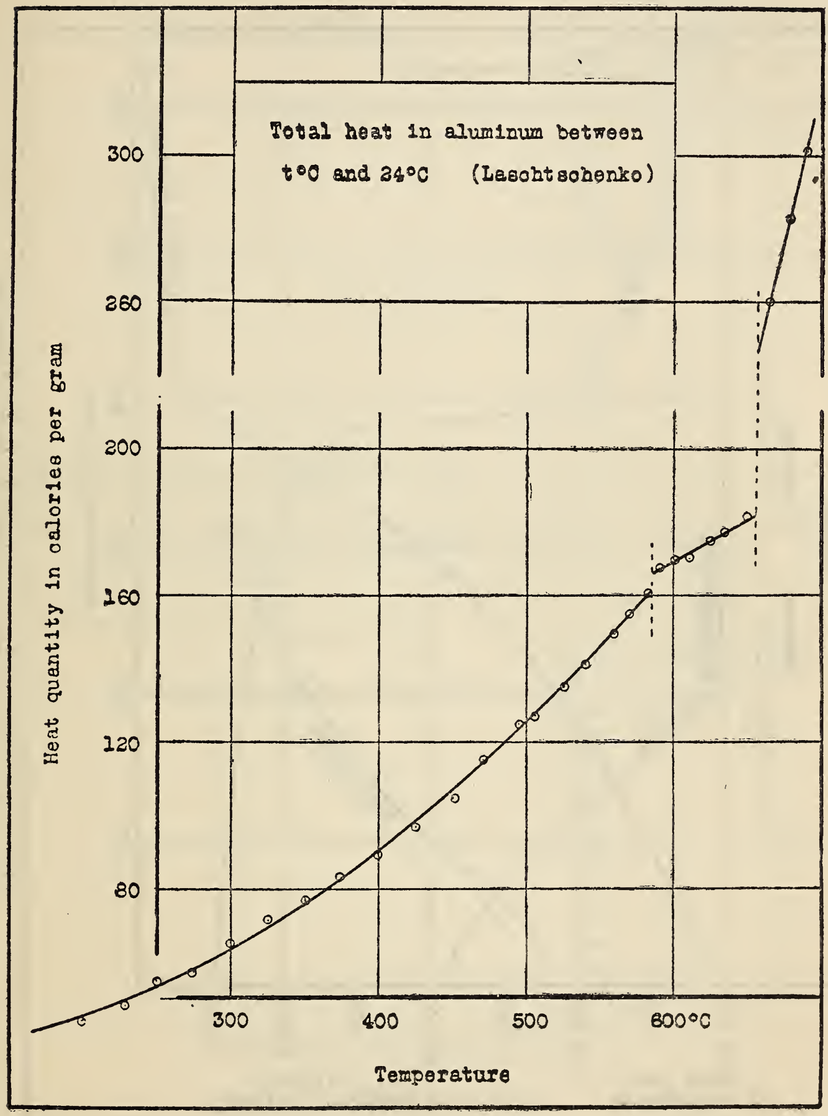

FIG. 7.—*Total heat of aluminum at higher temperatures.* (Laschtschento, 97)

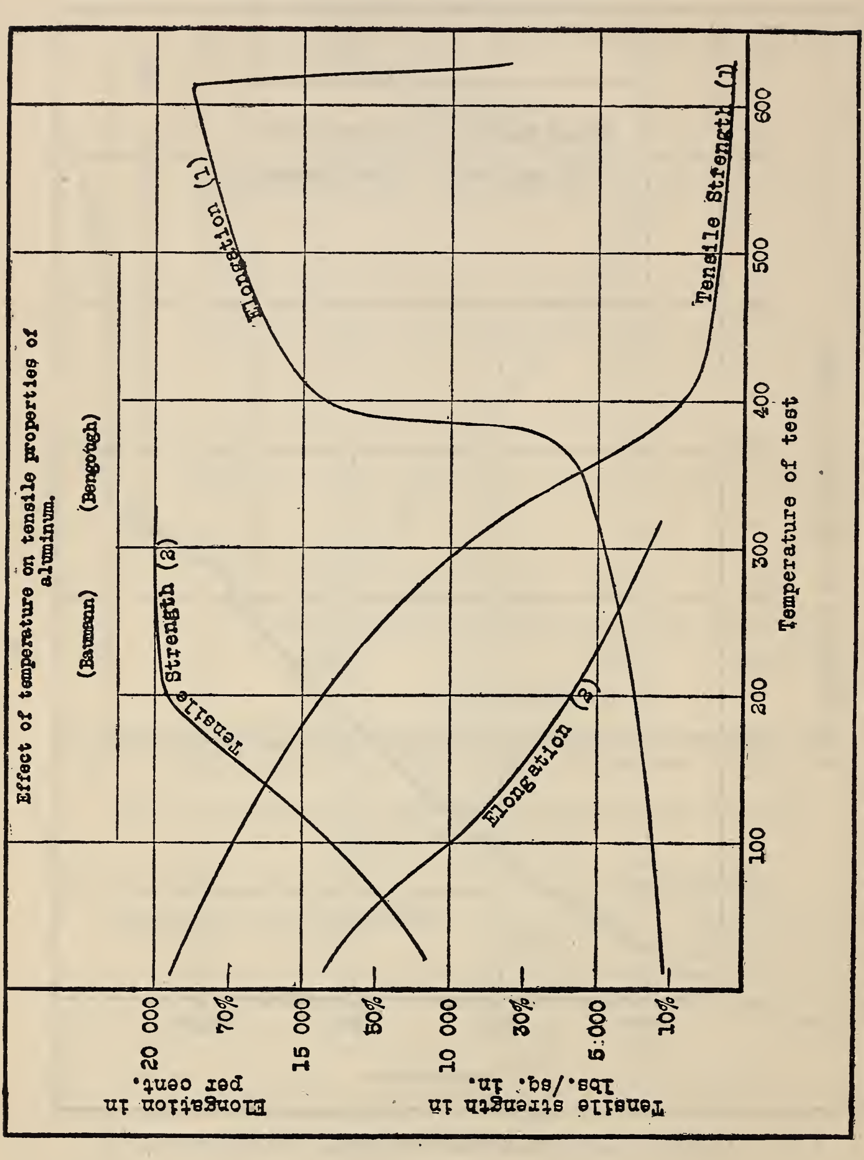

FIG. 8.—*Effect of temperature on the tensile properties of aluminum*

Curves 1 for an unannealed sample containing 99.56 per cent aluminum, by Bengough (198). Curves 2 for an annealed sample, by Baumann (199)

TABLE 7.—Tensile Tests of Aluminum Bars at Higher Temperatures[a] (Baumann 199)

ANNEALED

Temperature in degrees centigrade	Tensile strength		
	Tensile strength	Elongation in 5 centimeters (1.97 inches)	Reduction of area
	Lbs./in.^{2}	Per cent	Per cent
20	14 000	43.3	64.5
60	12 600	49.9	71.9
100	9860	66.8	76.6
200	5980	78.1	87.2
300	3360	79.8	92.8

NOT ANNEALED

20	19 900	16.3	43.7
100	13 700	35.8	66.0
200	9230	44.7	76.9
300	4270	59.9	83.7

[a] These tests were made on 99 per cent aluminum bars 17, 12, 8, and 4 mm. thick. The values given are averages of the results for the bars of the four thicknesses.

TABLE 8.—Effect of Temperature on the Tensile Properties of Aluminum[a] (Bengough, 198)

Temperature of test in degrees centigrade	Tensile properties		
	Tensile strength	Elongation in 2 inches	Reduction of area
	Lbs./in.^{2}	Per cent	Per cen
20	19 200	11	75
20	19 200	12	75
200	14 100	15	78
275	11 100	17.2	79
330	7 600	20.3	88
375	3 800	25	88
396	2 150	56	90
450	....	65	96
520	900	68.5	([b])
565	540	70.3	([b])
610	660	75.0	([b])
625	420	39.0	92

[a] The metal tested contained 99.56 per cent aluminum.
[b] Reduction of area to finest possible point.

VI. TECHNOLOGY

1. CASTING

Practically no aluminum is poured into sand or even chill castings to-day except for the production of rolling or melting ingots. "Aluminum" castings are made of an alloy of aluminum with copper, zinc, or other metal. The subject of casting alloys of aluminum is discussed in Section IX–1.

For rolling and drawing, aluminum is heated without flux in reverberatory or in crucible furnaces and poured into chill molds. Care is taken in melting to keep the temperature below 800° C. Above this temperature the aluminum absorbs gas, oxidizes, and a porous ingot may result. The melting is usually done at from 725 to 750° C. Quick cooling in the chill ingot molds is very necessary in order to secure a fine grain and, consequently, good mechanical properties, as well as ease of hot rolling. When starting to pour a chill mold for rolling ingots the mold is held at an angle, such that the metal flows down one side and does not splash. During the pouring the mold is continually and slowly tilted into the vertical position. In this manner cold shuts and similar flaws are prevented.

2. WORKING

Sheet aluminum is usually rolled from one of the standard rolling ingots (see p. 6). The ingots are reheated after casting to about 400° C and rolled down hot in from 10 to 12 passes to a sheet, one-fourth to three-eighths inch thick. This is then rolled cold to gage without intermediate annealing. Sheet as thin as 0.0005 inch may be rolled; this is of course foil. If soft sheet is desired, the cold-rolled sheet is annealed, generally at from 375 to 400° C for 18 to 30 hours, and cooled in air.

Rods and wire are first hot rolled and then drawn cold to size, the methods differing but little from those in vogue for copper. Wire, for example, may be rolled hot from a square section billet weighing about 85 pounds (usually about 4 inches square in section and 5 or 6 feet long), to from one-half to three-eighths inch. These rods are drawn cold to the wire sizes desired. Sometimes, particularly in European practice, all of the rolling is done cold instead. Tallow is used as a lubricant, and the wire may be drawn at from 150 feet (initial) to 600 feet per minute final speed.

Tubes are made by the cupping of plates, followed by drawing on the press, and then on the standard draw bench. This is done cold with intermediate annealing if necessary.

Sections, rods, and tubes are also made by extrusion at higher temperatures (about 400° C), by hydraulic pressure. Sections up to 6 inches in diameter are made in this manner with wall thicknesses as small as one-eighth inch. Continuous tubing may be made also by this method.

Aluminum is very readily stamped, drawn, and spun. Cooking utensils and vessels of various kinds are produced by spinning annealed aluminum sheet. "In thicknesses above No. 20 B. & S. gage, aluminum will take a draw of from one-fourth to one-third more depth than will copper, brass, or steel" (10).

Aluminum foil, 0.0005 inch in thickness may be still further beaten into aluminum leaf almost as fine as gold leaf.

Pure aluminum is not readily machined—the metal drags, the tools do not cut but tear, and files are "smeared" with the metal. The alloys of aluminum are much more readily machined, particularly the casting alloys. For the metal and its alloys the tool should be sharp, with a good clearance, as for wood, and the cut should be light and made under a suitable oil, such as lard oil or the same mixed with three parts of benzine. A cutting speed somewhat greater than that used for brass is suitable.

3. WELDING AND SOLDERING

Aluminum can be both soldered and welded, the latter by several different processes. In both cases a principal difficulty consists in the removal of the layer of oxide before the metal can flow together.

Aluminum may be welded by any of the different commercial processes. Aluminum sheet is generally welded by the oxy-acetylene or oxy-gas torch, the edges being butted for all but light gages, for which they are lapped or flanged. A flux should be used for sheet welding, and consists of a mixture in varying proportions of the chlorides and fluorides of sodium, potassium, lithium, aluminum, and calcium. A few typical compositions of fluxes are given in Table 9 below. These fluxes should be finely powdered and before using moistened down with alcohol.

TABLE 9.—Composition of Welding Fluxes (Pannell, 43, and Others)

	Sodium chloride	Sodium fluoride	Sodium sulphate	Lithium chloride	Potassium chloride	Potassium fluoride	Potassium sulphate	Calcium chloride	Cryolite
	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent
1	30	....	3	15	45	7	....	....	....
2	....	33	....	33	33	....	....	....	....
3	12.5	....	....	30.8	62.5	....	4.0	....	....
4	16	....	....	....	79	....	5.0	....	....
5	17	....	....	....	83	....	....	....	....
6	6.5	....	4.0	23.5	56	....	....	....	10
7	....	....	....	....	60	....	....	30	6

The flame must not be held so close to the work as in steel welding, and a slightly reducing flame is to be used. A feeding stick of the same composition should be used. If the joint edges are flanged, a feeding stick is not necessary.

Castings may be welded in the same manner, except that it is not necessary to use a flux, although results are generally better when it is used. The casting should be well supported, so that no stress comes upon the welded joint while it is hot, as the metal is fragile and brittle at a temperature little below the melting point.

In arc-welding work on castings the latter should preferably be preheated in order that internal stresses caused by shrinkage are not left in the welded casting when cool.

Arc welding may also be used for repair work on castings, but it is not used for sheet and thin work.

Rods and wires are best butt welded by a combined heating and pressure method. The older methods of Heroult and of Cowper-Coles consisted in squaring off the ends of bars, heating these ends to about 400° C, and bringing them together and hammering them (Heroult), or under pressure (Cowper-Coles). The electric-resistance, butt-welding machines have, however, furnished a much more suitable means of heating and applying pressure than the older processes, and are in general use.

Spot welding of sheet aluminum has been done, but does not seem to give as reliable a joint as the oxy-acetylene process.

Welding, chiefly oxy-acetylene, is now quite widely practiced, both on aluminum castings and on sheet. Large numbers of welded aluminum vessels, pans, and containers of various sorts are manufactured each year. The welds are in most cases so perfect that they can not be detected in the finished article. However, the welding of aluminum by any of the above methods is not easy, and requires experience. Welders familiar only with iron and steel work will generally make a complete failure of their first aluminum work.

Although welding is the only process to be recommended for joining aluminum when the joint must have strength and is exposed to the weather, it may, in many instances, be advisable to solder aluminum articles instead of welding them. The application of solder is easier, requires no especially skilled operator, and the temperature of application is not so high as to cause buckling or distortion in the welded piece. On the other hand, the metals used in such solders are all electronegative to aluminum. A soldered joint is rapidly attacked by water or moisture, the joint becoming completely disintegrated in a short time. Only when the joint may be varnished or protected or for very heavy joints where slight corrosion would not be serious should solder be used.

It would be useless to give a list of all of the recommended solders for aluminum now on the market. They consist for the most part of varying mixtures of zinc, tin, and aluminum, of which Table 10 will give some typical examples of those most generally used. Some mixtures contain copper, lead, bismuth, antimony, and iron, the function of which is certainly not clear; in fact, these metals are probably harmful.

TABLE 10.—Chemical Composition of Some Aluminum Solders

Reference	Chemical composition						
	Zinc	Tin	Aluminum	Lead	Copper	Cadmium	
	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	Per ct.	
Burgess and Hambuechen (144).	21	76	3				
Richards (256)	31	63	3				3 per cent phosphor-tin.
Auel (234)	35	63	.25		2		
Wüst	50		30		20		
Do	65		20		15		
Do	80		12		8		
Do	85		9				6 per cent brass.
Do	88		7				5 per cent brass.
Do	90		6				4 per cent brass.
Do	94		4		2		
Bates (255)		30	70				
Do			81		19		
Do		20	70		10		
Sterling	15.2	61.6	11.2	8.3	2.5		1.2 per cent antimony.
Roesch	50.2	48.6			.2		0.7 per cent antimony.
Crown	18	63	13	1	3		2 per cent antimony.
So-Luminum	33	55	11		1		
Seifert	21	73		5			1 per cent phosphor-tin.
Bureau of Standards:							
SN 1	8	78	9			5	
SN 3	9	86	5				0.25 per cent phosphorus.
SN 4	9	86	5				
Zn 1	75		5			20	
Geophysical laboratory, Carnegie Institution	90		6		4		

Solder is best applied without a flux. The edges of the aluminum are filed clean and tinned with the solder, which should be thoroughly rubbed into the surface with a wire brush or with waste. The joint is then readily made in the usual manner between the tinned surfaces, using an iron if necessary.

4. ELECTROLYTIC DEPOSITION

The deposition of aluminum from a bath of its fused salts has already been described under Section I–1. The electrolytic separation of aluminum from its aqueous solutions can be effected but the current efficiency is very low and the metal not adherent. It is therefore never done commercially.

The electroplating of other metals on aluminum is of somewhat more importance, but this operation is also attended with the greatest difficulty, due to the high chemical reactivity of the metal. The principal difficulties are: (1) The thorough cleansing of the surface of the aluminum, and (2) the securing of an initial layer of electro-deposited metal which is adherent. Aluminum behaves in this respect in a manner much similar to iron.

There are a number of patents claiming the accomplishment of these two operations. The firm of Mix & Genest has given a great deal of attention to this problem and describe in their patents a number of processes for the preparation of the metal for the plating bath. Some of them are:

(1) The use of hot or cold sodium hydroxide solution.

(2) The use of halogen acids with the addition of alcohol, glycerin, etc.

(3) The use of gelatine in a hot dilute alkaline bath (borax, sodium phosphate, etc.).

(4) The use of glycerin with potassium carbonate, alkali phosphate, etc.

Canac and Tassilly (258) describe a long process depending on the cleaning of the aluminum with potassium hydroxide or carbonate (KOH or K_2CO_3), brushing with milk of lime, dipping in 2 per cent potassium cyomide solution (KCN), dipping in a solution (A) of 500 g hydrochloric acid (HCl), 500 g water, and 1 g iron, followed by washing and repetition alternately of dipping in solution (A) and water until, as they claim, an adherent coating of iron has been produced upon the aluminum, upon which copper or any other metal may then be deposited in the usual manner.

The present processes for electroplating aluminum are not satisfactory. An adherent layer is not produced. Furthermore, the electrodeposition of metals upon aluminum as a measure of protection against corrosion is of most doubtful value, since a layer of all metals electronegative to it protects only mechanically, and actually by galvanic action accelerates corrosion once the layer is pierced, whereas metals electropositive to aluminum are too readily corroded to effect any protection to it. Much better protection is afforded by a varnish or a paint. (See Sec. III–1–(*a*).)

5. MISCELLANEOUS

(a) FINISH

Aluminum is given several types of finish. The two most important are the polished and the satin finish. The former is obtained in the usual manner by buffing with rouge. The latter is obtained:

1. *By Caustic Dipping.*—The metal is cleaned in benzine, dipped in boiling concentrated caustic soda, washed, dipped in hot strong nitric acid, washed in boiling water, and dried very quickly.

2. *By Scratch Brushing.*—The metal is carefully freed from grease and then brushed on the wire-brush wheel.

(b) GRANULATING

Granulated aluminum has been used in the manufacture of steel. It is made by pouring molten aluminum in thin streams into cold water, which is stirred. The metal may for this purpose be poured through a sieve.

(c) CALORIZING

Ruder (45) describes a process of coating metals with aluminum by heating in a mixture of aluminum and aluminum oxide at higher temperatures. This is accomplished at from 700 to 800° C for copper and from 900 to 950° C for iron and steel. The layer formed varies from 0.025 per cent to 0.010 mm in thickness.

(d) APPLICATION OF ALUMINUM BY SCHOOP PROCESS

Aluminum has been applied by the Schoop process.

(e) ALUMINUM POWDER

Aluminum powder for painting and the thermite reaction is produced by rubbing foil through a metal sieve under molten fat.

VII. THE PROPERTIES OF ALUMINUM AS AFFECTED BY MECHANICAL WORK AND BY HEAT TREATMENT

When aluminum is cold worked, the hardness or tensile strength is increased and the ductility or elongation in the tensile test decreased. The manner in which these properties vary with different amounts of cold working is shown in Fig. 9, drawn from data kindly supplied by the Aluminum Co. of America from tests on cold-rolled sheet.

The Shore scleroscope hardness number (magnifying hammer) increases also from 5 to 6 for annealed aluminum sheet to from 15 to 20 for hard sheet.

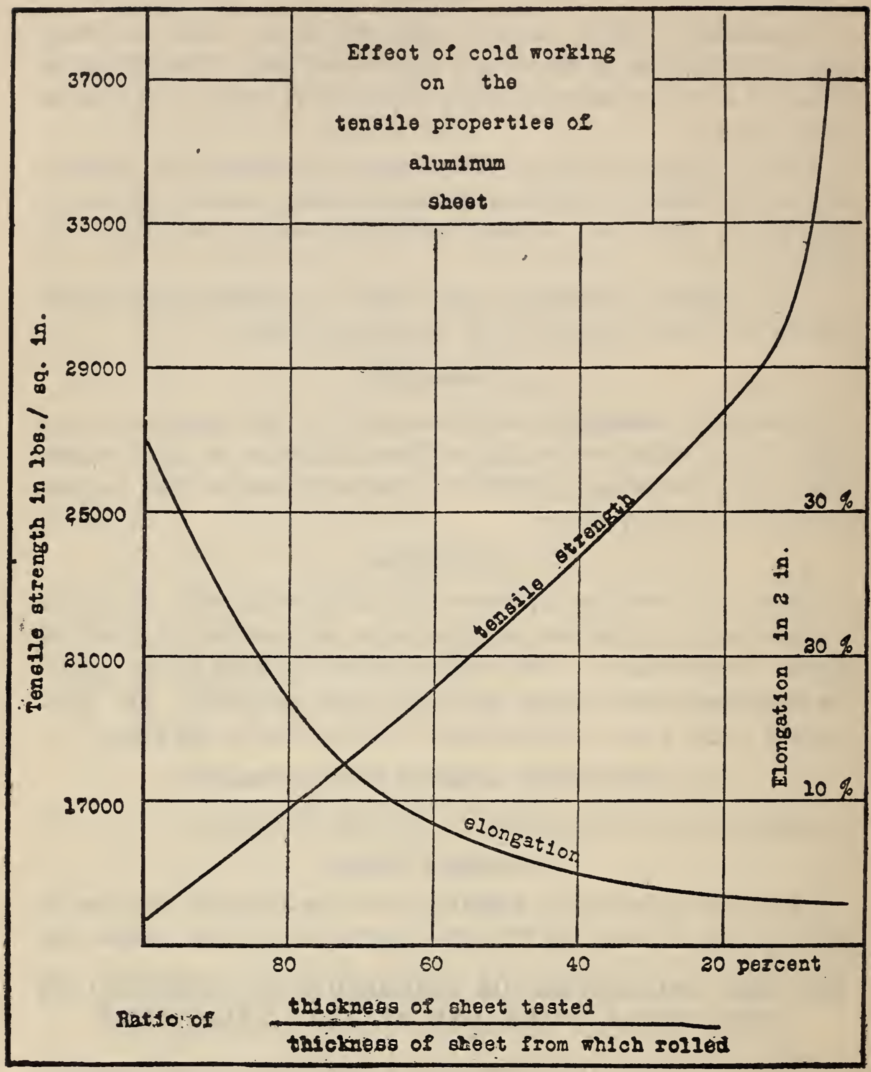

FIG. 9.—*The effect of cold working on the tensile properties of aluminum sheet; taken from the data of the Aluminum Co. of America*

The abscissas represent the ratio of the thickness of the sheet tested to that of the original annealed sheet from which it was rolled. The curves represent the average of 15 tests of sheet rolled from 12, 14, and 16 gage annealed sheet. The portion of the curve beyond a ratio of 30 per cent (i. e., between 30 per cent and 0) is drawn from results of tests of 22, 24, and 26 gage sheet drawn without annealing from ¼ to ⅜ inch hot-rolled sheet.

Annealing produces a recrystallization and softening of the metal. Only recently Carpenter and Taverner (205) have made a systematic study of the rate of softening of aluminum sheet by annealing at different temperatures. They used sheet cold rolled to 0.125 inch (probably from ⅜ inch, but the exact amount of cold reduction was not known to the authors) of four materials of the following average analysis: Silicon, 0.75 per cent (0.70 to 0.81 per cent); iron, 0.34 per cent (0.34 to 0.36 per cent); copper, 0.03 per cent.

A general idea of the results of their tests is gained from Figs. 10 and 11. The principal facts developed by this investigation are:

1. The hardness caused by mechanical work is lost very rapidly upon annealing at from 300 to 500° C. The same final tensile strength of about 12 700 pounds per square inch is obtained in all cases.
2. The softening is most marked within the first portion of the annealing period.
3. No hardening by annealing was noticed, as in the case of copper and brass.
4. Below 300° C the decrease in hardness is very slow but occurs within the temperature range 100 to 200° with no increase of ductility.

The authors did not study the effect of previous cold reduction on the rate of softening by annealing, but there is no doubt but that the extent of this reduction has a great effect upon the annealing of the metal, as has been shown to be the case with copper.

Some annealing tests on aluminum tubes are described by Breuil (202).

B. LIGHT ALUMINUM ALLOYS

VIII. INVESTIGATION OF ALLOY SERIES

1. ALUMINUM-COPPER

The constitution of these alloys has been studied by Gwyer (375), Carpenter and Edwards (378), Curry (379), and Guillet (381, 382). On the aluminum side of the constitution diagram a compound, $CuAl_2$, is formed which is partially soluble in aluminum. The exact solubility has not been determined, but is undoubtedly not far from 3 per cent of copper. The eutectic of aluminum and $CuAl_2$ is at 32 per cent copper and 545° C. No ther-

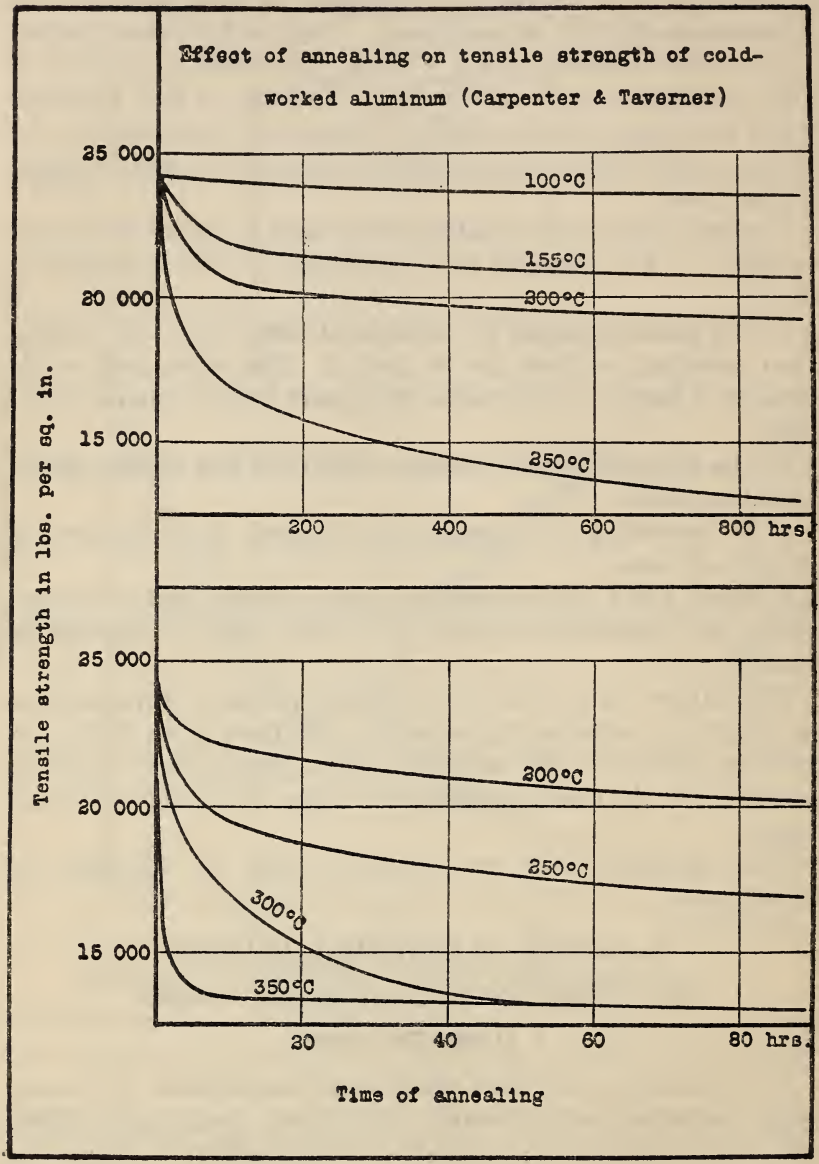

FIG. 10.—*Effect of annealing on tensile strength of cold-worked aluminum.* (Carpenter-Taverner, 205)

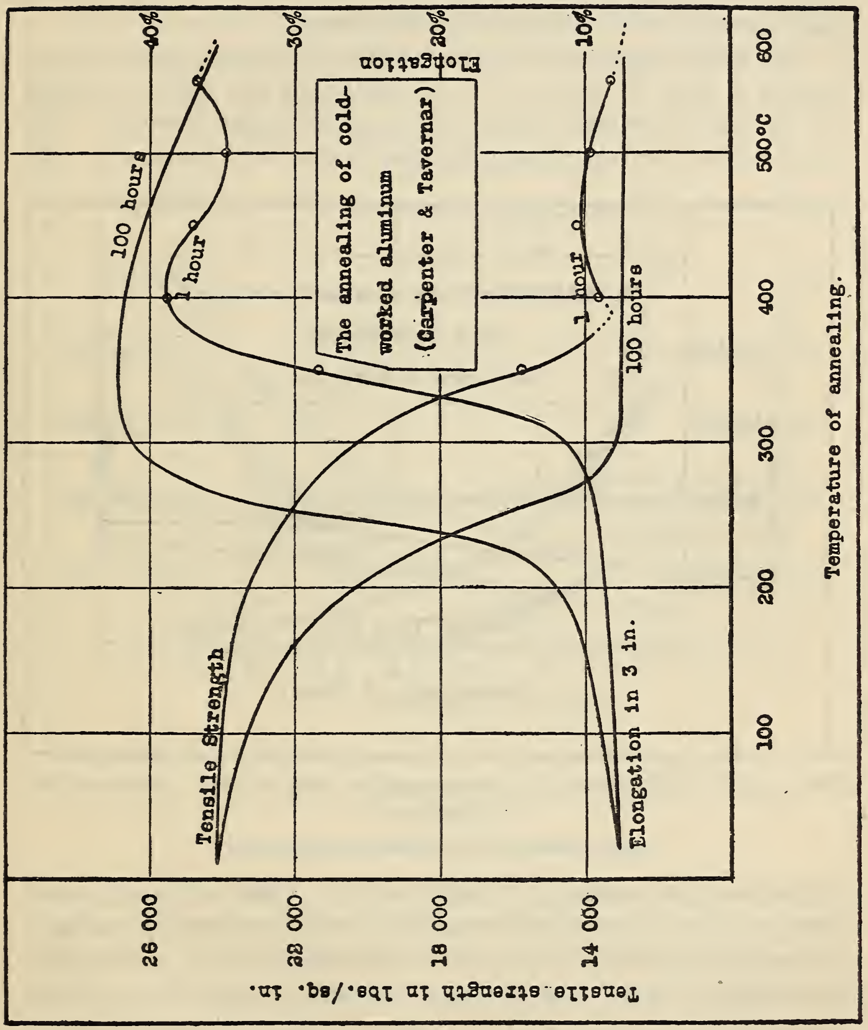

FIG. 11—*The annealing of cold-worked aluminum.* (Carpenter and Taverner, 205)

mal transformations have been noticed below the eutectic temperature.

The principal research on this series of alloys is that by Carpenter and Edwards (loc. cit.), who in addition to their studies of the constitution of this system contribute results of mechanical and corrosion tests, which are given below.

The tensile properties of these alloys as sand and chill cast are shown in Figs. 12 and 13. It is noted that the tensile strength of the alloy increases with the increase of copper content. The alloy containing 8 per cent of copper is one very commonly used in the aluminum-casting industry to-day. Tests were made upon sand castings to ascertain the effect of heat treatment, consisting of quenching from 450° C. and annealing at 450° C. The alloy containing 8.08 per cent of copper showed, as sand cast, a tensile strength of 16 600 pounds per square inch, with approximately 2 per cent elongation; as sand cast and annealed, a tensile strength of 15 900 pounds per square inch; and as sand cast and quenched, 18 000 pounds per square inch. Quenched alloys were consistently higher in tensile strength than the cast or cast and annealed alloys.

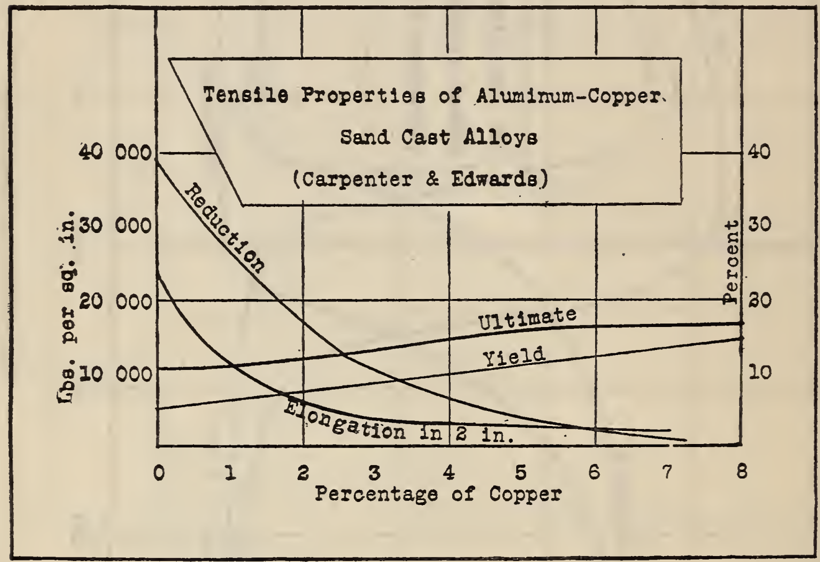

FIG. 12.—*The tensile properties of aluminum-copper sand-cast alloys.* (Carpenter and Edwards, 377)

The test specimens were cast to size, 0.564 inch in diameter

Ingots 3 inches in diameter and 20 inches long were heated to 400° C and rolled in round grooves to a diameter of 1¼ inches. From this rod portions were both hot rolled to 13/16 inch in diameter and drawn after annealing to 13/16 inch diameter. From 0 to 8 per cent of copper all of the alloys rolled well, and from 0 to 4 per cent of copper they could be drawn sound. In Fig. 15 are shown the results of the tests of 1¼-inch diameter hot-rolled bars. The bars rolled to 13/16 inch diameter showed throughout a higher tensile strength than those rolled to 1¼ inches, amounting to 2000 to 3000 pounds per square inch. The bars drawn with and without annealing showed a higher tensile strength but also a smaller elongation. In Table 11 are shown the test results of an alloy containing 3.76 per cent of copper in different conditions.

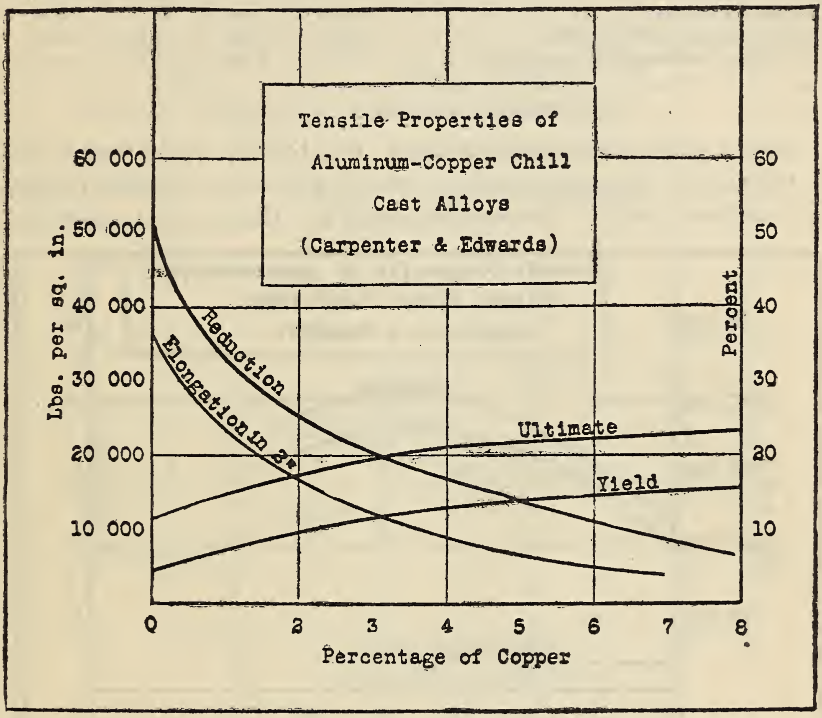

FIG. 13.—*The tensile properties of aluminum-copper chill-cast alloys.* (Carpenter and Edwards, 377)

Test specimens were cast to size, 0.564 inch in diameter

TABLE 11.—Tensile Properties of an Aluminum-Copper Alloy (Carpenter and Edwards, 378)[a]

	Tensile strength	Yield point	Elongation in 2 inches	Reduction of area
	Lbs./in.^{2}	Lbs./in.^{2}	Per cent	Per cent
Chill casting	21 500	12 100	10.5	21.46
1¼-inch hot-rolled bar	37 700	20 100	20.0	38.21
13/16-inch hot-rolled bar	38 000	26 000	21.0	49.76
13/16-inch bar drawn with annealing	37 900	34 600	8.0	21.79
29/32-inch bar cold-drawn, without annealing	44 900	41 500	7.5	20.84

[a] Alloy containing 3.76 per cent copper, in different forms.

Sheets were rolled from an ingot 6¾ by 9¾ by ⅝ inches by hot rolling to three-eighths inch, allowing to cool, and cold rolling to one-fourth inch. The resulting slab was then cut into portions and the portions rolled down to different thicknesses with intermediate annealing. In Fig. 14 are shown the results of tests upon a sheet rolled to 0.05 inch in thickness. The tensile test results on these sheets are very similar to those obtained on the same alloy in the form of rolled or drawn bars. The authors draw the conclusion that there is nothing to be gained by adding more than 4 per cent of copper for a rolling or forging alloy, as well as for a casting alloy. Their conclusion as regards the casting

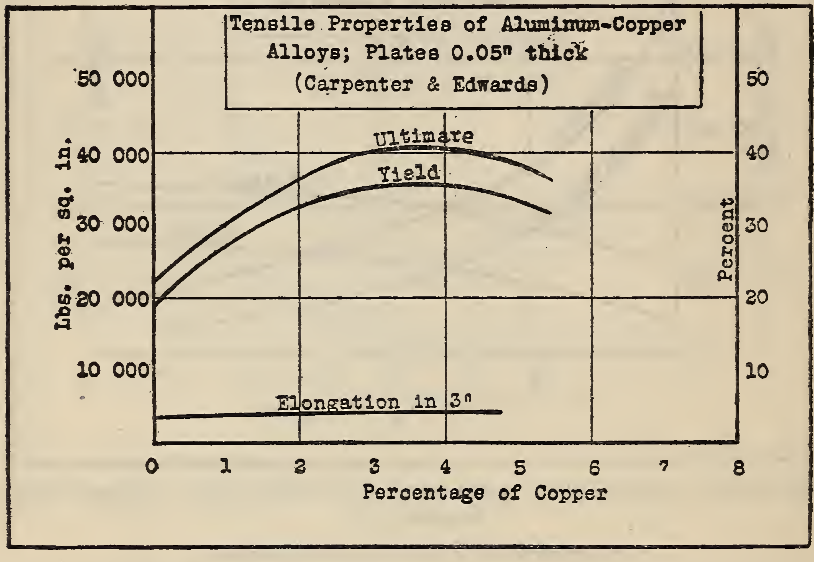

FIG. 14.—*The tensile properties of aluminum-copper alloys in the form of sheet, 0.05 inch thick.* (Carpenter and Edwards, 377)

The ingots were cast ⅝ inch thick, hot rolled to ⅜ inch, cold rolled to ¼ inch, annealed, cold rolled to 0.1 inch, annealed, cold rolled to 0.05 inch alloy is not in accord with modern practice, which favors the use of an alloy containing 8 per cent of copper.

Plates cut from rolled sheets of copper contents varying from 0 to 5.34 per cent were exposed for 62 days to the action of both sea water and of fresh water. Those exposed to fresh water were slightly corroded but gained in weight, due to the coating of aluminum hydrate formed. Those exposed to the action of sea water were badly corroded and pitted. The losses, in weight, are given below:

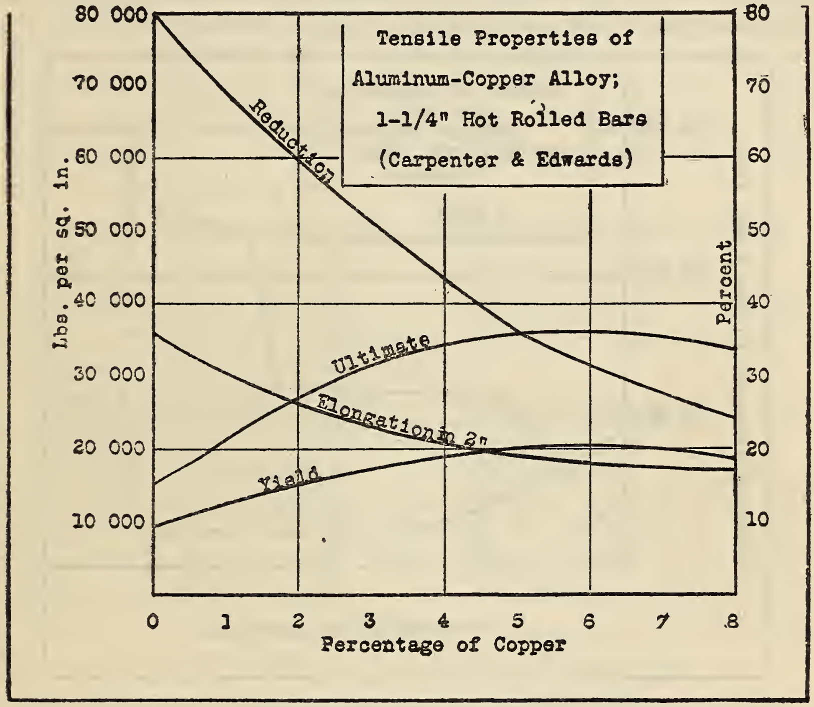

FIG. 15.—*The tensile properties of aluminum-copper alloys.* (Carpenter and Edwards, 377)

These results were obtained on 1.25-inch diameter bars hot rolled from 3-inch ingots to size

Per cent of copper	Loss of weight in sea water in pounds per square foot per month
0.00	0.008
.93	.008
1.57	.008
2.36	.007
3.74	.005
4.74	.004
5.34	.003

The loss of weight is considerable; for the first three alloys about 3½ times that which would be experienced by mild steel under the same conditions.

It is concluded that these alloys are not suitable for construction which will be exposed to sea water.

2. ALUMINUM-IRON

Gwyer (387) has studied the constitution of this system. On the aluminum side a compound, $FeAl_3$, is formed which gives a eutectic with aluminum at practically 0 per cent iron at 649° C. The compound is not appreciably soluble in aluminum.

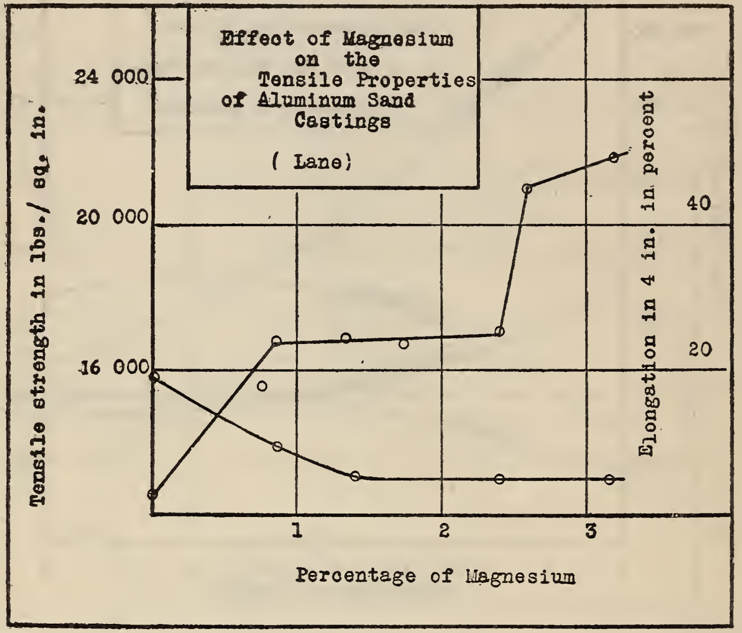

FIG. 16.—*The effect of magnesium on the tensile properties of sand-cast aluminum.* (Lane, 318)

The bars were presumably cast to size, and horizontally, in green sand.

Schirmeister (see p. 61) gives the results of some mechanical tests of iron-aluminum alloys.

3. ALUMINUM-MAGNESIUM

Grube (399) has investigated the constitution of the aluminum-magnesium alloy series, and has found that a compound, Al_3Mg_4, is formed, melting at 465° C. This compound forms a eutectic with aluminum at 453° C and 35 per cent magnesium. The solubility of Al_3Mg_4 in Al has never been determined; it is approximately 10 per cent.

Schirmeister (see p. 61) has investigated the rolling and mechanical properties of this series. Up to 6 per cent magnesium the alloys may be rolled hot and cold; beyond that they are too brittle.

Lane (318) has studied the effect of small amounts of magnesium in deoxidizing and hardening sand cast 99 per cent aluminum. Averages of his results are plotted in Fig. 16. It is interesting to note that the effect of the magnesium makes itself evident in stages.

Alloys of this series are lighter than aluminum and have attracted on that account much interest from those seeking strong light alloys. Under the name of magnalium, alloys of this series are used for casting purposes, and are described on page 78. This series has never become commercially important for rolling alloys. Alloys having 30 per cent and more of magnesium take a high polish and are used for mirror metal.

4. ALUMINUM-MANGANESE AND ALUMINUM-MANGANESE-COPPER

This binary system has been studied by Hindrichs (402). A compound, probably $MnAl_3$, is formed, giving a eutectic with aluminum at 3 to 4 per cent manganese and 650° C. This compound is not appreciably soluble in aluminum.

Schirmeister (see Sec. VIII–8–*a*) has contributed results of tests of light manganese-aluminum alloys.

Rosenhain and Lantsberry (463) have carried out some tests on light alloys of the manganese-copper-aluminum series. Their investigation concerns itself primarily with the alloys rich in copper. Only a few tests were made of the strength of the alloys at the aluminum end of the diagram. Table 12 shows the results of tests of sand and chill castings of different compositions of alloys up to about 4 per cent of copper and 2 per cent of manganese.

TABLE 12.—Tensile Properties of Cast Aluminum-Copper-Manganese Alloys (Rosenhain and Lantsberry, 463)

No.	Chemical composition		Tensile properties					
			Sand cast			Chill cast		
	Copper	Manganese	Tensile strength	Yield point	Elongation in 2 inches	Tensile strength	Yield point	Elongation in 2 inches
	Per cent	Per cent	Lbs./in.^{2}	Lbs./in.^{2}	Per cent	Lbs./in.^{2}	Lbs./in.^{2}	Per cent
022	2.15	0.88	13 800	10 400	5	19 100	12 400	6
023	3.11	.57	15 400	11 200	4	18 500	11 300	5.5
024	3.28	.98	14 000	11 300	4	18 700	14 200	5
025	1.27	2.06	15 300	12 600	4.7	13 900	13 800	6
026	2.02	1.90	14 300	13 100	3	21 900	13 900	7
026 A	2.15	1.91	18 100	14 900	5	22 400	17 500	5
027	2.89	1.76	17 100	14 100	3.5	15 200	13 600	5
028	4.13	1.92	3 200	3 200	2.5	18 600	14 300	3.5

After making these tests the authors selected two alloys, Nos. 10 and 11, and tested these alloys both in the sand and chill cast condition and as rolled and drawn from ingots 3 inches in diameter. The results of these tests are shown in Table 13. Impact tests made with the Izod machine on rolled alloys showed that the No. 10 required 4.1 foot-pounds and No. 11, 5.5 foot-pounds of energy per unit of section in fracture.

TABLE 13.—The Tensile Properties of Aluminum-Copper-Manganese Alloys (Rosenhain and Lantsberry, 463)

ALLOY No. 10. COPPER, 2.06 PER CENT; MANGANESE, 1.94 PER CENT

	Tensile strength	Yield point	Elongation in 2 inches	Reduction of area
	Lbs./in.^{2}	Lbs./in.^{2}	Per cent	Per cent
Hot rolled to 1⅛ inches	36 700	22 000	18.5	39.5
Hot rolled to 13/16 inch	38 200	27 100	16.0	37.6
Drawn with annealing to 13/16 inch	41 000	25 200	6.0	11.2
Sand cast	19 000	13 000	4.0	....
Chill cast	20 300	14 300	5.0	....

ALLOY No. 11. COPPER, 2.89 PER CENT; MANGANESE, 0.94 PER CENT

	Tensile strength	Yield point	Elongation in 2 inches	Reduction of area
Hot rolled to 1⅛ inches	35 300	19 700	20.0	32.8
Hot rolled to 13/16 inch	37 000	28 600	15.0	38.0
Sand cast	16 700	13 400	5.0	....
Chill cast	27 000	16 200	13.5	....

The authors conclude that the results on rolled and drawn bars are disappointing and that the superiority found in alloy No. 11 in the form of chill casting was not maintained in the rolled condition. The results show that these alloys have very nearly the same physical properties as the copper-aluminum alloys which were investigated by Carpenter and Edwards.

Alternating stress tests carried out on 13/16 inch diameter, rolled bars of Nos. 10 and 11 alloy gave the following values for the ranges of maximum safe stress under which these alloys would bear an unlimited number of reversals: Alloy No. 10, 21 000 pounds per square inch; alloy No. 11, 19 700 pounds per square inch.

The authors also carried out some corrosion experiments on chill castings of two alloys, the results of which are found in the table below.

Chill castings of—	Loss of weight per square foot per month (30 days)	
	Tap water	Sea water
	Pounds	Pounds
Pure aluminum	0.000121	0.0022
Alloy No. 10 (1.94 per cent Mn, 2.06 per cent Cu)	.000275	.00042
Alloy No. 11 (0.94 per cent Mn, 2.89 per cent Cu)	.000128	.00048

The specimens were machined from castings and immersed for 121 days. The resistance to corrosion in sea water of the alloys is much superior to that of aluminum. These results are contrary to usual experience with relative corrosion resistance of aluminum and its light alloys (Seligman; discussion on 463).

Tests of resistance to corrosion by sulphuric and nitric acids of alloys of from 1 to 10 per cent manganese showed that these alloys were less resistant to the attack of these acids than pure aluminum.

5. ALUMINUM-NICKEL AND ALUMINUM-NICKEL-COPPER

The constitution of this alloy series has been studied by Gwyer (406). A compound, $NiAl_3$, is formed which forms a eutectic with aluminum at 7 per cent nickel and 630° C. This compound is not soluble in aluminum. A thermal transformation occurs at 550° C in the alloys containing from 0 to 42 per cent nickel.

Reed and Greaves (453, 455) give results of some tests of these alloys.

The authors have made a study of the properties, microstructure, and corrosion of light aluminum alloys with nickel and copper.

Some preliminary tests of the working properties of such alloys were made. Strips 35 inches in length were rolled cold with the necessary annealings, if possible, to a thickness of 0.10 inch and then without further annealing to a strip having a thickness of 0.02 inch. Those alloys which were perfectly sound after this treatment and did not crack or break down are comprised within the following percentages:

Copper	Nickel
0	4.0
3.5	0
2	2

A portion of each 3/8-inch diameter rod was turned down to 3/16 inch diameter and drawn into wire. The diameter at which the drawing had to be abandoned serves as a measure of the relative ductility of the material. Alloys within the following compositions passed through a hole of 0.033 inch in diameter without cracking or hollow drawing:

Nickel	Copper
4	0
0	6
3	2
1	4

Small blocks of metal 1½ by 1 by 1½ inches were forged down hot to a thickness of 1/8 inch after heating to 450° C. Those compositions which remained perfectly sound under this treatment were comprised within the following:

Nickel	Copper
7.5	0
0	5.7
2	4
5	2

Tests of the alloys were made as chill cast and as rolled. The chill-cast ingots were 1 inch in diameter. For the rolled alloys an ingot was chill cast 2¼ inches in diameter by 18 inches long, weighing about 7½ pounds. This was rolled by the British Aluminum Co. to 1-inch-diameter rods at about 400° C. A portion of the resulting rod was cold-drawn in two passes to 7/8-inch diameter rods. Some of the 1-inch diameter hot-rolled rods were annealed. The results of these tests are shown in Fig. 17 and Table 14.

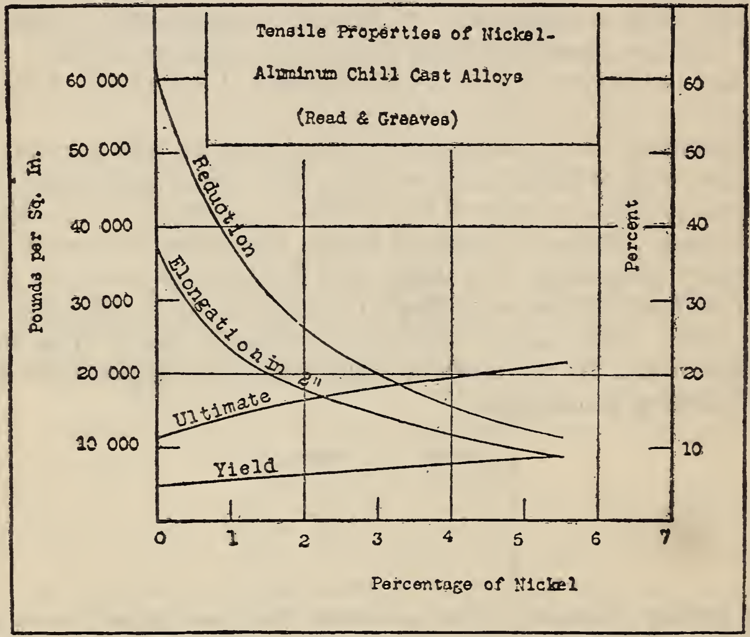

FIG. 17.—*The tensile properties of nickel-aluminum chill-cast alloys.* (Read and Greaves, 453, 455)

Specimens were cast to size, 0.564 inch in diameter

TABLE 14.—Tensile Properties of Aluminum-Copper-Nickel Alloys (Read and Greaves 453, 455)

PHYSICAL PROPERTIES

Number	Chemical composition of chill-cast alloys		As chill cast			
	Copper	Nickel	Tensile strength	Yield point	Elongation in 2 inches	Reduction of area
	Per cent	Per cent	Lbs./in.^{2}	Lbs./in.^{2}	Per cent	Per cent
23C		1.11	14 900	5 800	20.8	36.2
24C		2.22	16 900	6 500	16.7	22.1
25C		3.38	18 200	7 400	13.5	21.1
26C		5.52	21 700	9 000	9.0	11.1
27C	1.01	1.10	18 200	6 200	19.1	29.2
28C	1.00	2.18	18 600	7 400	10.0	15.3
29C	1.03	4.03	23 500	8 100	12.1	14.2
30C	1.02	5.51	24 800	10 700	6.1	8.5
11C	2.04	1.11	21 700	7 200	20.6	24.6
12C	1.92	2.18	22 600	8 100	11.4	15.8
13C	1.97	3.69	24 500	9 000	7.2	9.2
14C	1.99	5.27	28 600	10 300	5.7	7.4
15C	3.94	1.08	24 100	9 000	7.5	11.7
16C	4.05	2.02	23 400	8 300	6.1	7.0
17C	3.84	3.50	21 200	9 900	5.0	6.9
18C	4.04	4.36	25 200	9 900	4.4	5.0

Number	Chemical composition of wrought alloys		Cold-drawn rods [a]			
	Copper	Nickel	Tensile strength	Yield point	Elongation in 2 inches	Reduction of area
	Per cent	Per cent	Lbs./in.^{2}	Lbs./in.^{2}	Per cent	Per cent
23C		1.87	22 700	19 700	12.6	36.9
24C		4.31	27 900	22 900	8.5	24.0
25C	2.00	1.12	32 200	26 200	16.0	47.7
26C	1.97	2.22	30 600	26 000	11.8	33.1
27C	2.13	3.74	33 900	29 700	7.4	12.4
28C	2.10	5.33	37 800	31 700	7.5	15.3
29C	4.07	1.12	37 400	31 400	12.1	28.8
30C	4.13	2.16	36 300	31 700	8.0	19.3
11C	4.07	3.21	34 100	29 900	2.5	3.9
12C	4.08	4.30	36 800	29 600	3.8	6.2

Number	Chemical composition of wrought alloys		Annealed rods [b]			
	Copper	Nickel	Tensile strength	Yield point	Elongation in 2 inches	Reduction of area
	Per cent	Per cent	Lbs./in.^{2}	Lbs./in.^{2}	Per cent	Per cent
23C		1.87	16 300	5 600	34.1	55.8
24C		4.31	20 200	9 900	26.2	42.1
25C	2.00	1.12	23 400	8 300	30.5	56.6
26C	1.97	2.22	22 900	6 300	28.9	44.7
27C	2.13	3.74	23 800	6 300	27.2	37.8
28C	2.10	5.33	26 500	9 900	25.0	36.3
29C	4.07	1.12	29 000	7 400	28.7	44.3
30C	4.13	2.16	27 200	8 100	24.8	30.9
11C	4.07	3.21	25 400	6 300	22.8	28.0
12C	4.08	4.30	25 300	7 200	23.5	29.7

[a] The same as (c) cold drawn to ⅞ inch in 2 passes.
[b] The same as (c) annealed at 450° C.

TABLE 14—Continued

PHYSICAL PROPERTIES—Continued

Number	Chemical composition of wrought alloys		Hot-rolled rods [a]			
	Copper	Nickel	Tensile strength	Yield point	Elongation in 2 inches	Reduction of area
	Per cent	Per cent	Lbs./in.^{2}	Lbs./in.^{2}	Per cent	Per cent
23C		1.87	18 200	11 900	28.4	52.5
24C		4.31	22 300	13 500	22.0	36.4
25C	2.00	1.12	25 400	14 300	27.8	52.0
26C	1.97	2.22	26 600	17 000	21.3	38.6
27C	2.13	3.74	28 600	17 900	17.8	29.6
28C	2.10	5.33	31 500	18 160	16.0	23.6
29C	4.07	1.12	32 000	18 400	20.7	36.9
30C	4.13	2.16	30 700	17 900	17.8	28.0
11C	4.07	3.21	28 700	17 300	14.6	18.2
12C	4.08	4.30	29 500	17 000	13.5	18.6

[a] 2¼ by 18 inches ingot, chill cast, heated to 400° C, rolled hot to 1 inch diameter.

It will be noticed that although the ductility of the alloys of copper-nickel-aluminum in the chill cast and in the rolled state is high these alloys do not show a very high tensile strength. The highest tensile strength in the series is that of a cold-drawn rod containing 2.1 per cent of copper and 5.3 per cent of nickel. The tensile strength of this alloy in a cold-drawn state is only 37 800 pounds per square inch as compared to 55 000 pounds per square inch for duralumin.

The authors made no study of the effect of heat treatment upon rolled alloys.

Tests of the effect of annealing and of quenching on chill-cast alloys containing both copper and nickel showed that both annealing and quenching lowered the tensile strength slightly (from 1000 to 2000 pounds per square inch) with but slight increase (1 to 1.5 per cent) in elongation.

Alternating stress tests made on the Arnold machine showed that the resistance to this test decreases with increase of both copper and nickel content.

The authors carried out corrosion tests both in sea and in fresh water on plates, both cold rolled and annealed, 2 by 1 by 0.15 inches. Their results are given in Table 15. The results show that the alloys, although inferior to pure aluminum in their resistance to corrosion, are somewhat superior to other types of alloys in this respect. Copper appears to accelerate corrosion more than nickel.

TABLE 15.—Corrosion of Cold-Rolled and of Cold-Rolled and Annealed Sheets of Aluminum-Copper-Nickel Alloys (Read and Greaves, 453)

Chemical composition		Loss of weight in pounds per square foot per month			
		Sea water		Fresh water	
Copper, per cent	Nickel, per cent	Annealed	Cold rolled	Annealed	Cold rolled
Aluminum		0.00045	0.00041	0.00014	0.00020
Same, remelted		.00024	.00039	.00014	.00018
1.90		.00038	.00059	.00138	.00150
2.00	1.12		.00047	.00111	.00138
1.97	2.22	.00064	.00050	.00106	.00090
2.13	3.74	.00043	.00099	.00123	.00117
2.10	5.33	.00050	.00138	.00108	.00057
3.76		.00045	.00050	.00229	.00238
4.07	1.12	.00058	.00097	.00162	.00165
4.13	2.16	.00046	.00083	.00169	.00154
4.07	3.21	.00118		.00172	.00151
4.08	4.30	.00102	.00073	.00154	.00133
	1.42	.00092	.00104	.00030	.00037
	2.25	.00077	.00042	.00045	.00033

The authors also observed that the superiority shown by the nickel-aluminum alloys to ordinary corrosion in water was not maintained when dilute vinegar, oxalic acid, citric acid, and tartaric acid were used.

The authors draw no general conclusions from their work, but it is evident that the alloys of the compositions which they studied do not show a great enough strength that they can be considered for an alloy which is to be rolled into structural shapes. All the compositions were definitely inferior to duralumin.

On the other hand, the chill-cast alloys look somewhat more promising, and, in view of the superior resistance to corrosion of the alloys of nickel and aluminum over those of copper and aluminum, may compete with the latter series in this form.

6. ALUMINUM-SILICON

Fraenkel (417) has investigated the aluminum-silicon equilibrium. These metals form a simple eutectic series with the eutectic at 10 per cent of silicon and at 580° C. Silicon is not soluble in aluminum to the extent of more than approximately 0.5 per cent.

Schirmeister (see p. 61) gives the results of some mechanical tests of aluminum-silicon alloys.

7. ALUMINUM-ZINC

The constitution of this series of alloys has been studied by Lorenz and Plumbridge (433), Rosenhain (436), Shepherd (444), and others. Aluminum and zinc form a eutectiferous series, the eutectic lying at 95 per cent of zinc and 380° C; a compound Al_2Zn_3 is formed decomposing at 256° C. Aluminum takes up from 20 to 40 per cent of zinc in solid solution depending on the temperature.

The principal investigation of this alloy series is that of Rosenhain and Archbutt (435), who, besides their study of the constitution of the alloy series, carried out tensile, impact, and alternating stress tests of cast and wrought alloys. The tensile properties were studied at higher temperatures, and corrosion tests made on castings.

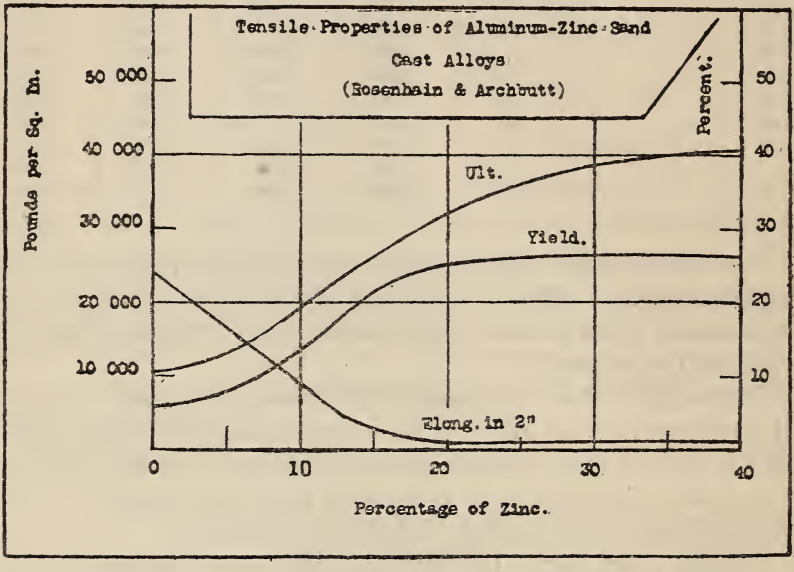

FIG. 18.—*The tensile properties of aluminum-zinc sand-cast alloys.* (Rosenhain and Archbutt, 435)

Test specimens were cast to size, 0.564 inch in diameter.

In Fig. 18 are shown the results of tensile tests of sand-cast alloys of aluminum-zinc melted in an oil furnace, care being taken to keep the temperature below 800° C. The castings were 7 inches long by ⅝ inch in diameter. It is seen that the tensile strength of the alloys increases with the percentage of zinc. In Fig. 19 are shown the results of tensile tests of chill-cast alloys poured into a chill mold 7 by ¾ inches in diameter. It will be noted that the strength of such chill castings is slightly greater at all compositions than that of the sand castings. This is due primarily to the greater density of such castings.

The authors made some tests to determine whether the cast alloys of this series were subject to spontaneous disintegration.

A certain number of sand-cast specimens of zinc contents varying from 9 to 75 per cent were laid on one side when the alloys were originally made and tested. These were tested after an interval of 15 months, and it was found that there was no sign whatever of any disintegration; so if these alloys are subject to any aging process at all it must be of an extremely gradual character. It was found, however, that in every case there had been an increase of tensile strength, varying from 500 to 4000 pounds per square inch, accompanied in some cases by decrease, in others by increase of elongation.

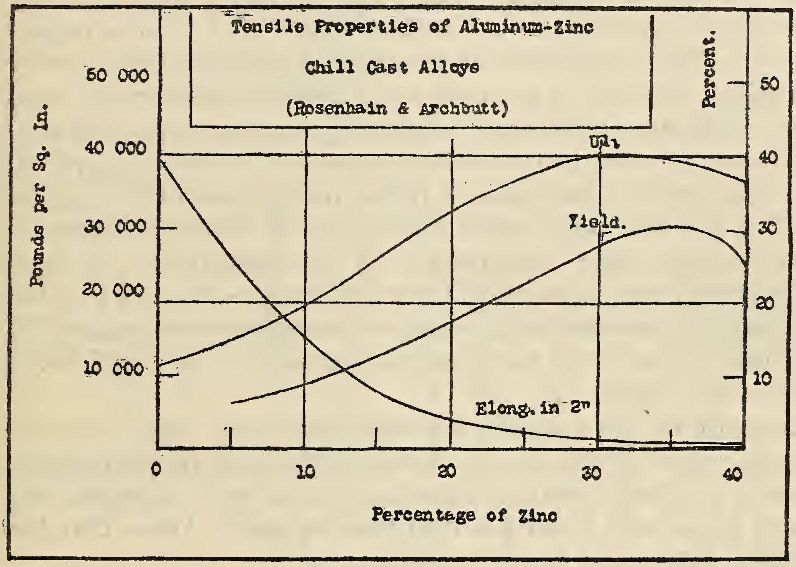

FIG. 19.—*The tensile properties of aluminum-zinc chill-cast alloys.* (Rosenhain and Archbutt, 435)

Test specimens were cast to size, 0.564 inch in diameter

This agrees with practical experience with these alloys in that immediately after casting they are not readily machined, but "drag." After aging for a few weeks a marked improvement in machineability occurs.

"Compression tests on both sand and chill castings showed that in general the compressive strength of these alloys is approximately proportional to their tensile strength, although the yield points in compression are also decidedly lower than the ultimate strength in tension."

In the discussion on this paper Seligman (British Aluminum Co. (Ltd.)) states that the reason why compositions above from 13 to 14 per cent of zinc had not hitherto been used for casting purposes was that it was the experience of the manufacturers that such alloys were sensitive to vibration and shock and hence not suitable for the motor industry.

Ingots were prepared of different compositions, 20 inches long and 3 inches in diameter. They were heated to approximately 400° C and hot-rolled to 1¼ inches, ⅞ inch, and ½ inch, respectively. The 25 per cent zinc-aluminum alloy could fairly readily be rolled, but the 30 per cent alloy cracked considerably, even upon rolling it to 1¼ inches in diameter, such that 25 per cent may be looked upon as the maximum composition which can be rolled.

For some of the later series a rolling temperature of from 315 to 364° C was used with better results than at the higher temperatures. Some other experiments on the malleability of these alloys under the hammer at higher temperatures showed that the malleability increased with increase of temperature up to 400° C, but that at 450° C the test specimen cracked, and at 500° C broke into coarse powder.

Samples of the 1¼-inch hot-rolled bars were used for cold-drawing experiments, the object aimed at being to reduce them by steps of 1/16 inch down to a diameter of 13/16 inch. Compositions up to 15 per cent stood this cold drawing well. Above that the samples either drew hollow or broke.

The 15 per cent and 20 per cent alloys were cast into slabs measuring 13¼ by 10¼ by ⅛ inch heated to 400° C, cooled to 300° C, hot rolled to 0.13 inch, annealed at 400° C, and cold rolled to 0.07 inch. The 15 per cent alloy behaved satisfactorily under this treatment. The 20 per cent alloy exhibited a small amount of cracking at the edge of the sheet, a defect which may have arisen from roughness of the original casting.

Fig. 21 shows the results of tests of hot-rolled bars 1¼ inches in diameter. These alloys exhibited a well-defined yield point, accompanied by a sharp drop of the beam of the testing machine similar to that found in the testing of mild steel. Similar curve series were obtained showing the results of tensile tests of hot-rolled bars ⅞ inch and ½ inch in diameter. The results of the former series are shown in Fig. 20. The curious fact is definitely ascertained that the alloys containing more than 15 per cent of zinc appear to deteriorate when a large amount of work is put upon them. It is seen that although for compositions below 15 per cent of zinc the strength of the ⅞-inch diameter rod is higher, as might be naturally expected, than that of the 1¼-inch diameter rod, above that percentage the reverse is true.

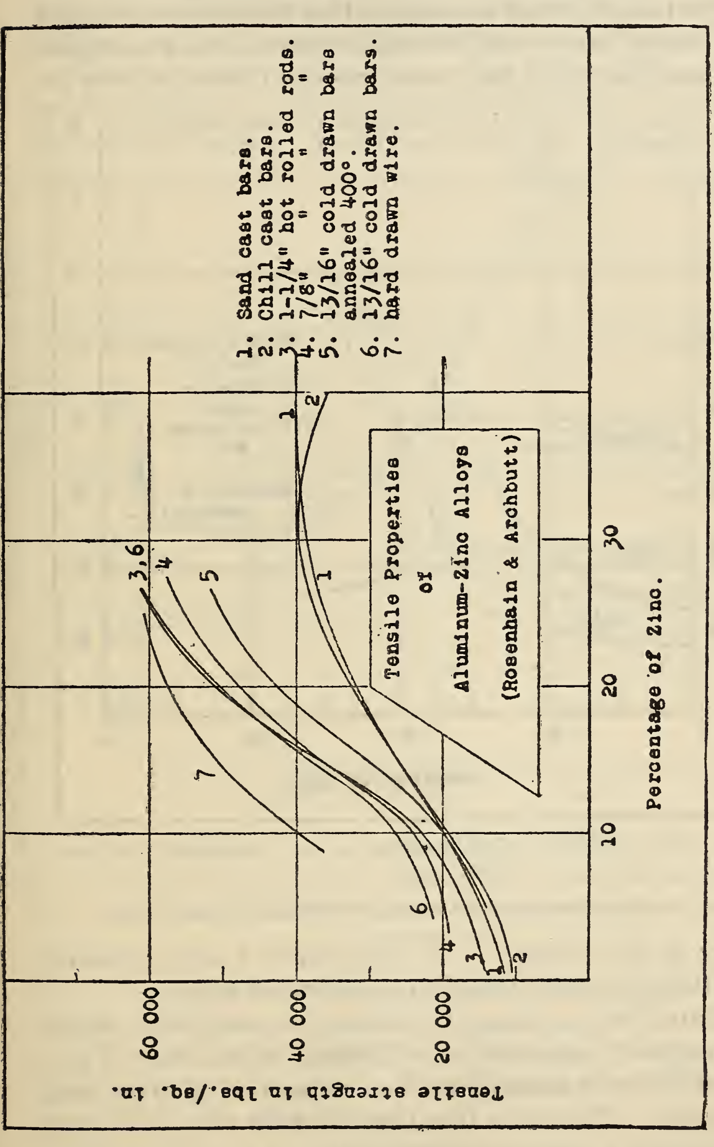

FIG. 20.—*The tensile strength of aluminum-zinc alloys.* (Rosenhain and Archbutt, 435.)

Curve 1 for sand-cast bars cast to size, 0.564 inch in diameter
Curve 2 for chill-cast bars cast to size, 0.564 inch in diameter
Curve 3 for hot-rolled rods 1.25 inches in diameter
Curve 4 for hot-rolled rods ⅞ inch in diameter
Curve 5 for cold-drawn bars 13/16 inch in diameter, annealed at 400° C
Curve 6 for cold-drawn bars 13/16 inch in diameter
Curve 7 for hard-drawn wire

A study of the tensile strength of hot-rolled and annealed bars shows that for compositions between 13 and 20 per cent the application of work upon the alloys appears to have a beneficial effect, which is not entirely removed by annealing. The results on one series are shown in Fig. 20. In considering the strength of cold-drawn bars drawn to 13/16-inch diameter from the hot-rolled 1¼-inch diameter rods it is most remarkable that the ultimate strength of the cold-drawn bars is very little higher than that of the original hot-rolled bars from which they were drawn. It is noted that the alloys higher in zinc (above 15 per cent) show a lower ultimate strength in the cold-drawn than in the hot-rolled state.

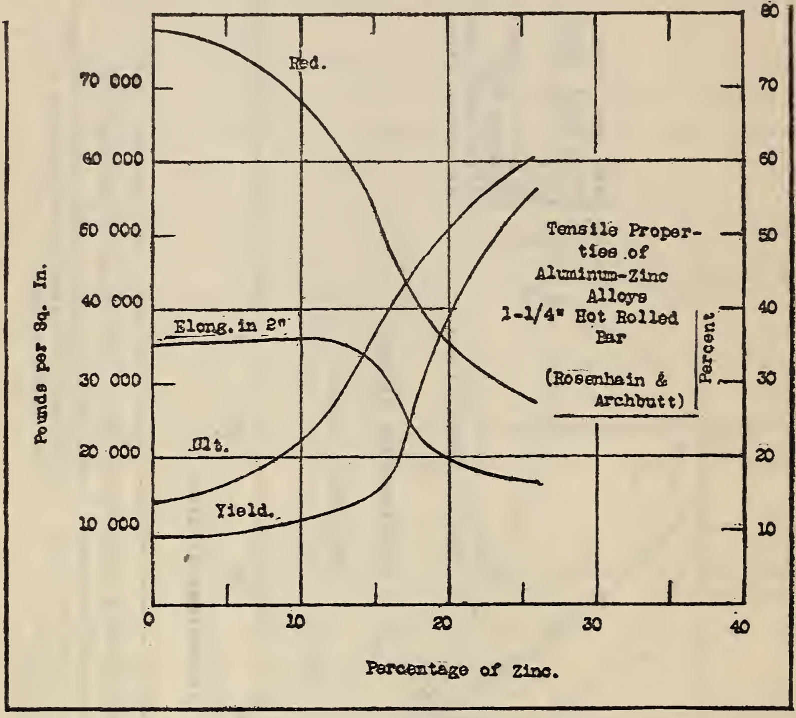

FIG. 21.—*The tensile properties of aluminum-zinc alloys.* (Rosenhain and Archbutt, 435)

These results were obtained on 1.25-inch diameter bars hot rolled from 3-inch ingots to size

Tests made on wire, 0.128 inch in diameter, as cold drawn, shows that the strength of such wire is considerably above that of any other form of the same material until a composition of 20 per cent of zinc is reached. Thereafter the strength of the wire is less than that of the original 1¼-inch hot-rolled bars.

"We thus arrive at the very remarkable result that no amount of further work, whether applied to the metal when hot or cold, increases the tensile strength of the 25 per cent alloy beyond that which is attained in the form of 1¼-inch hot-rolled bars, the only marked effect of cold work being to bring about some reduction in the ductility of the alloy."

The tensile strengths of the two compositions rolled out into sheet 0.07 inch in thickness were very nearly the same as that obtained on bars drawn with annealing, as shown below:

Fifteen per cent alloy sheet, as rolled and tested longitudinally; tensile strength, 47 000 pounds per square inch; elongation, 1.5 per cent in 2 inches. Twenty per cent alloy sheet, similarly; tensile strength, 50 500 pounds per square inch; elongation, 0.5 per cent in 2 inches.

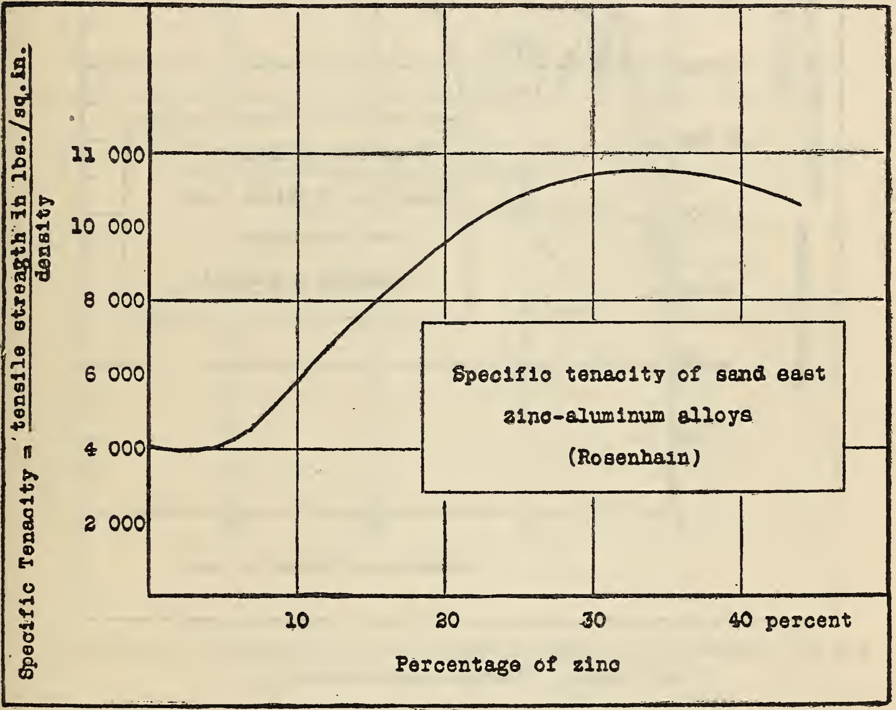

FIG. 22.—*The specific tenacity of sand-cast zinc-aluminum alloys.* (Rosenhain and Archbutt, 435)

After annealing at 400° C, these two alloys showed 33 000 and 43 000 pounds per square inch tensile strength, and 24 and 10 per cent elongation, respectively.

Figs. 22 and 23 show the specific tenacity, the tensile strength divided by the density, of sand-cast and hot-rolled aluminum-zinc alloys and of hot-rolled aluminum-copper alloys, the latter being taken from the data by Carpenter and Edwards. It will be noted that the aluminum-zinc alloy of 20 per cent shows a greater strength per unit mass than the highest alloy recorded by Carpenter and Edwards for the light aluminum-copper alloys.

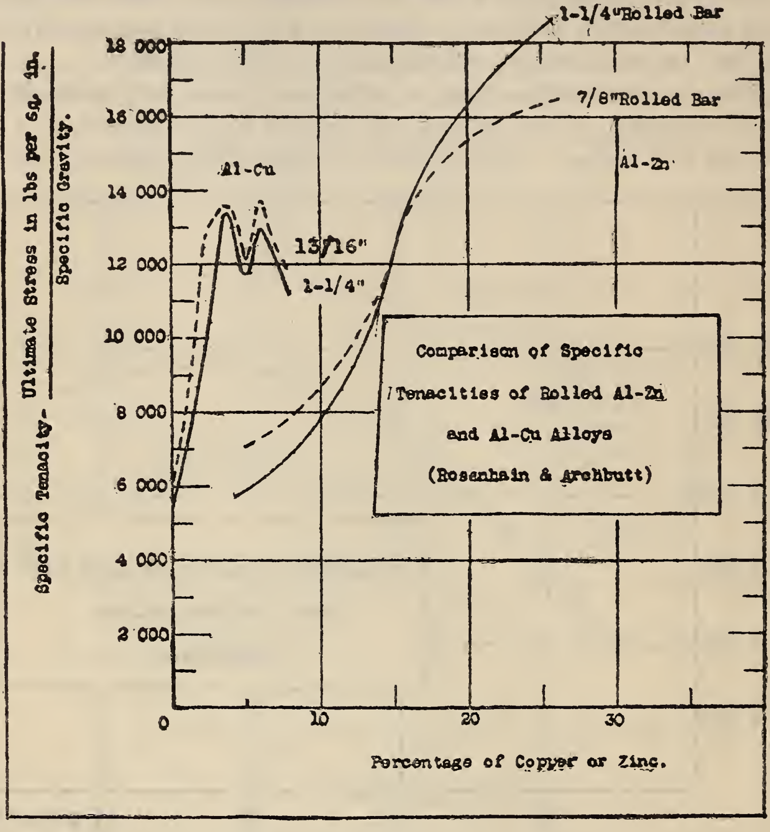

FIG. 23.—*Comparison of the specific tenacities of rolled aluminum-zinc and aluminum-copper alloys.* (Rosenhain and Archbutt, 435)

Alternating stress tests carried out with alternations of direct stress on specimens cut from ⅞-inch diameter hot-rolled bars gave the following results:

Zinc	Maximum safe range of stress [a]
Per cent	Lbs./in.[a]
5	11 200
9	15 000
11	19 200
17	22 400
26	26 900

[a] Giving about 1 000 000 reversals to rupture.

Impact tests carried out on the Izod machine gave the following results:

Zinc	Absorbed in rupture
Per cent	Ft. lbs./in.^{2}
5	3.9
9	4.3
13	5.4
15	5.8
17	5.75
20	5.8
26	4.1

Tensile tests were carried out at higher temperatures on several of the alloys. Some of the results are given in Table 16 below.

TABLE 16.—Tensile Properties of Zinc-Aluminum Alloys, in Form of 7/8-inch Rolled Bars, at Higher Temperatures (Rosenhain and Archbutt, 435)

ALLOY OF 13 PER CENT ZINC

Temperature in degrees centigrade	Tensile properties		
	Tensile strength	Yield point	Elongation in 2 inches
	Lbs./in.^{2}	Lbs./in.^{2}	Per cent
18	32 100	15 700	31
50	28 500	18 350	30
75	24 000	17 350	29
100	20 650	15 200	33
150	16 000	13 600	34
200	11 900	11 100	48

ALLOY OF 25 PER CENT ZINC

Temperature in degrees centigrade	Tensile strength	Yield point	Elongation in 2 inches
18	55 600	44 300	20
50	50 800	40 100	21
75	45 700	34 400	21
100	41 000	33 200	21
150	35 300	30 200	19
200	24 600	21 800	18

Determinations made of the coefficient of thermal expansion between 0° and 18° C of these alloys in the form of 13/16-inch diameter rolled bars yielded the following values:

Composition	Coefficient of thermal expansion
5 per cent zinc	0.0000227
15 per cent zinc	.0000231
20 per cent zinc (7/8 inch bar)	.0000234

Sand and chill castings 3 by 4 by ⅜ inches were machined and exposed for 521 days to the action of sea water. The losses in weight were measured and are given in the table below:

Corrosion of Zinc-Aluminum Alloy Castings

Per cent zinc	Loss of weight in pounds per square inch per month	
	Chill castings	Sand castings
5	0.0012	0.00054
9	.0017	.00092
13	.0018	.00062
15	.0023	.00145

The sand castings were thus superior to the chill castings in this respect.

In the appendix of this report the authors describe an alloy consisting of 25 per cent of zinc, 3 per cent of copper, and 62 per cent of aluminum. This alloy shows a tensile strength of about 41 000 pounds and 45 000 pounds in the sand and chill cast condition, respectively. The rolling of this alloy presents considerable difficulty, but if careful temperature control is exercised it can be hot rolled. This alloy gave a tensile strength, in the form of 1½-inch hot-rolled bar, of 71 000 pounds per square inch, a yield point of 61 000 pounds per square inch, and an elongation in 1 inch of 21 per cent. The specific gravity of this alloy is 3.29.

Summarizing the work of these investigators on the physical properties at ordinary temperatures, the following points may be noted:

1. It has been found possible to roll out into bars and even to draw into wire an alloy containing as much as 26 per cent of zinc. This alloy attains its maximum tensile strength when in the condition of hot-rolled bar 1¼ inches in diameter, the maximum strength being 62 000 pounds per square inch. This alloy has a density of 3.24 when hot-rolled.

2. Further rolling down of this alloy does not improve, but diminishes, the tensile properties of the material.

3. Both the binary and ternary alloys referred to differ from the majority of nonferrous alloys in the fact that in the rolled condition they exhibit a definite and well-marked yield point similar to that of mild steel.

4. A great defect of this group of alloys is their great sensitiveness to rise of temperature in relation to their tensile strength.

Thus the alloy containing 25 per cent of zinc loses 33 per cent of its tensile strength (at 20° C) when the temperature is raised to 100° C. The highest tensile strength of the cast alloys determined was 42 000 pounds per square inch for an alloy containing 50 per cent of zinc. The highest for the wrought alloys was that of the 1¼-inch hot-rolled bars of 26 per cent zinc content and having a tensile strength of 62 000 pounds per square inch, a yield point of 56 000 pounds per square inch, and an elongation of 16.5 per cent in 2 inches.

5. Tests made of the resistance of these alloys to alternations of direct stress gave a series of results for the safe range of alternating stresses which lies considerably below that of the static elastic limits. The 25 per cent alloy showed a safe range of 27 000 pounds per square inch. Single-blow impact tests made on the Izod machine showed that the work absorbed by fracture reaches a maximum for a zinc content lying between 15 and 20 per cent. This, for an alloy containing 15 per cent of zinc, is 5.8 foot-pounds. Under Prof. Arnold's alternate bending tests the endurance of the alloys falls rapidly with the increase of zinc content.

8. MISCELLANEOUS

(a) SCHIRMEISTER'S INVESTIGATIONS OF BINARY SYSTEMS

A very comprehensive investigation of the mechanical properties of rolled binary light alloys of aluminum was carried out in 1915 by Schirmeister (338).

Schirmeister rolled out several compositions of many binary alloys systems of aluminum and tested their hardness and tensile strength. His method of preparation for the alloys was the same for all series and was as follows:

About 900 g of the alloy were melted up in a small gas crucible furnace, poured into a chill mold to plates 25 mm thick. These were rolled in a 30-horsepower mill at the rate of 40 m per minute. The plates were first reheated after casting to from 400 to 500° C and rolled with intermediate annealing, with reductions of each pass of from 1 to 3 mm, to a thickness of 4 mm. They were then annealed and rolled cold to from 1.3 to 1.5 mm thickness. Only those alloys of which the melting point was very considerably lowered by the additions were rolled at lower temperatures or cold. Specimens cut from these sheets were then annealed at from 300 to 350° in a muffle furnace, allowed to cool, and tested after several days.

His results are given in the Table 17.

TABLE 17.—Mechanical Properties of Rolled Binary Aluminum Alloys (Schirmeister, 338)

Per cent composition	Tensile strength	Elongation in 5 cm	Brinell hardness (B. H. N.)[a]	Remarks
Antimony:	Lbs./in.^{2}	Per cent		
0.00	14 900	34	29	Rolled at 450–500° C, 8 m per minute, to 1.4 mm. It is only possible to roll these alloys up to 11 per cent of antimony; even at 8 per cent a certain amount of tearing and cracking takes place. Antimony is seen to be an undesirable addition to aluminum.
0.4	14 600	37	....	
1.0	14 600	40	29	
2.0	14 600	38	....	
3.2	14 800	36	30	
4.5	14 900	32	....	
6.0	14 900	29	....	
8.0	15 400	23	27	
10.5	14 900	17	....	
Bismuth:				
0.0	16 300	32	....	Rolled cold, 8 m per minute, to 1.4 mm. The working properties, both hot and cold, are very unfavorably affected by the influence of bismuth. The physical properties attained indicate that bismuth is an undesirable addition to aluminum.
0.4	16 600	33	....	
1.2	17 800	31	....	
3.0	16 500	30	....	
4.8	15 800	30	....	
Cadmium:				
0.0	16 300	32	31	Rolled at 100–150° C, 8 m per minute, to 1.4 mm. These alloys may be rolled up to 6 per cent or more. Results show that there is no advantage in the addition of cadmium.
0.4	16 500	33	....	
1.3	16 300	35	40	
1.8	16 300	36	....	
2.7	16 500	34	42	
4.0	16 500	32	....	
6.0	16 600	32	40	
Chromium:				
0.0	13 500	41	26	Rolled at 500° C, 8 m per minute to 1.4 mm. Chromium may be added to aluminum in amounts as great as 5 or 6 per cent and can be rolled at 500° up to a content of 4 per cent. Chromium does not seem to offer any advantages as an addition to aluminum, although it might be used to harden it in amounts up to 1 per cent.
0.3	17 600	26	37	
0.6	21 200	17	44	
0.9	22 100	17	47	
1.4	19 600	21	....	
1.9	17 500	22	38	
2.6	17 600	21	....	
3.7	18 300	19	42	
4.5	18 900	11	....	
Cobalt:				
0.0	14 900	34	29	Rolled 450–500 C, 8 m per minute, to 1.4 mm. These alloys may be rolled up to approximately 11 per cent of cobalt. 4 per cent of cobalt is about the most favorable composition.
0.6	15 500	35	32	
1.6	17 100	28	....	
2.3	17 500	25	....	
3.5	18 300	21	47	
5.5	22 100	18	....	
7.5	23 600	14	50	
9.4	23 500	11	51	
10.5	24 200	11	....	
12.0	26 300	6	61	

[a] The Brinell hardness numeral was determined with a 2.5 mm ball, using a pressure of 62.5 kg.

TABLE 17—Continued

Per cent composition	Tensile strength	Elongation in 5 cm	Brinell hardness (B. H. N.)	Remarks
Copper:		Lbs./im.^{2}	Per cent	
0.0	14 900	34	29	Rolled at 400–450° C, 8 m per minute, to 1.4 mm. These alloys may be rolled hot up to 12 per cent of copper. The author considers 3 to 4 per cent of copper to be the most advantageous composition.
0.5	19 200	30	....	
1.0	21 900	26	41	
2.1	24 300	23	46	
3.5	25 600	22	48	
5.1	25 300	21	49	
7.1	25 600	21	49	
8.9	26 600	19	52	
11.0	27 700	16	....	
Iron:				
0.9	14 900	34	29	Rolled at 450–500° C, 8 m per minute, to 1.4 mm. These alloys may be rolled up to a composition of 12 per cent, although it presents some difficulty in most of the alloys. The author considers that although the iron-aluminum alloys do not show properties which would make them of any utility it is shown by his work that 2 or 3 per cent of iron in aluminum alloys is not harmful.
1.3	15 500	36	....	
1.8	16 300	33	33	
2.7	17 500	31	....	
3.7	17 900	29	37	
5.0	17 800	25	....	
6.8	17 600	18	38	
8.8	17 100	12	....	
11.1	16 600	8	44	
12.5	16 200	7	....	
Lead:				
0.0	14 900	34	....	Rolled at 300° C, 8 m per minute, to 1.4 mm. These alloys can be rolled hot quite readily up to 4 per cent or more. The addition of lead in small amounts is not of any value. At the same time it has no marked ill effect upon the properties of the aluminum alloys.
0.4	14 200	40	....	
0.9	14 100	37	....	
1.5	14 400	35	....	
2.5	14 500	34	....	
4.0	14 200	34	....	
Magnesium:				
0.0	14 900	34	29	Rolled at 450° C, 8 m per minute, to 1.4 mm. It is possible to roll these alloys up to approximately 6 per cent. Above that the alloys crack and splinter. The author does not consider that magnesium is a valuable addition to aluminum for a rolling alloy.
0.3	15 500	34	33	
0.6	16 200	33	33	
1.2	15 900	33	33	
1.6	16 200	33	34	
2.6	21 700	25	42	
4.0	30 000	22	54	
6.0	41 800	21	69	
Manganese:				
0.0	13 500	41	26	Rolled at 500° C, 40 m per minute, to 1.4 mm. Manganese-aluminum alloys may be rolled to approximately 5 per cent without much tearing. The author considers that 1 or 2 per cent of manganese might be added with advantage to aluminum.
0.4	14 800	36	....	
0.6	15 300	33	31	
0.8	16 200	34	....	
1.3	17 100	28	35	
2.4	18 700	22	39	
3.2	19 100	19	....	
4.8	19 500	18	46	

TABLE 17—Continued

Per cent composition	Tensile strength	Elongation in 5 cm	Brinell hardness (B. H. N.)	Remarks
Molybdenum:	Lbs./in.^{2}	Per cent		
0.0	13 500	41	26	Rolled at 500° C, 40 m per minute, to 1.4 mm. These alloys can be rolled up to 5 per cent of molybdenum. The series shows, however, no improvement in properties.
0.4	15 900	36	33	
0.7	16 800	34	....	
0.9	16 800	33	34	
1.2	16 400	29	33	
1.9	16 500	25	....	
3.7	16 900	16	42	
4.9	17 200	16	....	
Nickel:				
0.0	13 500	34	29	Rolled at 400–500° C, 8 m per minute, to 1.4 mm. These alloys can be rolled up to from 11 to 12 per cent nickel without very considerable tearing. The author considers those alloys containing approximately 4 per cent of nickel the best alloys of the series.
0.6	15 900	33	....	
1.0	16 300	32	34	
1.9	18 100	29	....	
3.1	20 900	27	44	
4.5	21 600	25	....	
6.2	21 300	22	45	
8.1	21 200	16	47	
10.3	23 500	8	53	
Silicon:				
0.5	13 500	41	26	Rolled at 450–500° C, 40 m per minute, to 1.4 mm. These alloys may be rolled up to 20 per cent of silicon. The author finds that the resistance to atmospheric corrosion of this series is fairly good in spite of the fact that it has been claimed that silicon causes a great corrodibility in aluminum. The author believes that an addition of silicon is of advantage, and that from 5 to 7 per cent of silicon may be added for rolling and forging alloys.
1.7	14 900	41	....	
3.1	15 900	40	31	
4.9	17 800	35	....	
7.0	19 300	32	38	
9.8	21 600	27	43	
12.4	23 800	23	46	
15.1	22 300	17	47	
18.8	23 300	11	....	
Tantalum:				
0.0	13 500	41	26	Rolled at 500° C., 40 m per minute, to 1.4 mm. Only a few alloys were made of this series. Results show that tantalum can not be considered as a technical utilizable constituent for aluminum alloys.
0.3	14 200	38	....	
0.8	15 100	38	30	
1.5	14 600	38	....	
2.2	14 600	39	28	
3.5	14 800	39	....	
Tin:				
0.0	15 500	37	31	Rolled cold, 40 m per minute, to 1.4 mm. Tin diminishes the ease of working aluminum at higher temperatures; it is possible to roll these alloys only cold. Tin is an undesirable addition to aluminum.
0.4	15 400	33	....	
1.0	15 200	31	....	
1.9	15 300	29	31	
3.0	15 600	27	....	
4.8	15 600	24	....	
6.4	16 100	26	32	
8.2	16 600	20	....	
10.3	17 400	17	....	
12.4	18 500	15	31	

TABLE 17—Continued

Per cent composition	Tensile strength	Elongation in 5 cm	Brinell hardness (B. H. N.)	Remarks
Titanium:	Lbs./in.^{2}	P2r cent		
0.0	13 500	41	26	Rolled at 500° C., 40 m per minute, to 1.4 mm. These two metals are quite readily alloyed, although a high pouring temperature is necessary. Up to 6 per cent of titanium the alloys of this series are readily rolled. The physical properties are not such that to the alloys may be attributed any technical importance.
0.4	15 600	31	34	
0.8	16 400	31		
1.2	16 100	31		
1.6	16 400	30	33	
2.1	16 800	27		
3.1	17 400	23	35	
4.5	18 500	19		
6.2	20 100	16	42	
Tungsten:				
0.0	13 500	41	26	Rolled at 500° C., 40 m per minute, to 1.4 mm. The ease of rolling hot is not unfavorably affected by tungsten, which can be added to aluminum up to 6 per cent. Tungsten does not seem to offer any advantages as an addition to aluminum.
0.3	14 200	42	29	
0.6	14 800	42		
1.1	15 500	40	32	
2.0	15 400	36	34	
3.5	15 500	33		
6.0	15 400	32	33	
Vanadium:				
0.0	13 500	41	26	Rolled at 500° C., 40 m per minute, to 1.4 mm. The addition of vanadium to aluminum presents some difficulty, but it can be added and rolled up to 4 per cent. The author states that for a rolling alloy 1 or 2 per cent of vanadium might well be used.
0.4	15 500	38		
0.8	16 100	36	33	
1.2	16 800	34	34	
2.0	17 800	28	38	
2.8	17 800	27		
3.7	17 500	29	39	
Zinc:				
0.0	14 900	34	29	Rolled at 8 m per minute, 350–400° C, to 1.4 mm. Can be rolled up to 30 per cent; most suitable compositions are from 12 to 14 per cent. These alloys can be rolled up to 30 per cent of zinc. The author considers that the most suitable of them are those with from 12 to 14 per cent of zinc.
0.6	16 400	32		
1.3	17 900	24		
3.0	17 800	27	34	
4.0	17 800	27		
5.7	18 800	26	37	
7.8	20 200	28		
10.3	24 200	32	42	
12.7	29 000	33		
16.0	25 600	26	60	
18.5	41 000	20		
23.0	50 100	17		
25.3	53 500	15	124	
Zirconium:				
0.0	13 500	41	26	Rolled at 500° C, 40 m per minute, to 1.4 mm. Zirconium acts much as does titanium as an alloy constituent of aluminum. Alloys may be rolled up to 6 per cent of zirconium, do not show any remarkable good physical properties, however.
0.4	15 100	34		
0.8	15 200	34	31	
1.2	15 100	34		
1.6	15 400	34	31	
2.4	15 800	34		
3.2	16 100	33	33	
4.5	16 900	28		
6.0	17 800	25	37	

(b) EQUILIBRIA, BINARY AND TERNARY

In Table 18 are described the equilibria for binary alloy systems of aluminum as far as they are known. References are given for binary and ternary systems.

It is observed that most metals form compounds with aluminum. The solubility of the aluminum-rich compound in the solid aluminum is generally almost zero. The three prominent exceptions to this fact are zinc, copper, and magnesium.

The light alloys of aluminum with these metals contain only small quantities of the added metal, as with increasing amounts the alloy quickly becomes brittle.

Metallographically the light alloys are therefore usually heterogeneous, with a groundmass of almost pure aluminum and crystals of the compound of aluminum with the added metal. These are hard, brittle, and more resistant to corrosion than aluminum.

IX. COMMERCIAL ALLOYS

From the practical standpoint of the relative value of the various alloys which have been studied, the results of these investigations are summarized in a statement of the alloys which are in commercial use to-day. The industry has taken and developed further those alloys which the results of investigation have shown to be promising either from the standpoint of mechanical strength or of other special properties.

For casting alloys the aluminum-zinc-copper or the aluminum-copper alloys have been most largely used, whereas for forging and rolling the alloy duralumin has hitherto held its own in the commercial field. The only serious rival which duralumin has to-day as a rolling and forging alloy of maximum mechanical strength is one of aluminum-zinc-copper developed by Rosenhain and Archbutt (436).

1. CASTING AND DIE CASTING

Pure aluminum is but rarely used in the cast form, owing to its softness, high shrinkage, and poor machining qualities. Its alloys, however, with zinc, copper, or magnesium, or combination of these, are excellent and give, with proper care, excellent castings.

In general the casting practice for aluminum alloys follows that for brasses and bronzes. The alloys may preferably be melted in ordinary graphite crucibles in either oil, gas, coke, or coal furnace. Care should be taken not to overheat the metal, as it then oxidizes, absorbs gases, and may at higher temperatures absorb carbon and silicon from the crucible. Good practice favors keeping the temperature of the metal during melting down practically at its melting point by the continuous addition of solid metal. Pouring should be done at the lowest temperature at which it will completely fill the mold. A temperature of 700° C or below is satisfactory. A low-pouring temperature is particularly important for aluminum castings, because of the high specific heat of the metal. If poured at a high temperature the metal in cooling heats the mold so hot that the rate of cooling is very slow. A coarse grain and weak metal result.

No flux should be used in melting down, and the surface should not be covered with carbon, as this may be included in the casting. Just before pouring, however, a small amount of zinc chloride may be added with advantage. This thoroughly cleans the surface and prevents dross from entering the casting.

In molding castings to be poured in aluminum alloy two characteristics of the material should be borne in mind: (1) The metal and its alloys are quite brittle or "hot short" and fragile at temperatures just below the melting point, and (2) they are light. Consideration of the first fact means that the mold or cores should not be too hard. Ordinary green sand, not too fine, is to be recommended, and hard ramming is to be avoided. A large percentage of bad castings are probably due to nonadherence to this principle. The mold should be poured carefully and not too rapidly, as the metal may otherwise fail to fill finer parts of the mold. The casting should be stripped as soon as set in order to prevent cracking. Owing to the lightness of the alloys, chaplets are rarely needed in anchoring cores.

Commercial casting alloys may be obtained in ingot form, and it is perhaps in general best to use such material. If the metals are alloyed in the foundry, a hardener should first be made containing from 10 to 50 per cent of the alloying constituent. In melting down this hardener is first melted and the aluminum then added.

For the usual alloys 0.156 inch per foot is accepted as the pattern maker's allowance for shrinkage; for aluminum this is 0.203 inch per foot.

TABLE 18.—Equilibrium Diagrams of Aluminum Alloys

[A, B, C=Binary systems. D=Ternary systems]

(A) A COMPOUND OR COMPOUNDS OF THE METAL WITH ALUMINUM ARE FORMED; THE ALUMINUM-RICH COMPOUND FORMS A EUTECTIC WITH ALUMINUM

Alloy system	References [a]	Composition of aluminum-rich compound	Melting point of aluminum-rich compound	Eutectic with aluminum-rich compound		Solubility in aluminum of aluminum-rich compound	Compounds formed
				Temperature of melting	Per cent of alloying element	Per cent of alloying element	
Aluminum and—			°C	°C			
Antimony	Mathews, Campbell, and Mathews (384), Tammann (412).	SbAl	1065	655	(?)	Nearly zero [b]	SbAl
Calcium	Donski (361)	$CaAl_3$	(?)	610	5.6	do.[b]	$CaAl_3$
Chromium	Hindricks (368)	$AlCr_3$(?)	(?)	643	1(?)	do.[b]	$AlCr_3$(?)
Cobalt	Gwyer (365)	Co_3Al_{13}	(c)	630	5	do.[b]	CoAl, Co_2Al_5, Co_3Al_{13}(?)
Copper	Gwyer (375), Carpenter and Edwards (377), Curry (379).	Al_2Cu	(c)	545	32	About 4	Cu_3Al, $CuAl_2$
Gold	Heycock and Neville (356, 357)	Al_2Au		647	1.1	Nearly zero [b]	$AlAu_4$, Al_2Au_5, $AlAu_2$, Al_2Au
Iron	Gwyer (375)	$FeAl_3$	1150	649	1(?)	do.[b]	$FeAl_3$
Magnesium	Grube (399)	Mg_4Al_3	463	453	35	About 1	Mg_4Al_3
Manganese	Hindricks (402)	Al_3Mn	(?)	649	3(?)	Nearly zero [b]	$AlMn_3$(?), Al_3Mn(?)
Nickel	Gwyer (406)	$NiAl_3$	(c)	630	6	do.[b]	NiAl, $NiAl_2$, $NiAl_3$
Silver	Gautier and Petrenko (354)	Ag_2Al	(?)	567	30	do.[b]	Ag_3Al, Ag_2Al
Zinc	Lorenz and Plumbridge (433), Rosenhain and Archbutt (435).	Al_2Zn_3	(c)	[d] 380	[d] 95	20–40	Al_2Zn_3
Cerium	Vogel (363)	$CeAl_4$		638	10	Not known	Ce_3Al, Ce_2Al, CeAl, $CeAl_2$, $CeAl_4$
Platinum	Chouriguine (410, 411)	$PbAl_3$		639	9		$PbAl_3$
Vanadium	Czako (428)	VAl_3					

(B) THE METALS ARE NOT MISCIBLE OR ONLY SLIGHTLY SO IN THE LIQUID STATE

Alloy system	References [a]	Composition of aluminum-rich compound	Melting point of aluminum-rich compound	Temperature of melting	Per cent of alloying element	Per cent of alloying element	Compounds formed
Aluminum and—							
Bismuth	Gwyer (359)						
Cadmium	Gwyer (362)						
Lead	Gwyer (408)						
Potassium	Mathewson (390)						
Sodium	Mathewson (390)						

(C) THE METALS FORM A SIMPLE EUTECTIFEROUS SERIES

Aluminum and—							
Silicon	Roberts (414), Fraenkel (417)			576	10		
Tin	Gwyer (421), Shepherd (405), Campbell and Mathews (425), Lorenz and Plumbridge (420).			229.1	2.1		

(D) TERNARY SYSTEMS

Al-Mg-Zn	Eger (462)						
Al-Cu-Zn	Carpenter and Edwards (462)						
Al-Mn-Cu	Rosenhain and Lantsberry (463)						
Al-Cu-Sn	Andrews and Edwards (464)						

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[a] Latest references are given but not all, as earlier ones are always noted in the former. [b] Not determined. [c] Decomposes before fusing. [d] Eutectic of zinc *and* Zn_3Al_2.

(a) REMELTING OF ALUMINUM

The remelting of scrap aluminum alloy in coarse form offers no particular difficulty, but that of borings and chips is extremely difficult (Gillet, 304), owing to the fact that each particle is covered with an extremely tenacious coating of Al_2O_3, which effectually prevents its coalescence with its neighbor. Two remelting methods are in commercial use. In one the chips are puddled in iron pots until a pasty mass of metal accumulates, which is then heated to a red heat until the dross and dirt rises, leaving clear metal. In the other the chips are mixed with a chloride and fluoride flux and melted in a crucible until the metal collects at the bottom. In a modification of this method (McKinney, 304) a low melting-point chloride-fluoride flux is melted down in a crucible and the aluminum chips fed into it. The oxide is fluxed off of the chips, which melt and collect at the bottom.

By these methods from 50 to 95 per cent recovery of metal is accomplished, depending on the cleanliness of the chips. The metal should not be used except for unimportant castings of which the mechanical properties are not a prime consideration. Chips of magnalium, remelted by a method described by Coulson (392) gave much lower tensile strength than the original virgin metal and practically no ductility. The use of a deoxidizer, such as metallic calcium, caused a partial recovery of the former mechanical properties.

A more recent development has been the practice of briquetting light scrap of alluminum alloy (Stillman, 297). Tests made showed a shorter melting time and a lower melting loss for remelted briquetted "aluminum" than for remelted chips (8.1 per cent as against 13.8 per cent melting loss).

(b) EFFECT OF CASTING SECTION AND OF POURING TEMPERATURE ON MECHANICAL PROPERTIES

Gillett (314) has investigated the important question of the effect of pouring temperature on the mechanical properties of aluminum alloy castings.

A heat of No. 12 alloy (see Sec. IX–1–(*1*)) was poured at 703° C into test bars of different sizes, the tests results of which are given in Table 19. It is seen that the greater the cross section of the casting the lower is the resulting tensile strength.

TABLE 19.—Tensile Properties of No. 12 Casting Alloy (Gillett, 314)

A. EFFECT OF CASTING SECTION

Dimensions of section in inches	Area of section in square inches	Tensile strength in pounds per square inch
0.9 by 0.4	0.36	16 000
0.75 by 0.25	.188	18 000
0.40 round	.125	20 000
0.45 round	.157	19 000
0.50 round	.196	18 000
0.75 round	.440	16 000
1.00 round	.786	13 500

B. EFFECT OF POURING TEMPERATURE

Temperature, in degrees Fahrenheit	Tensile strength in pounds per square inch
1200	20 000
1250	19 500
1300	14 200
1350	18 500
1400	18 000
1450	17 800
1500	17 500
1550	17 000
1600	16 000

In part B of the same table are given Gillett's results on the effect of pouring No. 12 alloy into a (S. A. E.) cast-to-size test bar (0.5 inch diameter) in green sand from different temperatures. The hardness decreases with increasing pouring temperature. Gillett tested the effect of pouring temperature on 53 alloys in all (see Table 20), and concludes that in general the alloys are weaker by approximately 20 per cent when poured hot (1550 to 1600° F) than when poured cold (1225 to 1250° F). An exception was noted in the case of the 5 per cent magnalium and of the 2 per cent manganese alloy.

TABLE 20.—Effect of Pouring Temperature on the Tensile Strength of Light Aluminum Alloys (Gillette, 314)[a]

Chemical composition	Lower pouring temperature		Higher pouring temperature	
	Pouring temperature in degrees centigrade	Tensile strength in pounds per square inch	Pouring temperature in degrees centigrade	Tensile strength in pounds per square inch
Pure aluminum	760	10 500	871	8 000
Copper-aluminum alloys:				
2 per cent copper	668	13 800	871	11 500
4 per cent copper	668	15 500	871	13 000
6 per cent copper	668	17 600	871	14 500
8 per cent copper	668	20 000	871	15 500
10 per cent copper	668	21 000	871	16 000
12 per cent copper	668	22 500	871	17 500
Zinc-aluminum alloys:				
4 per cent zinc	668	13 000	843	10 000
8 per cent zinc	668	17 000	843	12 700
12 per cent zinc	668	21 000	843	14 000
16 per cent zinc	668	24 000	843	17 000
20 per cent zinc	668	27 000	843	20 000
24 per cent zinc	668	30 000	843	24 500
28 per cent zinc	668	33 000	843	27 500
32 per cent zinc	668	35 000	843	30 000
36 per cent zinc	668	37 000	843	33 000
Copper-zinc-aluminum alloys:				
8 per cent copper and 0.25 per cent zinc	668	20 000	843	17 000
8 per cent copper and 0.50 per cent zinc	668	20 500	843	17 000
7.5 per cent copper and 1 per cent zinc	668	18 000	843	14 000
7 per cent copper and 3 per cent zinc	668	19 500	843	15 500
7 per cent copper and 9 per cent zinc	668	25 000	843	18 000
6 per cent copper and 5 per cent zinc	668	20 000	843	15 000
5 per cent copper and 10 per cent zinc	668	24 000	843	18 500
4 per cent copper and 8 per cent zinc	668	23 500	843	17 000
4 per cent copper and 15 per cent zinc	668	32 000	843	23 000
3 per cent copper and 3 per cent zinc	668	17 000	843	13 000
3 per cent copper and 6 per cent zinc	668	19 000	843	13 500
3 per cent copper and 12 per cent zinc	668	26 000	843	18 500
3 per cent copper and 15 per cent zinc	668	28 500	843	19 500
3 per cent copper and 25 per cent zinc	668	37 500	843	29 500
2.5 per cent copper and 19 per cent zinc	668	33 000	843	25 000
2 per cent copper and 10 per cent zinc	668	23 000	843	15 500
2 per cent copper and 22 per cent zinc	668	36 000	843	28 000
2 per cent copper and 25 per cent zinc	668	37 000	843	33 000
1.75 per cent copper and 30 per cent zinc	668	42 000	843	34 000
3 per cent copper, 15 per cent zinc, and 0.50 per cent manganese	668	30 000	843	20 000
Miscellaneous:				
2 per cent manganese	649	19 000	843	18 500
5 per cent magnesium	676	20 500	760	20 000
8 per cent copper and 0.25 per cent manganese	649	20 000	814	17 500
7 per cent copper and 0.33 per cent manganese	649	19 000	814	16 000
6 per cent copper and 0.50 per cent manganese	676	18 500	814	16 500

[a] The bars were presumably poured into the S. A. E. cast-to-size test bar in green sand. Aluminum containing 0.3 per cent iron and 0.2 per cent silicon was used in the preparation of the alloys.

TABLE 20—Continued

Chemical composition	Lower pouring temperature		Higher pouring temperature	
	Pouring temperature in degrees centigrade	Tensile strength in pounds per square inch	Pouring temperature in degrees centigrade	Tensile strength in pounds per square inch
Miscellaneous—Continued				
4 per cent copper and 1 per cent manganese	676	16 000	814	15 000
8 per cent copper and 2 per cent tin	657	18 000	802	15 750
5 per cent copper and 3 per cent tin	657	16 800	814	15 000
6 per cent copper and 1 per cent nickel	703	18 200	871	14 500
8 per cent copper and 0.25 per cent titanium	676	19 000	814	18 400
8 per cent copper and 0.25 per cent chromium	649	19 500	814	15 900
8 per cent copper and 0.25 per cent antimony	676	20 000	814	17 400
8 per cent copper and 0.25 per cent vanadium	676	20 000	814	18 500
8 per cent copper and 0.25 per cent cadmium	676	18 600	814	15 800
8 per cent copper and 0.25 per cent bismuth	676	18 000	814	14 000
4 per cent copper and 8 per cent silver	703	19 700	843	15 400
8 per cent copper, 1.5 per cent iron, and 0.75 per cent silicon	676	21 000	814	18 000

Rosenhain and Lantsberry (463) have studied the effect of pouring temperature on the tensile properties of a chill-cast aluminum-manganese-copper alloy No. 10 (see Table 13) and find the following results:

Pouring temperature in degrees centigrade	Tensile strength	Elongation in 2 inches
	Lbs./in.²	Per cent
775–737	12 900	2
687–675	26 000	8
650	25 300	8

Other tests have been made by Donaldson (435, discussion), who finds a falling off in tensile strength and elongation for an alloy of 19 per cent zinc and 1 per cent copper when poured between 800 and 850° C.

Pouring temperature in degrees centigrade	Tensile strength	Elongation in 2 inches
	Lbs./in.²	Per cent
850	20 400	1.8
800	29 300	4.0
700	22 000	2.5

Tests by Carpenter and Edwards (377) give the following results for chill castings of an alloy of 4.63 per cent copper, balance aluminum:

Pouring temperature in degrees centigrade	Tensile strength	Elongation in 2 inches
	Lbs./in.^{2}	Per cent
650	21 700	8.5
724	15 700	5.5
707	10 900	3.0

Tests by Rosenhain (435, discussion), contribute the following values for chill castings of an alloy of 20 per cent zinc and 1 per cent copper:

Pouring temperature in degrees centigrade	Tensile strength	Elongation in 2 inches
	Lbs./in.^{2}	Per cent
850	24 000	2.5
800	30 800	4.0
750	31 500	3.0
700	31 700	4.0
650	30 900	5.0

(c) DIE CASTING

The term "die casting" is rather vaguely understood to connote the casting of metal in metallic molds either with or without the mechanical application of pressure.

Die castings may readily be made of aluminum alloys; particularly the copper-aluminum alloys are suitable for this class of work. Aluminum-zinc alloys are difficult to handle because of their hot-shortness (Norton, 308). Norton describes the use by the Aluminum Castings Co. of No. 12 alloy for this purpose. This metal gives castings which are of smooth surface, dense, and dimensionally true within a very small margin (±0.005 inch). Mechanical properties for die castings of No. 12 average:

	Sand castings	Die castings
Tensile strength in pounds per square inch	20 000	25 000
Yield point (stress for 0.01 inch elongation in 2 inches) in pounds per square inch	13 000	13 000
Elongation in 2 inches, per cent	1.7	3.1
Density	2.84	2.87

Many articles are now die-cast in this alloy, such as parts of cash registers, typewriters, adding machines, and cooking utensils. Pistons for gasoline motors are now produced of this alloy by die casting.

Pack (300) describes an aluminum-copper alloy which is being commercially die cast under pressure. The chief commercial difficulty with the die casting of aluminum is the cracking or heat checking of the iron or steel molds used. Cracks appear in the mold after about 2 000 castings have been made in it.

(d) COMPOSITION AND PROPERTIES

The physical properties of light casting alloys with which one is concerned are the tensile properties and the resistance to alternating stresses. The tensile properties of commercial alloys are, of course, well known. Practically no data on the resistance to alternating stresses of these alloys are published, although such data are of the utmost importance in view of the use of such castings for machine parts subject to vibration, such as motor-crank cases.

Some confusion exists with respect to the description of tensile properties. In this country a test specimen cast to size in green sand is usually used to determine these properties. This is usually 0.5 inch in diameter over the reduced section. In Great Britain a specimen cast to size in a chill is often used. Experience has shown that the tensile strength of chill-test castings of light alloys will usually average from 3000 to 5000 pounds per square inch higher than for sand-cast ones. This should always be borne in mind in comparing tests of these alloys.

Not only is the tensile strength of chill castings higher than that of sand castings, but also the elongation. In general any variation of casting condition which increases the tensile strength of a casting alloy increases also its ductility (elongation), and a double gain of hardness and toughness is thereby obtained.

Satisfactory results are obtained either on a cast-to-size test coupon, poured horizontally in sand with gate and riser, or with the Webbert type of cast-to-size coupon, cast in core sand and fed along its whole length by a gate and pouring head. The Naval Gun Factory (Washington) uses the latter form with a gate five-eighths inch thick.

1. "No. 12 alloy" (92 per cent aluminum, 8 per cent copper): Melting range, 637 to 540° C; shrinkage, 0.156 inch per foot.

Probably 95 per cent of all light alloy castings made in this country are of this alloy, probably the best known one to the trade. It is easily handled in the foundry, and does not suffer from hot-shortness to the same degree that some of the other alloys do. This alloy can be depended on to give the following tensile properties when properly cast:

Tensile strength, in pounds per square inch	18 000
Elongation in 2 inches, per cent	1. 5
Specific gravity	2. 89

If the alloy is overheated or poured too hot, the tensile strength may be as low as 15 000 pounds per square inch. On the other hand, with skillful handling in the foundry a greater hardness may be obtained, i. e., as high as tensile strengths from 20 000 to 24 000 pounds per square inch.

Jeffries[3] finds that this alloy when properly cast to give from 20 000 to 24 000 pounds per square inch tensile strength will withstand 1 000 000 alternations of stress between 0 and 12 000 pounds per square inch tension without failure. The alloy is not as strong in impact test as No. 31. (See 3 below.)

Broniewski (374) finds the electrical resistance of an alloy of this approximate composition to be 5.60 microhm-cm.

2. Copper alloys containing from 8.5 to 14 per cent copper: Melting range, 630 to 540° C (depending on copper content); shrinkage, 0.156 inch per foot.

These alloys are used for castings which are to be subjected to high temperatures, such as manifolds, pistons, and also for castings to withstand pressure, such as for pumps, etc.

The 8.5 to 11 per cent alloy is generally used for pistons, and the 11 to 14 per cent alloy used for pressure castings.

These alloys will ordinarily give the following physical properties.

Tensile strength, in pounds per square inch	18 000–19 000
Elongation in 2 inches	Usually less than 1 per cent.
Density 8.5 to 11 per cent	2. 95
Density 11 to 14 per cent	3. 00

Certain of the Lynite casting alloys manufactured by the Aluminum Castings Co. are almost identical with the above Nos. 1 and 2. The composition and physical properties of the Lynite alloys as guaranteed by the company are as follows:[4]

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[3] Private communication from the Aluminum Castings Co., through Prof. Z. Jeffries.

[4] Communication from the Aluminum Casting Co. through Prof. Z. Jeffries.

Lynite No. 146 (for general castings, such as propellers, crank cases, etc.):

Copper, per cent	7.0–8.5
Other elements, per cent	Not over 1.7
Aluminum	Balance
Density	Not over 2.89
Sand cast—	
Tensile strength in pounds per square inch	24 000–28 000
Elongation in 2 inches, per cent	1.4
Die cast—Tensile strength in pounds per square inch	About 28 000

Lynite No. 122 (for castings for use at higher temperatures, pistons, etc.):

Copper, per cent	9.25–10.75
Other elements, per cent	Not over 2
Aluminum	Balance
Density	Not over 2.95
Die cast—Tensile strength in pounds per square inch	About 28 000

Lynite No. 109 (for pressure castings):

Copper, per cent	11.5–13.5
Other elements, per cent	Not over 1.7
Aluminum	Balance
Density	Not over 2.97
Sand cast—Tensile strength in pounds per square inch	19 000

3. "No. 31" (zinc 15 per cent, copper 3 per cent, aluminum 82 per cent): Melting range, 625 to 440° C; shrinkage, 0.156 inch per foot.

This alloy has hitherto been used more extensively abroad, particularly in Great Britain, than in this country. Its higher tensile strength as compared with No. 12 has not in this country outweighed the doubt in the minds of many of its performance and its freedom from deterioration upon aging. This illusion has now, it is believed, been largely dispelled, and there seems no reason why the alloy should not become more popular.

This alloy can usually be depended on to give the following properties:

Tensile strength in pounds per square inch	22 000–25 000
Elongation in 2 inches, per cent	0.5–3
Specific gravity	3

When poured properly and at a low temperature a tensile strength of 30 000 pounds per square inch may be obtained with this alloy.

This alloy has a lower resistance to alternating stresses but is tougher in impact than the copper alloys (Nos. 1 and 2).[5]

4. Magnalium: Melting range, 625 to 450° C.

This alloy is one of the earliest commercial alloys. The term originally connoting an alloy of aluminum containing from 5 to

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[5] Communication from Prof. Jeffries of the Aluminum Castings Co.

30 per cent of magnesium now covers a variety of commercial alloys containing magnesium and also small quantities of copper and nickel.

A "magnalium" used at one time by the Westinghouse Electric & Manufacturing Co. (371) contains 5 per cent of magnesium. This alloy may be depended on to give the following tensile properties:[6]

Tensile strength in pounds per square inch	20 000
Elongation in 2 inches, per cent	0. 5–2
Specific gravity	2. 63

With care a tensile strength of 25 000 pounds per square inch and an elongation of 5 per cent may be obtained on this alloy.

5. Alloy containing 35 per cent zinc: Melting range, 585 to 440° C; shrinkage, 0.156 inch per foot.

This alloy is much used for general castings in which strength is not a principal consideration. It casts well but has little or no ductility. Its tensile strength is usually about 35 000 pounds per square inch as cast. Its specific gravity is 3.32.

6. Alloy containing 1 to 2 per cent of copper and 1 per cent of manganese: Melting range, 649 to 529° C.

This alloy is described by McKinney (450) and is suitable both for casting and for forging. Cupromanganese may be used in preparing it, and it is not apparently a difficult alloy to handle in the foundry. This alloy will usually have the following tensile properties or better:

Tensile strength in pounds per square inch	18 000
Elongation in 2 inches, per cent	8
Specific gravity	About 2.80

With care this alloy may be cast to have a tensile strength of 20 000 pounds per square inch, with an elongation in 2 inches of 10 per cent. This alloy is used almost entirely by the Naval Gun Factory, Washington, D. C.

2. ROLLING AND FORGING

Alloys for rolling or forging generally contain smaller percentages of the "hardener" metal than those for casting. Except when zinc is used, the total content of added metal to such alloys rarely exceeds 6 per cent, and is usually less. The rolling or forging of these alloys is usually carried out in a manner quite similar to the practice followed for aluminum, although the temperatures used for hot breaking down are often somewhat lower

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[6] Communicated by Mr. J. L. Jones of the Westinghouse Co.

owing to the lower melting point of the alloy, and the alloy is usually annealed during cold-rolling.

1. Aluminum-manganese alloy: An alloy (No. 3–S) containing manganese is rolled by the Aluminum Co. of America particularly into sheet, for use wherever a stiffer material than aluminum is desired. This alloy is superior in its resistance to corrosion to most other alloys of aluminum. The tensile properties of this alloy in sheet form average:

	Hard	Soft
Tensile strength in pounds per square inch	30 000	15 000
Elongation in 2 inches, per cent	2	25

2: Alloy containing 1 to 2 per cent copper and 1 per cent manganese: This alloy, used at the Naval Gun Factory (450) for small forgings, may be readily forged at a temperature of about 525° C. If finished at a temperature of about 250° C, the forging is much harder. Forgings of this alloy give the following tensile properties:

	Finished cold	Finished hot
Tensile strength in pounds per square inch	27 800	21 100
Yield point in pounds per square inch	27 800 (?)	12 200
Elongation in 2 inches, per cent	12	27
Reduction of area, per cent	47	49

The alloy is said to be quite satisfactorily resistant to corrosion in sea air.

3. A forging alloy used by the Aluminum Castings Co. has the following chemical composition: Copper, 2.75 to 3.25 per cent; aluminum, balance.

It will yield the following tensile properties:

Tensile strength in pounds per square inch	24 000
Yield point in pounds per square inch	16 000–17 000
Elongation in 2 inches, per cent	Not under 3.5

4. A machining rod alloy (No. 15–S) containing zinc and copper is produced by the Aluminum Co. of America. The average properties are:

Tensile strength in pounds per square inch	42 000
Elongation in 2 inches, per cent	10

5. The Aluminum Co. of America recommends an alloy of from 10 to 15 per cent zinc for general forgings. This is said to flow well in the dies, and has satisfactory physical properties.

3. DURALUMIN[7]

The most remarkable light alloy of aluminum is undoubtedly duralumin, the behavior and properties of which were discovered by Wilm (472) during his investigation during the years from 1903 to 1911. The remarkable feature about it is that its mechanical properties may be vastly improved by heat treatment.

The composition of this alloy varies somewhat. On the Continent the following range of compositions is used:

	Per cent
Copper	3. 5–5. 5
Magnesium	0. 5
Manganese	0. 5–0. 8
Aluminum	Balance

It is thus an alloy which can readily be rolled or forged. Indeed, it is always used in this condition, since the development of its highest physical properties involves the application of mechanical work to it.

The electrical resistivity of annealed duralumin is 3.43 microhm-cm. In the heat-treated condition, however, in which it is always used, the resistivity is much higher, being 4.73 microhm-cm. In this condition it has approximately 35 per cent of the volume conductivity of copper.

The density of duralumin varies from 2.75 to 2.84. Its melting point is about 650° C.

When this alloy is heated for a few minutes at temperatures from 400 to 520° C and quenched in water, the hardness is very little increased over that which would be obtained by slowly cooling the same alloy. But upon aging the quenched alloy for several days at ordinary temperature both the hardness and the ductility are increased from 15 to 50 per cent, depending on the composition of the alloy and the quenching temperature. Thus an alloy showed the following changes of properties:

	After rolling, before hardening	After hardening (quenching and aging)
Tensile strength, in pounds per square inch	37 000	58 000
Elongation, per cent	17	23

The change of hardness during aging is shown in Fig. 22.

After hardening this alloy by quenching and aging it may be still further hardened by cold work, at the cost, of course, of ductility. The curves, Fig. 23, show the increase of tensile strength and decrease of ductility that occur when both annealed and hardened duralumin are cold-worked.

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[7] Most of the data in the paragraphs on duralumin have been taken from articles by Cohn (469, 471, 474).

The hardness produced by hardening is, of course, lost upon annealing at rather low temperatures. The curve of Fig. 24 shows the effect of annealing at different temperatures followed by air cooling upon the hardness and ductility of a hardened duralumin. It is noticed that duralumin hardens slightly even when cooled in air.

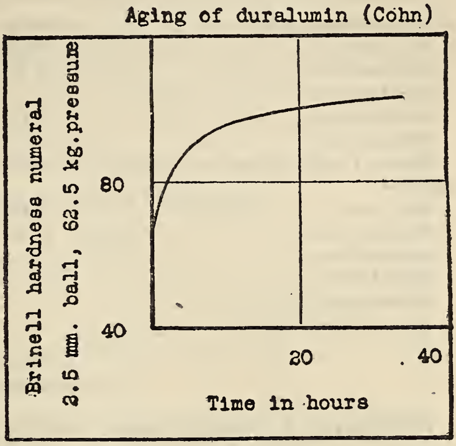

FIG. 24.—*Increase of hardness of duralumin upon aging after quenching.* (Cohn, 471, 474)

Duralumin loses its hardness at higher temperatures. Fig. 25 shows the effect of higher temperatures upon the hardness of this alloy.

Table 21 gives the results of a number of tests of commercial duralumin from the Dürener Metallwerke A. G.

Duralumin,[8] when heat-treated and cold-worked to give about 6 per cent elongation in 2 inches, corresponding to a yield point above 35 000 pounds per square inch, will withstand unlimited alternations of stress between 0 and 20 000 pounds per square inch tension.

TABLE 21.—Tensile Properties of Dürener Duralumin (Cohn, 471, 474)

Alloy and treatment	Yield point	Tensile strength	Elongation in 2 inches	Reduction of area
Alloy H; density, 2.75:	Lbs. in.^{2}	Lbs. in.^{2}	Per cent	Per cent
Soft, 7 mm	27 000	51 200	25.0	34
Rolled to 6 mm	....	54 000	10.0	22
Rolled to 5 mm	....	59 800	6.3	18
Rolled to 4 mm	....	61 900	5.0	13
Rolled to 3 mm	....	64 800	5.0	14
Rolled to 2 mm	....	67 500	4.0	12
Alloy 681-B:				
Soft, 7 mm	40 000	62 800	17.6	21.7
Rolled to 6 mm	67 000	71 100	8.0	16.3
Rolled to 5 mm	....	75 000	5.3	12.7
Rolled to 4 mm	....	78 300	4.0	9.7
Rolled to 3 mm	....	80 500	3.4	7.3
Rolled to 2 mm	....	83 200	2.5	6.6
Alloy 681-D; density, 2.83:				
Soft, 7 mm	36 900	65 300	17.5	21.0
Rolled to 6 mm	58 600	74 200	8.6	18.0
Rolled to 5 mm	64 200	78 500	6.6	15.0
Rolled to 4 mm	....	....	....	....
Rolled to 3 mm	75 400	84 000	4.6	11.0
Rolled to 2 mm	77 000	88 300	3.0	11.0

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[8] Private communication from the Aluminum Castings Co., through Prof. Jeffries.

TABLE 21—Continued

Alloy and treatment	Yield point	Tensile strength	Elongation in 2 inches	Reduction of area
Alloy 681–A; density, 2.79:	Lbs. in.^{2}	Lbs. in.^{2}	Per cent	Per cent
Soft, 7 mm	35 100	59 500	12.1	29.5
Rolled to 6 mm	65 900	67 700	9.0	21.5
Rolled to 5 mm				
Rolled to 4 mm	69 200	75 000	5.0	14.5
Rolled to 3 mm				
Rolled to 2 mm	75 400	79 600	4.0	13.2
Alloy 681–C:				
Soft, 7 mm	40 600	64 200	17.6	22.0
Rolled to 6 mm	67 800	73 200	7.4	14.5
Rolled to 5 mm		76 800	5.2	12.5
Rolled to 4 mm		80 000	4.5	8.7
Rolled to 3 mm		82 500	3.5	8.0
Rolled to 2 mm		85 800	3.1	6.3

(a) CORROSION

Duralumin in the hardened condition is remarkably resistant to corrosion, considering that it contains much copper which is recognized to be usually a harmful constituent of an aluminum alloy from the standpoint of corrosion. This fact is particularly important in view of the use of the alloy for construction purposes where it will be subject to weathering and corrosion.

The Dürener Metallwerke A. G. has made extensive investigation of this feature. Sheets 2.35 mm thick were immersed for 14 months in several solutions and the decrease in thickness measured as well as appearance observed after that time. Table 22 gives the principal results of these tests.

TABLE 22.—Corrosion of Duralumin (Cohn, 469, 471)

[Specimens were immersed for 14 months in solutions below.]

Solution or liquid	Concentration	Decrease in thickness	Description of sample
		mm	
HCl	1/10 *n*	0.28	Samples were all attacked with pits and holes.
	1/5 *n*	.25	
	1 *n*	2.05	
HNO_3	1/10 *n*	1.75	Attack uniform.
	1/5 *n*	.45	
	1 *n*	.10	
Acetic acid	50 per cent	0.03– .05	Attack uniform except where at surface exposed to acid and air.
	80 per cent	.03– .10	
H_2SO_4	1/10 *n*	.20– .25	Attack uniform.
	1/5 *n*	.38	
	1 *n*	.85	
NH_4OH	14 per cent (?)	.13– .35	Gray layer; attack uniform.
Acid vapors	In hood of laboratory	.11– .13	Uniform attack.
$HgCl_2$		0. 5– .75	Material attacked but not brittle.
Hg		.00	No action.[a]

[a] This is very questionable.

A mixture of concentrated sulphuric and nitric acids scarcely attacks duralumin, nor does concentrated sulphuric acid containing some dissolved potassium dichromate (K_2CrO_7). The latter is recommended as a cleansing solution for duralumin vessels.

The Lüftschiffbau-Zeppelin-Gesellschaft exposed angles and U profiles of duralumin, copper, iron, aluminum alloys, pure aluminum, and elektron to the action of sea air and spray on a light ship in the North Sea for three months. These sections were also riveted and screwed together. Duralumin resisted these conditions better than any of the other materials (Cohn, loc. cit.) and showed practically no oxidation.

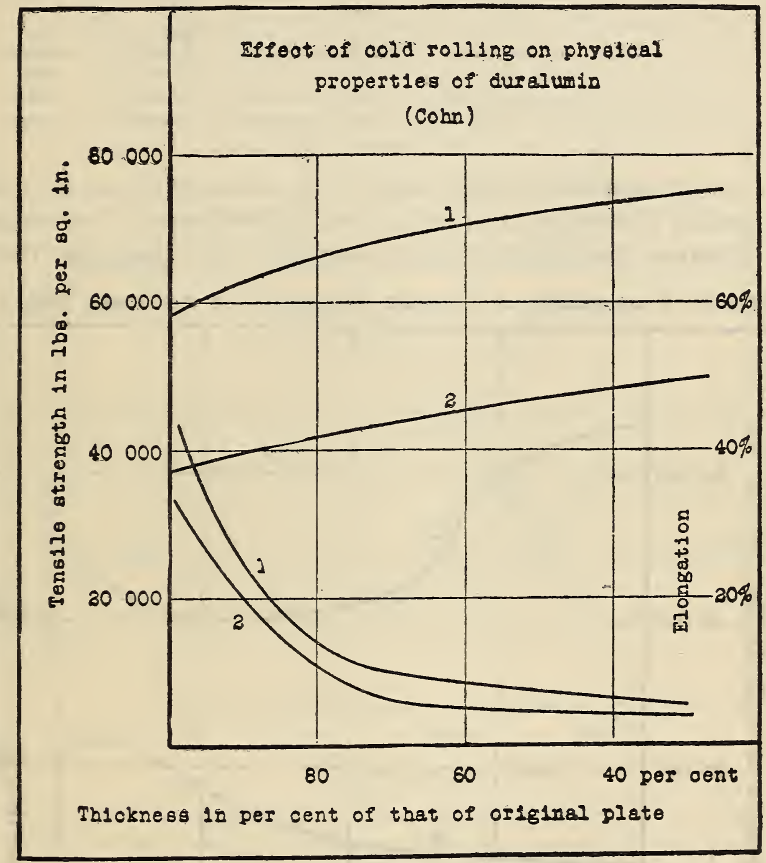

FIG. 25.—*Effect of cold working on the tensile properties of duralumin.* (Cohn, 471, 474)

(Samples were rolled cold from a thickness of 7 mm)
Curves 1, tensile strength and elongation of hardened duralumin
Curves 2, tensile strength and elongation of rolled but not hardened duralumin

Some tests made at the shipbuilding docks of Vickers (Ltd.), Barrow-in-Furness, indicate that duralumin in the hardened condition resists the action of sea water very well, indeed. Four strips, 1 foot square, were hung on the ways, such that at low tide they were above the water level; at high tide immersed. After six months the losses in weight and thickness were as follows:

Number	Loss in weight	Loss in thickness
	g/cm²	cm
1	0.00103	0.00038
2	.00107	.00039
3	.00045	.00016
4	.00062	.00023

Investigation has also been made of the alteration in mechanical properties of duralumin brought about by exposure to corrosion. It is known that some alloys of aluminum and aluminum itself often suffer deterioration in this manner. The Dürener-Metallwerke A. G. exposed bars and wire of different sizes of duralumin on the roof of one of their buildings for 2½ years. Samples were

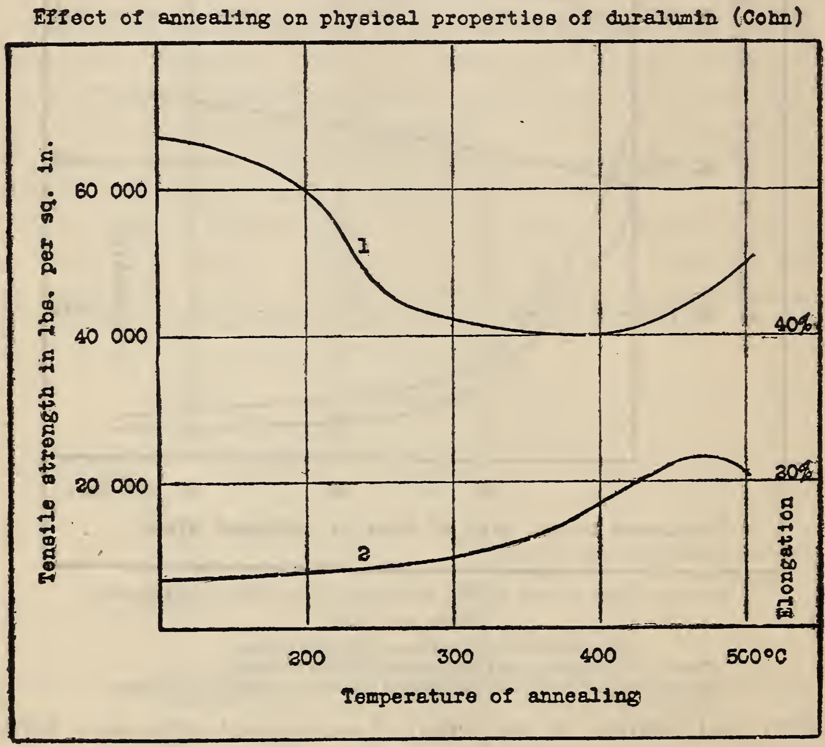

FIG. 26.—*Effect of annealing on the tensile properties of duralumin.* (Cohn, 471, 474)

The samples were annealed and cooled in air; curve 1 is that of the tensile strength; 2, of the elongation tested from time to time, and within that period no evidence of any alteration in hardness or ductility was shown. Evidently the properties of this material acquired by hardening are quite stable.

Under Section XI are described also some tests on the stability of aluminum alloys, including duralumin, when tested in a corroding medium.

From the foregoing paragraphs it is seen that duralumin has been subjected to rather extensive and severe tests covering its properties and their stability under different conditions. It is apparently a most excellent material for construction purposes, for the production of structural members, for forgings and for tubes, bars, and wire.

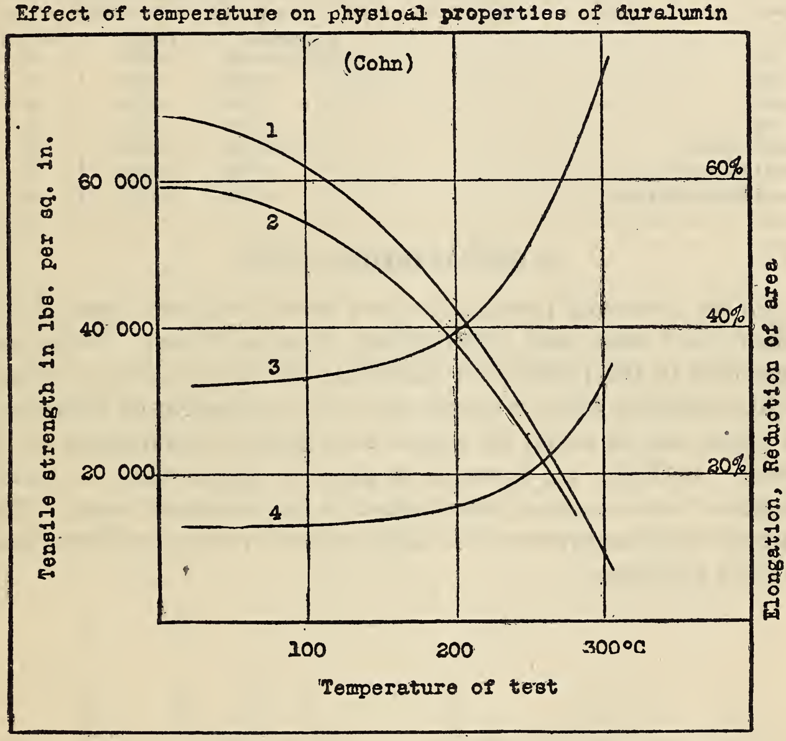

FIG. 27.—*Effect of temperature on the tensile properties (tension test) of duralumin.* (Cohn, 471, 474)

Curve 1, tensile strength Curve 2, yield point Curve 3, reduction of area Curve 4, elongation

It is possible to weld duralumin in the same manner as pure aluminum. The joint is not as strong as the original material, however, since the heat of welding destroys the properties produced therein by hardening. By cooling the joint rapidly after welding some improvement may be made. For the present, therefore, construction work with duralumin may best be done by riveting or other mechanical forms of jointing work.

In Table 23 are given the physical properties which may usually be obtained for duralumin in different forms.

TABLE 23.—Tensile Properties of Duralumin

Form	Tensile strength	Yield point	Elongation in 2 inches
	Lbs./in.^{2}	Lbs./in.^{2}	Per cent
Sheet	55 000–65 000	25 000	15
Do	50 000	25 000	20
Tubes	55 000	35 000	12
Do	50 000	25 000	20
Bars ¼ to 1 inch	55 000–65 000	25 000	15
Bars 1 to 2 inches	50 000	25 000	15
Bars 2 inches, and above	45 000	20 000	15

4. MISCELLANEOUS ALLOYS

In the foregoing paragraphs have been described those alloys which have been used commercially to some extent. There are described in the patent and periodical literature almost as many light aluminum alloys as there have been investigators interested in them, and it would be useless to attempt to enumerate all of them. In Table 24, however, is given a list of many of them, together with whatever information is known about them. The numerical values given in this table are merely those published and are not guaranteed.

TABLE 24.—Miscellaneous Light Alloys

Name of alloy	Manufacturer	Form in which alloy is used	Density	Chemical analysis									Tensile properties				
				Al	Cu	Zn	Mg	Mn	Ni	Fe	Si		Proportional limit	Yield point	Ultimate strength	Elongation in 2 in.	Reduction of area
			gr/cm.^{3}	P. cent	P. cent	P. cent	P. cent	P. cent	P. cent	P. cent	P. cent		Lbs/in.^{2}	Lbs/in.^{2}	Lbs/in.^{2}	P. cent	P. cent
Acieral[a]	Acieral Co. of America.	Sand castings	2.84		6.4	0.4			0.9	0.1	0.4		6 000		22 000	2.0	0.6
Do		Sheet			2.3		0.1	1.5		1.4			37 000		50 000	3.3	5.4
Do		do			3.7		0.2	1.0		1.3			51 000		67 000	2.9	7.0
Aero metal[a]	Garford Engng. Co.	Sand castings	3.3		4.2	27.8				0.5	0.5				24 600	1.0	0.3
Do		Sheet (0.1 in.)			0.2		2.9			0.3	0.4				41 000	3.8	11.6
Albidur-Aluminum.[b]	Otto Gruson & Co.		2.9												25 000–34 000	1–5	
Aluminite[a]	[W. J. Bruff]	Sand castings	3.3		2.7	23.3				0.4	0.2				40 000	0	0
Atherium[b]	Prett, Bowley & Co.		2.5												41 000	17	
Bearing metals[b]	Fletcher & Emperer.	Castings		95.5 92.2	3 7.5							1–Sn 0.58Sb 1/4 Sn					
Do	Krupp			87	8							5–Sn					
Do	Bersch			93					7								
Do	Le Ferro Nickel			94–98	1.5–4			¼–1¼				¼–1¼ Ag		14,000–20,000	28 000–40,000	16–18	
Elektrometall[b]	Chemische Fabrik Griesheim.		1.8														
McAdamite[a]	McAdamite Aluminum Co.	Sand castings	2.8		3.1	12–18	0.2						18 000		31 000	0	0
McLure[a]	[L. S. McClure]	do	2.94		8.2			0.2		0.9	0.3	5–6Sn	15 700		19 600	3.1	2.3
Magnalite[a]	Walker M. Levett Co.	do	2.8		2.5	0.5	1.3		1.5				10 000		26 000	2.5	1.6
Magnalium X	(a)	do			1.8		1.6		1.2						19 000–22 000		
Magnalium Y	(d)	do													31 000–47 000		
Magnalium Z	(d)	For rolling															
Maluminum[a]	H. D. Kramm Foundry Co.	Sand castings	2.85		6.4	4.8		0.1		1.4	0.2	0.15–P6	13 000		17 100	1.5	2.3
T Metal[a]	Light Metals Co.	do	2.7		0.1		3.8			0.5	0.5				15 700	3.0	1.1
Tiers Argent[b]	Krupp	(e)		66								33 Ag					
Verilite[a]	Verilite Metals Co.	Sand castings	2.8		2.5			0.3		0.7	0.4				16 000	4.0	4.0
Weidrium[b, c]	[Richard Weidner]		2.75–3.1												20 000–28 000	4–12	
Zimalium[b]			3.4														
Ziskon[d]	Carl Zeiss	Castings[f]	2.95	60?		40?									24 000		
Zisium[d]				85?		15?									11 000		

[a] Tests by Bureau of Standards.
[b] Mentioned by Krause (4).
[c] Contains Ni, Cu, and Zn, or Sn, Fe, and Mg.
[d] Mentioned by Law (270).
[e] Substitute for silver.
[f] For instrument parts.

A list of patents covering light aluminum alloys, complete for the United States and incomplete for other countries, is given in Table 25.

TABLE 25.—List of Patents Covering Light Aluminum Alloys

[This list is complete for United States patents, exclusive of those for aluminum solders]

United States patents	Date	United States patents	Date	United States patents	Date	German patents	Date
44 086	1864	1 104 369	1914	699 216	1902	144 777	....
633 743	1899	1 121 269	....	662 952	1900	113 935	1899
652 833	1900	1 117 308	....	639 600	1899	119 643	....
867 194	1907	1 121 268	....	646 442	1900	125 334	....
451 406	1891	1 121 267	....	662 951	....	204 543	1907
684 207	1901	1 080 155	1913	629 084	1899	244 554	....
1 212 374	1917	1 076 137	....	611 016	1898	112 546	1899
1 227 174	....	1 072 017	....	580 711	1897	170 085	1903
1 223 362	....	1 080 156	....	501 553	1893	218 970	....
1 175 655	1916	995 113	1911	480 445	1892	230 095	1909
1 146 185	1915	886 597	1908	451 405	1891	231 060	1909
1 130 785	....	856 392	1907	446 351	1891	242 313	1911
1 092 500	1914	759 617	1904	443 943	1890	137 003	....
1 095 653	....	721 814	1903	373 231	1887	134 582	....
1 099 561	....	743 566	1903	320 149	1879	268 515	....
1 102 618	....	697 544	1902	38 301	1862	203 557	1906
						257 868	1911

The alloys of magnalium have been studied by Mach (Krause, p. 107).

The alloys of aluminum, zinc, and magnesium have been studied by Murmann (Krause, p. 108).

D. R. Patent 231 060, 1909, describes the properties of alloys of aluminum, copper, manganese, and silver.

D. R. Patent 242 313, 1911, describes the properties of alloys of aluminum with cobalt and tungsten.

Rübel (Krause, p. 129) describes the properties of alloys of aluminum with phosphorus.

Borchers (Krause, p. 130) describes the properties of aluminum to which cerium has been added. This metal is a good deoxidizer and fluxes for aluminum, and is said to reduce its content of silicon.

Uyeno (Krause, p. 132) describes alloys of aluminum with mercury and zinc which are used to generate hydrogen (with hot water) for balloons.

X. PHYSICAL PROPERTIES OF LIGHT ALLOYS

Besides the usual mechanical properties of alloys the engineer (particularly the aircraft engineer) is interested in (1) the effect of temperature on the mechanical properties of the light alloys, and (2) the thermal conductivity of casting alloys (motor pistons).

Besides the tests by Rosenhain and Archbutt on aluminum-zinc alloys (435) some of which are described on page 59, and those on duralumin by Cohn (476), described on page 85, no results of tensile tests of light alloys at high temperature have been published. In general, however, a light alloy to withstand high temperatures should be made with a metal or metals of high melting point, such as iron, manganese, or nickel. An alloy containing somewhat more copper than No. 12 is manufactured by the Aluminum Castings Co. for service at elevated temperatures for pistons, etc. Much information covering both topics mentioned above is to be found in recent confidential military reports.

The alloys of magnesium and aluminum have attained some recognition as suitable for large optical mirrors. Mach and Schumann (288) have studied the adaptability of these alloys for this purpose and find that the alloy containing the compound Mg_3Al_4 is the best of the series. It is hard, and when polished has a reflecting power equal to or better than a silvered glass mirror. Special precautions must be taken to prevent the formation of blowholes. This is done by melting under a flux of salts, preventing the absorption of gas.

XI. CORROSION, DISINTEGRATION, AND DETERIORATION OF ALUMINUM AND ITS ALLOYS

The subject of the deterioration of aluminum and its alloys in service has naturally been of the greatest interest to the metallurgist and engineer alike. Unfortunately it must be admitted that such insufficient investigation has been made of the various rather obscure phases of it that some of the observed phenomena may not be regarded as in any sense explained.

It may be preferable to distinguish four types of deterioration of aluminum alloys.

1. CORROSION

The corrosion, uniform or local, of the metal and its alloys has already been discussed in Sections III–1, VIII–1, 4, and 7, and IX–3 in so far as it has been investigated. An adequate direct comparison of the corrodibility of the various commercial casting alloys has never been made, although such information would be quite valuable particularly to airplane designers and naval architects.

The following table gives an approximate comparison of the behavior of different alloys in sea water:

	Loss of weight in sea water in pounds per square foot per month
Rolled aluminum-copper alloys, 0 to 8 per cent copper	0.008 –0.003
Chill-cast aluminum-copper-manganese alloys	.0004
Sand-cast aluminum-zinc alloys	.001 – .002
Duralumin sheets	.0009– .002
Muntz metal	.0023
Naval brass	.0012
Mild steel	(.0022)

When it is considered that the loss of volume of the light alloys per unit loss of weight is about 2.8 times that of brass or steel it is realized that particularly the copper and the zinc alloys can not be used in sea water without some protective coating. The corrosion of alloys is often not such a serious matter, as they may be effectively protected from corrosion in most cases by a varnish or paint.

2. CRACKING

Many cases of mysterious cracking of aluminum alloy castings, particularly of the zinc-aluminum type, are undoubtedly due to shrinkage cracks originating during the solidification of the casting. It is well known that all aluminum alloys are fragile at temperatures just below the melting point or range. Cracking due to faulty molding or hard ramming is generally visible in the finished castings, but invisible and interior cracks may be formed, which open up subsequently when stress is applied. The remedy for such defects lies of course only in better foundry and casting designing practice and in the use of alloys of least fragility at these temperatures. It is the concensus of opinion of foundrymen that zinc-aluminum alloys are inferior to aluminum-copper alloys in this respect. The addition of copper to alloys containing zinc materially improves this condition.

3. DISINTEGRATION

The spontaneous disintegration of alloys of aluminum with high percentages (50 per cent and more) of iron, manganese, and nickle has been noted by investigators (Hindricks). These alloys when cast are hard and brittle, but upon standing actually fall to powder.

The same type of phenomenon is observed in the case of aluminum-zinc alloys containing 50 per cent zinc and more (Pack, 300; Williams, 293). Such alloys annealed after casting are sound and dense, but upon standing (under no stress) particularly when exposed to slightly higher temperatures and moist air, swell and warp, cracks appearing in the castings.

The final explanation of these changes has not been given; in fact the data are still discordant. Rosenhain and Archbutt (see Sec. VIII–a) found no evidence whatever of deterioration within 10 months in sand-cast aluminum-zinc alloys containing up to 75 per cent of zinc. The changes which occur are due probably either to some change in constitution progressing in the alloy, or to differences in the coefficients of thermal expansion of the different constituents of the alloy. These changes have also been somewhat vaguely ascribed to the presence of impurity in the alloy. (See Discussion on Rosenhain-Archbutt paper.)

4. CORROSION AND STRESS

Under this group are considered some very interesting cases of deterioration due to the combined effect of stress and corrosion.

The experiments of Heyn and Bauer (128) have been described (Sec. III–1) in which it was found that cold-rolled or hard aluminum sheet is exfoliated and blistered badly during corrosion in certain solutions, whereas the same material annealed corrodes quite uniformly in the same solutions. The effects of initial stress on the electrolytic solution of the metal and of the relief of initial stress by corrosion combine to produce this unusual phenomenon.

Somewhat more recently investigation by Cohn (469) has disclosed the fact that the tensile properties of hard-drawn bars of an aluminum-zinc-copper alloy are very unfavorably affected by simultaneous corrosion. His results, obtained on an alloy of the composition shown in the statement following, in the form of extruded bars, are given in Table 26.

	Per cent
Zinc	9.40
Copper	.32
Magnesium	.39
Aluminum	Balance

It is noted that in the hard or cold worked condition the alloy gave a much lesser ductility and strength when tested in water than when in air. After annealing this effect was reduced. Duralumin showed practically no sensitivity to such treatment either as heat treated or as heat treated and cold worked.

TABLE 26.—Effect of Combined Stress and Corrosion on Tensile Properties of Aluminum Alloys (Cohn, 469)

Alloy, temperature of tensile test, and medium in which test was made	Description of conditions of test	Tensile test		Remarks
		Tensile strength	Elongation in 2 inches	
Alloy consisting of 9.40 per cent zinc, 0.32 per cent copper, and 0.39 per cent magnesium extruded (and drawn). Tested at:		Lbs. in.^{2}	Per ct.	
0°, ice water	Tested as noted in column 1	45 300	16.0	Some fine cracks.
20°, air	do	45 900	16.1	Many cracks.
20°, air	Held in water at 70° for 1 hour in contact with iron; tested (column 1).	45 000	15.3	Specimen covered with cracks.
20°, water	Held in water at 20° for 2 hours in contact with iron before testing (column 1).	38 500	(a) 6.4	Do.
70°, water	Held in water at 70° for ½ hour; tested (column 1).	33 000 37 000	5–6 (a)	Do.
70°, water	Held in water at 70° for 1 hour; tested (column 1).	31 600	4.2	Do.
70°, oil	Held in oil at 70° for 1 hour; tested (column 1).	40 000	11.5	Some fine cracks.
Above alloy, annealed at 400° C:				
0°, ice water		44 000	21.1	
20°, air		42 600	20.8	
70°, water		35 800	17.4	
Duralumin, heat treated:				
0°, ice water		64 400	20	
20°, air		62 400	20	
70°, water		60 000	20	
Duralumin, heat treated and cold worked:				
0°, ice water		75 300	6.9	
20°, air		76 000	6.1	
20°, water	Held in water for 3 hours, in contact with iron; tested (column 1).	75 100	6.9	
70°, water		72 800	5.5	

[a] Broke outside of gage length.

These experiments were undertaken in order to explain the cracking which had been noticed of sections, rods, and tubes of this commercially much used alloy when stored and under no stress. Similar experience has been recorded in the case of the breaking and embrittling of hard-drawn aluminum-wire electric conductors.

It seems that some, at least, of the alloys of aluminum and the metal itself are subject to "season" or "corrosion cracking," so well known to those familiar with brass. Care must, therefore, be taken to protect such alloys from corrosion when under stress or when in the hard-drawn condition.

XII. COMPARISON OF DENSITY AND MECHANICAL PROPERTIES OF ALUMINUM ALLOYS WITH OTHER MATERIAL OF CONSTRUCTION

In Table 27 are compared the tensile properties for several materials used for construction in relation to their densities. Steels have been chosen for comparison which have approximately the same ductility as the duralumin. Douglas fir has been included as representing the best wood available for air-craft wood construction. The values given bring out the fact that, weight for weight, duralumin and similar light alloys are as strong as the best steels and for the same strength give greater stiffness. There appears to be no doubt of the adequacy of such light alloys as substitutes for both steel and wood in construction in which both strength and lightness are a prime requisite.

TABLE 27.—Comparison of Mechanical Properties of Some Materials of Construction

Material	Density	Tensile test						Ratios of some physical values of round bars of different materials of same length and of same weight to those of duralumin taken as unity					Ratios of some physical values of round bars of different materials of same length dimensioned to support the same working load to those of duralumin taken as unity (using values of allowable working stress given in column 8).				
		Modulus of elasticity	Tensile strength	Yield point	Elongation in 2 inches	Reduction of area	Working stress [a]	Ratio of working load using value of working stress given in column 8	Ratio of diameter	Ratio of transverse stiffness (simple beam) [b]	Ratio of tensile stiffness [b]	Ratio of energy absorbed in deformation up to yield point	Ratio of weight	Ratio of diameter	Ratio of transverse stiffness (simple beam) [b] [c]	Ratio of tensile stiffness [b]	Ratio of energy absorbed in deformation to yield point
	g/cm ^{3}	Lbs./in.^{2}×10^{-6}	Lbs./in.^{2}	Lbs./in.^{2}	Per cent	Per cent	Lbs./in.^{2}										
Heat-treated alloy steel [d]	7.80	30	150 000	115 000	14	45	55 000	1.32	0.60	0.39	1.08	1.75	0.75	0.52	0.53	0.82	1.26
Rolled alloy steel sheet [e]	7.80	30	100 000	75 000	20	....	37 000	.89	.60	.39	1.08	.74	1.12	.64	.88	1.22	.85
Rolled carbon steel sheet [f]	7.80	30	75 000	45 000	25	....	23 000	.55	.60	.39	1.08	.27	1.82	.81	1.70	1.96	.50
Rolled and heat-treated duralumin	2.85	10	60 000	30 000	15	....	15 000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Rolled zinc-aluminum-copper alloy [g]	* 3.29	10	71 000	61 000	21	38	30 000	1.74	.93	.74	.87	3.60	.58	.71	.39	.50	2.06
	† 3.29	10	52 400	36 000	18	....	18 000	1.04	.93	.74	.87	1.24	.98	.91	.77	.83	1.20
Douglas fir [h]	.47	1.64	6 100	4 400	....	....	1 200	.48	2.46	5.88	.99	.79	2.06	3.54	4.70	2.05	1.63

[a] Using working stress equal to $\frac{\text{yield stress}}{2}$.

[b] Stiffness defined as $\frac{\text{total load}}{\text{deflection}}$, and is taken not of the material but of the bars themselves, which are of different dimensions for different materials.

[c] The comparisons in this column are made on the basis of bars of equal transverse working load, using working stress values of column 8.

[d] Commercial nickel, nickel-chromium or chrome-vanadium steel, according to specification 3S5 of the International Aircraft Standards Board, 1917.

[e] Commercial nickel, nickel-chromium or chrome-vanadium steel, according to specification 3S28 of the International Aircraft Standards Board, 1917.

[f] Commercial carbon steel, of carbon content from 0.15 to 0.30 per cent, according to specification 3S27 of the International Aircraft Standards Board, 1917.

[g] Containing 25 per cent zinc and 3 per cent copper in form (*) of one-half inch hot-rolled bar and (†) as rolled, 0.156 inch sheet, annealed (Rosenhain-Archbutt).

[h] Values given were adopted by American Railway Engineering Association. These values are determined in the transverse test.

XIII. "HEAVY" ALUMINUM ALLOYS

The use of aluminum as an alloying element is perhaps as extensive in alloys containing an excess of other metals as in the light alloys.

Alloys of from 3 to 10 per cent of aluminum in copper are manufactured in both the cast and in the rolled or wrought form under the name of aluminum bronzes. The properties of these alloys are described by Corse and Comstock (476), Corse (479, 480), Read (487), Carpenter and Edwards (496), and many others.

An aluminum bronze containing 10 per cent of aluminum will have the following tensile properties when cast to size (476):

Tensile strength, 75 000 pounds per square inch; elongation in 2 inches, 24 per cent.

A modification of this alloy containing 1 per cent of iron, 10 per cent of aluminum, and treated with titanium will give the following tensile properties when cast to size:[9] Tensile strength, 80 000 pounds per square inch; elongation in 2 inches, 30 per cent.

Aluminum bronze for rolling containing usually about 7.5 per cent of aluminum. This alloy when rolled will give the following approximate values of the tensile properties: Tensile strength, 80 000 to 90 000 pounds per square inch; yield point, 15 000 to 20 000 pounds per square inch; elongation in 2 inches, 20 to 30 per cent.

Aluminum is extensively used as a deoxidizer in both iron, steel, and nonferrous metals, and also in the manufacture of steel to produce blowhole-free ingots of steel. Brinell (506) finds that this effect of aluminum of preventing blowhole formation in acid-steel ingots is about 18 times as great as that of silicon and about 90 times as great as that of manganese. He gives the formula:

$$D = \mathrm{Mn} + 5.2\mathrm{Si} + 90\mathrm{Al}$$

If $D = 2$, blowhole-free acid-steel ingots are produced, 24 by 24 cm, when poured into an almost cold iron mold 5 cm thick.

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[9] Private communication from W. M. Corse.

APPENDIX

1. DEFINITIONS OF PHYSICAL TERMS

Absorption Index.—When monochromatic light traverses a distance equal to its own wave length, λ, in a material the ratio of the amplitude of the emergent J'_λ to that of the entering light, J_λ°

$$\frac{J_\lambda'}{J_\lambda^\circ}=e^{-2\pi\kappa}$$

when κ is the absorption index.

(A variety of usage prevails regarding the definition of this term. This definition is used by the Smithsonian physical tables.)

Density.—The density of a substance is the mass per unit volume. It is usually expressed in terms of grams per cubic centimeter.

Electrical Conductivity and Resistivity (χ, ρ).—There are two methods of expressing electrical resistivity in common use, each being defined quantitatively in terms of the resistance of a unit specimen. The volume resistivity is ρ in the equation

$$R=\frac{\rho l}{s}$$

in which R = resistance, l = length, and s = cross section. The volume resistivity thus defined may be expressed in various units, such as microhm-cm (michrom per centimeter cube), ohms per foot of a uniform wire 1 mil in diameter, etc. The commonly used units, in abbreviated terminology, are:

microhm-cm.
microhm-inch.
ohm (meter, mm).
ohm (meter, mm^2).
ohm (mil, foot).

The other kind of resistivity is mass resistivity, and is defined as δ in the equation

$$R=\frac{\delta l^2}{m}$$

in which m = mass of the wire. The usual units of mass resistivity are:

ohm (meter, gram).
ohm (mile, pound).

Per Cent Conductivity.—The term "conductivity" means the reciprocal of resistivity, but it is used very little in wire calculations. In connection with copper, however, extensive use is made of the per cent conductivity, which is calculated in practice by dividing the resistivity of the International Annealed Copper Standard at 20° C by the resistivity of the sample at 20° C.

Temperature Coefficient of Resistance.—The temperature coefficient of electrical resistance is the fractional change of resistance per degree change of temperature. Its value varies with the temperature, and hence the temperature from which the resistance change is measured must always be stated or understood. For a temperature t_1, the temperature coefficient t_1 is defined, for a metal like copper, by

$$R_t = R_{t_1}[1 + \alpha_{t_1}(t - t_1)],$$

in which R_{t_1} = resistance at the temperature t_1 and R_t = resistance at any other temperature t. The temperature coefficient that is usually used at 20°, for example, is

$$\alpha_{20} = \frac{R_t - R_{20}}{R_{20}(t - 20)}$$

Boiling Point.—The boiling point of a liquid is the temperature at which it boils under atmospheric pressure, or better the temperature at which its vapor pressure is equal to the external pressure.

Brinell Test.—An indentation is made, by pressure, on a polished surface of the material, using a hardened steel ball. There are several ways of expressing the hardness:

The commonest definition of the Brinell hardness is the pressure in kilograms per unit area (square millimeters) of the spherical indentation. (Hardness numeral = H. N.)

$$\text{H. N.} = \frac{\text{Pressure}}{\text{area of spherical indentation}} = \frac{P}{t\pi D}$$

where

$$t = D/_2 - \sqrt{D^2/_4 - d^2/_4}$$

P = pressure used.
t = depth of indentation.
D = diameter of sphere.
d = diameter of indentation.

Electrolytic Solution Potential (E).—At the junction of a metal and any conducting liquid there is developed a solution potential, which is a measure of the free energy change of the chemical reaction which is possible at the surface of the metal liquid. In particular if the chemical reaction consists in the solution of the metal, forming ions, the emf is given by the formula

$$E=\frac{RT}{nF}\log_e\frac{P}{p}$$

R = the gas constant.
T = absolute temperature.
n = valence of metal.
F = 96 500 coulombs, the Faraday constant.
P = solution pressure of metal.
p = osmotic pressure of metal ion formed in solution.

In any electrolytic cell the sum or difference of two such potentials is measured, one of which may be a standard electrode; e. g., the hydrogen or the calomel electrode. The emf of an electrolytic cell of the following type: Metal – solution – normal hydrogen electrode is often called the single emf (ϵ_λ) for the metal in the solution; i. e., arbitrarily assuming the emf of the normal hydrogen electrode to be zero.

Emissivity (E *or* E_λ).—The coefficient of emissivity E for any material represents the ratio $\frac{J'_\lambda}{J_\lambda}$ of the intensity, J'_λ, of radiation of some particular wave length or color, λ, emitted by the material at an absolute temperature T to that, J_λ, emitted by a black body radiator at the same temperature.

The coefficient of total emissivity E for any material represents that ratio $\frac{J_1}{J}$ of the intensity of radiation of all wave lengths, J_1, emitted by the material at an absolute temperature, T, to that, J, emitted by a black body radiator at the same temperature.

This coefficient is always less than 1, and for metals is equal to 1 minus the reflection coefficient for normal incidence (Kirchhoff's law).

For any optical pyrometer using monochromatic light a value of the observed or "black body" temperature of any substance (not inclosed) is reduced to the true temperature by the following formula:

$$\frac{1}{T}-\frac{1}{T_0}=\frac{\lambda\log_{10}E_\lambda}{6232}$$

T = true absolute temperature.
T_0 = observed absolute temperature.
λ = wave length in microhm (0.001 mm).
E_λ = relative emissivity of substance for wave length.

Erichsen Test.—This test is carried out to determine the ductility of sheets. An indentation is made in the sheet with a die with hemispherical end. The greatest depth of indentation which can be made without incipient cracking of the sheet, measured in inches or millimeters, is known as the Erichsen value for the sheet.

Heat of Fusion.—The heat of fusion of a substance is the quantity of heat absorbed in the transformation of unit mass (1 g) of the solid substance to the liquid state at the same temperature.

Magnetic Properties.—The usual magnetic characteristics of a substance are given either by the permeability, μ, or the susceptibility, κ. Permeability is the ratio of the magnetic induction (B: in Maxwell's per square centimeter) to the magnetizing force (H: in Gilbert's per centimeter). This is indicated by the relation

$$\kappa=\frac{B}{H}$$

Susceptibility is given, in corresponding units, by

$$\kappa=\frac{\mu-1}{4\pi}$$

For all materials except iron and a few other ferro-magnetic metals μ is very nearly unity and κ is only a few millionths. When κ is positive in sign the substance is diamagnetic. The susceptibility as thus defined is sometimes called volume susceptibility and indicted by κ_v. A quantity called mass susceptibility is also used, and is equal to the volume susceptibility divided by the density of the material; it is represented by κ_m.

Melting Point.—The melting or fusing point of a substance is the temperature at which it fuses (under atmospheric pressure), or more accurately the temperature at which the solid and the liquid metal are in equilibrium with each other.

Peltier Effect (π).—When at the junction of two metals current flows from one to the other, heat is in general absorbed or libererated (see "thermoelectromotive force" below); the coefficient, the amount of heat liberated when a unit quantity of electricity flows across the junction, is known as π (measured either in calories per coulomb or in volts), the Peltier Effect.

Refractive Index.—The ratio of the velocity of light in vacuum to that in any material is called the refractive index (η) of that material. (This physical quantity ceases to have a meaning at or near an absorption band in the material.)

Scleroscope Test (*Shore*).—A hardened hammer falls from a constant height onto a polished surface of the material, and the distance of rebound is measured on a scale 10 inches long, divided into 140 equal parts. The scleroscope hardness is expressed as the distance of rebound on this arbitrary scale the value 100 representing the hardness on this scale of hardened steel.

Specific Heat (σ).—The true specific heat of a substance is $\frac{du}{dt}$ when u is the total internal heat or energy of unit mass of the substance. The mean specific heat is defined as $\frac{q}{t_1-t_2}$ per unit mass when q is the quantity of heat absorbed during a temperature change from t_2 to t_1. It is generally considered as the quantity of heat (calories) required to raise the temperature of unit mass (grams) by unity (degrees centigrade), either at constant volume or at constant pressure. Unless otherwise noted the specific heat of solids refers to that at constant (atmosperic) pressure. The true specific heat (constant pressure) of metals may usually be expressed sufficiently by an equation of the type

$$\sigma = A + Bt + (Ct^2 \ldots\ldots.)$$

Tensile Test.—The quantities determined in the tension test are the following:

The *ultimate tensile strength* is the maximum load per unit area of original cross section borne by the material.

The *yield point* (American Society for Testing Material) is the load per unit of original cross section at which a marked increase in the deformation of the specimen occurs without increase of load.

The *elastic limit* (American Society for Testing Materials) is the greatest load per unit of original cross section which does not produce a permanent set.

The *proportional limit* (American Society for Testing Materials) is the load per unit of original cross section at which the deformations cease to be directly proportional to the loads.

The *percentage elongation* is the ratio of the increase of length at rupture between arbitrary points on the specimens to this original length.

The *percentage reduction of area* is the ratio of the decrease of cross section at the "neck" or most reduced section at rupture to the original section.

Thermal conductivity (λ).—The coefficient of thermal conductivity (λ) expresses the quantity of heat (small calories) which flows in unit time (seconds) across a unit cube (centimeter) of the material whose opposite faces differ in temperature by unity (1° C). Its *temperature coefficient* is expressed as

$$\alpha_{to} = \frac{\lambda_t - \lambda_{to}}{\lambda_{to}(t-to)}.$$

Thermal Expansion.—If l_t is any linear dimension of a solid at any temperature, $\frac{1}{l}\frac{dl}{dt}$ is the linear thermal expansivity of that solid in the direction of 1. It is not in general proportional to the temperature except approximately over small temperature intervals, but may be expressed in the following manner:

$$\frac{1}{l}\frac{dl}{dt}=a+bt+ct^2\cdots$$

For small temperature intervals a mean coefficient (α) is often determined; i. e.,

$$\alpha_{to}=\frac{l_t-l_{to}}{l_{to}({}^{t}-{}^{to})}$$

Thermoelectromotive Force (E).—In an electric circuit composed of two dissimilar conductors, the two junctions being at different temperatures, there exists in general an electromotive force, called the thermoelectromotive force, between the two metals, the value of which is a function both of the temperature and the difference of temperature between the two junctions. It is shown thermodynamically that this emf is related to the Thomson and Peltier effects in the following manner:

$$\left.\begin{aligned}\pi&=\frac{T}{J}\,\frac{dE}{dt}\\ \sigma_1-\sigma_2&=-\frac{T}{J}\,\frac{d^2E}{dt^2}\end{aligned}\right\}\ \text{and expressed in calories per coulomb}\quad J=\frac{418\ \text{dynes}\times 10^6}{\text{calories}}$$

when E is the thermal emf, T the absolute temperature, $\frac{dE}{dt}$ the thermoelectric power (see below), and $\sigma_1-\sigma_2$ the difference in the Thomson effect of two materials. The form of the function $E=E(T)$ is not known. In general the equation $\frac{dE}{dt}=A+BT$ satisfactorily fits the experimental data over a limited range of temperature of a few hundred degrees.

It has been shown that the Thomson effect for lead is practically zero. This metal has served as a comparison metal in studying the thermoelectric forces of others.

Thermoelectric Power.—If E is the thermoelectromotive force of any two dissimilar metals, $\frac{dE}{dt}=$ the thermoelectric power; it is at any temperature therefore approximately the thermal emf of a couple of which the temperatures of the two junctions differ by 1 °C.

The Thomson Effect.—When a current flows in a conductor from a point at one temperature to one at another, heat is in general liberated, or absorbed, and an emf or counter emf is produced. The coefficient of the Thomson effect is the amount of heat liberated or absorbed when unit quantity of electricity flows from a point at temperature, t, to one at a temperature, $t+dt$, and is equal to σdt calories per coulomb where σ is the so-called Thomson specific heat of electricity. It is called positive for any material when heat is generated in that material as a current flows from a region of higher to one of lower temperature.

2. SPECIFICATIONS FOR ALUMINUM AND ITS LIGHT ALLOYS

There are given below references to published specifications for commercial aluminum and its light alloys, some of which are reproduced in full:

a. ALUMINUM

(*a*) Ingot aluminum (U. S. Navy Department, No. 47A1a, 1915; International Aircraft Standards Board, No. 2N1, 1917).

(*b*) Aluminum sheet (International Aircraft Standards Board, No. 3N12, 1917).

(*c*) Aluminum bars (International Aircraft Standards Board, No. 3N23, 1918).

(*d*) Aluminum tubes (International Aircraft Standards Board, No. 3N20, 1917).

b. ALUMINUM ALLOYS

(*e*) No. 12 casting alloy (Society of Automotive Engineers, No. 30, 1912; International Aircraft Standards Board, No. 3N11, 1917).

(*f*) No. 31 casting alloy (Society of Automotive Engineers, No. 31, 1912).

(*g*) Casting alloys (U. S. Navy Department, No. 49A1, 1915).

(*h*) Duralumin sheet (International Aircraft Standards Board, No. 3N16, 1917).

(*i*) Duralumin bars (International Aircraft Standards Board, No. 3N18, 1918).

(*j*) Duralumin tubes (International Aircraft Standards Board, No. 3N17, 1918).

Specifications for Ingot Aluminum

[International aircraft standards, 2N1, October, 1917]

General.—The general specifications, 1G1, shall form, according to their applicability, a part of these specifications.

Material.—2. (*a*) Three grades of ingot aluminum are recognized:

		Per cent
Standard No. 1, aluminum	not less than	99.0
Standard No. 2, aluminum	do	98.0
Special, aluminum	do	99.5

Analysis.—(*b*) One sample ingot of each heat shall be taken for analysis, and in any case not less than one sample ingot from each 500 pounds (226.8 kg.) of metal.

(*c*) Samples shall be obtained by drilling completely through the ingot or half through from top to bottom. The weight of the samples obtained by drilling the ingot or ingots should not be less than 120 grams.

Manufacture.—3. No scrap shall be used except such as shall accumulate at the manufacturer's plants from material of the same composition and of their own make.

SPECIFICATIONS FOR ALUMINUM ALLOY CASTINGS

[International Aircraft Standards, 3N11, October, 1917]

GENERAL.—1. The general specifications, 1G1, shall form, according to their applicability, a part of these specifications.

USE.—2. Two alloys are described:

Alloy 1 is suitable for crank cases and general purposes for which tensile strength is required.

Alloy 2 is suitable for die castings for bearing surfaces and pistons for use at higher temperatures.

MATERIAL.—3. (*a*) These alloys shall have the following compositions:

	Alloy No. 1	Alloy No. 2
Specific gravity	2.80	2.95
Copper	7.0 to 8.5 per cent	9.25 to 10.75 per cent
Impurities	Not over 1.7 per cent	Not over 1.7 per cent
Aluminum	Balance	Balance

(*b*) Ingot aluminum of grades Standard No. 1 and Standard No. 2 may be used in making these alloys.

WORKMANSHIP AND FINISH.—4. (*a*) The castings are to be clean, sound, and free from blowholes, misruns, cracks, shrinks, and similar defects.

(*b*) No repairing, plugging, or welding will be allowed unless previous permission in writing has been obtained from the inspector; such permission will only be given when the defects to be repaired are small and do not affect the strength of the casting.

PHYSICAL PROPERTIES AND TESTS.—5. (*a*) The alloys shall have the following minimum physical properties:

Tensile Test.—

	Alloy No. 1, sand cast	Alloy No. 2, sand or die cast
Tensile strength	18,000 pounds per square inch (12.65 kg/mm ^{2}).	18,000 pounds per square inch (12.65 kg/mm ^{2}).
Elongation in 2 inches (50.8 mm	1.5 per cent	

(*b*) These alloys when poured hot into very thin difficult sections, such as crankcase pans, carburetors, and manifolds, shall not be required to show a greater tensile strength than 14 000 pounds per square inch (9.84 kg/mm ^{2}).

SELECTION OF TEST SPECIMENS.—6. (*a*) At least one sample is to be cast to represent each crank case or other large casting; this is to be attached to the casting; no chills may be applied to the test specimen.

(*b*) The number of test samples for smaller castings is left to the discretion of the inspector, who is to satisfy himself that the quality of the metal used is satisfactory and uniform.

(*c*) The latter samples are to be cast separate, but also in sand and without the use of chills.

DIMENSIONS AND TOLERANCES.—7. (*a*) The castings are to be accurately in accordance with the drawings, and sufficient allowance is to be made to enable them to be machined where required to the finished dimensions without leaving evidence of the cast surface.

(*b*) A tolerance of 3 per cent is allowed in the weight of the individual castings.

SPECIFICATIONS FOR SHEET ALUMINUM

[International Aircraft Standards, 3N12, October, 1917]

GENERAL.—1. The general specifications, 1G1, shall form, according to their applicability, a part of these specifications.

MATERIAL.—2. (*a*) Two grades are recognized: Standard No. 1, aluminum, not less than 99 per cent; standard No. 2, aluminum, not less than 98 per cent.

Analysis.—(*b*) Samples for analysis shall be obtained from a random sheet, representing each 500 pounds (226.8 kg) of aluminum, or any lot weighing less than 500 pounds (226.8 kg), as agreed upon between the seller and the purchaser.

MANUFACTURE.—3. No scrap shall be used except such as shall accumulate at the manufacturer's plant from material of the same composition and of their manufacture.

WORKMANSHIP AND FINISH.—4. All sheets shall be sound, flat, free from buckles, seams, discoloration, or other surface defects.

PHYSICAL PROPERTIES AND TESTS.—*Tensile test.*—*5.* (*a*):

Grade	Minimum tensile strength	Minimum elongation in 2 inches (50.8 mm)
Soft-annealed	12,000 pounds per square inch (8.44 kg/mm^2)	30 per cent.
Half-hard	18,000 pounds per square inch (12.65 kg/mm^2)	10 per cent.
Hard.rolled	22,000 pounds per square inch (15.47 kg/mm^2)	2 per cent.

Bend test.—(*b*) Soft and half-hard sheets shall withstand being bent double in any direction over a pin having a radius equal to the thickness of the sheet without cracking.

SELECTION OF TEST SPECIMENS.—6. Test pieces shall be cut from random sheets representing each 500 pounds (226.8 kg) of aluminum or any lot weighing less than 500 pounds (226.8 kg) as agreed upon between the seller and the purchaser. Test pieces may be used for purposes of analysis as under paragraph 2 (*b*).

DIMENSIONS AND TOLERANCES.—7. Tolerances on all sheets shall be as follows:

Thickness, American wire gage (B. & S.)	Tolerances	
	Inch	Millimeter
10–11	0.003	0.08
12–14	.003	.08
15–17	.003	.08
18–20	.002	.05
21–23	.002	.05
24–26	.002	.05

SPECIFICATIONS FOR ALUMINUM ALLOY SHEET

[International aircraft standards, 3N16, December, 1917]

GENERAL.—1. The general specifications, 1G1, shall form, according to their applicability, a part of these specifications.

MATERIAL.—2. The aluminum alloy of these sheets shall be made from standard No. 1 aluminum conforming to I. A. S. B. specification 2N1. The specific gravity of the aluminum alloy shall not be greater than 2.85.

MANUFACTURE.—3. No scrap shall be used other than that produced in the manufacturer's own plants and which is of the same composition as the material specified.

WORKMANSHIP AND FINISH.—4. (*a*) All sheets shall be sound, flat, free from buckles, seams, discoloration, or other surface defects.

(*b*) Any sheet may be rejected because of injurious defects or faults in manufacture at any time, notwithstanding that it has previously passed inspection. It shall be returned to the manufacturer at the latter's expense. This clause shall not be taken to apply to materials fabricated after export.

PHYSICAL PROPERTIES AND TESTS.—5. The sheets may be specified in either of two tempers as desired. Specimens cut in any direction from the sheets must have the following physical properties:

Tensile Test.—(*a*)

	Temper 1		Temper 2	
	Pounds per square inch	Kilograms per square millimeter	Pounds per square inch	Kilograms per square millimeter
Minimum tensile strength..............	55,000	38.6	50,000	35.1
Minimum yield point..................	25,000	17.5	25,000	17.5
Minimum elongation in 2 inches........	15 per cent		20 per cent	

Bend Test.—(*b*) Strips cut from sheets of either temper shall withstand being bent cold through an angle of 180° around a diameter equal to four times the thickness of the sheet.

SELECTION OF TEST SPECIMENS.—6. Test specimens shall be cut from a sheet selected from each 500 pounds or individual lot submitted of less than 500 pounds.

DIMENSIONS AND TOLERANCES.—7. The tolerances upon sheets shall be those given in the table below:

Brown & Sharpe gage	Thickness	Tolerance	Thickness	Tolerance
	Inch	*Inch*	*Millimeters*	*Millimeter*
10–17	0.1019–0.0453	±0.003	2.588–1.151	0.076
18–26	.0403– .0159	± .002	1.024– .404	.051

DELIVERY, SHIPPING, AND PACKING.—8. The sheets shall be delivered in boxes of gross weight not greater than 220 pounds (100 kg).

SPECIFICATIONS FOR ALUMINUM ALLOY TUBING

[International aircraft standards, 3N17, March, 1918]

GENERAL.—1. The general specifications, 1G1, shall form, according to their applicability, a part of these specifications.

MATERIAL.—2. The specific gravity of the aluminum alloy of this specification shall not be greater than 2.85.

MANUFACTURE.—3. No scrap shall be used in the manufacture of this tubing other than that produced in the manufacturer's own plants and which is of the same composition as the material specified.

WORKMANSHIP AND FINISH.—4. The tubing shall be straight, clean, smooth, and free from all injurious defects both inside and outside.

PHYSICAL PROPERTIES.—5. *Tensile Test.*—(*a*)

	Minimum tensile strength		Minimum yield point		Elongation in 2 inches, per cent
	Pounds per square inch	Kilograms per square millimeter	Pounds per square inch	Kilograms per square millimeter	
Temper 1	55,000	38.6	35,000	24.6	12
Temper 2	50,000	35.1	25,000	17.6	20

Bend Test.—(*b*) A section of the tubing of a length approximately equal to the outside diameter of the finished tube shall withstand being flattened into an oval of which the minor interior axis shall be not less than 4 for temper 2, and 6 times for temper 1, the thickness of the wall of the original tube.

Hydrostatic Pressure Test.—(*c*) Each tube shall be subjected to a hydrostatic pressure which will develop a tensile stress of 7,000 pounds per square inch (4.92 kg/mm^2) in the tube, but in no case shall a test pressure of more than 1,000 pounds per square inch (0.703 kg/mm^2) be required. Each tube must withstand this test without cracks, flaws, leaks, or other defects such as bulging.[10]

SELECTION OF TEST SPECIMENS.—6. Each bar shall be subjected to a hydrostatic test. A tensile and a bend test specimen shall be taken from each 100 feet of tubing or lot of less than 100 feet.

DIMENSIONS AND TOLERANCES.—7. (*a*) The following tolerances shall be allowed on aluminum alloy tubing.

Outside Diameter.—(*b*) For tubes less than 2 inches in outside diameter, ±0.003 inch; for tubes from 2 to 3 inches in diameter, ±0.005 inch.

Wall Thickness.—(*c*) The wall thickness of the tube shall be not less than the specified gage and shall not be exceeded by more than 0.004 inch for tubes less than 0.008 inch in wall thickness nor by more than 5 per cent for thicker tubes.

Variation.—(*d*) The variation in thickness, due to eccentricity of the bore may not exceed ±10 per cent of the specified wall thickness.

Length.—(*e*) When tubing is ordered in definite lengths, no length furnished shall be less than that specified.

INGOT ALUMINUM

[Navy Department Specifications. 47A1a, July 1, 1915. Superseding 47A1, Oct. 20, 1910]

GENERAL INSTRUCTIONS.—1. General specifications for the inspection of material, issued by the Navy Department, in effect at date of opening bids, shall form part of these specifications.

PROCESS OF MANUFACTURE.—2. Aluminum to be manufactured from bauxite or other high grade ore. Metal reclaimed from scrap will not be acceptable under these specifications.

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[10] The pressure to be applied shall be calculated from the formula

$$P=\frac{7,000\,T}{R}$$

Where P= the hydrostatic pressure in pounds per square inch.
T= the thickness of the tube wall in inches.
R= the internal radius of the tube.

CHEMICAL PROPERTIES.—3. The chemical requirements shall be in accordance with the following table:

Aluminum (minimum)	Iron (maximum)	Silicon (maximum)	Other impurities (maximum)	Sum of iron and silicon and other impurities
Per cent 99.40	*Per cent* 0.60	*Per cent* 0.60	*Per cent* 0.10	*Per cent* 0.60

SAMPLING.—4. At least one ingot shall be taken at random from each lot of 2000 pounds or fraction thereof. Not less than four ingots shall be samples for the entire shipment. Samples shall be taken by drilling with a dry drill through each ingot from the top to within ¼ inch of the bottom. The drillings from the first ¼ inch shall be discarded. Drillings from all the ingots representing the shipment shall be thoroughly mixed and a portion taken therefrom for analysis unless the question of homogenity of the metal arises, in which case separate analysis shall be made as may be deemed expedient by the inspector.

FORM AND FINISH.—5. Ingots to be of commercial standard form and shape, to be clean, free from adhering dirt, slag, or foreign matter, and shall have normal and uniform shrinkages.

PURPOSE FOR WHICH USED.—6. Material bought under these specifications is suitable for the manufacture of casting and ingots for forging purposes of aluminum, aluminum bronze, manganese bronze, etc.

SPECIFICATIONS, WHERE OBTAINABLE.—Copies of the above specifications can be obtained upon application to the various Navy pay offices or to the Bureau of Supplies and Accounts, Navy Department, Washington, D. C.

REFERENCES—

S. E., 149078–687–S, May 15, 1915.
C. & R., Z47A1a–M, May 24, 1915.
S. & A., 380–15.

ALUMINUM OR LIGHT ALLOY CASTINGS

[Navy Department Specifications. 49A1, July 1, 1915]

GENERAL INSTRUCTION.—1. General specifications for the inspection of material, issued by the Navy Department and in effect at date of opening of bids, shall form part of these specifications.

SCRAP.—2. Miscellaneous scrap shall not be used in the manufacture. Analyzed ingots and returns from material of the same composition of the manufacturer's own make may be used.

CHEMICAL COMPOSITION.—3. The chemical composition shall be as follows:

Aluminum (minimum)	Copper (maximum)	Iron (maximum)	Silicon (maximum)	Manganese (maximum)
Per cent 94	*Per cent* 6	*Per cent* 0.50	*Per cent* 0.50	*Per cent* 3

Physical Characteristics.—4. The physical characteristics shall be as follows: Minimum tensile strength, 18000 pounds; minimum elongation, 8 per cent.

Workmanship.—5. Castings must be in accordance with drawings and specifications, free from cracks, flaws, shrinks, and other defects.

Physical Test.—6. A "cast-to-size" separately poured test bar may be used for all castings up to 250 pounds in weight. For castings above 250 pounds in weight the test bar must be attached to the casting. Material for at least two bars shall be cast from each melt. The color of the fracture section and the grain of the metal must be uniform. Test bars showing "local physical defects" will be replaced by sound bars.

Purposes for which Used.—7. Material is suitable for the following: Objects not liable to corrosion where lightness is desirable, muzzle disks, dotter parts, handwheels, brackets, etc., not requiring special strength.

Specifications, where Obtainable.—Copies of the above specifications can be obtained upon application to the Bureau of Supplies and Accounts, Navy Department, Washington, D. C.

References:

S. E., 155466–687–S, May 22, 1915.
C. & R., SPS–M, May 29, 1915.
S. & A., 380–1227.

ALUMINUM ALLOY No. 1

[S. A. E. Specification No. 30 (revised July, 1912). This is one of the lightest of the alluminum alloys, possessing a high degree of strength, and can be used where a tough, light alloy of these characteristics is required in automobile construction]

	Per cent
Aluminum, not less than	90. 00
Copper	8. 50–7. 00

Total impurities shall not exceed 1.7 per cent, of which not over 0.2 per cent shall be zinc. No other impurities than carbon, silicon, iron, zinc, and manganese shall be allowed.

ALUNINUM ALLOY No. 2

[S. A. E. Specification No. 31. This mixture possesses strength, closeness of grain, and can be cast solid and free from blowholes. It is a light metal, its specific gravity being in the neighborhood of 3]

	Per cent
Aluminum, not less than	80. 00
Zinc, not over	15. 00
Copper, between	2. 00 and 3. 00
Manganese, not to exceed	0. 40

Total impurities shall not exceed 1.65 per cent, of which not more than 0.50 per cent should be silicon, not more than 1 per cent iron, and not more than 0.15 per cent lead.

3. BIBLIOGRAPHY

[The Bureau bibliography on this subject was supplemented by a very comprehensive one assembled by the library of the United Engineering Societies and presented to the Bureau by Prof. Zay Jeffries]

Text references	Year	Name and title
		REFERENCE BOOKS
1	....	Aluminum Co. of America, Pittsburgh, Pa., Aluminum electrical conductors.
2	1916	Smithsonian Physical Tables.
3	1915	British Aluminum Co., Aluminium facts and figures.
4	1914	Krause, H., Das aluminium.
5	1912	Landolt-Börnstein-Roth, Physikalisch-Chemische Tabellen.
6	1912	Pitaval, R., Die elektrochemische Industrie Frankreichs, pp. 69–84.
7	1912	Flusin, G., L'industrie de l'aluminium.
8	1911	U. S. Geological Survey, Washington, Mineral Resources of the United States, 1910—Pt. I, Metals, pp. 722–723.
9	1909	Gmelin-Kraut, Handbuch der anorganischen Chemie.
10	1909	Aluminum Co. of America, Pittsburgh, Pa., Methods of working aluminum.
11	1909	Aluminum Co. of America, Pittsburgh, Pa., Alloys of aluminum.
12	1909	Aluminum Co. of America, Pittsburgh, Pa., Properties of aluminum.
13	1909	Aluminum Co. of America, Pittsburgh, Pa., Fabricated aluminum.
14	1908	Richards, J. W., Metallurgical calculations, pt. 3, pp. 362 et seq.
15	1908	Borchers, W., Electric furnaces, The production of heat from electrical energy and the construction of electric furnaces, pp. 5–27, 210–211.
16	1905	Minet, Adolphe, The production of aluminum and its industrial use.
17	1905	Goldschmidt, H., Aluminothermics, Internat. Elec. Cong. Trans., 2, p. 85.
18	1904	Buck, H. W., Use of aluminum as an electrical conductor, Internat. Elec. Cong. Trans. 2, p. 313.
19	1904	Schnabel, C., Handbuch der Metallhüttenkunde.
20	1903	Winterler, F., Die Aluminum-Industrie.
21	1902	Minet, Adolphe, Die Gewinnung des Aluminiums und dessen Bedeutung für Handel und Industrie.
22	1897	Pittsburgh Reduction Co., Aluminium and aluminium alloys.
23	1897	British Aluminium Co. (Ltd.), Notes on aluminium and its alloys.
24	1896	Waldo, L., Aluminium bronze seamless tubing.
25	1890	Richards, J. W., Aluminum: Its history, properties, including its alloys.
		COMMERCIAL ALUMINUM
26	1918	The Aluminum Industry in 1917, Eng. and Min. Jour., 1918, p. 67, Jan. 15.
27	1915	U. S. Geological Survey, Mineral Resources of the United States, p. 166.
28	1910	Sheet aluminium, its advantages, Mêtaux et Alliages, Dec., 1910, p. 161
		Composition
29	1916	Clennell, J. E., Estimating metallic aluminium in aluminium dust, Eng. and Min. Jour., **102**, Aug. 12, 1916, No. 7, pp. 309–310.
30	1916	Withey, Analysis of aluminum and its alloys, Jour. Inst. Metals, **15**, p. 207.
31	1913	Czochralski, J., Chemical analysis of aluminium, Z. anorg. Chem., **26**, pp. 501–503.
32	1913	Boulanger, C., and Bardet, J., Presence of gallium in commercial aluminium, and its separation, C. R., **157**, pp. 718–719.
33	1909	Kohn-Abrest, E., Analysis of aluminium, direct determination of metallic aluminium, Ann. Chim. Anal., **14**, pp. 285–289.
34	1909	Delachanal, B., Gases occluded in common metals, C. R., **148**, pp. 561–563.
35	1908	Kohn-Abrest, E., Analysis of powdered aluminium, C. R., **147**, pp. 1293–1296.
36	1902	Goldschmidt, Silicon content of aluminium, Z. Elektrochemie, **8**, p. 123.
37	1902	Haber and Geipert, On the silicon content of aluminium, Z. Elektrochemie, **8**, pp. 163–164.
		Applications
38	1917	Richards, J. W., Aluminum, Met. and Chem. Eng.
39	1916	Reinhold, O. F., Modern developments of the aluminium industry, Metal Record and Electroplater, **11**, No. 5, pp. 127–131.
40	1915	Sherbondy, E. H., Analyzing heat flow; use of aluminium for automobile motor construction, Automobile, **33**, pp. 834–835.
41	1915	Clayden, A. L., Aluminium in automobile chassis, Automobile, **33**, No. 8, p. 330.
42	1915	Aluminium in the gas industry, J. Ind. Eng. Chem., **7**, pp. 255–256.
43	1915	Pannell, E. V., Recent developments in aluminium, Metal Industry (n. s.), **13**, pp. 453–455.
44	1915	Richards, J. W., The engineering uses of aluminium, Trans. Internat. Eng. Cong., 1915, pp. 17.
45	1915	Ruder, W. E., Calorizing metals, Trans. Am. Elec. Chem. Soc., **27**, p. 253.
46	1914	Schipper, J. Edward, Aluminum—a featherweight, The Automobile, **30**, pp. 673–677.
47	1914	British Aluminum Co. (Ltd.), Progress of aluminium, Bull. 144.
48	1914	Aluminum in automobile industry, Mêtaux et Alliages, **7**, p. 7; J. Inst. Metals, **12**, p. 295.
49	1913	Anonymous, Aluminium foil, Eng., **116**, p. 199.
50	1912	Anonymous, Report to the French Government by M. St. Germain on "aluminium coinage," Jour. du Four Electrique, 21, p. 148.
51	1912	Seligman, Rich., Modern uses of the metal aluminium, Sci. Amer. Suppl., **73**, No. 1904, pp. 405–407.
52	1911	Aluminium as a material for jigs, Amer. Machinist, p. 959.
53	1911	Nonferrous materials in railway work, J. Inst. Metals, **6**, pp. 74–135.
54	1909	Echevarri, J. T. W., Aluminium and some of its uses, Jour. Inst. Metals (London), **I**, pp. 125–143. Discussion, pp. 144–163.

3. BIBLIOGRAPHY—Continued

Text references	Year	Name and title
		COMMERCIAL ALUMINUM—Continued
		Applications—Continued
55	1907	Fournier, Industry of Aluminium foil, Nature (Paris), 35-II, pp. 147-150.
56	1906	Aluminium paints, Paint, Oil, and Drug Rev., Aug. 15, 1906, p. 30.
57	1906	Laren, Aluminium sheets as bookmaking material for blind persons, Archiv. f. Buchgewerbe, 43, p. 425.
58	1905	Bichel, C. E., Aluminum in explosives, Z. Anorg. Chemie, 18, pp. 1889-1892.
59	1904	Simon, Use of aluminum for weaving appliances (as a substitute for wood), Rev. Industrielle, 35, pp. 185-186.
60	1902	Weiss, R., Discharges with powdered aluminum and magnesium in tissue printing, Bull. Soc. Ind. de Mulhouse, No. 2, pp. 4-6.
61	1902	Pastrovich, P., Use of aluminium in the stearin industry, Chem. Rev. Fett.- u. Harz-Industrie, 9, No. 12, pp. 278-279.
62	1901	Blake, The use of Aluminum in the construction of instruments of precision, Trans. Amer. Inst. Min. Eng., 18, p. 503.
63	1897	Hunt, Utilization of Aluminum in the arts, Jour. Franklin Inst., 144, pp. 81-113.
64	1895	Yarrow, A. F., Aluminium for construction purposes, such as building torpedo boats, etc., Inst. Naval Architects; (Abst.) Eng., 59, pp. 470-472.
65	1894	Hart, Notes on the application of aluminium for naval construction, Mem. Soc. Ing. Civils de France, 47, p. 601.
		Electrical
66	1916	Wyssling, Prof. D., The use of aluminium for electric current transmission lines, Bull. Assoc. Suisse des Electriciens, VII, No. 5, pp. 121-134.
67	1914	British Aluminium Co., Pamphlet on Aluminium network feeders (Abst.), Iron and Coal Trades Rev., 89, p. 203.
68	1913	Anonymous, The use of aluminium for electric cables, Eng., 95, p. 812.
69	1913	Aluminum for electrical work, Eng., 95, p. 812.
70	1913	Pannell, E. V., Value of aluminium line conductors, Elec. News (Canadian), Nov. 15, 1913, pp. 46-47.
71	1910	Hobart, H. M., Bare aluminium cables, Elec. Times, 37, p. 356.
72	1910	Aluminium lightning arresters for underground cables, Jour. Elec. Power and Gas, Aug. 27, 1910.
73	1909	Buono, V. del, Use of aluminium as electrical conductor, Atti Assoc. Ellettroteen Ital., 13, pp. 261-289.
74	1904	Krull, F., Application of aluminium wire for electrical transmission, Z. anorg. Chem., 17, pp. 1058-1060.
75	1903	Stillwell, Use of aluminium for electric power transmission in the United States, Z. Ver. deutsch. Ing., 47, pp. 1826-1828.
76	1903	Kershaw, The use of aluminium as an electrical conductor, Electr. Rev. (N. Y.), 43, pp. 470-471.
77	1900	Guillaume, Use of aluminium for electrical conductors, Éclairage, Electrique, 22, pp. 321-328.
78	1900	Perrine and Baum, The use of aluminium line wire and some constants for transmission lines, Trans. Amer. Inst. Elec. Eng., 17, pp. 391-423.
79	1898	Wilson, E., Aluminium as an electrode in cells for direct and alternating currents (Aluminium rectifier cells), Proc. Roy. Soc., 63, pp. 329-347.
80	1898	Hunt, Aluminium as a rival of copper and brass for electrical conductors, Eng., 86, 1898, p. 81, Iron and Coal Trades Rev., 56, pp. 339-350.
		Vessels
81	1914	Anonymous, Aluminium and aluminium wares, Board of Trade Bull., No. 77, London.
82	1912	Wild, J., AluminiumGärgefässe, Z. ges. Brauw., 35, pp. 61-65; Chem. Zm. Bl., I, p. 1060.
83	1912	Bleisch, C., Aluminium fermentation and storage vats, Zeits. ges. Brauwesen, 35, pp. 49-53.
84	1911	Chapman, A. C., Investigation of aluminium with reference to its suitability for the construction of brewery plant, Jour. Inst. Bres., 17, pp. 660-678.
85	1905	Schoenfeld, F., Use of aluminium for beer filters, Wochenschr. f. Brauerei, 22, pp. 79-80.
86	1897	Norton, T. H., The use of aluminium condensers, J. Amer. Chem. Soc., 19, pp. 153-156.
		Deoxidation
87	1915	Aluminium as a check to sulphide segregation in steel ingots, Iron Age, 96, p. 130.
88	1905	Talbot, B., Use of aluminium to reduce segregation in steel ingots, Eng. News, 54, p. 443.
		Aluminothermy
89	1913	Hart, R. N., Welding, McGraw-Hill, New York City.
90	1909	Weston, F. E., and Ellis, H. R., Heats of combustion of aluminum, calcium, and magnesium, Faraday Soc. Trans.; (Abst.) J. Soc. Chem. Ind., 28, No. 2, p. 94.
91	1902	Bertin, H., Heating by Aluminium and its applications, Mem. de la Soc. des Ing. Civils de France, 1902, pp. 218-249.
92	1900	Matignon, C., Metallurgy founded on reduction with aluminium and the production of high temperatures, Moniteur Scientifique, June, 1900, pp. 353-366.
93	1898	Goldschmidt, New process for producing metals and alloys by means of Aluminium powder, Liebig's Annalen der Chemie, 301, pp. 19-28.
94	1898	Goldschmidt, H., and Vautin, Claude, Aluminium as a heating and reducing agent, J. Soc. Chem. Ind., 17, pp. 543-545; Discussion, same journal, pp. 649-650.

3. BIBLIOGRAPHY—Continued

Text references	Year	Name and title
		METALLOGRAPHY
95	1918	Anderson, R. J., Metallography of aluminum, Met. and Chem. Eng., 1918, p. 172, Feb. 15.
		Transformation
96	1914	Cohen, Allotrophy of metals, Proc. Roy. Akad. of Sciences (Amsterdam), 1914, 17, p. 200.
97	1914	Laschtschenko, P. N., Specific heat of aluminium; Jour. Russ. Phys. Chem. Soc., (X) 56, p. 311.
		CHEMICAL PROPERTIES
98	1917	Seligman, R., Williams, P., Action of acids on aluminium, Jour. Soc. Chem. Ind., 36, p. 409.
99	1917	Seligman, R., Williams, P., Action of acetic acid on aluminium, Jour. Soc. Chem. Ind., Apr. 30, 1917; Jour. Soc. Chem. Ind., 1916, pp. 35–88; Met. and Chem. Eng. (Abst.) 1917, July, p. 38.
100	1916	Briner-Senglet, The Carbides of aluminum, nickel, and copper, Rev. Met., p. 155.
101	1916	Seligman-Williams, Action of HnO_3 on aluminium; Jour. Soc.Chem. Ind., 35, p. 665.
102	1913	Bamberger, M. and V., Jueptner, H., Explosion of aluminium when granulating, Z. anorg. Chem. 26, pp. 353–355.
103	1913	Matignon, C., Reduction of magnesium by aluminium, C. R., 156, pp. 1157–1159.
104	1913	Kohn-Abrest, E., Application of activated (amalgamated) aluminium for the precipitation of tannin, Bull. Assoc. Chim. Sucr., 30, pp. 862–868.
105	1912	Nicolardot, P., Action of salts of mercury and mercury upon aluminium; application to the analysis of aluminium, Bull. Soc. Chim., 11, pp. 410–413.
106	1911	Kohn-Abrest, E., Some new applications of amalgamated aluminium and its use in analysis, Bull. Assoc. Chim. Sucr., 28, pp. 938–943.
107	1910	Kohn-Abrest, E., Action of heat on aluminium in vacuo in presence of carbon, Bull. Soc. Chim., 7, pp. 277–283.
108	1908	Matignon, C., Preparation of aluminum carbide, Bull. Soc. Chim., 3, pp. 355–361.
109	1905	Watts, O. P., Use of aluminium as a reducing agent, Amer. Electrochem. Soc. Trans., 1905; (Abst.) J. Soc. Chem. Ind., 24, 1905, p. 1116.
110	1905	Kohn-Abrest, Oxidation of aluminium powder, C. R., 141, pp. 323–324.
111	1904	Kohn-Abrest, E., Aluminium powder and the oxidation of aluminium, Bull. Soc. Chem., 31, pp. 232–339.
112	1902	Alt, M., Discharging paranitraniline red with aluminium powder, Meeting Soc. Ind. Mulhouse, 1902, Mar. 14; (Abst.) J. Soc. Chem. Ind., 21, 1902, p. 546.
113	1901	Duboin, A., Reducing properties of magnesium and aluminium, C. R., 132, No. 13, pp. 826–828.
114	1900	Matignon, C., Certain properties of aluminium and the preparation of phosphine, C. R., 130, No. 21, pp. 1391–1394.
		Corrosion
115	1915	Aluminium: Its origin and susceptibility, The Metal Industry, 13, pp. 105–106.
116	1914	Pikos, P., Destruction of aluminium apparatus by the galvano-catalytic action of copper, Z. anorg. Chem., 27, p. 152.
117	1913	Scala, R., Action of distilled water on impure aluminium, Atti. R. Acad. dei Lincei, Roma, 22, pp. 43–37, 95–102; (Abst.) J. Soc. Chem. Ind., 32, p. 368.
118	1913	Droste, Action of 3 per cent hydrogen peroxide on aluminium, Chem. Ztg., 37, 1913, p. 1317.
119	1913	Mohr, O., Gefährdung von Aluminiumgefässen durch Quecksilber, Brau. W. Schr., 30, 1913, pp. 309–310; Chem. Z. Bl. (5), 17, 1913, II, p. 320.
120	1913	Bailey, The corrosion of Aluminum, Jour. Inst. Met., 1913, I, 9, pp. 79–109; (Abst.), Jour. Soc. Chem. Ind., 32, 1913, No. 6, p. 293.
121	1913	Guillet, L., The influence of "drawing" on the properties of metallurgical products, Rev. Metallurgie, 10, 1913, pp. 769–777.
122	1912	Schoenfeld, F., and Himmelfarb, G., Behavior of aluminium toward water and air, Wochenschrift für Brouereiwesen, 29, 1912, pp. 409–411.
123	1912	Kohn-Abrest, E., Action of water on aluminium "activated" by mercury, Bull. Soc. Chim., 11, 1912, pp. 570–576.
124	1912	Bleisch, C., Zur Frage der Aluminum Gär und Lagergefässe, Z. Ges. Brauw., 35, 1912, pp. 49–53; Chem. Z. Bl., 1912, I, p. 1060.
125	1912	Strunk, H., Ursache von Fleckenbildung auf geschwärtztem Aluminium Kochgeschirr, Verh. a. d. Gebiete des Militär-Sanitätswesen 1912 Heft 52, Chem. Z. Bl. 1912, p. 1937.
126	1912	Nicolardot, Action of Hg salts on aluminum, Bull. Soc. Chem., 11, p. 410.
127	1912	Barillé, A., Action of seltzer water on aluminium, Jour. de Pharmacie et de Chimie, 6, VII, 1912, p. 110.
128	1911	Heyn, E. and Bauer, O., Corrosion of aluminium and aluminium ware, Mitt. Kgl. Materialprüfungsamtes, 29, 1911, pp. 2–28.
129	1909	Kohn-Abrest, E., Action of hydrochloric acid gas on aluminium, and quantitative analysis of metalic aluminium, Bull. Soc. Chem., 5, 1909, pp. 768–775.
130	1908	Fillinger, V. A., Behavior of Aluminium when in contact with milk, wine, and some saline solutions, Z. Unters. Nahr.- u. Genussmittel, 16, 1908, pp. 232–234.
131	1907	Van Deventer, C. M., So-called "passivity" of aluminium toward nitric acid, Chem. Weekblad, 4, 1907, pp. 69–72; Chem. Zentrabl., 1907 I, p. 1017.
132	1904	Mott, W. R., Protection of aluminium against corrosion, Electrochem. Ind., 2, 1904, pp. 129–130.
133	1906	Sabin, Technology of paint and varnish.
134	1904	Smith, W., Action of certain solutions upon aluminium and zinc, Jour. Soc. Chem. Ind., 23, pp. 475–477.

3. BIBLIOGRAPHY—Continued

Text references	Year	Name and title
		CHEMICAL PROPERTIES—Continued
		Alterability
135	1913	Cohn, L. M., Änderung der Eigenschaften von Aluminium, Elektrotech u. Maschinenbau, 31, p. 430; Elekt. Masch., 1913, pp. 430–433.
136	1913	Wilson, E., Exposure tests of copper, aluminium, and duralumin, Eng., 96. p. 387.
137	1912	Goldberg, G., Disintegration of aluminium articles, Giesserei Ztg., 9, p. 534.
138	1911	Le Chatelier, H., Alterability of aluminium, C. R., 152, pp. 650–652.
139	1910	Law, E. F., The failure of the light engineering alloys, particularly the aluminum alloys, Trans. Far. Soc. 6, 1910, pp. 185–198.
140	1892	Winkler, C., On the durability of aluminium, Z. anorg. Chemie, 1892, p. 69.
		PHYSICAL PROPERTIES
141	1913	Brislee, F. J., Density of aluminium, Trans. Far. Soc., May 7, 1913, p. 162; (Abst.) Jour. Soc. Chem. Ind., 32, p. 539.
142	1912	Brislee, Density and coefficient of expansion of aluminium Trans. Far. Soc., 7, pp. 221–228.
143	1907	Schnurpfeil, The properties of aluminium, its manufacture and alloys, Giesserei Ztg., 4, pp. 558–559.
144	1903	Burgess, C. F. and Hambuechen, C., Some laboratory observations on aluminium, Electrochem, Ind. (Philadelphia), 1903, pp. 165–168; (Abst.) Jour. Soc. Chem. Ind., 22, p. 1135.
145	1902	Granger, A., The pasty state of aluminium below its melting point and the utilization of this property in subdividing the metal, Bull. Soc. Chem., 27, p. 789.
146	1890	Hunt, E. A., Langley, J. W., and Hall, C. M., Properties of aluminium, Eng. and Min. Jour., 49, pp. 284–285, 314–316, 334–336; Trans. Amer. Inst. Min. Eng., 18, p. 528.
		Electrical Conductivity
147	1914	Bureau of Standards, Copper Wire Tables, Circular No. 31, p. 13.
148	1912	Stein, A., Melting point and electrical resistance, Phys. Z., 13, p. 287.
149	1910	Wolff, F. A., and Dellinger, J. H., The electrical conductivity of commercial copper, Bureau of Standards Sci. Paper No. 148, 7.
150	1901	Kershaw, J. B. C., Aluminium as an electric conductor, with new observations upon the durability of aluminium and other metals under atmospheric exposure, Inst. Elect. Eng., 1901, Electrician, 46, No. 13, pp. 464–466.
151	1900	Jaeger, W., and Dieselhorst, H., Wiss. Abhl. P. T. R., 3, p. 269.
152	1898	Northrup, Conductivity of aluminium, Elec. World, 32, p. 598; (Abst.) Eclair. Electrique, 17, p. 576.
153	1897	Richards, J. W., and Thomson, J. A., Recent determinations of electrical conductivity of aluminium; Jour. Franklin Inst., 143, pp. 195–199.
		Thermoelectromotive Force
154	1917	Northrup, E. F., Resistivity and thermal emf., Met. and Chem. Eng., 15, pp. 193–197.
155	1908	Wagner, E., Ann. d. Phys., (4) 27, p. 955.
156	1900	Jaeger, W., and Dieselhorst, H., T. E. F., Wiss. Abh., 3, p. 269.
157	1895	Dewar and Fleming, Phil. Mag., (5) 40, p. 95.
		Electrolytic Solution Potential
158	1894	Neumann, B., Über das potential des Wasserstoffs und einiger Metalle, Z. Phys. Chem., 14, p. 193.
		Magnetic Characteristics
159	1910	Honda, K., Mag. Thermomagnetische Eigenschaften der Elemente, Ann. d. Phys., (4) 32, p. 1027.
160	1905	Wills, A. P., Phys. Rev., 20, p. 188.
		Changes of State
161	1915	Bureau of Standards, Melting points of chemical elements, Circular No. 35.
162	1909	Greenwood, Proc. Roy. Soc., 82, p. 396.
163	1908	Wartenberg, H., Z. anorg. Chem., 56, p. 320.
		Thermal Conductivity
164	1908	Lees, C. H., Thermal and electrical conductivity of metals and alloys at low temperatures, Phil. Trans., pp. 208, 381.
165	1900	Jaeger, W. and Dieselhorst, H., Wiss. Abhandl. P. T. R., pp. 3, 269.
		Thermal Expansion
166	1913	Chamberlain, J. H., A study of the volume change in alloys, Jour. Inst. Metals, X, p. 193.
167	1911	Brislee, F. J., Determination of density and coefficient of linear expansion of aluminium, Trans. Far. Soc., 7, p. 221; (Abst.) Jour. Soc. Chem. Ind., 31, p. 30.
168	1910	Ewen, D., and Turner, T., Shrinkage of — and the Al-Zn alloys during and after solidification, Jour. Inst. Metals, IV, p. 128.
169	1909	Turner, T., and Murray, M., The volume change in Cu-Zn alloys, Journ. Inst. Metals 2, p. 98.
170	1907	Henning, F., Ann. d. Phys., (4) 22, p. 631.
171	1902	Dittenberger, W., Über die Ausdehning von Eisen, Kupfer, Aluminium, Messing und Bronze in hoher Temperatur, Z. Ver. deutsch Ing., 46, p. 1532.

3. BIBLIOGRAPHY—Continued

Text references	Year	Name and title
		PHYSICAL PROPERTIES—Continued
		Specific Heat
172	1916	Brislee, F. J., The specific heat of hard and soft aluminium, Paper read at the meeting of the Faraday Society (Paper II), Trans. Far. Soc., 12, p. 57.
173	1904	Glaser, Schmelzwärmen- und specifische Wärme Bestimmungen von Metallen bei höheren Temperaturen, Metallurgie, 1, pp. 103, 121.
174	1903	Tilden, Atomic and specific heats, Proc. Roy. Soc., 71, p. 220.
175	1892	Richards, J. W., The specific heat of aluminium, Jour. Franklin Inst., 133, pp. 121–124; Chem. News, 65, p. 97; (Abst.) Chem. Ztg. Repert, 16, p. 97.
176	1892	Le Verrier, M., Sur la chaleur spécifique des métaux, C. R., 114, p. 907.
		Optical
177	1913	Coblentz, Diffuse reflecting power, Bulletin Bureau of Standards No. 195, 9, p. 281.
178	1911	Coblentz, Bulletin Bureau of Standards, 7, p. 197.
179	1890	Drude, Ann. der Phys. u. Chem., 39, p. 481.
		Elasticity
180	1915	Koch, K. R., and Dannecker, C., Elasticity at high temperatures, Ann. d. Physik (IV), 47, p. 197.
181	1913	Brislee, F. J., Elastic modulus of aluminium, Trans. Far. Soc., 9, Nos. 1–2, pp. 155–161.
182	1913	Brislee, Elastic modulus of Aluminium, Trans. Far. Soc., 9, pp. 155–161.
183	1903	Cardani, P., Direkte Bestimmung der Poissonschen Beziehung in Drähten, Phys. Z., 4, p. 449.
184	1903	Angenheister, G., Beiträge zur Kenntniss von der Elastizitat der Metalle?
		Mechanical Properties
185	....	Herman A. Holz, booklet describing the Ericksen machine.
186	1918	Anderson, R. J., Annealing and recrystallization of cold-rolled aluminum sheet, Met. and Chem. Eng., 18, p. 523.
187	1914	Elmendorf, A., Tables and charts resulting from the testing of cast aluminium on a White-Souther rotary testing machine, Amer. Mac., 41, 1914, p. 811.
188	1913	Stress-strain relations for aluminium wire according to experiments by the British Insulated and Helsby Cable Co., Eng., 96, p. 197.
189	1913	Wyss, W., Resistance to bending, extension, specific gravity, and hardness of cast rods of aluminium, cast iron, and bronze, Ferrum, 10, pp. 167, 184, 207–217.
190	1913	Deinhardt, K., The machining of aluminium and white metals, Machinery, 19, p. 970.
191	1913	Chamberlain, J. H., A study of volume changes in alloys, Jour. Inst. Metals, X, p. 193.
192	1909	Smith, A., The elastic breakdown of nonferrous metals, Jour. Inst. Metals, 2, pp. 131–231.
193	1906	Morley, A., and Tolinson, G. A., Tensile overstrain and recovery of aluminium-copper and aluminium-bronze, Phil. Mag., 11, pp. 380–392.
194	1902	Wilson, E., and Gavey, J., Jour. Inst. Elec. Eng., 31, p. 154.
		EFFECT OF TEMPERATURE ON THE PROPERTIES OF ALUMINUM
195	1916	Ludwik, P., Change of hardness with temperature, Z. Phys. Chem., 91, p. 232.
196	1914	Nernst, W., and Schwers, F., Specific heat at low temperatures, Sitzungsber, der Kgr. Akad. Wiss., Berlin, p. 355.
197	1913	Rosenhain, W., and Ewen, D., Intercrystalline cohesion of metals, Inst. of Metals, 10 (Abst.) Jour. Soc. Chem. Ind., 32, No. 18, p. 914.
198	1912	Bengough, G. D., A study of the properties of alloys at high temperatures, Jour. Inst. Metals, 7, p. 123.
199	1911	Baumann, R., Tests with welded and nonwelded aluminium at ordinary and at high temperatures, Mitteilungen über Forschungsarbeiten auf dem Gebiete des Ingenierwesen, 1911, No. 112, pp. 23–40; also in Z. Verein Deutscher Ingenieure, p. 2016 et seq.
200	1911	Nernst and Lindemann, Specifische Wärme u. Quantentheorie, Z. Elektrochem., 17, p. 817.
201	1910	Schimpff, H., Über die Wärmekapazität von Metallen und Metallverbindungen, Z. f. Phys. Chem., 71, p. 257.
202	1907–8	Breuil, P., Fabrication a froid des tubes et profiles, Genie Civil, pp. 41, 369; Proc. Inst. Civil Eng., No. II, p. 361.
203	1907	Niccolai, G., The electrical resistance of some metals at higher and lower temperatures, Lincei Rend. (5) 16, p. 576, 906, II, 185.
204	1893	Dewar and Fleming, The electrical resistance of metals and alloys, Phil. Mag. (5) 36, p. 271.
		EFFECT OF MECHANICAL WORK AND HEAT TREATMENT ON THE PHYSICAL PROPERTIES
205	1917	Carpenter, H. C. H., and Taverner, L., The effect of heat at various temperatures on the rate of softening of cold-rolled aluminum sheet, 18, pp. 115–156, 156–171.
206	1916	Seligmann, R., and Williams, Percy, Annealing of aluminium, Paper read at meeting of the Faraday Society, Trans. Far. Soc., pp. 64–65.
207	1915	Beevers, L., Annealing of aluminium stampings, Mech. World, 58, p. 135.
208	1915	Lowry, T. M., Parker, R. G., The properties of cold-worked metals, Pt. I, Jour. Chem. Soc., 107, p. 1005.
209	1914	Hanriot, Lahure, Annealing of aluminum, C. R., 158, p. 263.
210	1913	Gewecke, H., The effect of heat treatment on the conductivity of aluminium, The Electrician, 72, pp. 450–451.
211	1913	Robin, F., Recherches sur le développement des grains des métaux par recuit aprés écrouissage, Rév. Mét., 10, p. 722.
212	1913	Müller, W., Thermische Behandlung der Metalle, Metall. u. Erz, I, p. 219.
213	1911	Matweef, M., Notes sur le recuit des métaux, Rév. de Mét., VIII, p. 708.

3. BIBLIOGRAPHY—Continued

Text references	Year	Name and title
		TECHNOLOGY
214	1917	Krom, L. J., Manufacture of seamless tubes, Met. Ind., 15, p. 1.
215	1916	Clevenger, G. H., Aluminium dust, Min. and Sci. Pres., 112, p. 118.
216	1914	Pannell, E. V., Electrolytic insulation of aluminium Elec. World, 64, p. 916.
217	1914	Skinner, C. E., and Chubb, L. W., Electrolytic insulation of alumiuim wire, Trans. Amer. Electrochem. Soc., 26, pp. 137–147; Met. and Chem. Eng., 12, pp. 712–713; (Abst.) Elect. World, 64, p. 766.
218	1914	Lang, Coloring of aluminium The Foundry, 43, p. 361.
219	1914	Anonymous, Straightening aluminium tubes, Amer. Mach., 41, p. 44.
220	1914	Anonymous, New method of coloring aluminium (introduced by A. Lang, Karlsruhe), Foundry, 43, p. 361.
221	1914	Anonymous, Methods of producing a satin finish on aluminium, Foundry, 43, p. 500.
222	1913	Aluminium foil, Eng., 116, p. 199.
223	1912	Guillet, L., Manufacture of aluminium foil and powder, Revue de Metallurgie, 9, pp. 147–159.
224	1906	Goutschi and Jaquier, Manufacture of flexible aluminium foil, Erfindungen u. Erfahrungen (Neueste), 33, pp. 114–115.
225	1906	Hoskins, Apparatus for granulating Aluminium, Metallurgie, 3, p. 612.
		Working
226	1917	Lyon, Jr., G., Aluminium rolling-mill practice, Met. Ind., 4, pp. 109.
227	1915	Working aluminium at 400° F, Horseless Age, 36, p. 373.
228	1915	Cutting aluminium rapidly with a buzz planer, Jour. Franklin Inst., 180, p. 634.
229	1903	Woodworth, Working aluminium (samples of pure aluminium ware), Amer. Mach., 26, pp. 434–436.
230	1902	Granger, The pasty state which Al assumes on heating near its fusion point, and the application of this property to the division of this metal, Bull. Soc. Chim., Paris, 27, pp. 789–790.
231	1895	Pittsburgh Reduction Co., A train for rolling aluminium, Iron Age, 56, p. 1091.
232	1891	Smith, Aluminium in the drawing press, Trans. Amer. Inst., Min. Eng., 18, p. 476.
		Welding
233	1916	Welding of sheet aluminium, Met. and Chem. Eng., 14, p. 548.
234	1915	Pannell, E. V., Aluminium welding, Jour. Am. Inst. Met., 9, pp. 182–193.
235	1915	Mawson, R., Oxy-acetylene welding on aluminium parts, Amer. Mach., 41, p. 1065.
236	1915	Autogenous soldering or welding of aluminium, Machinery, 21, pp. 369–371.
237	1915	Methods of joining aluminium, Machinery, 21, pp. 470–473.
238	1915	A new aluminium solder, Autocar, 35, p. 156.
239	1915	Successful acetylene aluminium, Metal Worker, Plumber and Steam Fitter, 84, pp. 173–174.
240	1915	Aluminium solder, Elect. Rev. and West. Elect., 67, pp. 670–671.
241	1915	Jointing of aluminium, Machinery, 5, p. 708 (British); (Abst.) Jour. Inst. Met., 13, p. 332.
242	1915	Welding of aluminium, Machinery, 5, p. 488 (British); (Abst.) Jour. Inst. Metal., 13, p. 332.
243	1915	Soldering and brazing aluminium, Machinery (British), 5, pp. 397–399, No. 117.
244	1914	Hart, R. N., Welding.
245	1912	Carnevali, F., Autogenous welding by means of oxygen and acetylene of copper and its principal alloys and aluminium, Inst. of Metals, 9; (Abst.) Jour. Soc. Chem. Ind., 31, p. 990.
246	1911	A new aluminium solder, Turbine, Aug. 5, p. 388.
247	1909	Seligman, Dr. Rich, The welding of aluminium, Jour. Inst. Metals, II, pp. 281–287.
248	1909	Schoop, M. V., Aluminium welding, Electrochem, and Met. Ind., 7, pp. 193–194.
249	1908	Wüst, Legier- und Lötkunst (Leipzig).
250	1907	Schoop, M. V., The autogeneous welding of aluminium, Chem. Ztg., 31, pp. 749–750.
251	1906	Anonymous, Cowper-Coles process for welding aluminium, Giesserei Ztg., 3, pp. 281–283.
252	1904	Cowper, Coles, S., Aluminium welding, West. Electrician, 34, p. 111; Int. Marine Eng., 26, p. 71.
253	1903	Lange, Hjalmar, Soldering aluminium, Amer. Mach., 26, pp. 1185–1186.
254	1903	Cowper-Coles, S., Welding of aluminium, Electrochemist and Metall., 3, pp. 240–243.
255	1898	Bates, W. S., Jour. Am. Chem. Soc.
256	1894	Richards, J. W., Method of soldering aluminium, Jour. Franklin Inst., 137, p. 160.
		Electrolytic Deposition
257	1915	Nickel-plating on aluminium, Sci. Amer. Suppl., 80, Sept. 25, p. 197.
258	1915	Canac, J., and Tassilly, E., Plating aluminium with nickel, Bull. Soc. d'Encouragement de l'Industrie Nationale; (Abst.) Brass World, 11, No. 6, pp. 229–230.
259	1914	Allison, H. B. C., and Hawkins, L. A., Calorizing—Coating metals with a layer of aluminium-alloy for protection against high temperatures, Metal and Chem. Eng., 12, p. 730.
260	1914	Tassilly, E., Nickel-plated aluminium, Rev. Metallurgie, 11, pp. 670–673.
261	1914	Canac, J., and Tassilly, E., Electroplating aluminium with nickel, C. R., 158, pp. 119–121; (Abst.) Jour. Soc. Chem. Ind., 33, No. 3, pp. 142.
262	1912	Regelsberger, F., Galvanizing aluminium, Elektrochem. Zeitschrift, No., pp. 213–220.
263	1909	Szarvasy, E. C., Aluminium methoxide and the coating of aluminium with metals, Proc. Seventh Int. Cong. Applied Chem., London, Sec. X, 1909, pp. 62–63.
264	1905	Lodyguine, Electrodeposition of metals on Al, Electrochem. Ind., 3, pp. 177–178.

3. BIBLIOGRAPHY—Continued

Text references	Year	Name and title
		IMPURITIES
265	1912	Kohn-Abrest, E., and Rivera-Maltes, Influence of various impurities on the activation of aluminium, C. R., 154, pp. 1600–1602.
266	1912	Guichard, M., and Jourdain, R. P., Gases in aluminium, C. R., 155, pp. 160–163.
267	1909	Pecheux, H., Influence of impurities on the thermoelectric properties and electric resistance of aluminium, C. R., 148, pp. 627–628.
		LIGHT ALLOYS OF ALUMINIUM
268	1915	Clayden, A. L., How scientific design and use of aluminium alloys will cheapen motoring, Automobile, 34, pp. 225–230.
269	1914	Law, E. F., Alloys and their industrial applications.
270	1914	Improvement of aluminium, Elektrochem. Z., 20,, p. 295.
271	1914	Anonymous, Aluminium alloys, Elektrochem. Zeit., 20, pp. 264–265.
272	1914	Review of literature on light aluminium alloys, Mêtaux et Alliages, No. 4, 7, p. 5.
273	1913	Ivinson, C. H., Aluminium alloys, Metal Industry (N. Y.), 11, (n. s.), pp. 340–341.
274	1913	Light aluminium alloys, Mêtaux et Alliages, 9, p. 214.
275	1912	Levi-Malvano and Marantonio, Light aluminium alloys, Gaz. Chim. Italiana, 42, 1, p. 353.
276	1911	Grimshaw, R., The use of aluminium spark-emitting alloys, Brass World, 7, p. 250.
277	1911	Alloys of aluminium, Foundry, 38, No. 5.
278	1911	Anonymous, Aluminium-bronze bearing (92 per cent Al and 8 per cent Cu), Eng., 112, p. 489.
279	1910	Belin, Jour. Soc. Chem. Ind., p. 1211.
280	1907	Stacy-Jones, J. E., Light aluminium alloys, Industrial World, May 11, pp. 593–596.
281	1903	Richards, J. W., Light aluminium alloys, Eng. and Min. Jour., 76, p. 508.
282	1902	Guillet Leon, Alloys of aluminium, Bull. Soc. d'Encouragement p. l'Ind. Nat., 101, No. 2, pp. 221–273.
283	1902	Campbell, W., and Matthews, J. A., Alloys of aluminium, Jour. Amer. Chem. Soc., 24, No. 3, pp. 253–266.
284	1901	Houtzschel, Proc. Inst. Civ. Mg. Mg., 146, p. 49.
		Properties
285	1911	Littleton, J. T., Optical constants of alloys, Phys. Rev., 33, p. 453.
286	1904	Campbell, The structure of alloys (aluminum alloys), Jour. Amer. Chem. Soc., 26, pp. 1290–1306.
287	1902	Wilson, E., The physical properties of certain aluminum alloys, and some notes on aluminum conduction, Jour. Inst. Elec. Eng., 31, p. 321.
288	1899	Mach, L., and Schumann, L., Über ein neues Spiegelmetall, Sitzungsb. Wien. Akad., C–VIII–A, p. 135.
		Electrical
289	1912	Broniewski, W., Electrical properties of aluminum alloys, Ann. de Chimie et de Physique, (VIII), 25, p. 5.
290	1904	Pecheux, H., Thermoelectricity of aluminum alloys, C. R., 139, pp. 1202–1204.
291	1904	Anonymous, Electrical conductivity of aluminum alloys, Eng., 78, p. 333.
292	1903	Wilson, E., Electrical conductivity of certain aluminium alloys as affected by exposure to London atmosphere, Electrician (London), No. 1322, p.898.
		Corrosion and Disintegration
293	1917	Williams, H. M., The swelling of zinc base die castings, Jour. Am. Inst. Met., XI, pp. 221–225.
294	1895	Richards, J. W., Resistance to corrosion of some light aluminum alloys, Jour. Franklin Inst., 139, pp. 69–72.
		Casting
295	1918	Anderson, R. J., The practice of melting and casting aluminum, Foundry, 46, p. 104.
296	1917	Gamut, J., Production of aluminium castings, The Mach. Eng., Apr., p. 323.
297	1917	Stillman, A. L., Briquetting of nonferrous light metal scrap, Jour. Am. Inst. Metals, 11, p. 207.
298	1916	Melting of aluminium, Met. and Chem. Eng., 14, p. 221.
299	1916	Hall, I., Furnaces for metal-melting (AC), Brit. Pat. 3874, Mar. 11 (Chem. Abst.), 10, 1916, p. 2088.
300	1915	Pack, Chas., Aluminium die casting, Met. Ind., 13, p. 412; Trans. Am. Inst. Metals, 9, p. 145.
301	1915	Monoreiff, V. J., Aluminium or iron crank cases, a comparison of the two materials on the basis of weight, strength, and cost. Horseless Age, 35, pp. 582–583.
302	1915	Aluminium aeroplane motor castings, Automobile, 33, p. 371.
303	1915	Anonymous, Aluminium pistons pass unchanged. The Automobile, 32, pp. 1116–1117.
304	1915	Gillett, H. W., Melting aluminium chips, Metal Industry (n. s.), 13, October, pp. 417–418; same, Foundry, 43, pp. 462–463; same, Iron Trades Rev., 57, pp. 942–943; Amer. Inst. Metals, 9, pp. 205–210.
305	1915	Melting aluminium by gas, Jour. Gas Lighting and Water Supply, 130, p. 752.
306	1914	Norton, A. B., Making aluminium test specimens on castings, Trans. Am. Inst. Metals, 8, pp. 128–134.
307	1914	Norton, A. B., A hot-shortness testing machine for aluminium alloys, Amer. Inst. of Metals, 8, pp. 124–127; (Abst.) Jour. Soc. Chem. Ind., 33, p. 1013.
308	1914	Norton, A. B., Aluminium die castings, Amer. Inst. Metals, 8, pp. 104–109; (Abst.) Jour. Soc. Chem. Ind., 33, p. 1013.
309	1914	Anonymous, Sollis' aluminium centrifugal casting method, Amer. Mach., 41, p. 99.

3. BIBLIOGRAPHY—Continued

Text references	Year	Name and title
		LIGHT ALLOYS OF ALUMINUM—Continued
		Casting—Continued
310	1914	Chill castings of aluminium in automobile industry, Metaux et Alliages, 7, p. 7.
311	1914	Anonymous, Aluminium in automobile industry (chill casting superseding), Metaux et Alliages, 7, p. 7.
312	1914	Anonymous, Polishing aluminium castings, Foundry, 43, p. 302.
313	1913	Ivinson, C. H., Alloying of aluminium, Brit. Foundrymen's Assoc., June 21, pp. 1–6; (Abst.) Jour. Soc. Chem. Ind., 32, p. 702; Foundry Trade Jour., 15, p. 446.
314	1912	Gillett, H. W., Influence of pouring temperature on aluminium alloys; Eighth Internat. Cong. Applied Chem., 1912, Sec. II, Orig. Comm. 2, pp. 105–112; (Abst.) Jour. Soc. The Metal Industry, 11, April, pp. 167–169.
315	1912	Thurman, J. B., Peculiarities of aluminium castings, Mech. Eng., 29, pp. 116–117.
316	1912	Practical hints on molding and casting aluminium, The Mech. Eng., 29, p. 299.
317	1911	Use of magnesium in deoxidizing aluminium alloys, Castings, February, p. 164.
318	1910	Lane, H. M., Use of magnesium in deoxidizing aluminium alloys, Amer. Brass Founders' Assoc., pp. 103–116.
319	1910	Jones, J. L., Zinc-hardened versus Copper-hardened Aluminium for making aluminium castings, Met. Ind., 8, p. 16.
320	1910	Anonymous, Remelting of aluminium chips or borings, Brass World, 6, p. 278.
321	1909	Anonymous, Use of chloride of zinc in melting aluminium, Mech. Eng., Sept. 3; (Abst.) Jour. Inst. Metals, II, No. 2, p. 320.
322	1909	Anonymous, Casting aluminium in green-sand molds, Mech. Eng., Sept. 3, p. 301; (Abst.) Jour. Inst. Metals, II, No. 2, p. 311.
323	1907	McAdams, Method of casting aluminium alloys, Amer. Mach., 30, II, p. 347.
324	1907	Lake, Aluminium castings, Foundry (Cleveland), 30, pp. 160–165.
325	1907	Fay, Cast aluminium for automobile work, Automobile, 17, pp. 229–231.
326	1906	May, Melting aluminium and its alloys, Mech. World, 40, p. 165.
327	1905	May, Cored work in aluminium casting, Perct. Eng., 32, pp. 71–72.
328	1902	Anonymous, Rules for casting aluminium, Mech. World, 31, p. 298.
		Mechanical
329	1916	Ludwik, P., The hardness of metal alloys, Z. anorg. u. allg. Chem., 94, No. 2; (Abst.) Metall. u. Erz. 13, No. 6, pp. 156–158.
330	1901	Tetmayer, Methods and results of tests of aluminium and alloys of the same, Metallarbeiter, 27, pp. 656–657; Stahl u. Eisen, 21, pp. 811–815.
		Composition
331	1914	Belasio, R., Analysis of commercial aluminium and its light alloys, Annal. Chim. Appl., 1, pp. 101–110; (Abst.) Jour. Soc. Chem. Ind., 33, 1914, No. 8, p. 424.
332	1913	Von John, W. E., Contribution to the constitution and analysis of aluminium alloys, Chem. Ztg., 37, p. 363.
333	1911	Smith, F., Analysis of aluminium alloys, Met. and Chem. Eng., 9, pp. 85–86.
334	1911	"Atherium," a new alloy, The Electrician, 66, p. 525.
335	1911	Kleist, G., Analysis of aluminium and its alloys, Chem. Ztg., 35, pp. 668–669.
336	1911	Aluminium, its alloys and impurities, Zeit. f. Dampfkessel u. Machinenbetrieb, Jan. 6, p. 10.
337	1910	Seligman, R. and Willott, F. J., Analysis of aluminium and its alloys, Inst. of Metals, 3; (Abst.) Jour. Soc. Chem. Ind., 29, No. 4, pp. 217.
		BINARY
338	1915	Schirmeister, H., Investigation of binary aluminium alloys, Stahl u. Eisen, 35, 1916, pp. 648-873-996; Rev. Mettallurgie, 12, 1915, No. 12 and 996, pp. 464–470.
339	1914	Petrenko, G. I., Hardness of the systems Ag-Zn and Ag-Al, J. Russ. Phys. Chem. Soc., 46, p. 176; (Abst.) Bull. Soc. Chem., 16, pp. 738–739.
340	1914	Schirmeister, Elektrochem. Z., 20, p. 295.
341	1914	Schirmeister, Metaux et Alliages, 7, p. 5.
342	1911	Schirmeister, Mechanical and chemical properties of aluminium-cobalt; also molybdenum and tungsten alloys, Mettalurgie , 8, pp. 650–655.
343	1910	Ewen, D. and Turner, T., Shrinkage of antimony-lead alloys and aluminium-zinc alloys, Jour. Inst. Metals, 4; (Abst.) Jour. Soc. Chem. Ind., 29, No. 19, p. 1163.
344	1908	Portevin, Les alliages d'aluminium, Rev. Met., 5, p. 274.
345	1908	Gwyer, A. G. C., Alloys of aluminium with copper, iron, nickel, cobalt, lead, and cadmium, Z. anorg. Chemie, 57, pp. 113–153; (Abst.) Chem. Zentralblatt, I, pp. 1033–1035.
346	1906	Gwyer, A. G. C., Al-Bi and Al-Sn alloys, Z. anorg. Chemie, 49, pp. 311–319.
347	1906	Pecheux, H., Determination of melting points of Al-Pb and Al-Bi alloys by thermoelectric pyrometers, C. R., 143, pp. 397–398.
348	1905	Pecheux, H., Alloys of Al with Sn, Bi and Mg, C. R., 140, pp. 1535–1536.
349	1904	Pecheux, H., Alloys of Al with Bi and with Mg, C. R., 138, pp. 1501–1503.
350	1904	Pecheux, H., Alloys of aluminium with Mg and with Sb, C. R., 138, pp. 1606–1607.
351	1902	The Al, Ni, and Cu alloys and their applications (partinium and nickel-aluminium), Metallarbeiter, 28, No. 2, pp. 656–657 Melting and casting.
352	1902	Guillet, L., Alloys of Al with Fe and with Mn, C. R., 134, No. 4, pp. 236–238.
		Ag-Al
353	1912	Anonymous, Argental—an Al-Ag alloy, Metal Ind., 4, p. 368.
354	....	Petrenko, G. I., Ag-Al alloys, Z. anorg. Chemie, 46, pp. 49–59.
355	....	Broniewski, W., Electrical properties of aluminium-silver alloys, C. R., 150, pp. 1754–1757.

3. BIBLIOGRAPHY—Continued

Text references	Year	Name and title
		BINARY—Continued
		An-Al
356	1914	Heycock, C. T., and Neville, F. H., Al-Au alloys, Phil. Trans. Roy. Soc., 214, (A), p. 267 et seq.
357	1900	Heycock, C. T.. and Neville, F. H., Au-Al alloys, Proc. Roy. Soc., 66, p. 2021.
		Be-Al
358	1917	C. R, 2630, Jour. Chem. Soc., 112, II, p. 89.
		Bi-Al
359	1906	Gwyer, Bismuth-Aluminum alloys, Z. anorg. Chem., 49, p. 316.
		Ca-Al
360	1910	Breckenridge, Al-Ca alloys, Met. and Chem. Eng., 8, pp. 340–341.
361	1908	Donski, L., Ca-Al alloys, Z. anorg. Chem., 57, pp. 185–219; (Abst.) Chem. Zentralblatt, I, pp. 1035–1038.
		Al-Cd
362	1908	Gwyer, Al-Cd alloys, Z. anorg. Chem., 57, p. 149.
		Ce-Al
363	1912	Vogel, R., Cerium-aluminium alloys, Zeitschr. f. anorg. Chemie, 75, p. 41, et seq.
364	1911	Barth, O., Increase in chemical resistance of alloys capable of being mechanically worked, and suitable for constructional use; Pt. II, Al; Influence of cerium on its mechanical and chemical properties, Metallurgie, 9, pp. 261–276.
		Co-Al
365	1908	Gwyer, A. G. C., Al alloys with Cu, Fe, Ni, Co, Pb, Sn, Z. anorg. Chem., 57, p. 113.
366	1911	Schirmeister, Light alloy of Al and Co, Met., 8, p. 650.
367	....	Neuburger, A., Improving the properties of aluminium (Al-Co alloys), Elektrochem. Zeitschr., 26, p. 295.
		Cr-Al
368	1908	Hindrichs Über einige Chrom. u. Manganlegierungen, Z. anorg. Chem., 59, p. 430.
		Cu-Al
369	1916	Edwards, Prof. C. A. (Manchester Univ.), Copper-aluminium alloys, Metal Industry (London), 9, No. 2, pp. 47–49.
370	1915	Rolla, L, Thermochemistry of Cu-Al series, Gazzetta Chimica Italiana, 55, I, p. 185.
371	1912	Bromieski, W., Propriétés Electriques des Alliages d'aluminium, Ann. d. Chim. et d. Physique, 25, p. 5.
372	1910	Breckenridge, J. M., Al-Cu alloys, Met. and Chem. Eng., 8. p. 349.
373	1909	Pecheux, H., Electrical properties of Cu-Al alloys (thermoelectricity and resistance), C. R., 148, pp. 1041–1042.
374	1909	Broniewski, W., Electrical properties of Al-Cu alloys, C. R., 149, pp. 853–855.
375	1908	Gwyer, A. G. C., Al alloys with Fe, Cu, Ni, Cu, Cd, Pb, etc., Z. anorg. Chem., 57, p. 113.
376	1908	Rowland, W. S., Electrolytic corrosion of copper-aluminium alloys, Jour. Phys. Chem., 12, pp. 180–206.
377	1907	Carpenter, H. C. H., and Edwards, C. A., Alloys of aluminium and copper, Appendix to Eighth Report of Alloys Research Committee of Inst. Mech. Eng. (London), Eng., 63, pp. 253–254; (Abst.) Journ. Soc. Chem. Ind., 26, p. 206.
378	1907	Carpenter, H. C. H., and Edwards, C. A., Alloys of aluminium and copper, Eighth Report to the Alloys Research Committee of Inst. Mech. Eng.; Eng., 83, pp. 127–129, 158–162.
379	1907	Curry, B. E., Constitution of alloys of Cu with Al, Jour. Phys. Chem., 11, p. 425.
380	1907	Curry, B. E., and Woods, S. H., Tensile strength of Cu-Al alloys, Jour. Phys. Chem., 11, pp. 461–491.
381	1905	Guillet, L., Cu-Al alloys, C. R., 141, pp. 464–467.
382	1905	Guillet, L., Cu-Al alloys, Bull. Soc. d'Encouragement de l'Ind. Nat., 107; Revue de Metallurgie, pp. 367–388.
383	1903	Lougouinine, W., and Schukareff, A., Thermal examination of some alloys of Cu and Al, Arch. Sci. Phys. et Nat., Geneva, 15 (4), pp. 49–77; (Abst.) Chem. Zentralblat, I, No. 9, p. 498; (Abst.) Jour. Soc. Chem. Ind., 22, pp. 368.
384	1902	Campbell and Mathews, Jour. Amer. Chem. Soc., 24, p. 253.
385	1901	Guillet, Leon, Alloys of aluminium and copper, C. R., 133, pp. 684–686.
		Fe-Al
386	1908	Portevin, Les Alliages d'Aluminium, Rev. Met., 5, p.274.
387	1908	Gwyer, Fe-Al (also Cu-Al, Ni-Al, Co-Al, Pb-Al, Cd-Al), Z. A., 57, p. 113.
388	1901	Brunck, O., Ber., 34, p. 2733.
389	1901	Lownds and Richardson, The magnetic properties of the alloys of cast iron and Al, Phil. Mag., 6, pp. 601–624.

3. BIBLIOGRAPHY—Continued

Text references	Year	Name and title
		BINARY—Continued
		K-Al
390	1906	Mathewson, Alloys of Al with K and Na, Z. Anorg. Chem., 48 p. 192.
		Mg-Al
391	1917	Jones, J. L., Al alloy, Met. Ind. (problem), p. 522.
392	1915	Coulson, J., Reclamation of magnalium from turnings, Met. Ind., 13, p. 455; Trans. Am. Inst. Met., 1915.
393	1914	Schirmeister, H., Supplement to the phase diagram of aluminium-magnesium alloys, Metall. u. Erz., 11, pp. 522–523.
394	1913	Gillett, H. W., Casting temperature for Al alloys, Met. Ind., 11, p. 167.
395	....	Wilm, A., Physical properties of Mg-Al alloys, Rev. Met., Ex. 8, p. 831; Metallurgie, 8, p. 225.
396	1911	Broniewski, W., Electrical properties of aluminium-magnesium alloys, C. R., 152, pp. 85–87.
397	1908	Portevin, Les Alliages d'Aluminium, Rev. Met., 5, p. 274.
398	1905	Barnett, Magnalium and other light alloys, Jour. Soc. Chem. Ind., 24, pp. 832–834.
399	1915	Grube, Mg-Al alloys, Z. anorg. Chemie, 45, pp. 225–237.
400	1901	Boudouard, O., Alloys of Al and Mg, Bull. Soc. d'Encouragement, p. l'Ind. Nat., 101, pp. 773–780; Jour. Soc. Chem. Ind., 1901, p. 814, 1902, p. 258; C. R., 132, (1901), p. 1325.
401	1900	Miethe, production and properties of magnalium and of products made therefrom, Verh. Vereins z. Beförd. Gewerbefleisses, Ltz. B, 1900, pp. 93–98.
		Mn-Al
402	1908	Hindrichs, G., Über einige Chrom-und Mangan Legierungen, Z. anorg. Chem., 59, p. 441.
403	1902	Guillet, L., Aluminium-Manganese alloy series, C. R., 134, p. 236.
		Mo-Al
404	1901	Guillet, L., Alloys of Al and Mo, C. R., 133, No. 5, pp. 291–293.
405	1901	Guillet, L., Al-Mo alloys, C. R., 132, No. 22, pp. 322–325.
		Ni-Al
406	1908	Gwyer, A. G. C., Alloys of Al with Cu, Fe, Ni, Co, Pb, Cd, Z. anorg. Chem., 57, p. 113.
407	1900	Anonymous, Nickel-Al as bell metal, Uhlands' Verkehrszeitung u. ind. Rundschau, 14, p. 229.
		Pb-Al
408	1908	Gwyer, A. G. C., Aluminium-lead alloys, Z. anorg. Chem., 57, p. 147.
409	1904	Pecheux, H., Pb-Al alloys, C. R., 139, pp. 1042–1044; Metallurgie, 1, p. 513.
		Pt-Al
410	1912	Chouriguine, M., Aluminium-platinum alloys, C. R., 155, p. 156.
411	1912	Chouriguine, M., Alloys of Pt and Al, Rev. d. Metallurgie, 9, pp. 874–883.
		Sb-Al
412	1905	Tammann, Sb-Al alloys, Z. anorg. Chem., 48, pp. 53–60.
413	1901	Lippmann, Density of Al-Sb alloy, C. R., 132, No. 21, pp. 1266–1267.
		Si-Al
414	1914	Roberts, C. E., The alloys of Al and Si, Chem. Soc. (London), Trans., 105, pp. 1383–1386.
415	1911	Frilley, R., Recherches sur quelques alliages métalliques siliciés, Rev. Met., 8, p. 457.
416	1909	Portevin, Si-Al, Rev. Met., 1909, pp. 951–962.
417	1908	Fränkel, W., Si-Al alloys, Z. anorg. Chem., 58, pp. 154–158; (Abst.) Chem. Zentralbl., II, p. 143.
418	1907	Vigouroux, E., Action of silicon on pure and impure aluminium, Bull. Soc. Chim., 1, pp. 789–792.
419	1905	Vigouroux, E., Action of silicon on impure and pure aluminium; aluminosilicides, C. R., 141, pp. 951–953.
		Sn-Al
420	1913	Lorenz-Plumbridge, Al and Sn alloys, Z. anorg. Chem., 133, p. 243.
421	1906	Gwyer, Aluminium-tin alloys, Z. anorg. Chem., 49, p. 311.
422	1904	Shepherd, E. S., Al-Sn alloys, Jour. Phys. Chem., 8, pp. 233–247.
423	1904	Pecheux, H., Properties of Sn-Al alloys, C. R., 138, pp. 1170–1171.
424	1903	Anderson and Lean, Properties of the Al-Sn alloys, Proc. Roy. Soc., 72, pp. 277–284.
425	1902	Campbell and Mathews, Aluminium-tin alloys, Jour. Am. Chem. Soc., 24, p. 258.
426	1902	Guillet, L., Contribution to the study of the Sn-Al alloys, C. R., 133, pp. 935–937.
		Th-Al
427	1906	Hoenigschmidt, O., Alloy of thorium and aluminium, C. R., 142, pp. 280–281.

3. BIBLIOGRAPHY—Continued

Text references	Year	Name and title
		BINARY—Continued
		Vd-Al
428	1913	Czako, N., Vanadium-aluminium alloys, C. R., 156, pp. 140–142.
		W-Al
429	1901	Guillet, L., Alloys of Al and W, C. R., 132, No. 18, pp. 1112–1115.
		Zn-Al
430	....	Banroft, Al-Zn alloys, Mech. Eng., 25, p. 206.
431	1915	Bauer, O., and Vogel, O., Information on Al-Zn alloys, Mittlg. aus dem Kgl. Materialprüfungsamt, No. 3 and 4; (Abst.) Metall. u. Erz., 13, pp. 158–161.
432	1916	Bauer, O., and Vogel, O., Al-Zn alloys, Int. Z. Met., 8, p. 101; Jour. Inst. Met., (Abs.) 17, 1917, p. 328.
433	1913	Lorenz, R., and Plumbridge, D., The binary system Al-Zn, Z. anorg. Chem., 83, pp. 243–245.
434	1912	Smirnoff, W., Thermal expansion of Al-Zn alloys, C. R., 155, pp. 351–352.
435	1912	Rosenhain, W., and Archbutt, L. S., Alloys of aluminium and zinc, Tenth Report to the Alloys Research Committee (with an appendix on a ternary alloy of Al with Zn and Cu); Inst. Mech. Eng.; (Abst.) Jour. Soc. Chem., Ind., 31, No. 10, p. 493.
436	1911	Rosenhain, W., The constitution of alloys of aluminium and zinc, Proc. Roy. Soc. (London), 85 (Ser. A), No. 580, pp. 389–392.
437	1911	Portevin, A., Aluminium-zinc alloys, Rev. Metallurgie, 8, pp. 721–727.
438	1911	Rosenhain and Archbutt, Alloys of Al-Zn, Jour. Inst. Met., 6, p. 236.
439	1910	Ewen-Turner, Shrinkage of Al-Zn alloys, Jour. Inst. Met., 4, p. 128.
440	1909	Bancroft, W. D., The tensile strength of Al-Zn alloys, Trans. Amer. Brass Founders' Assoc., pp. 47–54.
441	1908	Saposhnikow, A., Hardness of Al-Zn alloys, Jour. Russ. Phys. Chem. Soc., 40, pp. 95–100.
442	1907	Anonymous, Aluminium alloys cracking (Al-Zn) overcome by addition of a very small percentage of Cu), Pract. Eng., 35, p. 738.
443	1907	Anonymous, Alzene and its properties (two-thirds Al and one-third Zn, melted together), Mechanical World, 41, p. 41; Durand's texts on the strength and other characteristics.
444	1905	Shepherd, E. S., Aluminium-zinc alloys, Jour. Phys. Chem., 9, pp. 504–512; (Abst.) Chem. Zentralbl., II, pp. 537–538.
445	1904	Pecheux, H., Zn-Al alloys, C. R., 138, pp. 1103–1104.
446	1904	May, Casting aluminium and Al-Zn alloys, Engl. Mechanic and World of Science, 79, pp. 420–422.
447	1903	Carrick, W., and Leau, G., Properties of Al-Zn alloys, Proc. Roy. Soc., 72, pp. 277–284.
448	1902	Lougouinine, W., and Schukareff, A., Thermal investigation of certain alloys of Al and Zn, Arch. Sci. Phys. et Nat., Geneva, 13. No. 4, pp. 5–29.
449	1901	Richards, J. W., Al-Zn alloys, Eng. and Min. Jour., 72, No. 22, p. 715.
		TERNARY
450	1916	McKinney, P. E., Aluminium castings and forgings, Trans. Am. Inst. Metals, X, p. 166–172.
451	1916	Diamond, Aluminum-alloy piston design, S. A. E., 11, I, p. 238.
452	1915	Gruenewald, Al alloy pistons, S. A. E., 10, II, p. 135.
453	1915	Read, A. A., and Greaves, R. H., The properties of some Al-Ni and Cu-Ni-Al alloys, Jour. Inst. Metals, XIII, I, pp. 100–159.
454	1914	Aluminium in motor industry, Elektrochem. Z., 20, p. 264.
455	1914	Read, A. A., and Greaves, R. H., Influence of Ni on some Cu-Al alloys, Jour. Inst. Metals, March, 11, p. 169; (Abst.) Jour. Soc. Chem. Ind., 33, p. 316.
456	1914	McAdams, W. A., A new Al alloy (patent), Met. and Chem. Eng., 12, p. 352.
457	1913	Cox, C. E., Al alloys, S. A. E., 8, p. 322.
458	1913	Alloys for motor-bus construction, Engineering, 95, p. 99.
459	1913	Eger, E., Mg-Al-Zn alloys, Constitution of these ternary alloys, Int. Zeits. Metallographie, 4, pp. 29–128.
460	1912	Busch, Al solder (patent), Met. and Chem. Eng., 10, p. 309.
461	1912	Levi-Malvano, M., and Marantonio, M., Light alloys of Al, Zn, and Cu, Gaz. Chim. Ital., 42, I, pp. 353–360.
462	1912	Carpenter, H. C. H., and Edwards, C. A., The liquidus curves and constitutional diagram of the ternary system Al-Cu-Zn, Internat. Zeitschr. Metallographie, 2, pp. 209–242.
463	1910	Rosenhain, W., and Lantsberry, F. C., Properties of some alloys of Cu, Al, and Mn; Ninth Report to the Alloys Research Committee, with an appendix on the corrosion of alloys of Cu and Al when exposed to the sea; Inst. Mech. Eng., pp. 119–339; (Abst.) J. Soc. Chem. Ind., 29, No. 6, p. 356.
464	1909	Andres, J. H., and Edwards, C. A., Liquidus curves of Al-Cu-Sn alloys, Proc. Roy. Soc. (Series A), 83, pp. 568–579.
465	1909	Ross, A. D., and Gray, R. C., Magnetic properties of alloys of Mn, Al, and Cu, Z. anorg. Chem., 63, pp. 349–352.
466	1901	Haentzschel, New alloys of nickel, copper, and aluminium, Verhandl. des Vereins zur Beförd des Gewerbefleisses; (Abst.) Proc. Inst. Civil Eng., 146, No. 4, p. 39; (Abst.) Jour. Soc. Chem. Ind., 20, p. 1217.

3. BIBLIOGRAPHY—Continued

Text references	Year	Name and title
		TERNARY—Continued
		Duralumin
467	1915	Koch u. Dannecker, Elasticity at high temperatures, Ann. d. Phys., IV, 47, p. 197.
468	1914	Fendler, C., and Stueber, W., Use of aluminium alloy (duralumin) for the manufacture of domestic and cooking utensils; Hygien. Rdschau., 24, pp. 59–62; (Abst.) Chem. Zentralblatt, 1914, Pt. I, p. 693.
469	1913	Cohn, L. M., Changes in the physical properties of aluminium and its alloys, with special reference to duralumin, Elektrotechnik u. Machinenbau, 31, May 18, pp. 430–433.
470	1912	McKechnie, Dur-alumin. Discussion on Rosenhain-Archbutt paper; Trans. Inst. Mech. Eng., p. 500.
471	1912	Cohn, L. M., Duralumin, Elektrotechnik u. Machinenbau, 30, pp. 809, 829.
472	1911	Wilm, A., Physico-metallurgical investigations of aluminium alloys containing magnesium, Metallurgie, 8, pp. 225–227.
473	1911	Wilm, A., Light aluminium alloys (Hardening of), Metallurgie, 8, p. 650. 225
474	1910	Cohn, L. M., Duralumin, Ver. z. Förd. d. Gewerbefleisses, 89, p. 643.
		HEAVY ALLOYS
475	1916	Read, A. A., and Greaves, R. H., Sn-Al-Cu alloys, Inst. Metals, Mar. 29, p. 264; Jour. Soc. Chem. Ind., 35, No. 8, p. 472, advance copy.
476	1916	Corse, W. M., and Comstock, G. F., Tests of aluminium-bronze, paper presented to Amer Soc. for Test. Materials at Atlantic City, June 30; Iron Age, 98, No. 2, pp. 80–81.
477	1916	Anonymous, Aluminium bronze, Metal Industry (London), 9, July 28, No. 4, pp. 102–103.
478	1915	Andrew, J. H., Some experiments with Cu-Al alloys, Jour. Inst. Met., 13, pp. 249–261.
479	1915	Corse, W. M., Ti-Al bronze castings, Met. and Chem. Eng., 13, pp. 511–512.
480	1915	Corse, W. M., Properties of Al-bronze alloys, Foundry, 43, pp. 459–460.
481	1915	Vickers, C., How Ti-Al bronze is produced, Foundry, 43, pp. 273–278.
482	1914	Guillet, Leon, Alloys of Cu-Ni and Al, C. R., 158, pp. 704–706.
483	1914	Kremann, R., Lorber, J., and Maas, R., Electrolytic separation of alloys and their metallographic and mechanical investigation, III. Attempts to produce zirconium, aluminium, antimony, and chromium bronze, Monatshefte, Chemie, 35, pp. 581–601.
484	1914	Wickhorst, M. H., Influence of aluminium on Bessemer ingots (Report of tests), Iron Trades Rev., 54, p. 589.
485	1913	Hanemann, H., and Merica, P., Cu-Al alloys with 84 to 90 per cent of Cu, Int. Zeits. Metallographie, 4, pp. 209–227.
486	1913	Portevin, A., The B-constituent of aluminium-bronze, Int. Zeits. Metallographie, 4, pp. 257–260.
487	1913	Read, A. A., Influence of phosphorus on some copper-aluminium alloys, Inst. of Metals, Aug.; (Abst.) Jour. Soc. Chem. Ind., 32, No. 18, p. 914.
488	1913	Robin, F., Special bronzes of aluminium and tin. The "needle" constituents of alloys; Bull. Soc. d'Encouragement, 119, pp. 12–41; (Abst.) Jour. Soc. Chem. Ind., 32, No. 7, p. 367.
489	1912	Arnou, G., and Portevin, A., Tempering of aluminium bronzes, C. R., 154, pp. 511–514.
490	1912	Heusler, F., and Take, E., The nature of the Heusler magnetic alloys, Trans. Far. Soc., Apr. 23; (Abst.) Jour. Soc. Chem. Ind., 31, No. 10, p. 494.
491	1912	Knowlton, A. A., and Clifford, O. C., Heusler magnetic alloys (aluminium-manganese bronzes), Trans. Far. Soc., Apr. 23: (Abst.) Jour. Soc. Chem. Ind., 31, No. 10, p. 495.
492	1912	Ross, A. D., Magnetic properties and microstructure of Heusler magnetic alloys; Trans. Far. Soc., (Abst.) Jour. Soc. Chem. Ind., 31, No. 10, p. 495.
493	1912	Edwards, C. A., Twin crystals and hardness of copper-aluminium alloys, Intern. Zeitschr. f. Metallographie, 3, p. 179.
494	1911	Levi-Malvano and Marantino, M., Constitution of aluminium brasses, Gaz. Chim. Ital., 41, II, pp. 282–297.
495	1910	Sperry, E. S., Aluminium-bronze, Mech. Eng., 25, No. 630, p. 206; Jour. Inst. Metals, 3, No. 1, p. 278 (Abst.).
496	1910	Carpenter, H. C. H., and Edwards, C. A., Production of aluminium-bronze castings to withstand high pressures, Inst. Mech. Eng. (London), 110, pp. 701–703.
497	1910	Johnson, Fr., The effect of Ag and Al upon the mechanical properties of "tough-pitch" copper containing arsenic, Jour. Inst. Metals, IV, No. 2, pp. 163–205; Discussion, pp. 206–234.
498	1909	Edwards, C. A., and Andrew, J. H., The constitution and properties of Al-Cu-Sn alloys, Inst. of Metals, pp. 29–47; (Abst.) Jour. Soc. Chem. Ind., 28, No. 21, p. 1138.
499	1909	Barree, M., Transformation points of copper-aluminium alloys (Relation of electrical resistance to temperature), C. R., 149, pp. 678–681.
500	1907	Curry, B. E., Constitution of aluminium-bronzes, Jour. Phys. Chem., 11, pp. 425–436.
501	1906	Edelmann, O., Explosions in the aluminium-bronze industry, Chem. Ztg., 30, pp. 925–926, 951–952.
502	1906	Richter, M. M., Cause and prevention of explosions in the aluminium-bronze industry, Chem. Ztg., 30, pp. 324–326.
503	1906	Stockmeier, Explosions of aluminium-bronze powders, Chem. Ztg., 30, p. 580.
504	1906	Gray, Housler's magnetic alloy of Mn, Al, and Cu, Proc. Roy. Soc., 77, pp. 256–259.
505	1905	Guillet, Leon, Aluminium steels, Rev. de Metallurgie, 2, pp. 312–327.
506	1901	Brinell, J. A., Stockholm.

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