

AN ABSTRACT OF THE THESIS OF

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Title: ISOTHERMAL AGING OF VAPOR DEPOSITED ALUMINUM-
COPPER ALLOY FILMS

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Abstract approved: _____
Dr. John A. McComb

Aluminum 4 weight percent copper alloy films were prepared by vapor deposition of an aluminum 5 weight percent master alloy.

Films 2600A in thickness were isothermally aged at 400°C, 450°C, and 500°C for times ranging from 10 to 960 minutes and subsequently examined directly by transmission electron microscopy. Calculations were performed on the growth data obtained from the electron micrographs both directly and by applying a time correction to compensate for experimental error. The grain growth rates after aging 100 minutes at 400°C, 450°C, and 500°C were found to be 1.8, 2.4, and 3.2A/minute, respectively uncorrected, and 2.0, 2.7, and 3.3A/minute, respectively with the time correction. The grain growth time exponent, n , was found to be constant between 400°C and 500°C with an uncorrected value of 0.18 and a corrected value of 0.20. The activation energy for grain boundary migration was also

constant between 400°C and 500°C with an uncorrected value of 30 Kcal/mole and a corrected value of 25 Kcal/mole. The observed growth behavior was found to obey the empirical equation $D = Kt^n$.

Films ranging in thickness from 0.1 μ to 0.4 μ were aged in-situ at temperatures ranging from 230°C to 280°C. Precipitates of θ -CuAl₂ were found to nucleate on the surface of the film. The number of precipitates observed was found to increase with increasing foil thickness.

Isothermal Aging of Vapor Deposited
Aluminum-Copper Alloy Films

by

William C. McBee

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ISOTHERMAL AGING OF VAPOR DEPOSITED ALUMINUM-COPPER ALLOY FILMS

I. INTRODUCTION

Aluminum and Aluminum-Copper Thin Film Applications

Vapor deposited metal films have found wide spread usage in the electronics industry as interconnection in hybrid and monolithic integrated circuits. The metal used must be a good conductor; it must adhere well to the oxide substrate and must be capable of making good ohmic contacts to either N or P type silicon. Since aluminum metal possesses all these attributes and also is relatively easy to evaporate, it is used almost exclusively.

In practice the vapor metallization is applied to substrates held either at ambient or elevated temperature. After deposition, the substrates are often subjected to elevated temperature treatments either during further processing or while in service. Heating can cause microstructural changes in the thin film.

Until recently pure aluminum was used extensively for integrated circuit vapor metallization, however, electromigration phenomenon has led to premature open circuit failures. Electromigration in metallic conductors refers to the transport of matter by an electric current. Recently, Ames and d'Heurle (3) reported extending the lifetime of thin film strips subjected to a high current density by

a factor of 70 by the addition of copper to the aluminum.

Because of the practical significance of these thin films, the growth and precipitation behavior has been the subject of several recent studies. Mader and Heard (14) compared the precipitation behavior of single crystal Al-3% Cu alloy films with that reported in the literature for bulk alloys of the same composition. The structure of pure aluminum films evaporated onto heated, oxidized silicon substrates was studied by d'Heurle, Bernbaum, and Rosenberg (9) who found that the grain size of the thin film was drastically effected by the substrate temperatures and that the grain size to film thickness ratio decreases with decreasing temperature. Grain coalescence during annealing of thin vapor deposited aluminum films at temperatures as low as 100°C has been observed by Ferraglio and Antonio (10).

Objectives

Grain growth behavior in polycrystalline aluminum-copper thin films has not been reported in the literature. For this reason a thesis topic was selected with the following principal objectives:

1. To prepare vapor deposited aluminum-copper alloy films suitable for direct examination by electron microscopy.
2. To measure the rate of grain growth as a function of temperature in the temperature region of 400 to 500°C.

3. To calculate the activation energy necessary for grain boundary migration.

The secondary objective was to observe the equilibrium precipitate θ -CuAl₂ in thin films of various thicknesses and if possible, correlate the observed precipitation with that reported in the literature for thin and bulk specimens.

The Aluminum-Copper System

The Al rich portion of the Al-Cu equilibrium phase diagram is shown in Figure 1. As shown by the diagram, Al has a solid solubility limit for Cu of 5.6 weight percent at 548° C. This solubility decreases very rapidly with temperature and is about 0.1 weight percent at 200° C. θ (CuAl₂) phase precipitates upon cooling and has a tetragonal crystal structure with $c = 6.066\text{\AA}$ and $a = 4.874\text{\AA}$ (8). Aging bulk Al-Cu alloys above 200° C produces the equilibrium θ -CuAl₂ precipitates which exhibit a characteristic habit plane related to the matrix orientation (13). Aging Al-Cu thin films above 200° C also produces the equilibrium CuAl₂ precipitates, however, here the precipitates occur on the surface of the foil and do not exhibit the characteristic habit plane (14).

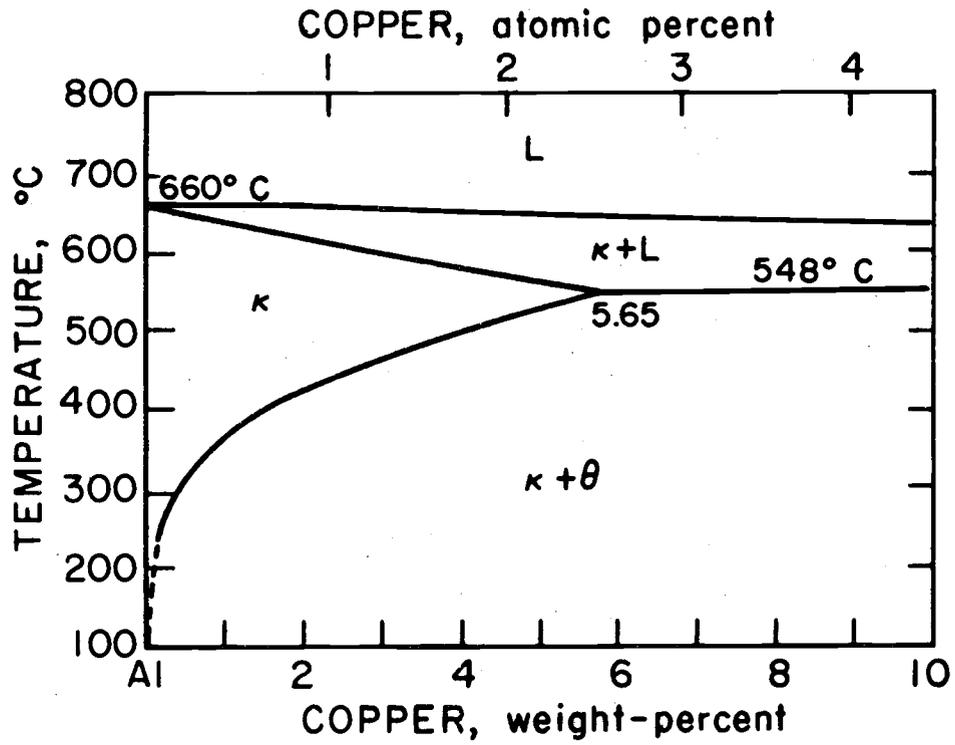


Figure 1. The aluminum rich portion of the aluminum-copper equilibrium diagram.

Grain Growth

Grain growth studies on thin films of Al-Cu alloys have not been reported. The effect of a dispersed phase on grain growth in Al-Mn alloys was reported by Beck, Holzworth and Sperry (4), who found the finely dispersed Al-Mn precipitates cause a considerable grain growth inhibiting effect. Beck et al. (5) also studied the grain growth of pure Al and found the growth rates obeyed the empirical equation $D = Kt^n$ where

D = average grain diameter

t = annealing time

n = time exponent

K = constant = $K_0 e^{-Q/RT}$ where K_0 = rate constant

Q = activation energy

T = absolute temperature

R = gas constant

II. EXPERIMENTAL PROCEDURES

Preparation of Specimens

Master Alloy

An aluminum 5 weight percent copper alloy was prepared by compacting 99.999 percent pure aluminum and copper powders into 2.5 cm diameter discs which were approximately 6 mm thick. Two of these discs were melted to produce an elongated button approximately 5.7 cm long, 2.7 cm wide and 6 mm thick.

Melting of the alloy was conducted in a non-consumable electrode arc furnace which was evacuated to a pressure of 2×10^{-4} mm of Hg and back filled to a pressure of 760 mm Hg with argon before melting was begun. Ti gettering was used during melting. The sample was inverted and re-melted four times. The elongated button was then shaved along the edges to produce flat surfaces and hot step forged at 300°C into a square bar approximately 1 cm thick and 9 cm long.

The bar was homogenized in a vacuum of 5×10^{-6} mm of Hg and a temperature of 540°C for 72 hours. After homogenization, the specimen surfaces were cleaned on 600 grit SiC abrasive paper and 1 mm slices to be used for vapor deposition sources were cut from the bar with a diamond cut off wheel.

Vapor Deposited Films

Thickness Measurements. To facilitate the deposition of films of known and constant thickness, the equation $W = M/4\pi dR^2$ used by Hall (12) was employed. Here W is the foil thickness, M is the total weight evaporated, d is the density of the alloy, and R is the distance from the filament to the substrate. It is assumed here that the evaporant is radiated from a point source and that the flux of evaporated metal is uniform.

Initially the above equation was verified by measuring the surface area and total mass of a glass microscope slide and evaporating a known weight of Al-5% Cu alloy onto the slide. The metal was then dissolved from the glass surface and the total weight of the metal coating calculated by weight difference. From this weight and the density of the alloy, the specimen thickness was calculated directly using the equation $T = M/dA$, where M is the weight of the alloy on the glass plate, T is the total specimen thickness, d is the density of the alloy and A is the area of the glass plate surface. Identical thicknesses were obtained using these two methods.

Alloy Evaporation. The master alloy slices were cut into triangular pieces weighing approximately 0.4 mg for use as vapor deposition sources. Pieces weighed precisely to yield the desired thickness were placed in a conical 0.74 mm tungsten wire basket 4mm in diameter and 7 mm high. The basket was clamped to the

resistance heating terminals within a Varian VE-10 vacuum evaporator.

A 2.5 by 7.5 cm glass microscope slide covered with 0.025 mm thick cellulose acetate film was placed 10 cm directly below the tungsten basket to collect the vaporized metal. The substrate temperature was ambient.

The entire system was evacuated to a vacuum of 1×10^{-6} mm of Hg with mechanical and diffusion pumping. Usually a pump down time of 24 hours was used to achieve the vacuum. After vacuum was reached, the tungsten basket was heated by resistance heating until white emission was achieved and held in this temperature region until all of the aluminum alloy was vaporized.

After cooling for one hour, the alloy coated cellulose acetate film was removed from the vacuum chamber and 2 mm square sections were cut out to be studied. The remainder of the film was stored in a vacuum dessicator which after evacuation was back filled to atmospheric pressure with argon.

The 2 mm sections were placed on 3.2 mm diameter 200 mesh copper microscope screens and refluxed in methyl acetate vapor for 45 minutes to dissolve away the cellulose acetate backing, leaving the metal film mounted on the screen.

The copper content of the vapor deposited films was determined by atomic absorption spectroscopy and found to be 4.1 percent by

weight. Films ranging in thickness from 0.1μ to 0.4μ were prepared for in-situ studies. Films 2.6μ thick were prepared for isothermal aging studies.

Aging of Specimens

Isothermal Aging

The alloy films mounted on microscope screens were placed inside a #2 Coors ceramic boat for isothermal aging. The boat was then placed inside a 15 mm I.D. by 20 mm O.D. vycor tube which was approximately 1 M long. The vycor tube was joined to a stainless steel flange by a Kovar seal. The tube with flange was then attached through a copper seal to a specially constructed high vacuum system shown by Figure 2. The system which is constructed from Varian components and consists of a sorption pump, an ion pump, ultra-high vacuum polyimide sealed valves and ancillary plumbing. The system was evacuated using liquid nitrogen sorption pumping and Ti ion pumping to a vacuum of 1×10^{-7} mm of Hg. Usually a pump-down time of 3 to 4 hours was required.

Heat treating was accomplished by sliding a pre-heated electric tube furnace over the vycor tube. The temperature of the furnace was controlled by a Honeywell thermostatic controller activated by a chromel-alumel thermocouple in contact with the vycor tube. Temperature control was $\pm 5^{\circ}\text{C}$. The specimens were isothermally aged

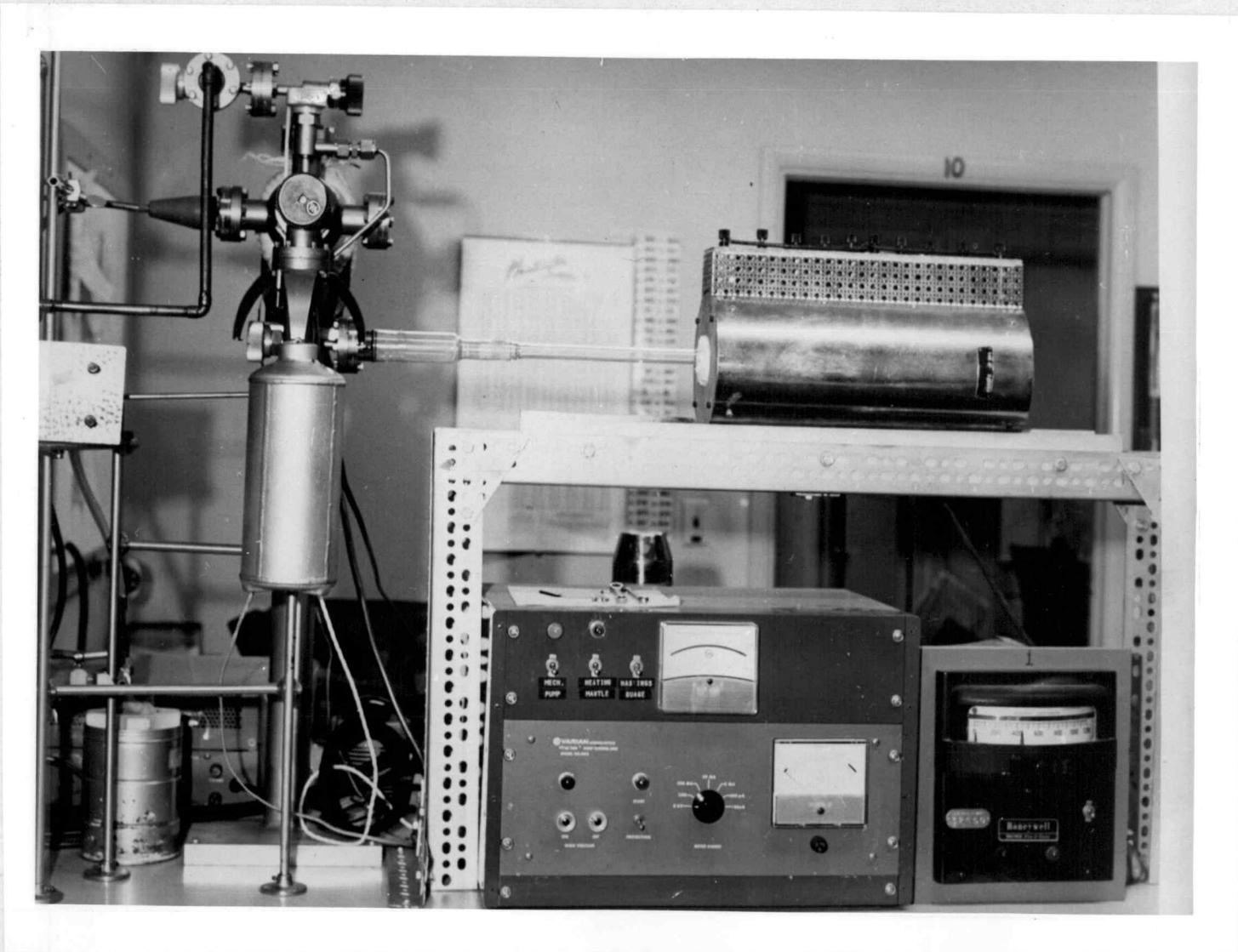


Figure 2. High vacuum aging furnace.

at 400°C, 450°C, and 500°C for times ranging from 10 to 960 minutes.

In-Situ Aging

The vapor deposited foils of various thicknesses mounted on 3.2 mm Cu microscope screens were heat treated in the hot stage of a Hitachi HU 125 electron microscope. Because of the extremely fine initial grain size (approximately 300Å), the samples were given a solution heat treatment at 525°C for approximately 10 minutes until the grain size reached approximately one micron in diameter. The samples were then quenched by turning off the furnace power and cooling by convection from the liquid nitrogen cooled contamination trap.

The samples were then aged isothermally for various times as shown by Table 1.

Table 1. In-situ aging data.

Foil	Thickness (μ)	Aging Time	Aging Temperature
3-26	0.12	55 hr.	230°C
4-9	0.17	34.5 hr.	280°C
4-24	0.32	45.5 hr.	280°C
12-20	0.40	55 hr.	230°C

Grain Size Measurement

Three transmission electron micrographs of each isothermally aged sample were prepared using an RCA EMU 3h electron microscope. The grain size was measured directly from these micrographs using the method similar to that described by Abrams (2). The procedure is based on the intercept method using a 479mm total length circular pattern consisting of three concentric circles whose radii obey an arithmetic progression. A magnification is selected which will yield approximately 100 intercepts. Normal intercepts are given a count of one and triple points are given a count of two. From the length of the line and the number of intercepts, the grain size is calculated using the following equation:

$$D = L/MN \text{ where}$$

$$D = \text{grain size}$$

$$L = \text{length of line}$$

$$M = \text{magnification}$$

$$N = \text{number of intercepts}$$

Raw data are shown in Appendix 1.

III. RESULTS

Grain Growth

Growth Rates and Time Constant

Isothermal growth data taken at 400°C, 450°C, and 500°C are given in Table 2 and plotted in Figure 3. Representative transmission electron micrographs corresponding to each data point of Figure 3 are shown in Figures 4 through 6. In all, 19 separate specimens were aged isothermally. The aging operations lasted from 10 to 960 minutes.

The experimentally measured time is composed of the time used in raising the specimen to temperature plus the time at temperature. The measured grain size is dependent upon the initial grain size, the growth achieved during heating to temperature, and the growth at temperature. In practice, time and initial grain size corrections are not applied if the time required to achieve temperature is small compared to the time of the run and if the initial grain size is small when compared to the final grain size. Because the initial grain size of the vapor deposited foils was very difficult to measure and seemed to be on the border line in terms of what is considered small relative to the grain size achieved after aging, it was decided to present the results both with and without a time correction.

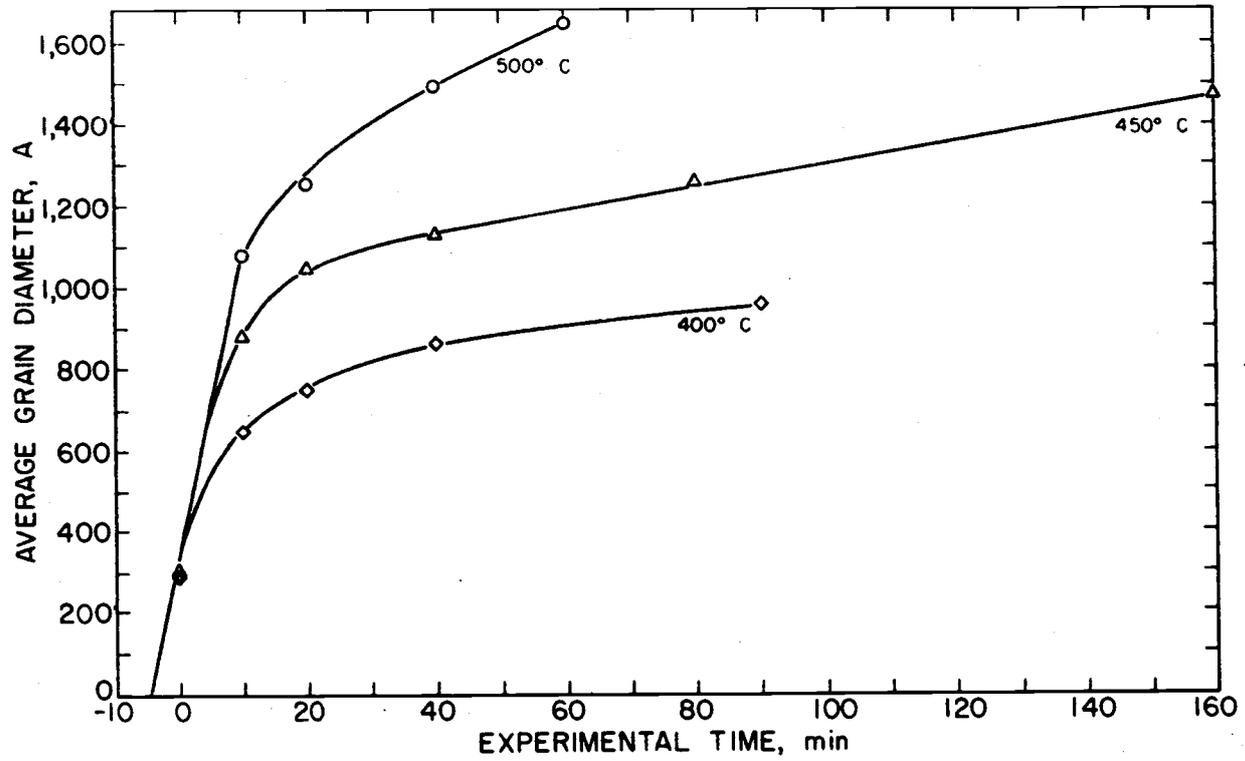
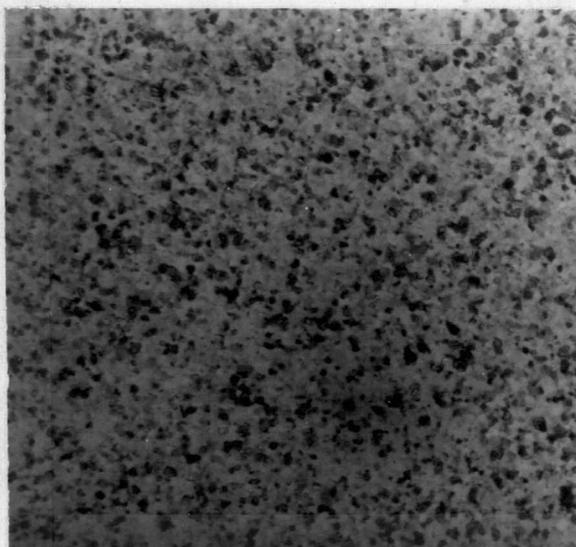


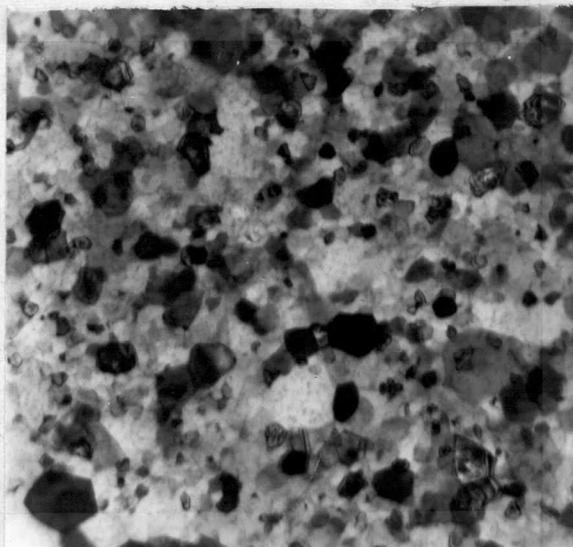
Figure 3. Plot of average grain diameter developed at different temperatures versus experimental time.

Table 2. Grain growth data.

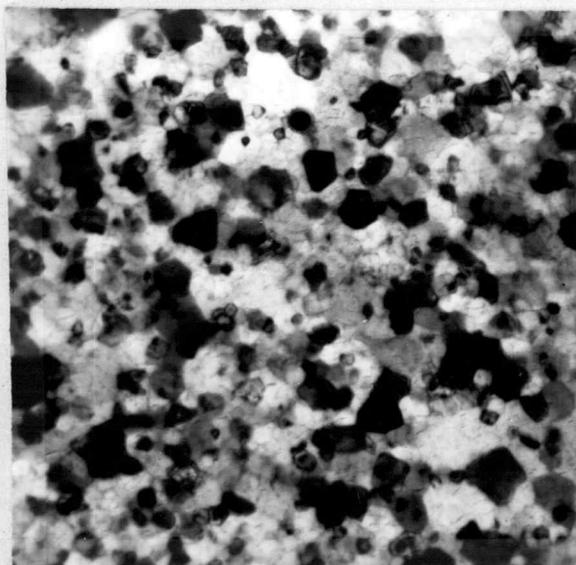
Experimental Time (min.)	Corrected Time (min.)	Grain Size A
Al-4% Cu Aged at 400°C		
0	5	285
10	15	648
20	25	748
40	45	868
90	95	960
180	185	1154
390	395	1310
960	965	1480
Al-4% Cu Aged at 450°C		
0	5	314
10	15	885
20	25	1050
40	45	1130
80	85	1260
160	165	1470
320	325	1682
Al-4% Cu Aged at 500°C		
0	5	285
10	15	1084
20	25	1260
40	45	1496
60	65	1646
210	215	1920
420	425	2253



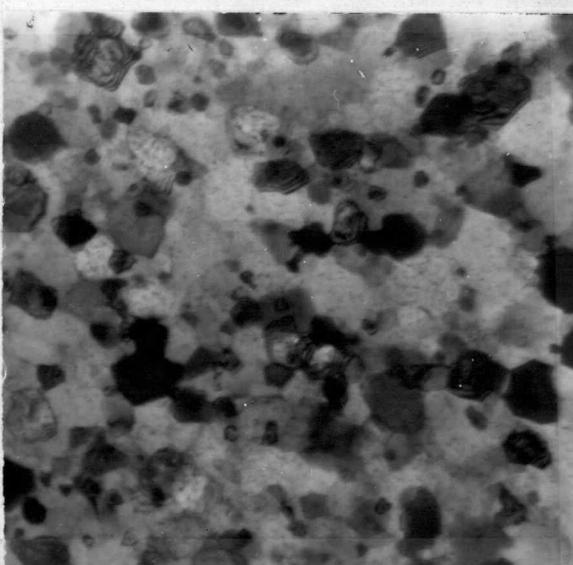
A. Initial



B. 10 minutes



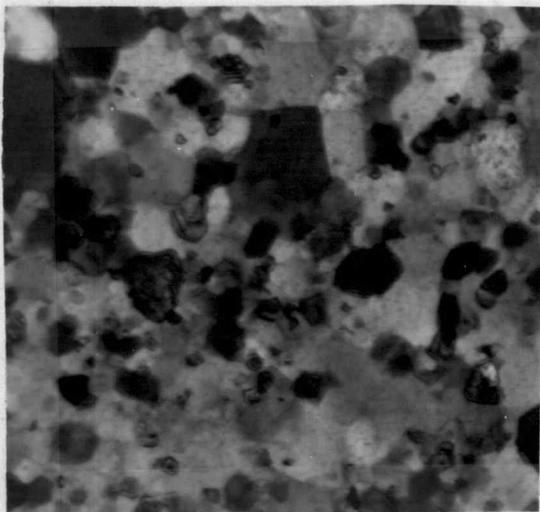
C. 20 minutes



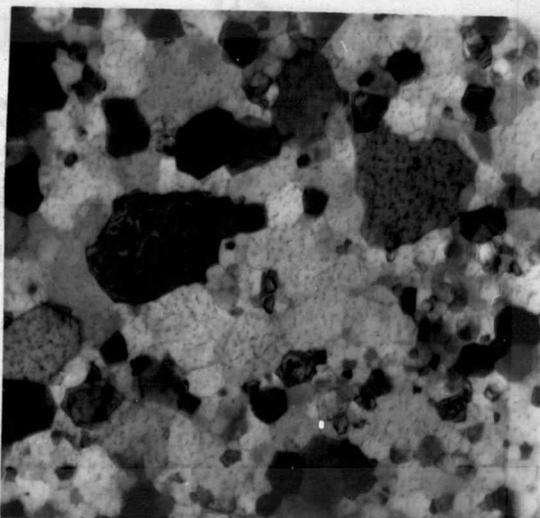
D. 40 minutes

Figure 4. Microstructures of Al-4% Cu thin foils aged at 400°C. All micrographs are at 45,000X.

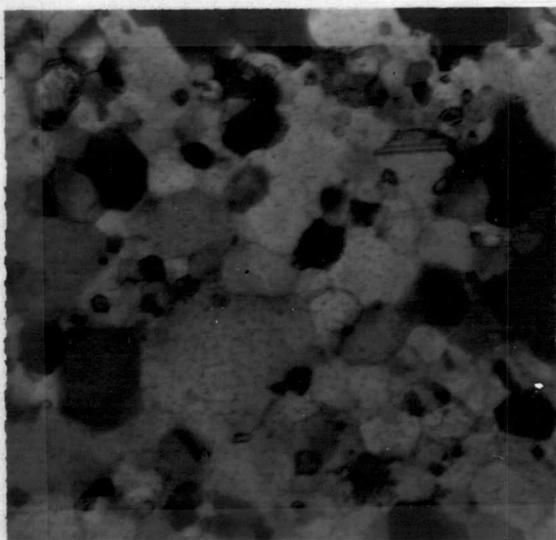
Figure 4. Continued



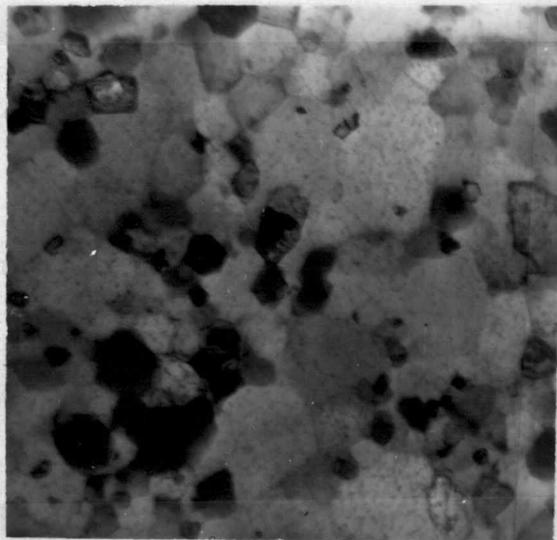
E. 90 minutes



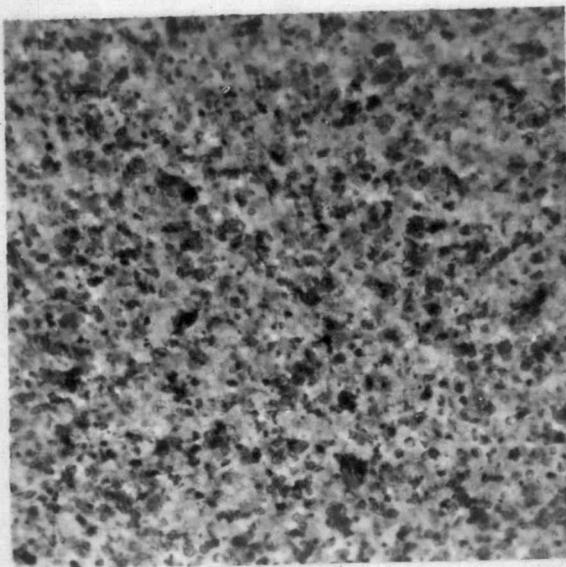
F. 180 minutes



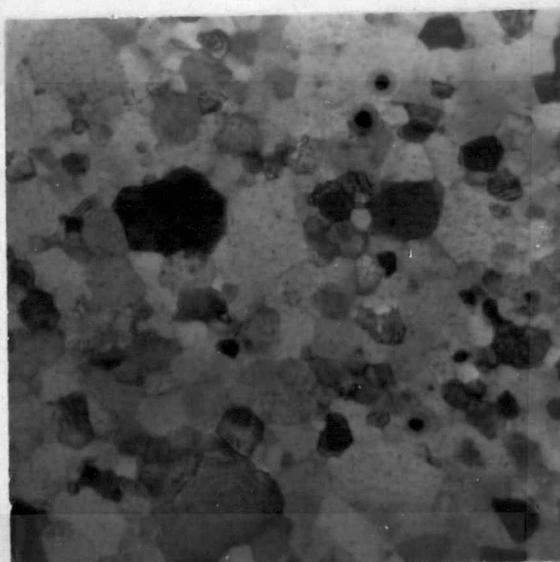
G. 390 minutes



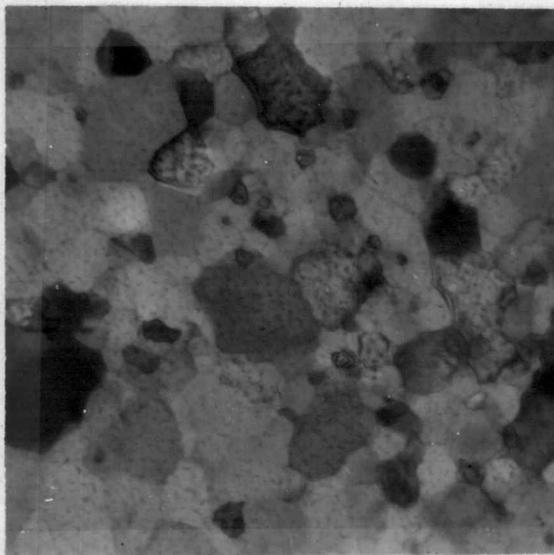
H. 960 minutes



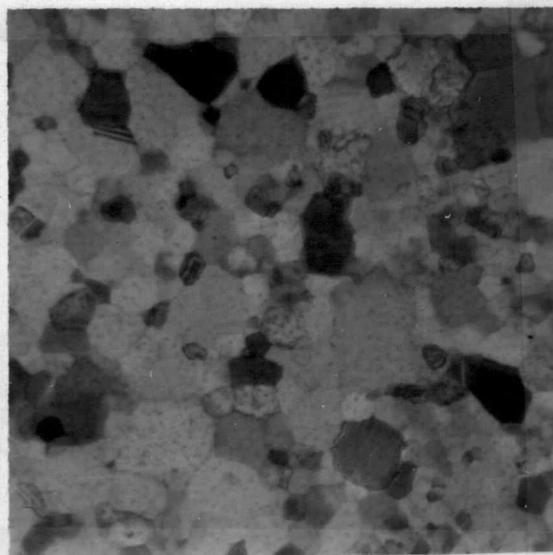
A. Initial



B. 10 minutes



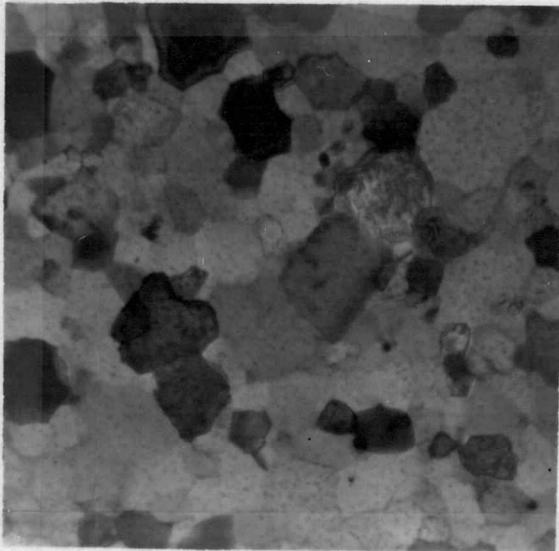
C. 20 minutes



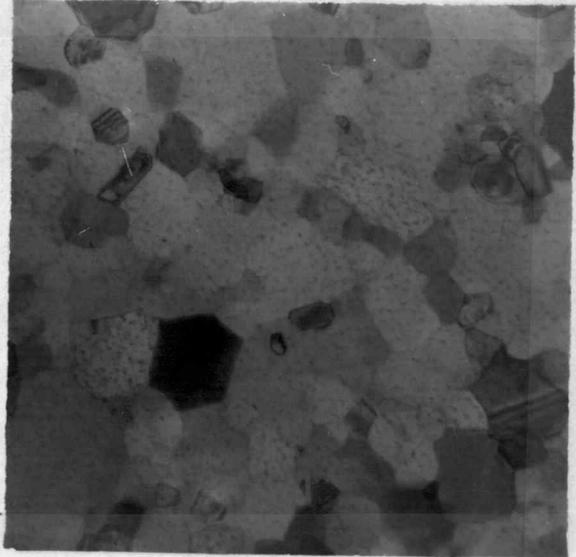
D. 40 minutes

Figure 5. Microstructures of Al-4% Cu thin foils aged at 450°C. All micrographs are at 45,000X.

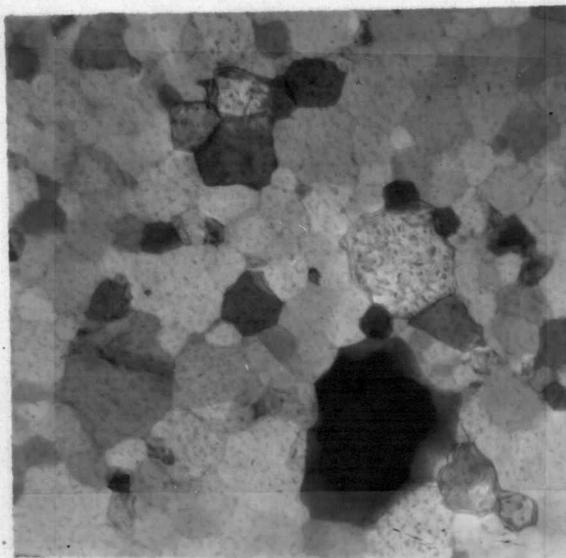
Figure 5. Continued



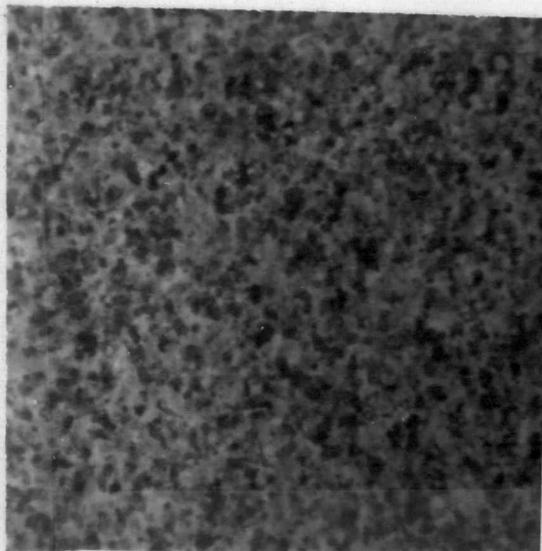
E. 80 minutes



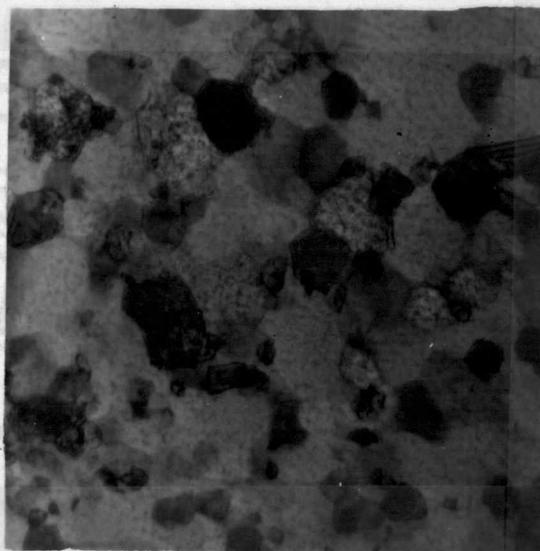
F. 160 minutes



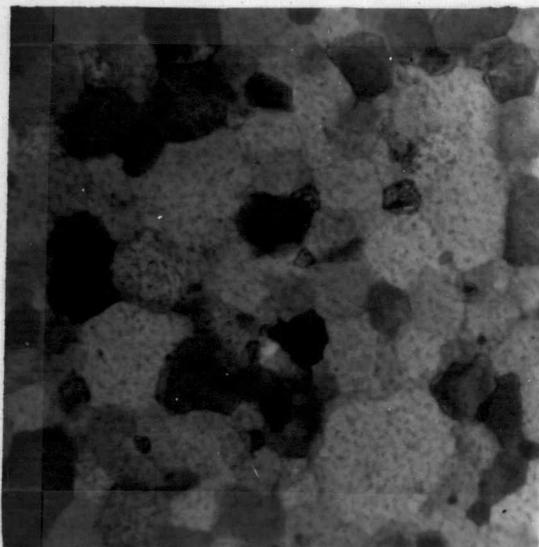
G. 320 minutes



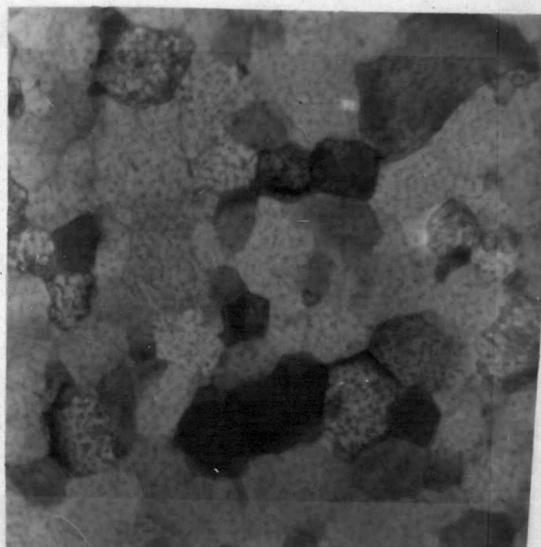
A. Initial



B. 10 minutes



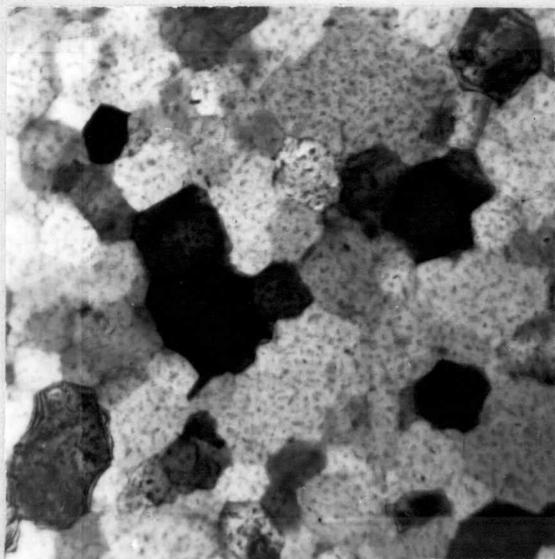
C. 20 minutes



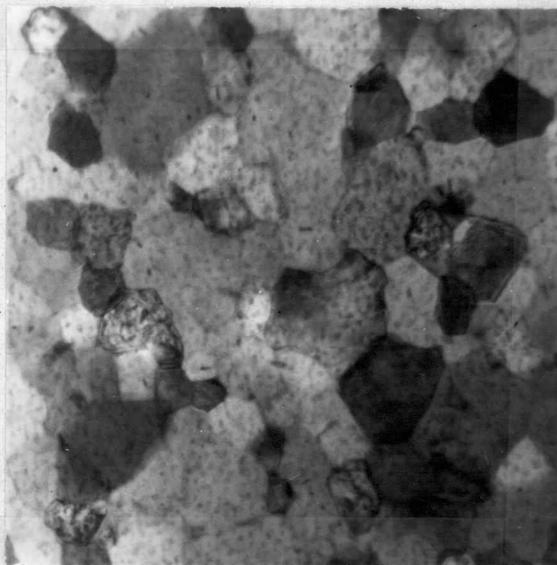
D. 40 minutes

Figure 6. Microstructures of Al-4% Cu thin foils aged at 500°C. All micrographs are at 45,000X.

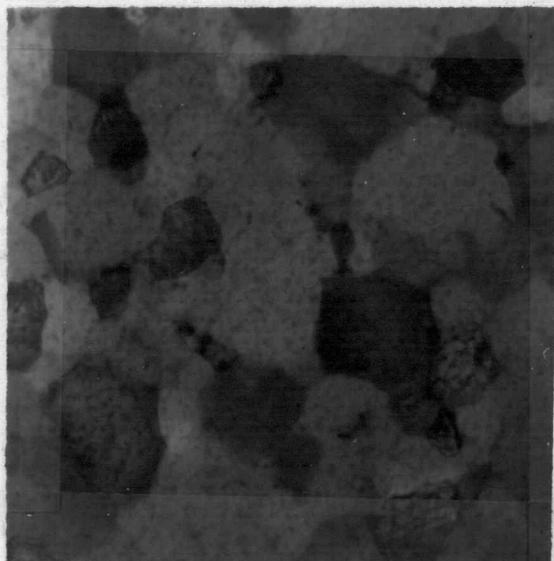
Figure 6. Continued



E. 60 minutes



F. 210 minutes



G. 420 minutes

The time used in the correction was obtained by extrapolating the raw data plotted in Figure 3 to zero grain diameter. A negative five minutes was obtained. To shift the experimental data to a zero intercept, the five minute correction was added to the experimental time. This correction should compensate for all inherent experimental errors. Plots of $\log D$ versus $\log t$ and \log corrected t are shown by Figure 7. A linear regression analysis was carried out on the data for each aging temperature to determine the line which best fits the data. As shown by Figure 7, essentially parallel straight lines were obtained. The linear plots are in agreement with the empirical equation for solid state thermally activated processes (15, 16)

$$D = Kt^n \quad (I)$$

which was used by Beck (5) to describe grain growth in pure aluminum. Since the plots are essentially parallel, the time exponent, n , which is the slope of the line, is independent of temperature in the range of 400 to 500°C.

Isothermal growth rates calculated at a time of 100 minutes from the differential form of equation I are shown in Table 3. The mean value of the slope n was determined to be 0.183 ± 0.003 without the time correction and 0.202 ± 0.004 with the correction.

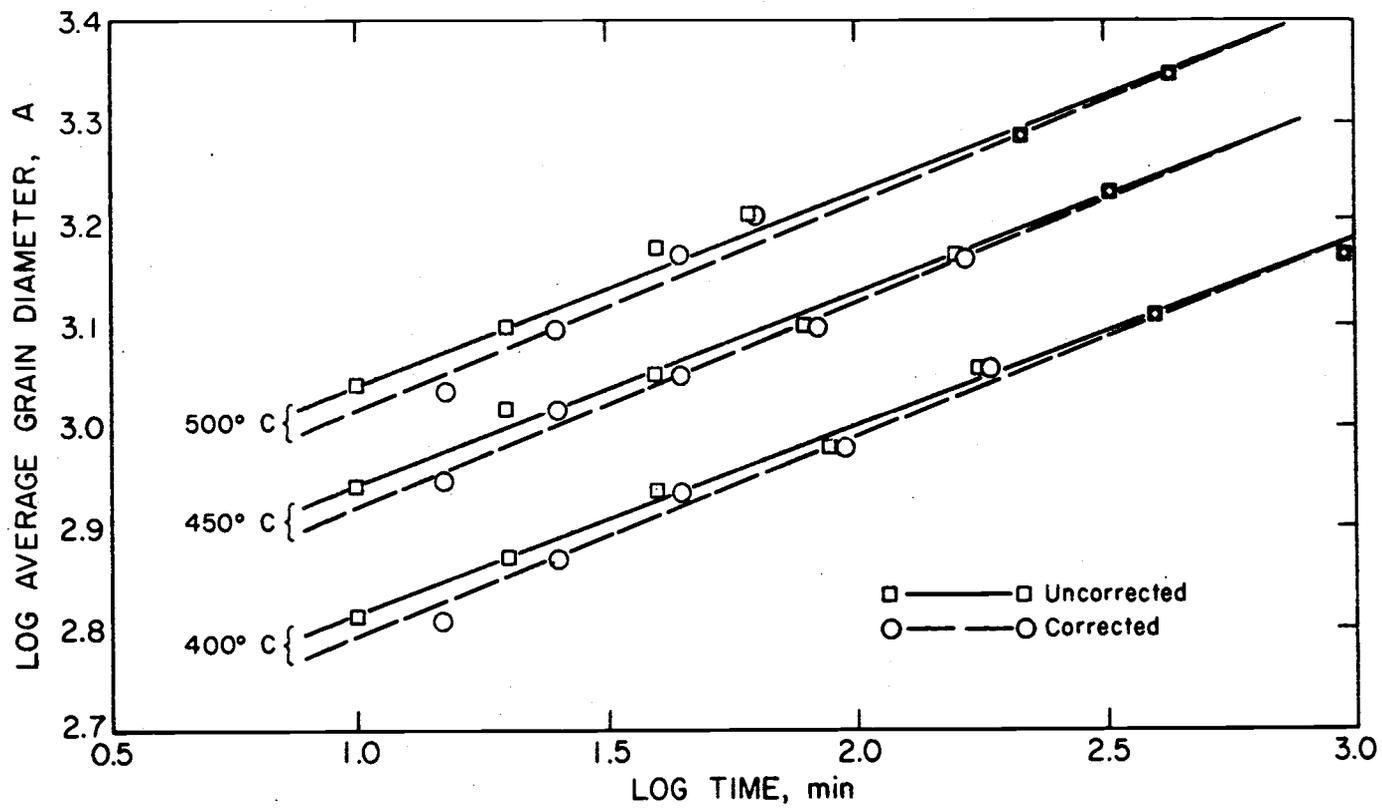


Figure 7. Log-log plot of the average grain diameter developed at different temperatures versus the total and corrected times.

Table 3. Instantaneous growth rates (A/minute) for Al-4% Cu thin films after aging 100 minutes at temperature.

Temperature °C	Corrected	Uncorrected
400	2.02	1.80
450	2.72	2.45
500	3.32	3.17

Activation Energy

The activation energy for grain growth was determined from the differential form of equation I.

$$\frac{dD}{dt} = nKt^{n-1} \quad (II)$$

By substituting for K where $K = K_0 e^{-Q/RT}$

then

$$\frac{dD}{dt} = nK_0 e^{-Q/RT} t^{n-1} \quad (III)$$

The calculated values of the natural log of the rate ($\ln dD/dt$) were plotted versus the reciprocal of the absolute aging temperature ($1/T$) for the corrected and uncorrected data and are shown by Figure 8. From the slope of this plot, an activation energy of 30 Kcal/mole for the uncorrected data and 25 Kcal/mole for the corrected data was obtained.

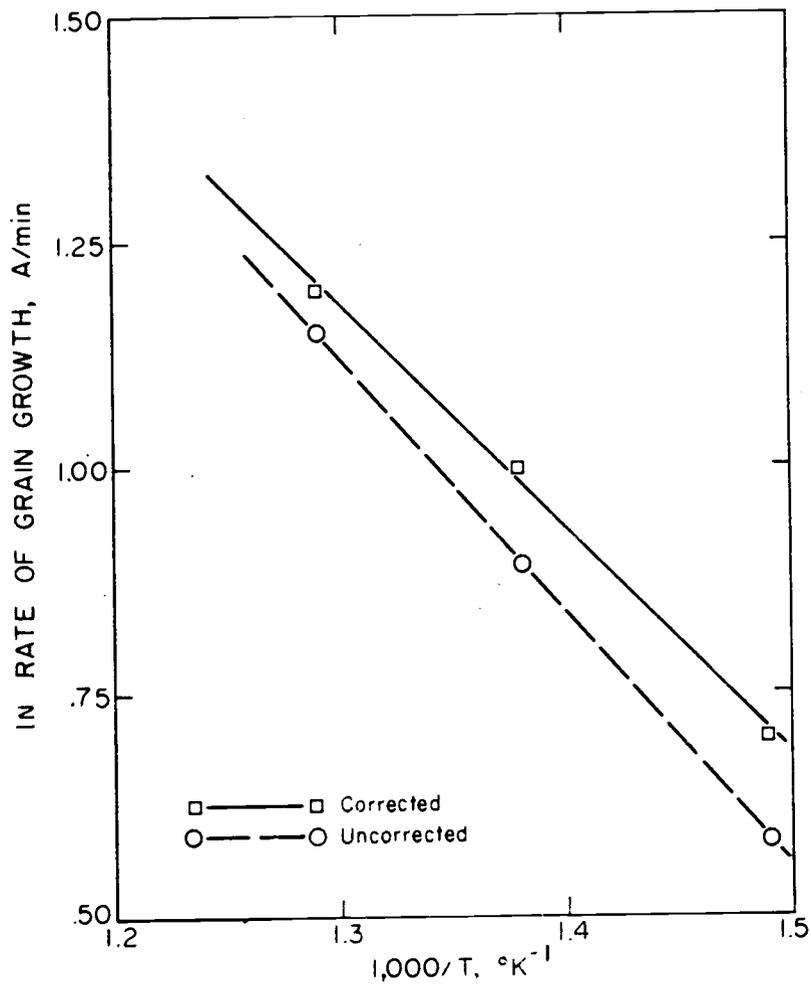


Figure 8. Plot of the natural log of the rate of grain growth at 100 seconds versus $1000/T^{\circ}\text{K}$.

Microstructural Features

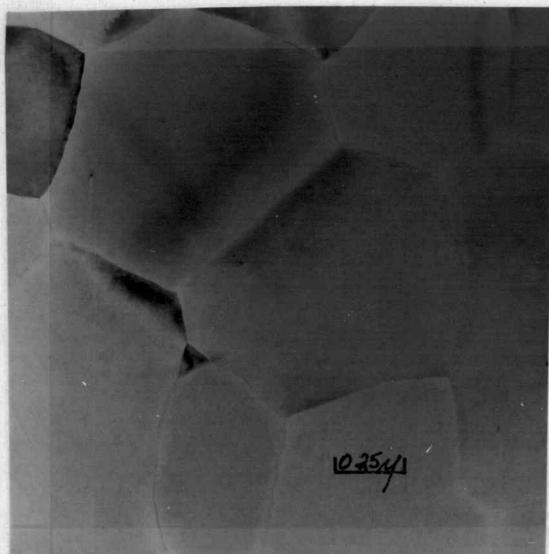
For the three temperatures studied, the appearance of precipitates was observed after aging for only 10 minutes. These precipitates appeared to be fairly uniform in size and do not exhibit any characteristic morphology change from grain to grain. Since the grains are of random orientation, the precipitates are probably on the surface of the foil. The precipitates exhibit very little growth upon aging.

The grains appear to grow by the normally encountered mechanism of grain annihilation. As shown by the micrographs, in the early stages of aging there are many smaller grains being consumed by the larger grains. In the later stages of aging smaller grains are less evident. Since the energy for grain growth is derived from the boundary free energy, the growth rates should slow considerably after long time aging. This was evident in samples aged at all three temperatures.

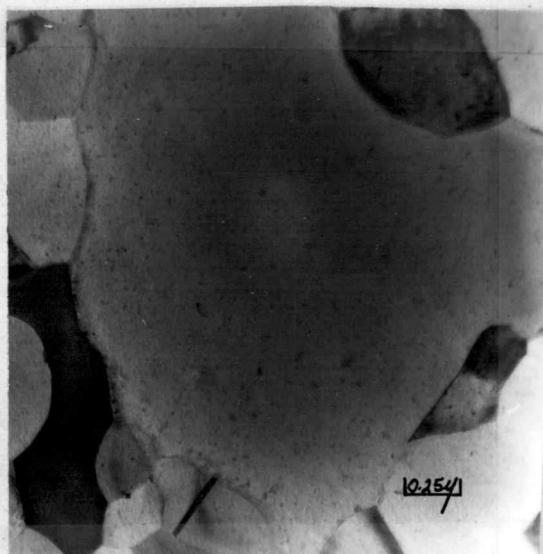
In-Situ Precipitation

Precipitate Changes with Thickness

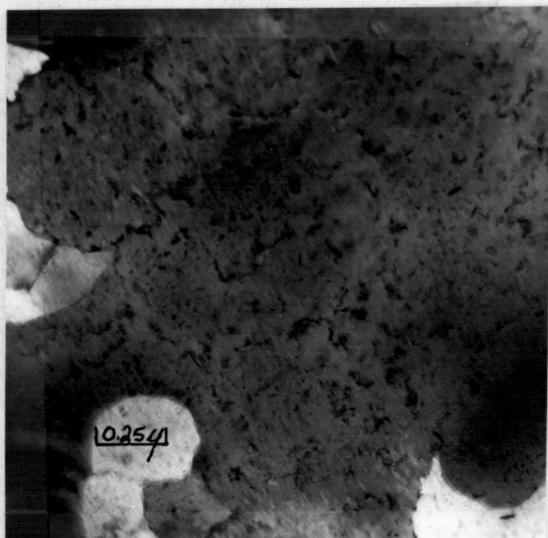
Typical transmission electron micrographs taken after the indicated times and at the indicated temperatures are shown by Figure 9. From direct examination of the micrographs, an increase in the



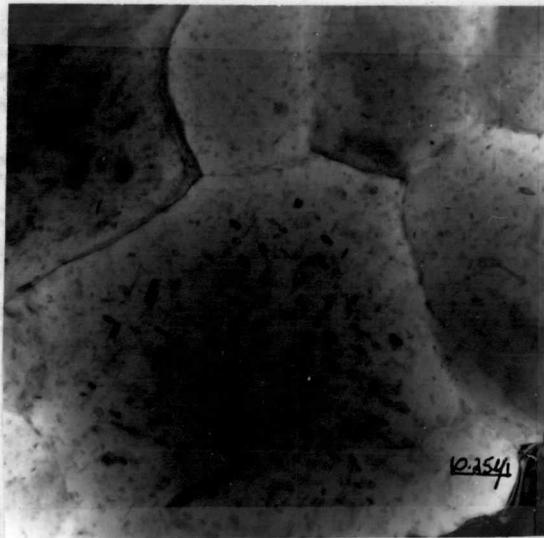
A. 0.12 μ thick foil after aging 55 hours at 230 $^{\circ}$ C



B. 0.17 μ thick foil after aging 34.5 hours at 280 $^{\circ}$ C



C. 0.32 μ thick foil after aging 45.5 hours at 280 $^{\circ}$ C



D. 0.40 μ thick foil after aging 55 hours at 300 $^{\circ}$ C

Figure 9. Transmission electron micrographs of in-situ aged Cu-4% Al foils.

number of precipitates per unit volume with increasing foil thickness was detected. The approximate values are given in Table 4. Only θ -CuAl₂ precipitates were detected by electron diffraction patterns taken from the specimens.

Microstructural Features

An equiaxed grain size of greater than 1μ was achieved on each of the thin specimens. All precipitates observed appear to occur on the surface of the film. Precipitates were not resolvable on the 0.1μ thick sample at the temperature indicated. The absence of precipitates here could possibly be related to denuded zones along grain boundaries approximately 0.1μ wide which have been observed in bulk Al-4% Cu alloys (18), however, Mader (14) has reported precipitates in Cu-3% Al films approximately 0.1μ thick aged at 150°C and cooled to room temperature for examination.

Table 4. In-situ precipitation data.

Foil Thickness (μ)	Aging Time (hr)	Total Particles per cm^3
0.12	55	---
0.17	34	5.8×10^{14}
0.32	46	7.5×10^{14}
0.40	55	8.9×10^{14}

IV. INTERPRETATION AND DISCUSSION

The isothermal growth plots obtained for the Al-4% Cu thin foils cannot be compared to behavior observed in the bulk or thin films for this alloy because this information is unavailable in the literature. When compared to the pure bulk aluminum studies of Beck (5), several differences are encountered. In pure bulk aluminum n is dependent on temperature and increases from 0.056 at 350°C to 0.32 at 600°C, whereas, in the alloy films studied n is independent of temperature with a value of approximately 0.2. The magnitude of n in both cases is much lower than the value of 0.5 which would be expected theoretically for a single phase alloy if grain growth were a function of only interfacial free energy and inclusions are absent. In the case of the thin films, a lower value would be expected since precipitates are known to form and these should retard grain growth and thus lower the slope of the plot of $\log D$ versus $\log t$.

A significant difference is evident upon comparison of the growth rates observed after aging 100 minutes at temperature. As shown in Table 5, the pure aluminum growth rates increase very rapidly with increasing temperature whereas in the thin films studied only very slight increases in growth rate with increasing temperature were observed. Also, the pure aluminum growth rates are approximately 1,000 times greater in magnitude than those for the alloy films.

Table 5. Growth rates at 100 minutes.

Temperature °C	Rate A/min * Pure Al	Uncorrected Rate A/min Al-4% Cu Films	Corrected Rate A/min Al-4% Cu Films
400	1.0×10^3	1.8	2.0
450	3.9×10^3	2.4	2.7
500	1.3×10^4	3.2	3.3

* From Beck's (5) data.

These gross differences could be used to help explain the increased time to failure life of Al-4% Cu over pure aluminum in electromigration studies. Ion flux during electromigration is known to proceed predominately along grain boundaries (7). Any point in the film where the ion mobility along grain boundaries changes will, therefore, represent an ion flux divergence site. If the grain boundaries are essentially immobile to migration, then fewer ion divergence sites could be expected resulting in enhanced component life.

A comparison of activation energy values for grain boundary migration between the thin Al-4% Cu films and bulk aluminum is not possible. A discrete value for pure aluminum cannot be calculated due to the dependency of n on temperature. Only when $n = 1$ can an activation energy be assigned to the process. The activation energy for thin Al-4% Cu films in the temperature range of 400 to 500°C is of a single value. This value both corrected and uncorrected is of

the same order of magnitude as the diffusion values given by Bishop and Fletcher (6) for bulk diffusion of both aluminum and copper in aluminum. The calculated activation energy values both corrected and uncorrected are well above the values of 12.8, and 15 Kcal/mole calculated for interphase boundary diffusion in Al-4% Cu (1) and grain boundary diffusion in Al-Cu alloys (11), respectively. This would indicate that grain boundary migration in Al-4% Cu thin films is controlled by a bulk diffusion process and not the normally encountered process of atom transfer across boundaries.

It is interesting to note that even though the foils were quite thin, the grains did not seem to approach an ultimate grain size. The micrographs of the aged grain growth samples still exhibit many smaller grains. As long as large grains are growing at the expense of smaller ones, one would expect to be able to grow grains whose average diameter is much greater than the sheet thickness. This was done on the in-situ aged samples where grain sizes in excess of 1μ were obtained. In the isothermally aged samples the average grain diameter approached the sample thickness with no apparent indication of a limiting grain size. This would indicate that the sheet thickness effect observed by Beck (5), where grain growth decreases rapidly after the grain size reaches approximately 0.6 of the sample thickness, would not apply in this study.

All precipitates observed both on the grain growth samples and

the in-situ aged samples were surface precipitates of θ -CuAl₂. This is not surprising since Mader (14) found that there are insufficient voids retained within Al-3% Cu foils aged above 150^oC to nucleate θ -CuAl₂ precipitates within the bulk. Also since θ -CuAl₂ crystals do not form a coherent boundary with the matrix, preferred precipitation may occur at the surface. Sufficient energy would be available from the matrix surface and the nucleation barrier is reduced since the particle-matrix interface area is reduced.

The surface precipitation effect is further illustrated by the fact that increasing the foil thickness increased the number of resolvable precipitates. Thus the thicker samples would contain a greater amount of copper available to diffuse to the surface and these samples should exhibit a greater density of surface precipitates.

V. CONCLUSIONS

From the experimental results obtained on Al-4% Cu thin foils, the following results were obtained:

1. Thin Al-4% Cu alloy films undergo grain growth in the temperature region of 400 to 500°C. Growth rates calculated after aging 100 minutes at temperature ranged from 1.8 to 3.2 A/minute uncorrected and from 2.0 to 3.3 A/minute with a time correction.

2. The grain growth time exponent, n , was found to be constant over the temperature range of 400 to 500°C. A value of 0.18 was calculated without a time correction and 0.20 with a time correction.

3. A discrete activation energy of 30 Kcal/mole without a time correction and 25 Kcal/mole with a time correction was calculated. These values are of the same order of magnitude as the bulk diffusion values of both aluminum and copper in aluminum.

4. The observed grain growth behavior is in agreement with the empirical equation $D = kt^n$.

5. The equilibrium precipitate θ -CuAl₂ was found to occur on the surface of the thin films. The number of precipitates observed was found to be a function of the foil thickness.

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Appendix 1. Raw grain growth data taken from electron micrographs at a magnification of 45,000X.

Time Minutes	Number of Intercepts on a 479 mm Line			Intercept Average	Average Grain Size (A)
	Plate 1	Plate 2	Plate 3		
Al-4% Cu Aged at 400 ^o C (2600 A thick)					
0	379	366	368	371	285
10	162	168	163	164	648
20	135	146	147	143	748
40	121	126	121	123	868
90	95	122	117	111	960
180	92	88	95	92	1154
390	86	80	78	81	1310
960	72	73	72	72	1480
Al-4% Cu Aged at 450 ^o C (2600 A thick)					
0	338	335	343	339	314
10	120	117	123	120	885
20	99	102	102	101	1050
40	86	98	98	94	1130
80	84	87	82	84	1260
160	72	71	72	72	1470
320	61	70	59	63	1682
Al-4% Cu Aged at 500 ^o C (2640 A thick)					
0	381	365	367	371	285
10	85	103	109	99	1084
20	85	85	83	84	1260
40	74	65	74	71	1496
60	66	64	63	64	1646
210	58	55	53	55	1920
420	44	49	49	47	2253