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SOME MECHANICAL PROPERTIES OF A HEAT-TREATED ALUMINUM-SILICON-COPPER-MAGNESIUM CASTING ALLOY

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ABSTRACT

The mechanical properties of ultimate tensile strength and per cent. elongation in two inches for an aluminum-silicon-copper-magnesium casting alloy, after heat treatment by a solid-solution treatment of heating for 12 hours at 980° F., followed by quenching for varying times in molten salt baths at temperatures varying from 300 to 400° F., are compared to the same mechanical properties of the alloy after conventional heat treatments as recommended by the Aluminum Company of America. It has been found that a single-cycle heat treatment, as described in the paper, gives comparable mechanical properties to the double-cycle heat treatments normally practised in industry. The single-cycle heat treatment is more simple and less costly to perform, and gives equivalent or superior mechanical properties. The proposed single-cycle heat treatment should prove to be economically advantageous to industry, especially the aeronautical industry.

I. INTRODUCTION

The sand cast aluminum-silicon-copper-magnesium alloy was developed by the Aluminum Company of America to improve the mechanical properties of the binary aluminum-silicon alloy. The Al-Si-Cu-Mg alloy retains the excellent casting characteristics of the binary alloy of aluminum with 5 to 10 per cent. silicon and, in addition, is capable of developing, by suitable heat treatment, superior mechanical properties. Castings of the improved alloy are produced in a number of heat-treated conditions, the heat treatments varying in time and temperature for the aging treatment to give a specified range of mechanical properties. Table I gives the average mechanical properties to be expected from the heat treatments recommended by the Aluminum Company of America.

The Al-Si-Cu-Mg alloy, known under the trade name of ALCOA 355, was developed for specific applications where good castability, weldability, and pressure tightness are required. The alloy possesses casting characteristics for the economical production of complicated sections; and pressure tight castings are more easily produced with this alloy than with any other casting alloy. The alloy maintains reasonable mechanical properties after prolonged exposure at temperatures

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as high as 400° F. However, its corrosion resistance is not so good as that of the copper-free, heat-treated, aluminum-silicon-magnesium alloy, or that of the aluminum 5 per cent. silicon alloy.

TABLE I

Mechanical Properties of Al-5 Si-1·3 Cu-0·5 Mg Alloy [*American Society for Metals*, Metals Handbook (1948), *pp.* 836–37]

Condition†	Tensile Strength lbs./sq. in.	per cent. Elongation in 2 inches, tension	Hardness Brinell
ALCOA T 51 Treatment ..	28,000	1·5	65‡
ALCOA T 6 Treatment ..	35,000	2·5	80
ALCOA T 61 Treatment ..	39,000	1·0	90
ALCOA T 7 Treatment ..	38,000	0·5	85
ALCOA T 71 Treatment ..	35,000	1·5	75

† *ALCOA T 51 Treatment*.—Sand cast and precipitation treated at 435 to 445° F. for seven to nine hours.

ALCOA T 6 Treatment.—Sand cast, solution heat treat at 975 to 985° F. for twelve hours, quench in boiling water, precipitation heat treat at 305 to 515° F. for three to five hours.

ALCOA T 61 *Treatment*.—Sand cast, solution heat treat and quench in boiling water as above, precipitation heat treat at 305 to 515° F. for eight to ten hours.

ALCOA T 7 Treatment.—Sand cast, solution heat treat and quench in boiling water as above, precipitation heat treat at 435 to 445° F. for seven to nine hours.

ALCOA T 71 Treatment.—Sand cast, solution heat treat and quench in boiling water as above, precipitation heat treat at 470 to 480° F. for four to six hours.

‡ Conversion of Brinell Hardness Numbers to Rockwell E Hardness Numbers:

Brinell 500 kg. Load	Rockwell E $\frac{1}{8}$ inch ball, 100 kg. load
65	72·5
75	81·5
80	85
85	88
90	90·5

Typical industrial uses of the Al-Si-Cu-Mg alloy include: aircraft supercharger covers, fuel-pump bodies, air-compressor pistons, liquid-cooled cylinder heads, liquid cooled aircraft engine crankcases, water jackets, blower housings, and water-cooled exhaust manifolds.

II. Purpose of Investigation

The Aluminum Company of America has developed a series of heat treatments for this alloy, to improve mechanical properties, consisting of a solution heat treatment for twelve hours at 980° F., quenching in water at a temperature of 150 to 212° F., and aging at temperatures of 305 to 480° F. for times varying from three to ten hours at temperature. The improved properties are developed by the precipitation of a phase, or phases, from super-saturated solid solution at the aging temperature. The mechanism of precipitation, during aging, from super-saturated solid solution is well understood, and a voluminous literature is in existence. The theory for hardening by precipitation will not be reviewed here.

There would be a decided economic advantage to industry if the aging process could be carried out by quenching directly from the solution heat treating temperature to the aging temperature; such a process would eliminate the water quench and subsequent reheating to aging temperature for relatively long periods of time, which represents a heavy burden in processing costs. This paper, is therefore, concerned with the mechanical properties that are produced by quenching the Al-Si-Cu-Mg alloy, following the normal solution heat treatment, in a molten salt bath, at temperatures approximating the normal temperatures usually used for precipitation heat treatments for varying lengths of time.

III. Specimen Materials

All the specimens used in the tests reported herein are sand cast and have an average composition as follows:

Silicon	..	5·0 per cent.	Zinc	..	0·1 max.
Copper	..	1·3 per cent.	Titanium	..	0·2 max.
Magnesium	..	0·5 per cent.	Others	..	0·1 max.
Iron	..	0·6 max.	Aluminum	..	Balance
Manganese	..	0·1 max.			

The specimens were cast as standard tensile-specimens with 0·75-inch diameter grip area, 0·625-inch shoulder, 0·50-inch diameter by 3·0-inch center section for determining ultimate tensile strength and per cent. elongation. The tension tests were made on a 40,000-pound Riehle Universal Testing machine. The per cent elongation was determined by remeasuring standard gauge marks after failure in tension.

IV. Experimental Procedure and Data

A. Mechanical Properties

Experiments were devised so that a comparison of mechanical properties could be made of the Al-Si-Cu-Mg alloy in the various conditions of: (1) as cast; (2) as cast and aged; (3) solid solution treated, quenched in boiling water and aged; (4) solution heat-treated, quenched in oil and aged; (5) solution heat-treated, quenched in hot oil and aged; (6) solution heat-treated and quenched in molten salt. The experimental data for these various treatments are tabulated as follows:

1. *As-cast Condition.*—The average of values for the mechanical properties of a group (group usually refers to ten test specimens) of specimens as received in the as-cast condition were as follows:

Rockwell E Hardness	Ult. Ten. Str. lbs./sq. in.	Per cent. Elongation in 2 inches
63	26,000	2·3

2. *As-cast and Aged Condition.*—A group of as-cast specimens were aged at 440° F. for eight hours. The average values for the mechanical properties were as follows:

Rockwell E Hardness	Ult. Ten. Str. lbs./sq. in.	Per cent. Elongation in 2 inches
69·5	26,250	1·45

3. *Solid Solution Treated, Quenched in Boiling Water and Aged Condition.*—A group of specimens were solution heat-treated at 980° F. for twelve hours, quenched in boiling water, and aged at various temperatures for varying times. The average values for the mechanical properties were as follows:

Aging Time Hours	Aging Temp. ° F.	Rockwell E Hardness	Ult. Ten. Str. lbs./sq. inch	Per cent. Elongation in 2 inches
0	75	70·5	32,000	3·25
4	310	84·7	34,500	2·90
10	310	89·5	38,700	2·00
4	350	96·0	41,000	0·35
4	375	93·0	40,000	0·45
4	400	98·0	42,000	0·25
4	435	92·0	40,000	0·50

4. *Solution Heat-treated, Quenched in Oil and Aged Condition.*—A group of specimens were solution treated at 980° F. for twelve hours, quenched in oil at 75° F., and aged at various temperatures for varying times. The average values for the mechanical properties were as follows:

Aging Time Hours	Aging Temp. ° F.	Rockwell E Hardness	Ult. Ten. Str. lbs./sq. inch	Per cent. Elongation in 2 inches
0	75	69·0	34,600	2·50
4	310	85·0	36,500	1·21
10	310	91·5	40,500	1·05
4	350	96·0	42,000	0·30
4	375	97·0	42,500	0·25
4	400	99·0	45,500	0·00
4	435	96·0	42,000	0·24

5. *Solution Heat-treated, Quenched in Hot Oil and Aged Condition.*—A group of specimens was solution heat-treated at 980° F. for twelve hours, quenched in oil at 150° F., and aged at various temperatures for varying times. The average values for the mechanical properties were as follows:

Aging Time Hours	Aging Temp. ° F.	Rockwell E Hardness	Ult. Ten. Str. lbs./sq. inch	Per cent. Elongation in 2 inches
0	75	77·0	29,250	3·00
4	350	90·0	39,800	1·00
4	375	92·5	40,300	0·52
4	400	94·5	40,800	0·45

6. *Solution Heat-treated and Quenched in Molten Salt Condition.*— A group of specimens was solution heat-treated at 980° F. for twelve hours and quenched in molten salt at three different temperatures and for varying times. The average values for the mechanical properties were as follows:

Quenching Temp. ° F.	Quenching Time Minutes	Rockwell E Hardness	Ult. Ten. Str. lbs./sq. inch.	Per cent. Elongation in 2 inches
300	10	82·3	34,300	1·00
300	20	86·5	38,200	0·81
300	30	89·8	40,300	0·41
350	3	89·0	39,000	0·60
350	6	90·9	40,000	0·50
350	12	92·7	40,400	0·40
350	24	94·5	42,200	0·20
350	30	94·0	38,700	0·71
400	2	89·0	37,000	1·00
400	4	92·0	37,300	0·90
400	8	93·9	37,000	0·90
400	12	91·0	38,300	0·75
400	30	91·3	38,000	0·80

B. Residual Stresses

The residual stresses remaining in metals and alloys after heating and cooling cycles are of considerable importance in determining their usefulness in industrial applications. The residual stresses in representative samples of the as-cast, cast and annealed, and cast and heat-treated conditions were determined by using X-ray back-reflection techniques. Copper Kα monochromatic radiation was used in making the diffraction patterns. A voltage of 38 KV, amperage of 10 milli-amperes, exposure time of thirty minutes, defining pin-hole of 0·063 inches, back pin-hole of 0·078 inches, and a collimating tube length of 7·5 centimeters were used in the experimental apparatus. The film to specimen distance was determined by the use of gold foil, for which the theta angle for the (333) plane is given as 78° and 56′. The aluminum ring for the (511) plane was used for the determination of stresses. Standardization was accomplished by making back-reflection patterns of annealed aluminum specimens, to which different amounts of tension stresses were applied—this afforded a quantitative evaluation of the effect of stresses in shifting the diffracted rays. Residual stresses were calculated by the use of the formula:

$$S = \frac{D - D_0}{D_0} \cdot E$$

where S is the residual stress in lbs./sq. inch; D_0 is the interplanar distance, in Angstroms, in the stress-free condition; D is the interplanar distance in the strained condition; E is the modulus of elasticity for the alloy.

The applied stresses were determined by the use of the formula:

$$S = \frac{D - D_0}{D_0 \cdot R} \cdot E$$

where S is the applied stress in lbs./sq. inch; R is Poisson's ratio; D. D_0 and E are as above.

The calculated stresses from back-reflection diffraction patterns were found to be as follows:

Condition of Specimen	Calculated stress, psi
Annealed§ ..	.. None
Quenched in oil at 75° F. ..	.. – 2,300†
As-Received ..	.. – 5,550
Quenched in Boiling Water ..	.. – 3,270
Quenched in Oil at 150° F. ..	.. – 945
Quenched in salt at 350° F. 20 min.	.. None

§ Heated at 980° F. for twelve hours, furnace cooled.
† Negative quantity indicates compression.

C. Microstructure

Microscopic examinations were made on metallographic specimens representing all the conditions in which the alloy was tested. Systematic identification of the microconstituents present in the structure resulted in the following:

1. *As-Received Condition.*—Alpha solid solution (consisting of Cu, Si and Mg in Al); $CuAl_2$; Silicon; Beta Al-Fe-Si.

2. *Solution Heat-treated and Quenched Condition.*—$CuAl_2$ disappeared by going into solution in alpha phase; silicon particles were spheroidized and perhaps some went into solution in aplha phase; Beta Al-Fe-Si remained unchanged.

3. *Solution Heat-treated, Quenched and Aged Condition.*—The microstructure was the same as in the solution heat-treated and quenched condition. No precipitate could be found, and this is in accordance with theory that the precipitated particles are sub-microscopic in size.

4. *Solution Heat-treated and Quenched in Molten Salt Condition.*—The same microstructure as in Nos. 2 and 3 above. No precipitate could be found in the structure.

Because of the small changes in microstructures resulting from the various treatments only four structures are illustrated in Figure 1.

V. Summary of Experimental Results

A. The mechanical properties for specimens in the solution heat-treated and quenched condition may be summarized as follows:

1. Quenching in oil at 75° F. yields the highest ultimate strength, but with lowered per cent. elongation.

2. Quenching in boiling water yields the highest per cent. elongation, but with somewhat lower ultimate strength.

3. Quenching in oil at 150° F. yields the lowest ultimate strength and less per cent. elongation than quenching in water.

4. Quenching in molten salt at 300° F. for ten minutes yields an ultimate strength equivalent to oil quenching at 75° F., but with much lower per cent. elongation. Higher ultimate strengths, but with lowered per cent. yields, may be secured by increasing the time and temperature of quench in molten salt to an optimum of 24-minute quench at 350° F.

B. The mechanical properties for specimens in the solution heat-treated, quenched, and aged condition may be summarized as follows:

1. The maximum ultimate strength is produced by quenching in oil at 75° F. and aging for four hours at 400° F., but the per cent. elongation drops to zero, which indicates a brittle condition, and its usefulness in industrial applications is questionable.

2. Aging at temperatures above 400° F. results in lowered ultimate strength and improved per cent. elongation through agglomeration and growth of the precipitated particles. This is in accordance with the theory of precipitation hardening.

3. If an arbitrary specification for minimum mechanical properties of 40,000 lbs./sq. inch and an elongation equal to 0·5 per cent. in two inches is considered, the specification may be met by the following quenching and aging treatments, following a solution heat treatment for twelve hours at 980° F.:

(*a*) Quench in oil at 75° F. and age ten hours at 310° F.

(*b*) Quench in oil at 150° F. and age four hours at 375° F.

(*c*) Quench in boiling water and age four hours at 435° F.

C. The mechanical properties for specimens quenched in molten salt may be summarized as follows:

1. Equivalent ultimate tensile strengths are secured but with lowered per cent. elongations, as compared to the more conventional heat treatment of quench and age.

2. A satisfactory combination of properties equivalent to 40,000 lbs./per sq. nch ultimate strength and 0·5 per cent. elongation in two inches may be secured y quenching in a molten salt bath at 350° F. for six minutes.

D. Quantitative determination of internal stresses by X-ray back-reflection echniques is very delicate, because great precision is required in measuring small lifferences in diffraction patterns recorded on photographic film. Furthermore, nly stresses below the elastic limit can be determined. A good resolution of he monochromatic characteristic radiation doublets is a good indication of low tresses, the better the resolution the lower the stresses.

It is believed that the results recorded for internal stresses are in the right lirection but are not necessarily exact. It would be expected that annealed specinens should not show internal stresses, but the specimen showing maximum ultinate strength in the oil-quenched condition has lower stresses than specimens quenched in boiling water with a lower ultimate strength. Aging coincident with quenching in molten salt apparently does not produce internal stresses, because of the higher temperature.

E. Excepting for solution of the $CuAl_2$ phase and the spheroidization of the silicon phase during the solution heat treatment, no changes in the microstructures were detected. No microscopic evidence of a precipitated phase during the aging treatments was detected, which is in accordance with previous work and with the theory that the precipitation of the hardening phase is in sub-microscopic particle size.

VI. Conclusions

These experiments demonstrate that suitable and equivalent mechanical properties in this aluminum base alloy may be secured by a heat treatment consisting of: (*a*) solution heat treatment, of the alloy as cast, at 980° F. for twelve hours; (*b*) quenching in molten salt at temperatures of 300 to 400° F. with time of quench suitably adjusted to produce optimum properties.

These experiments demonstrate that precipitation hardening is coincident with quenching when the quenching bath is in the range of temperatures normally used for aging. It, therefore, becomes obvious that a single solution heat-treating and quenching cycle is feasible, and that such a cycle obviates the necessity for a double heat treatment of quenching and aging as is normally practiced. This single cycle heat treatment should have economic and practical advantages to industry by reason of its simplification and the lowered costs of the heat-treating processes. In this connection it may be stated that molten salt for hot quenching is not required since quenching oils with flash points well in excess of the quenching temperatures required are commercially available.

If an arbitrary specification for an ultimate tensile strength in excess of 38,000 lb./sq. inch and a minimum elongation of 0·5 per cent. in two inches is accepted, these mechanical properties can be easily attained through the simplified single heat-treating cycle as proposed. The industrial uses for which this

FIG. 1 (*a*)
As-Cast Condition. Magnification, 500 ×.

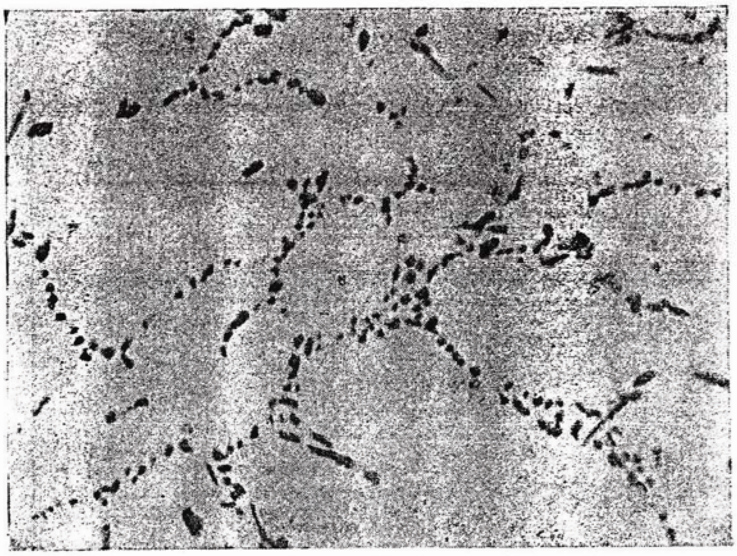

FIG. 1 (*b*)
Solution heat-treated and quenched in boiling water. Magnification, 250 ×.