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AN INVESTIGATION OF THE
HARDENING PROPERTIES OF SOME
ALPHA COPPER-INDIUM ALLOYS

by

CHARLES W. McPHERSON

A THESIS

SUBMITTED to the DEPARTMENT of
METALLURGY in PARTIAL FULFILLMENT
of the REQUIREMENTS for the
DEGREE of BACHELOR of SCIENCE in
METALLURGICAL ENGINEERING

MONTANA STATE SCHOOL of MINES

BUTTE, MONTANA

MAY 12, 1952

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INTRODUCTION

Precipitation hardening alloys has assumed a major role in modern day development of alloys. In his search for stronger, harder materials, the metallurgist has often been limited by the cost of metals which posses the needed properties. Partially as a result of this limitation and partially because of the non-existence of materials satisfying his requirements, the metallurgist has turned to heat treatment to obtain desired characteristics.

From the studies of various research men, precipitation hardening and work hardening have developed. Heat treating technique has so improved that metallurgists can now magnify many properties far beyond their ordinary values. Both metallurgists and physicists have advanced theories to explain the phenomena, and although most research men agree on fundamentals, their detailed explanations are often conflicting and misleading.

This thesis will not attempt to correlate the numerous

theories on precipitation hardening or work hardening, but will merely list the main ideas necessary for background. the main function of this paper is a rudimentary study of copper-indium alloys and the effects of time, temperature, and composition on their hardening properties in the alpha or solid solution state. In conjunction with this investigation some research has been initiated on recrystallization and grain growth of these same alloys.

Previous Work

Little information on age hardening of these particular alloys is available, this lack of information being due to the high cost of indium and the resulting reluctance of industry to experiment in this field. Two German scientists, Weibke and Eggers, have done considerable work with this system. They determined a constitutional diagram by approximate X-ray methods. Although William Hume-Rothery later modified their diagram by more precise thermal analysis, a portion of the diagram concerning the present work follows.

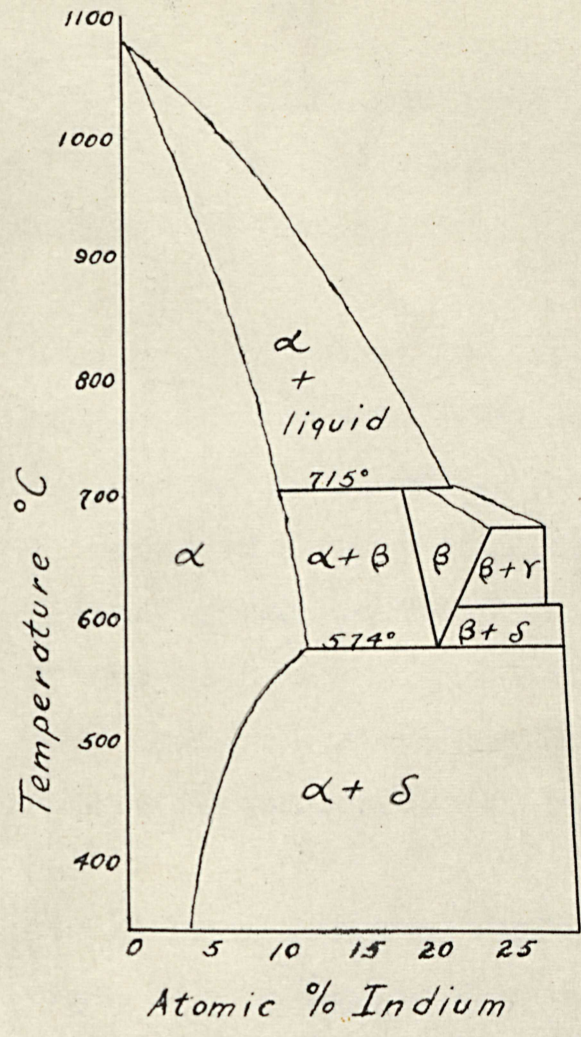Fig. 1- Part of Copper-Indium Phase Diagram

In their determination of the copper-indium diagram Weibke and Eggers noted that the hardness of copper was only slightly increased by the addition of indium. In their work on age hardening they found that the hardening effect increased with the percentage of indium. They reheated the various homogenized alloys at 200, 300 and 400°. At 200° they noted *no*

hardening effect up to 400 hours; at 300° and 100 hours these investigators obtained a maximum hardness four times as great as that of the homogenized sample.[1]

Hardness

The investigator of hardening properties must have a knowledge of hardness and its measurement. Hardness may be defined as (1) the resistance to indentation, (2) stiffness or temper of wrought products, and (3) machinability characteristics.[2] These are the principal methods of explaining hardness, but they do not completely satisfy all possibilities. "Colonel Martel defines hardness of metals as the resistance to displacing the molecules at the surface unit volume.[3]

Actually hardness cannot be explained so simply, as it is dependent on many complex interatomic forces. Therefore, an actual measurement of hardness cannot be expressed in terms of the fundamental physical untis of length, time, force, and mass. Hardness has been divided into two major

1. Weibke and Ploger, Precipitation Hardening in the System Copper-Indium and the Effect of Nickel and Cadmium on It; C.A. 30,7524.

2. Metals Handbook, The American Society for Metals, 1948, P. 7., Cleveland Ohio

3. Landau, D., Hardness, The Nitralloy Corporation, 1943, New York, P. 14.

fields, "static" hardness, measured by permanent deformation of the tested material and related to the elastic limit of the material, and "dynamic" hardness, measured in terms of elasticity.

The Rockwell Hardness Tester employed in this investigation actually measures the permanent deformation produced in the metal. A 10 kilogram load is first applied to the metal to overcome any surface imperfections; then a major load is applied, the weight being dependent upon the penetrator used. The major load is then removed and the difference in depth of the impressions of the major and minor loads is registered in terms of hardness on the appropriate scale.

Conversion of readings from one scale to another is difficult because the conditions for one method of testing vary from the others. The only possible way to translate from one scale to another is by comparing readings of the first scale with reading of the second scale, such values being obtained from identical material. Such a material may not exist for comparison of the desired scales.[4]

4. Symposium on the Significance of the Hardness Test of Metals in Relation to Design, American Society for Testing Materials, 1943, Philadelphia, Pa. pp. 841-42

THE ALLOYS

Six alloys of different composition were cast from
indium donated by the Consolidated Mining and Smelting
Company of Canada and Anaconda wire bar copper, the
specimens ranging from 3 to 18 per cent indium. Although
no chemical analyses were run on the alloys, subsequent
microscopic study of each sample revealed very few oxide
inclusions.

To conserve indium the first alloy cast contained
18 per cent indium. A sample was then cut from the bottom
of the cast alloy, a bottom section being used to avoid
inclusions and insure homogeneity. Sufficient copper was
then added to the remainder of the first casting to obtain
a second alloy of 15 per cent indium. A second specimen
was then prepared. This process was repeated until six
samples had been obtained, one each of 3,6,9,12,15, and 18
per cent indium.

All alloys were melted in a small induction furnace.
No flux was required in the melt. The mold was cut from
graphite and consisted of three pieces clamped together.
The dimensions of the mold were approximately 3/8 in. by
2 in. by 2 in.. The size of the samples cut from the casting
was 3/8 in. by 1/2 in. by 2 in..

Graphite liners were placed in the induction furnace and a graphite mold was used to decrease the possibility of oxidizing the copper. All specimens were reduced 35 per cent in thickness by repeated passes through a set of hand rolls. The rolled alloys were then heated to 600° C for a period of three hours and quenched. This process promoted recrystallization, which in turn tended to homogenize the samples. Each sample was then cleaned of oxide coating and smoothed on opposite side to provide a good surface for subsequent Rockwell B hardness measurements.

Metallographic Studies

A sample was cut from each of the homogenized samples for study under the microscope. After the alloys had been polished, they were etched with ammoniacal hydrogen peroxide. Microscopic study revealed a single phase in all but one alloy. The alloy containing 18 per cent indium revealed the presence of a second phase. This second phase, however, is probably beta and does not give a true picture of solid solution hardening. Small amounts of impurities, probably oxides, were revealed in the specimens.

A sample of each alloy at 40 per cent reduction was also mounted for study along with other samples which had been heated at 300° C and 500° C for various lengths of

time to study recrystallization and grain growth. The
lack of a suitable etching agent on some of the higher
indium alloys made the results of this investigation
rather inconclusive. Some values were obtained for the
lower indium alloys by using ammoniacal hydrogen peroxide
or concentrated sulphuric acid as the etching reagent.
The grain size of each of the specimens was then measured
by a micrometer eyepiece for measuring grain size.

Effect of Increasing Indium on Rockwell B Hardness

Rockwell B hardness tests were run on all the
quenched, homogenized specimens. These tests showed an
increasing hardness with increasing amounts of alloying
elements (see page 29). The curve produced by plotting
atomic per cent indium against Rockwell B hardness shows
several irregularities.

Norbury explained this increased hardness as being due
to residual stresses set up in the parent lattice by atoms
of the solute metal. In his work he found the indentation
hardness increased linearly with the atomic per cent of
alloying element. Norbury also found that the hardening
effect was directly proportional to the difference in atomic
radii of the solute atoms and solvent atoms. The stresses
set up by solute atoms oppose the dislocation of the lattice

of an alloy.

Grain size also influences hardness, which increases with decreasing grain size. Smaller grain size means a greater number of crystals. This presents a greater variety of crystal orientation and thereby increases resistance to deformation. The factor of different grain size may account for some of the variance in the hardness as atomic per cent indium curve. Because of the irregularity of the curve, comparison of the copper-indium alloys in solid solution is difficult.

Work Hardening

After a small section of each specimen had been removed for mounting and microscopic study, the alloys were cut in half. One half was used for the study of cold-working properties; the other half of each alloy was later used in age-hardening tests.

Theory

Work hardening is the hardening of a metal by cold working. Cold working is defined as "deforming a metal plastically at such a temperature and rate that strain hardening occurs."[5] A metal which has been deformed below

5. Metals Handbook, P. 7

its elastic limit tends to return to its original atomic
location in equilibrium with regards to its original lattice
structure. If a metal is strained beyond its elastic
limit, however, plastic deformation takes place by block
movement along grain boundaries or successively preferred
slip planes of the grain. The most favorably oriented
grains, those in which the gliding planes are at an angle
of 45 degrees to the direction of strain, will undergo
deformation first. The degree of deformation is limited
by surrounding grains in polycrystalline material. After
the first deformation, and increased load is necessary
for further deformation. As deformation continues more
and more slip planes are rotated into the planes of the
applied force until a preferred orientation results. This
process may be continued until the ultimate strength is
reached and the specimen fractures.

The plastic deformation of the metal is accompanied
by an increase in the hardness of the metal. Various ex-
planations offered as reasons for this phenomenon have
proved inadequate. Following is a list explanations offered
for the mechanism of work hardening.

    1. The shattering of the lattice forms a
       large number of small crystalline blocks
       whose slip planes are out of line and
       therefore prevent slip.

2. The preferred orientation of the grains
   has been listed as a possibility for
   work hardening, but this explanation
   fails to explain the hardening up to
   the 30 to 50 per cent deformation re-
   quired for preferred orientation.

3. The bending and roughening of slip planes
   by elastic deformation cause frictional
   resistance to slip.

4. Localized slip regions have curved ends
   that hinder further slip.

5. The disregistry of slip planes in normal
   grains due to their "mosaic" structure
   is increased with continued slip.

6. The calculated strength of atomic bonds
   would indicate that metals are much stronger
   than measured values. Since imperfections
   of mosaic structure result in weak planes,
   slip occurs first in the weakest planes
   and as these planes work harden, deformation
   takes place along stronger or more nearly
   perfect planes. The limiting strength of
   the work hardening is therefore that of
   the theoretical lattice.

7. The amorphous cement theory proposes a
   noncrystalline metal along grain boundaries
   and slip planes formed by movement of planes
   and grains. This amorphous material is
   much harder than crystalline metal and in-
   creases resistance to further derformation.
   This theory has met with insurmountable
   objections.[6]

Results

The first step in cold-working was the reduction of
all 6 samples 5 per cent in cross section by rolling. The
hardness of each specimen was then checked with the Rockwell

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6. Doan & Mahla, The Principles of Physical Metallurgy,
   McGraw-Hill, 1941, New York.

Hardness Lester. The samples were reduced another
5 per cent and the hardness again checked. This pro-
cedure was repeated several times until a total re-
duction of about 40 per cent was obtained on all alloys.
The per cent reduction was then plotted against Rockwell
B hardness.

All curves thus obtained were similarly shaped
although several irregularities were noted in some. Most
differences from regular curves may be attributed to errors
in making hardness tests. Because hand-rolls were used
for rolling the alloys, some sections of each sample may
have been strained to a greater extent than the rest of
the sample. This differential cold working may have in-
fluenced the hardness readings to a slight degree.

Values obtained range from 81 Rockwell B in a 3 per
cent indium alloy at 40 per cent reduction to 23 Rockwell
C in an 18 per cent indium alloy at 40 per cent reduction.
With other methods a greater reduction might have been
obtained and subsequent higher values for the hardness.

Age Hardening

The procedure for the age hardening or precipitation
hardening was relatively simple. Each of the homogenized

samples was placed into an electric furnace for a period of time ranging from 10 minutes to 32 hours, removed, and quenched. The operation necessitated a large number of samples because the process was repeated at 200°, 300°, 400° and 500°. Small samples used may have contributed to errors in hardness measurements.

Theory

A German scientist, Dr. Alfred Wilm discovered age hardening about forty years ago while he was working with the alloy "duralumin".[7] Since that time, numerous theories have been advanced to explain this phenomenon. In 1919, Merica, Waltenberg and Scott offered the first explanation for age hardening. These investigators explained the increased resistance to slip of age hardened alloys as being due to the formation of a second phase along the grain boundaries and slip planes of the alloy.

Subsequent investigators have since offered many theories clarifying and changing the orginal explanation of Merica and his associates. Most of these discussions are conflicting and add little in material value to the earliest theory. A great number of the modern proposals

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7. _Age Hardening of Metals_, The American Society for Metals, 1940, Cleveland, Ohio P.1

depend on the formation of one or more transition phases between the solid solution and final discrete particles of the precipitate. Conclusive evidence supporting any single theory is lacking, however.

A necessary requirement for age hardening is a decreasing solid solubility with decreasing temperature.[8] This statement means that at a definite temperature an alloy of a certain composition of one phase only. With suitable heat treatment a second phase precipitates from the solid solution. This precipitate may form either preferentically at the grain boundaries and the slip planes or generally throughout the matrix. Dispersion of the precipitate depends on the type of heat treatment. A system with an equilibrium diagram of the type shown in Fig. 2 is required for age hardening. To prepare an age-hardened alloy, one msut first homogenize a sample of the necessary composition at an elevated temperature where only one phase exists, a process called solution heat treatment. The alloy is drastically quenched from the elevated temperature to preserve the homogeneous structure. At the quenched temperature the alloy is supersaturated with respect to the second phase. To age harden

8. _Age Hardening of Metals_   p. 343

the alloy, one must heat the sample to a temperature
where both phases exist at equilibrium and hold at this
temperature for the required time. After this treatment,
the alloy is again cooled to room temperature. Both
time and temperature of the heat treatment are determined
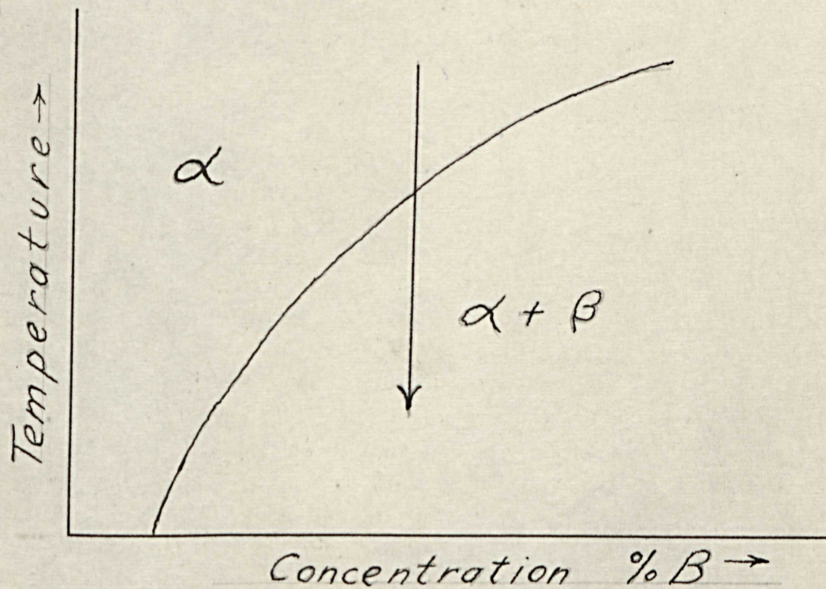by the composition of the alloy and the properties re-
quired.

Fig. 2 - Diagram Showing Phase Relations for
Precipitation

Alloys of this type may be homogeneous at room
temperature but thermodynamically unstable. Therefore,
when the alloy is heated to a higher temperature,
stabilization of the alloy tends to take place. If the

free energy of the second phase is less than that of the initial solid solution, second phase growth is encouraged. The first phase of growth found in the copper-aluminum system is Guinier-Preston zones, named in honor of their discoverers.[9] These consist of very thin plates of second phase aggregates. The size of these platelets depends on the age hardening temperature and their diameters range in copper-aluminum alloys from less than $50A^{\circ}$ at 25° C to $800 A^{\circ}$ at 200° C.

On further treatment according to Wassermann and Weerts, a tetragonal lattice appears in the copper-aluminum alloys, the lattice differing from the original structure. With continued aging this transition lattice is finally transformed to the lattice of the second phase. The sequence of the precipitation may therefore be written:

Matrix - Guinier-Preston zone -

transition lattice -- second phase.[10]

This theory has been offered in explanation for low temperature hardening. Accordingly initial hardening is caused by Guinier-Preston zones, while further hardening

9. Seitz, The Physics of Metals, McGraw-Hill, 1943, New York, P. 131

10. Age Hardening of Metals, P. 403

is due to the formation of the transition lattice and the second phase lattice. These phases may overlap, but the fact that they are formed has been substantiated by X-ray analysis.

Several assumptions have been made to explain the mechanism by which the precipitated particles strengthen the matrix. Jeffries and Archer's slip interference theory states that the particles act as mechanical keys.[11] A second theory is based on the deformation of the crystal lattice in the area surrounding the precipitated particle. This distortion increases the resistance to slip.

Results

The expected precipitation hardening in the alpha phase of the copper-indium system definitely appears in the graphs (pp. 31-36). The decreasing solubility of the indium in copper with decreasing temperature predicted this precipitation hardening. Because the homogenizing temperature was in excess of the maximum solubility temperature, precipitation in the high indium alloys occurred from the alpha plus beta phase rather than from homogenized alpha alone. The effect of this treatment

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11. Meyer, Robert H., Engineering Physical Metallurgy, D. W. Naostrand Co., Inc., New York, 1939, P. 71.

upon the results is not known, no attempt being made to treat other specimens for comparison. Probably the difference would not be appreciable since the amount of beta was small and may possibly have been transformed to alpha before precipitation of delta began.

A definite age hardening was evident in the alloys containing from 9-18 per cent indium with maximum hardening resulting at 300° C within the time limits employed in the experiment. Precipitation hardening occurred sooner at the 400° and 500° temperatures, but the maximum hardness in all alloys which precipitation hardened was found at 300° C. At 200° C no appreciable hardening was noticeable, although the possibility of such hardening at longer annealing time cannot be ruled out. The age hardening curves would lead one to believe that the greatest hardness of all such alloys at 400° and 500° took place within 32 hours, the maximum time employed in the annealing. At 300° C the maximum hardness was not definitely obtained for any alloy but 6, which contains all alpha even at room temperatures and therefore should undergo no precipitation hardening.

Although many fluctuation of the precipitation hardening curves may be attributed to errors in hardness

testing, the 300° curves for alloys 2, 3, 4, and possibly
5 show a preliminary hardening. This early hardening may
be a result of transition phases prior to final precipi-
tation of delta. Other curves do not show this stage but
the action may be so rapid in these cases that the results
do not appear on the graphs.

The curves for alloy 6 (see p36) show no precipi-
tation hardening, but a definite hardening does occur at
a short time interval, this hardening being greater at
lower temperatures. One possible explanation is that
weakening stresses are removed by the low temperature
annealing, the process hardening rather than softening
the metal. Rapid grain growth at the higher temperatures
is shown by the rapid decrease in hardness.

One may conclude that within the limits of the ex-
periment the critical size and distribution of the precipi-
tated particles for maximum hardness occurs at 300° C.
The maximum hardness reached was in alloy 1 which had a
hardness of 28.5 Rc at 16 hours.

Recrystallization and Grain Growth

The study of recrystallization and grain growth was
made on the cold worked samples reduced 40 per cent in
cross sectional area by repeated passage through a set of

hand rolls. These deformed alloys were cut into a
sufficient number of piecestto enable specimens of all
to be treated at 300° and 500° for times ranging up to
2 hours in an electric furnace. On removal from the
furnace, they were mounted, polished and etched for
microscopic study and grain size determination.

Theory

A work hardened metal, although it has great hardness
and strength, is in a state of unstable equilibrium.
Distortion of the crystal lattice by cold working produces
areas in which the symmetry of the atom arrangement has
been disturbed. These disturbed zones have an excess of
energy over the normal crystal structure. The greater
the distortion in an area, the greater the excess energy.

Recovery - Three distinct processes occur on annealing
a metal, the first of these operations being recovery. As
the temperature of the metal is raised, the residual
stresses in the deformed areas are gradually relieved.
This recovery of the metal may be seperable from subsequent
recrystallization, or the processes may overlap. The
relief of these residual stresses may be accompanied by
an increase in hardness and an improvement of magnetic,

electrical, and miscellaneous properties.[12] Recovery
is not the complete relief of stress but a partial relief.
One explanation offered for recovery is the straightening
of bent planes and mending of microscopic cracks and
regions of high stress. Although physical properties may
vary, there is no change in microstructure during the
recovery operation.

Recrystallization - After a cold-worked metal has
been held at a sufficiently high temperature for a period
of time, the energy of the distorted areas increases until
it is high enough to break down the distorted lattice and
form nuclei for stress-free crystals.

Softening of the metal may be sharply defined at the
point of recrystallization if the material has not partially
recovered previously. Grain growth may extend the change
of strength and hardness properties. The rate of re-
crystallization is determined by the rate of formation of
nuclei and the rate of grain growth. These two processes
continue simultaneously until the entire metal has a new
crystal structure.

Impurities which do not form solid solutions seem to

12. Metals Handbook p. 261

have a variable influence upon recrystallization. One
generalization of somewhat doubtful nature states that
impurities have little effect on recrystallization
temperatures. However, in alluminum alloys, such im-
purities, especially in a fine state of subdivision,
exert a powerful influence in raising the recrystallization
temperature. Soluble impurities or alloying elements
definitely raise the recrystallization temperature, the
effect of successive additions being less as the solution
approaches saturation.

Four other factors determine the grain size after
recrystallization: (1) the amount of deformation, (2)
the annealing temperature, (3) the time at the annealing
temperature, and (4) the original grain size. Rate of
heating to recrystallization temperature and the temper-
ature at which the original deformation is made are
variables having a lesser influence on recrystallization.

Each factor may be evaluated from the viewpoint of
the amount of energy which it contributes to the crystal
lattice. When the energy content of the deformed lattice
exceeds a certain minimum value, recrystallization takes
place. Both deformation and temperature contribute to
the minimum energy required for recrystallization. If

a few small areas only have sufficient energy at a
given temperature, few nuclei will be formed and large
grains will result.

Grain Growth - On heating beyond the recrystallization
point the new grains tend to grow. This fact is based on
fundamental physical theory which states that at a given
temperature a body tends to approach its lowest energy
level, a condition characterized by a large grain size.
Under ideal conditions, therefore, a metal would exist
as a single crystal. The opposing force, the rigidity
of the lattice is in equilibrium with the tendency to
form a single crystal when the maximum grain size for
a certain temperature has been attained. Undissolved
impurities cause a small grain size at low temperatures
and a narrow temperature range of extreme grain growth.

Generally grain size and hardness are effected by
annealing temperature as shown in the following diagram.
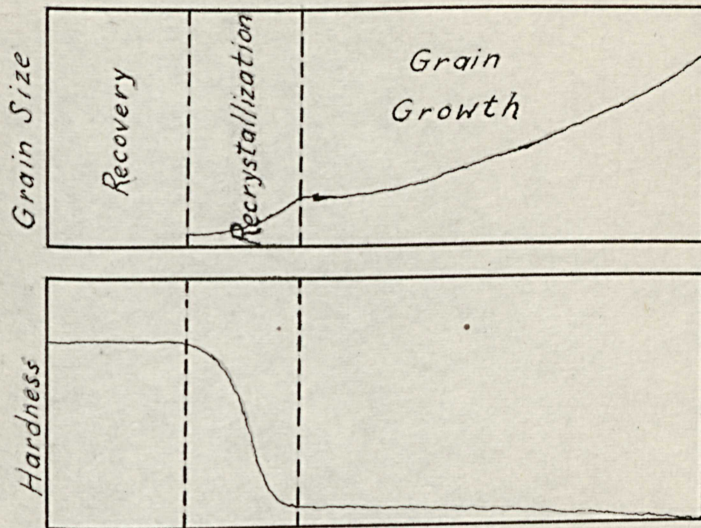
Fig. 3 Effects of Recrystallization on
Hardness and Grain Size. [13]

Results

Results of the recrystallization and grain growth
studies are neither consistent nor easily interpreted.
Difficulties in etching alloys of higher indium content
made grain size measurements impossible in some instances.
At first this failure to find a suitable etching reagent
was credited to the corrosion resistance of the alloy,
but further study established the probability that wide-
spread precipitation of delta from the cold-rolled alloy
made the surface appear uniformly dark.

The two temperatures used for recrystallization
studies were 300° C and 500° C. Since recrystallization
and grain growth are usually accompanied by a softening

13. The Principles of Physical Metallurgy, P. 125

of a metal, the hardening of alloy 1 at 300° C does not conform with expected behavior. If recrystallization does not take place, there should be no substantial decrease in hardness. A possible explanation is precipitation hardening or recovery. A major decrease in hardness of alloy 1 at 500° indicates recrystallization at less than $7\frac{1}{2}$ minutes. Further decrease in hardness indicates grain growth.

Alloy 2 shows increasing grain size at 300° C between 30 minutes and 60 minutes but hardness is not materially affected. These contradictory results are probably due to errors in estimating grain size. Grain size could not be measured at 500° C, but hardness measurements show a definite softening before $7\frac{1}{2}$ minutes and further softening at longer times. Alloy 3 shows a decreasing grain size at 300° C, a probable error in measuring grain size, since there is no material fluctuation in hardness over the interval.

Alloys 4, 5, and 6 behave similarly to the others at 500° C; that is, they recrystallize at short annealing time with subsequent grain growth. From the graphs one can see that no recrystallization is apparent in alloys 4 and 6 at 300° C, and although recrystallization seems

indicated by grain size in alloy 5, hardness measurements show no apparent change.

In summary, the graphs show definite recrystallization at 500° C with short annealing times. At 300° C recrystallization is doubtful up to a period of 2 hours. Despite indications of recrystallization in some alloys, the fact that low indium specimens showed no apparent grain growth at 300° contradicts any indication of recrystallization in alloys of higher indium content. This follows from the generalization that increasing the alloying component tends to raise the temperature of recrystallization.

Conclusions

Although no precise quantitative results were obtained in this investigation, several general facts can be stated as regards the hardening properties of the alpha phase of the copper-indium system

The solid solutions showed a definite increase in hardness with increasing indium content. The hardness increased rapidly at low indium content, but the rate of hardening was less at higher indium contents. The hardness of the specimen containing 18 per cent indium is not a true alpha phase measurement because of improper homogenizing temperatures and the resulting presence of a small amount

of beta. The measured hardness of each of these alloys
may be obtained from the graph.

The cold working of these homogenized specimens to
a reduction of area of 40 per cent produced alloys rang-
ing from 80 to 100 Rockwell B. Following is a table of
hardnesses of other cold-rolled copper alloys for
comparison.[14]

Alloy %	% Reduction	Hardness (Rockwell B)
70 Cu 30 Ni	50	87
80 Cu 20 Ni	50	83
95.19 Cu 4.66 Al	40	90
88.83 Cu 10.02 Al	10	87
91.44 Cu 7.50 Sn	50	95
80 Cu 20 Zn	44	87

Recrystallization studies of this cold-worked metal
proved unsatisfactory. From the data obtained, however,
one can assume that recrystallization occurs for the 40
percent deformed alloys between 300° and 500° C. No
study of the effect of prior grain size on the recrys-
tallization was attempted.

The major study involving are hardening produced
insufficient results for any sweeping conclusions. The
best temperature for maximum precipitation hardening occurs
in the neighborhood of 300° C. Results indicte that

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14. Wilkins and Bunn, Copper and Copper-base
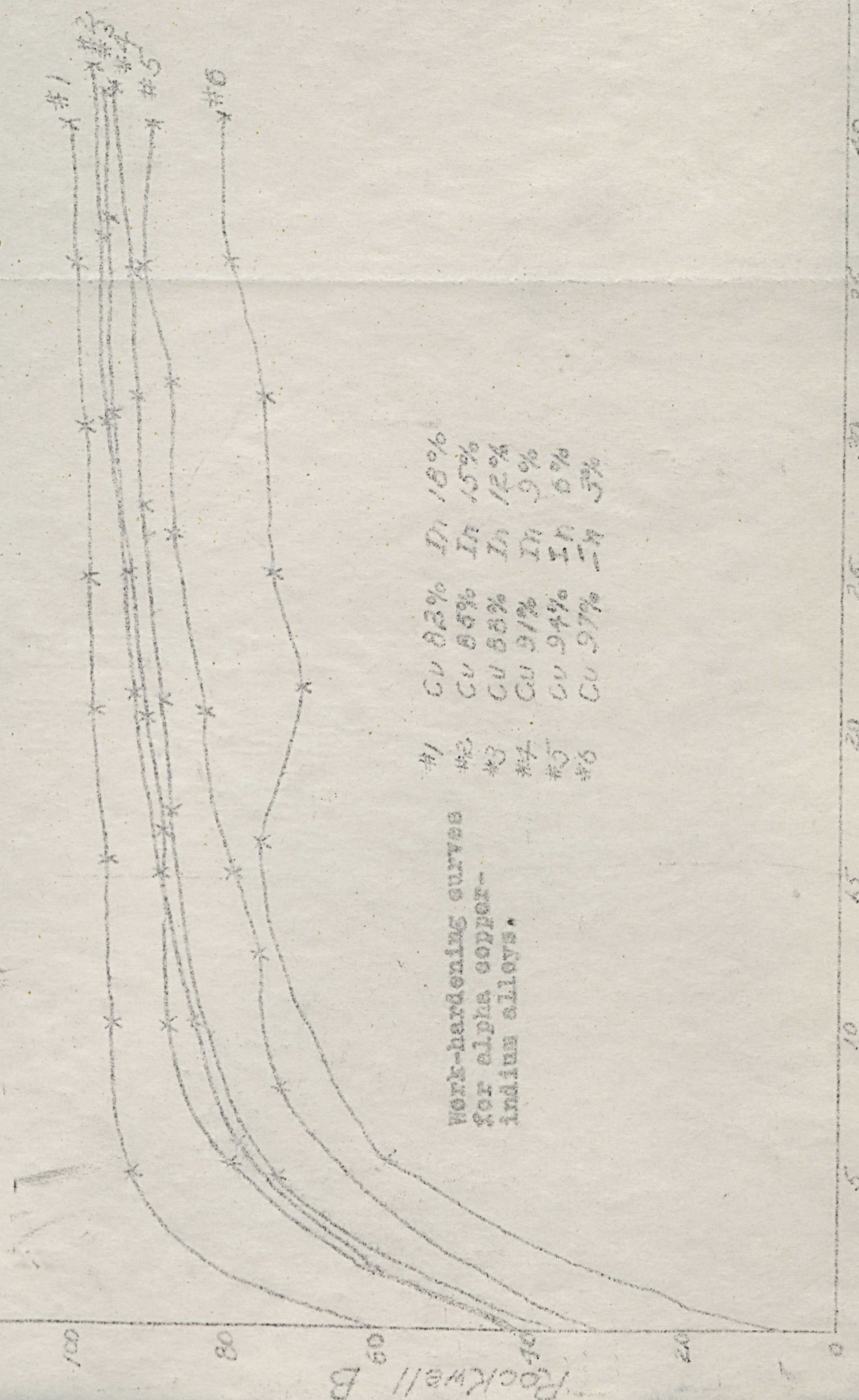alloys, McGraw-Hill, 1943, N.Y.

maximum hardness lies far beyond the aging time of 32 hours employed in the test.

The preceding paragragraphs summarize the results of the investigation conerning alpha phase hardening and heat treating properties of copper-indium alloys. Better controlled operations and temperatures might have produced more valuable results, although present data indicates trends and may narrow further investigation. Increased time of precipitation hardening at $300°$ is necessary to find the maximum obtainable hardness. Studies in combined age hardening and cold working might instrument the discovery of harder copper-indium alloys, as shown by alloy 1 in the recrystallization data.

The color of alpha phase copper-indium alloys ranged from that of copper to a light bronze. The corrosion resistance of copper is increased by the addition of indium also. This property was evident from the difficulty found in etching some of the higher indium alloys.

The alloys are of no practical value at present, their limitations resulting mainly from the high cost and scarcity of indium and the fact that other alloys of copper having similar properties are cheaper.
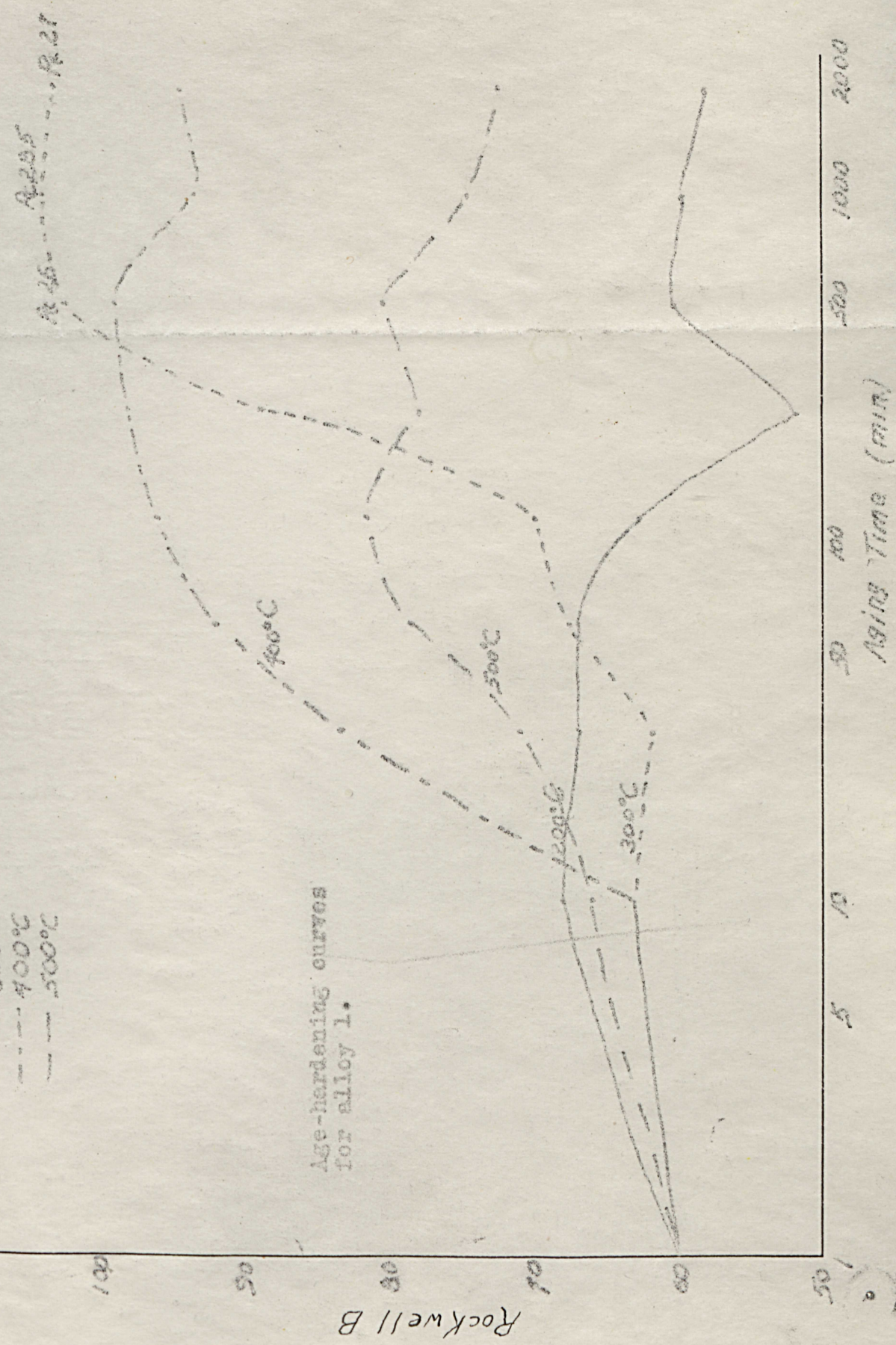
Curve showing effect of increasing indium content on hardness of alpha copper-indium alloys.

#1 #2 #3 #5 #6

Work-hardening curves
for alpha copper-
indium alloys.

#1	Cu 82%	In 18%
#2	Cu 85%	In 15%
#3	Cu 88%	In 12%
#4	Cu 91%	In 9%
#5	Cu 94%	In 6%
#6	Cu 97%	In 3%

Rockwell B

100 80 60 40 20 0

5 10 15 20 25 30 35 40 45 50
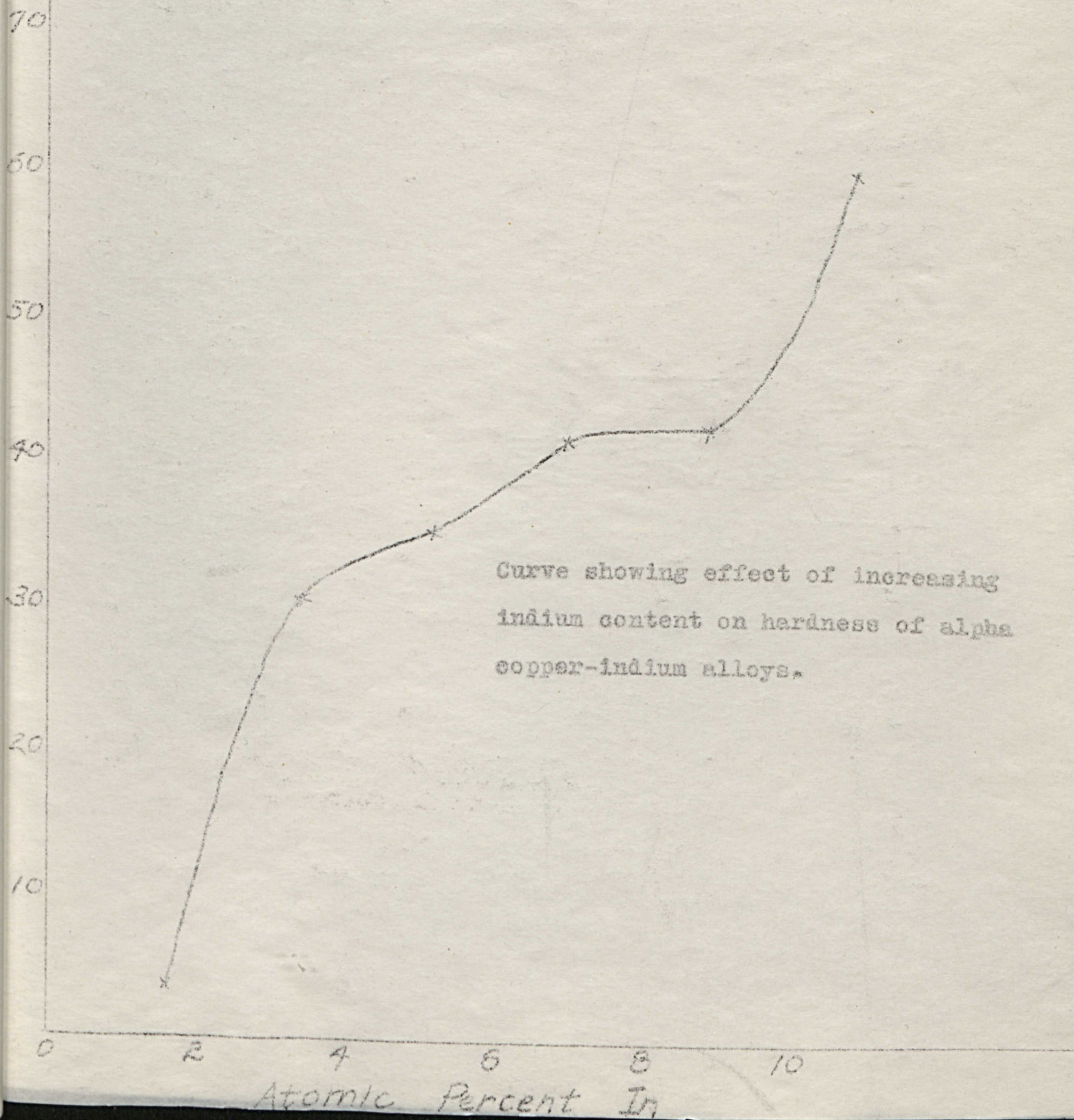
Age-hardening curves for alloy 1.

Alloy #2   Cu 85% Zn 15%

200°C
300°C
400°C
500°C

Age-hardening curves for alloy 2.

Rockwell B

90
80
70
60
50
40
30

200°C
300°C
400°C
500°C

10   100   1000   2000
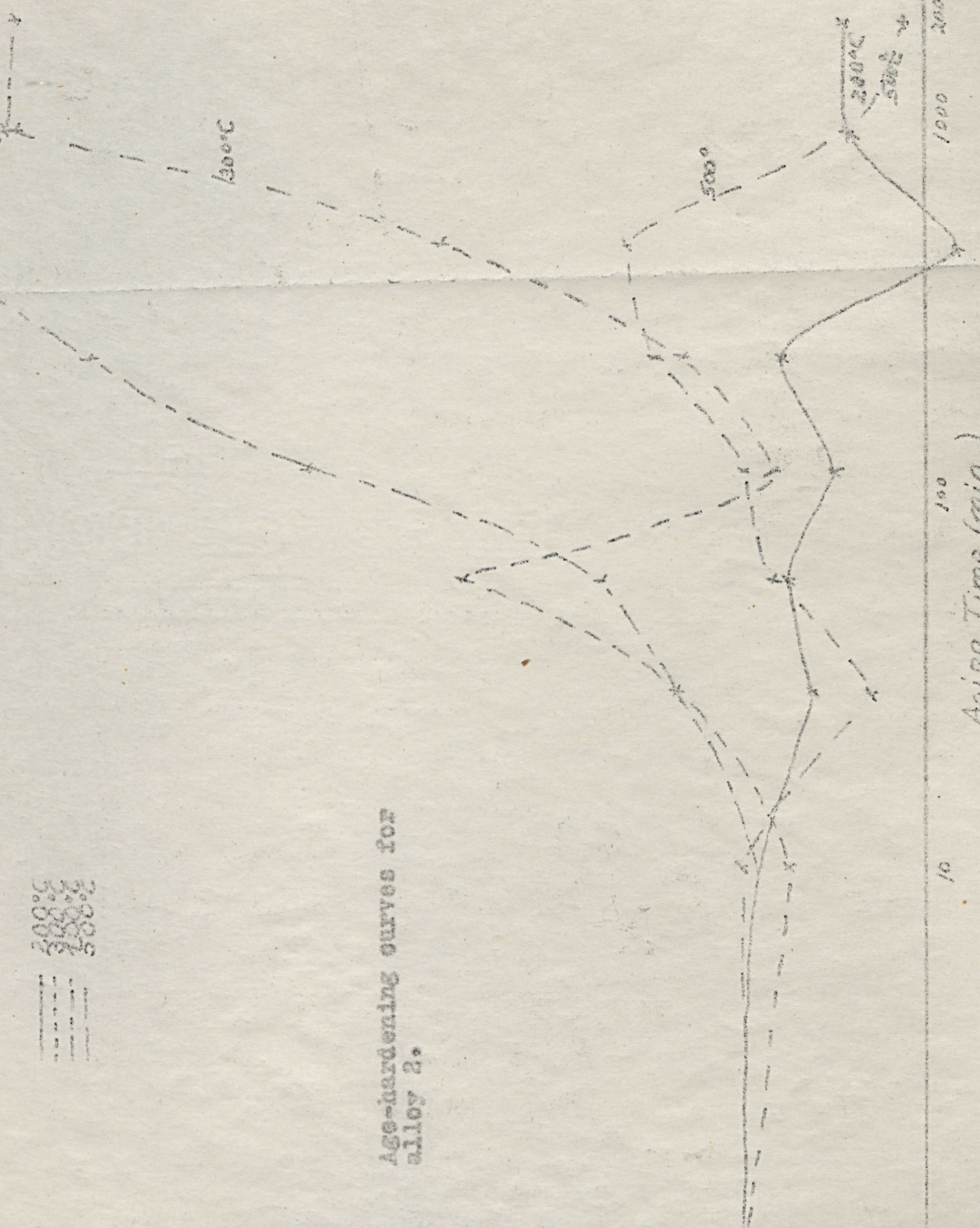
Aging Time (min.)

Alloy #3 Cu 88% Zn 12%

Age-hardening curves for
alloy 3.

200°C
300°C
400°C
500°C

Rockwell B

100°C
200°C
300°C
400°C
500°C
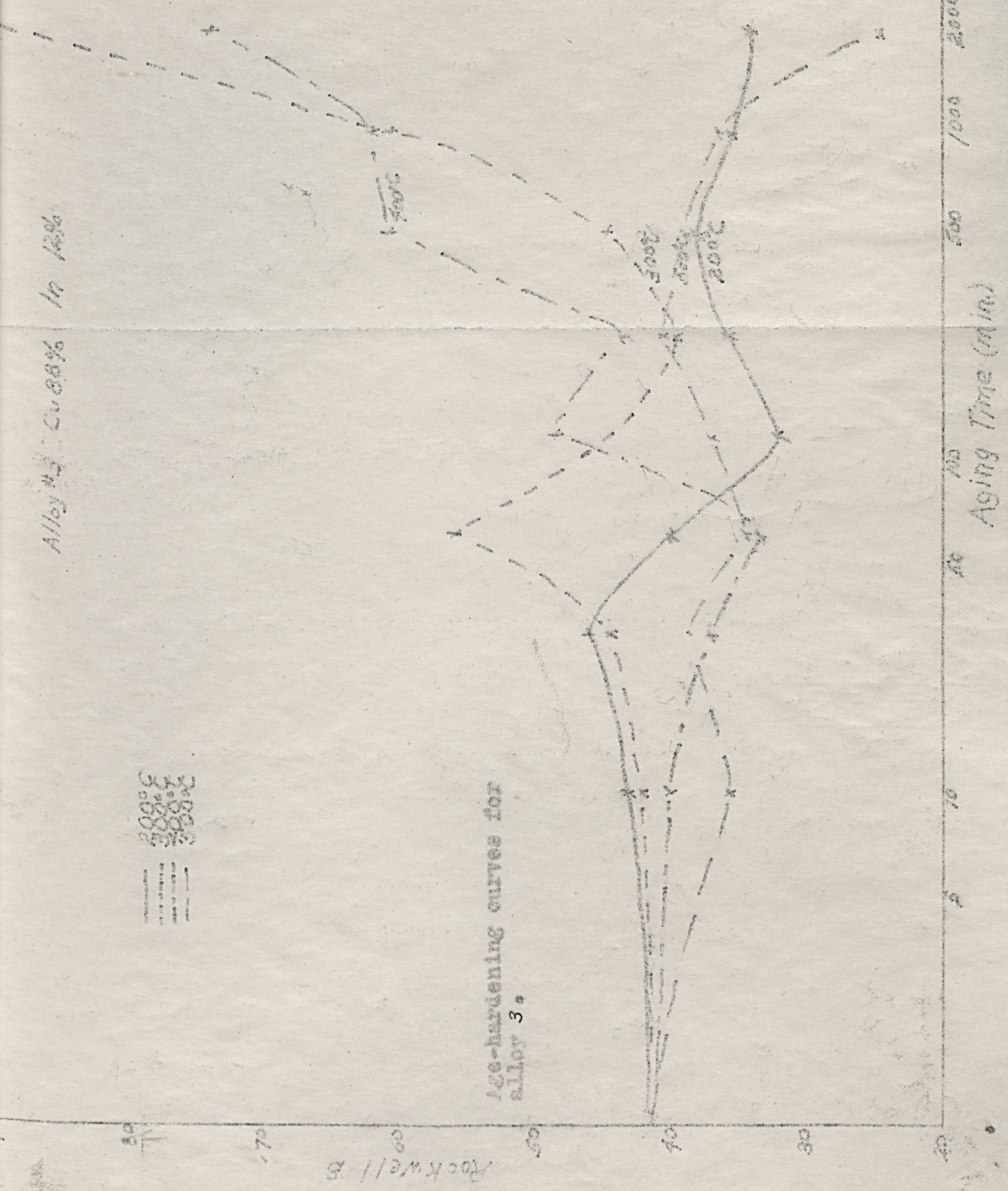
Aging Time (Min.)
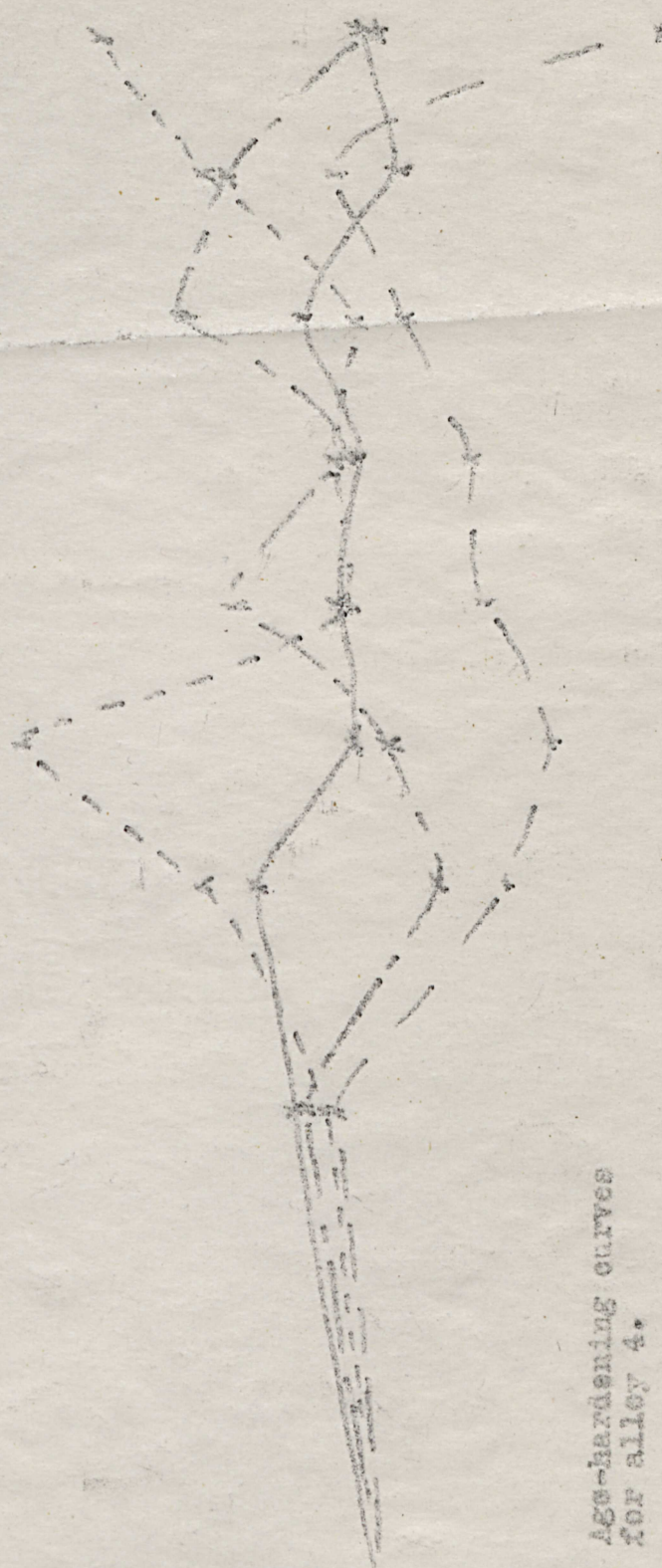
Age-hardening curves
for alloy 4.

Rockwell B

Alloy #5: Cu 94% Zn 6%

200°C
300°C
400°C
500°C

Age-hardening curves for alloy 5.

Aging Time (min)

5   10   50   100   500   1000   2000

Rockwell B

Alloy #5
Cu 97% In 3%

200°C
300°C
400°C
500°C

Rf63
Rf61
Rf60.5
Rf55
Rf65
Rf60.5
Rf61

Age-hardening curves for alloy 5.

Aging Time (min)

50 40 30 20 10 0 -10 -20

1   5   10   50   100   500   1000   2000
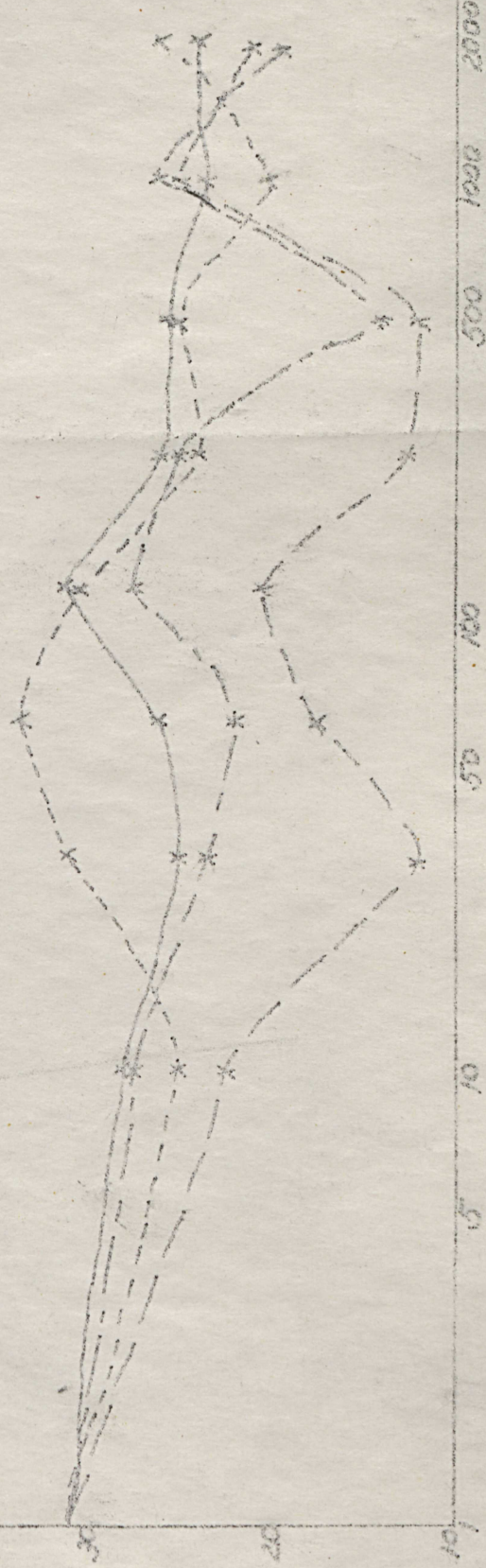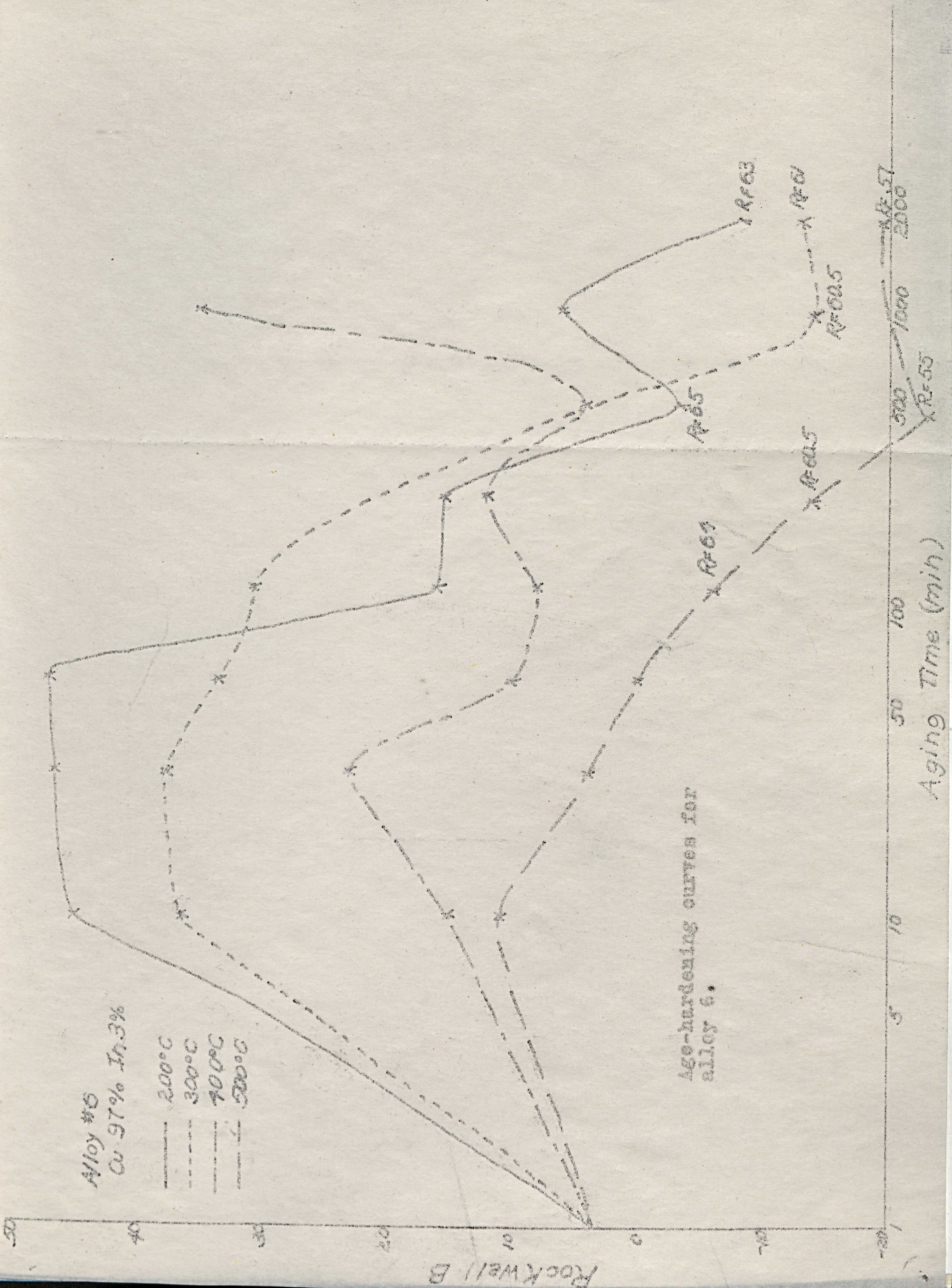
Alloy #1 Cu 82% Zn 18%
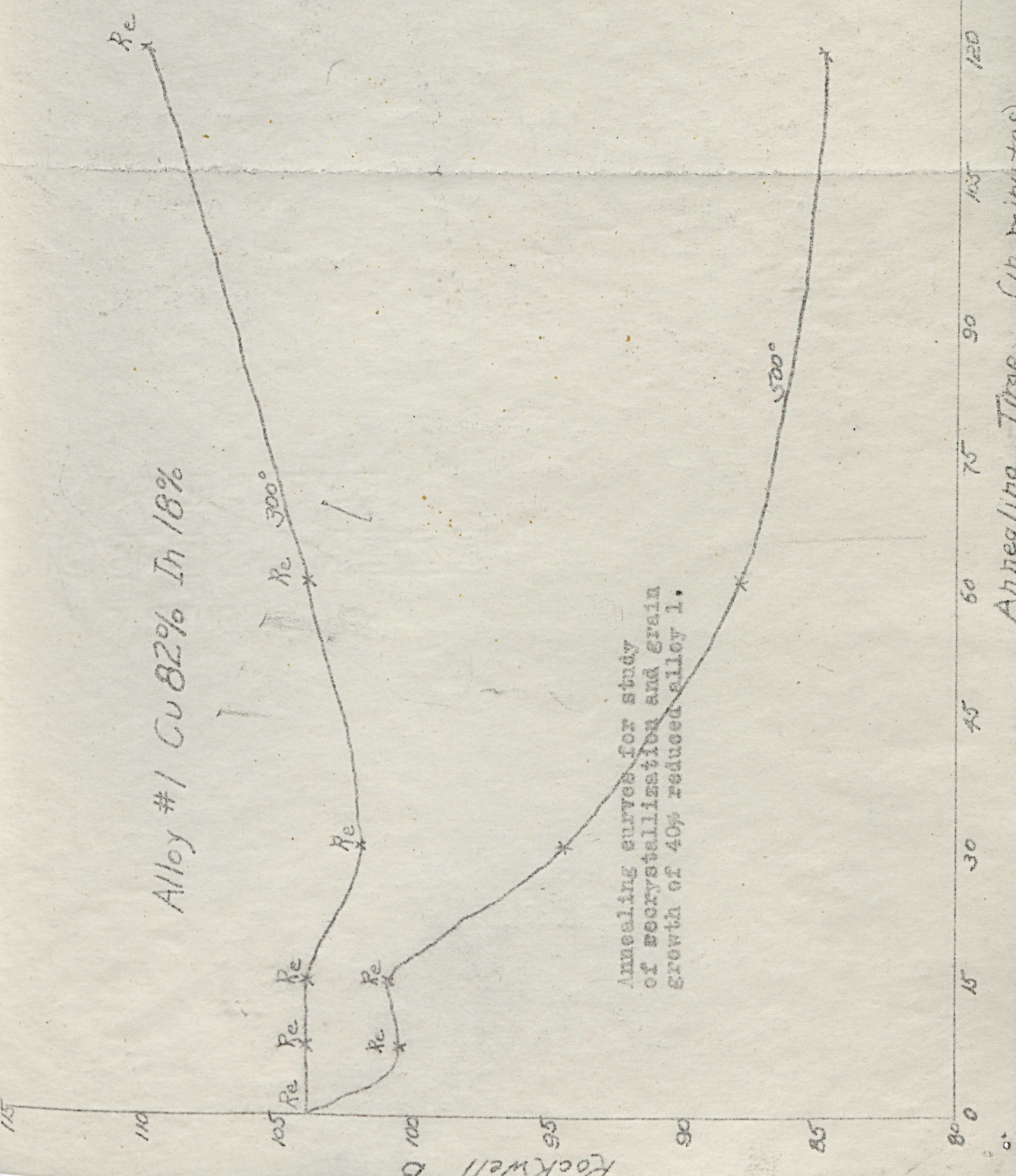
Annealing curves for study
of recrystallization and grain
growth of 40% reduced alloy 1.

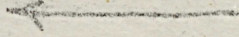Rockwell B
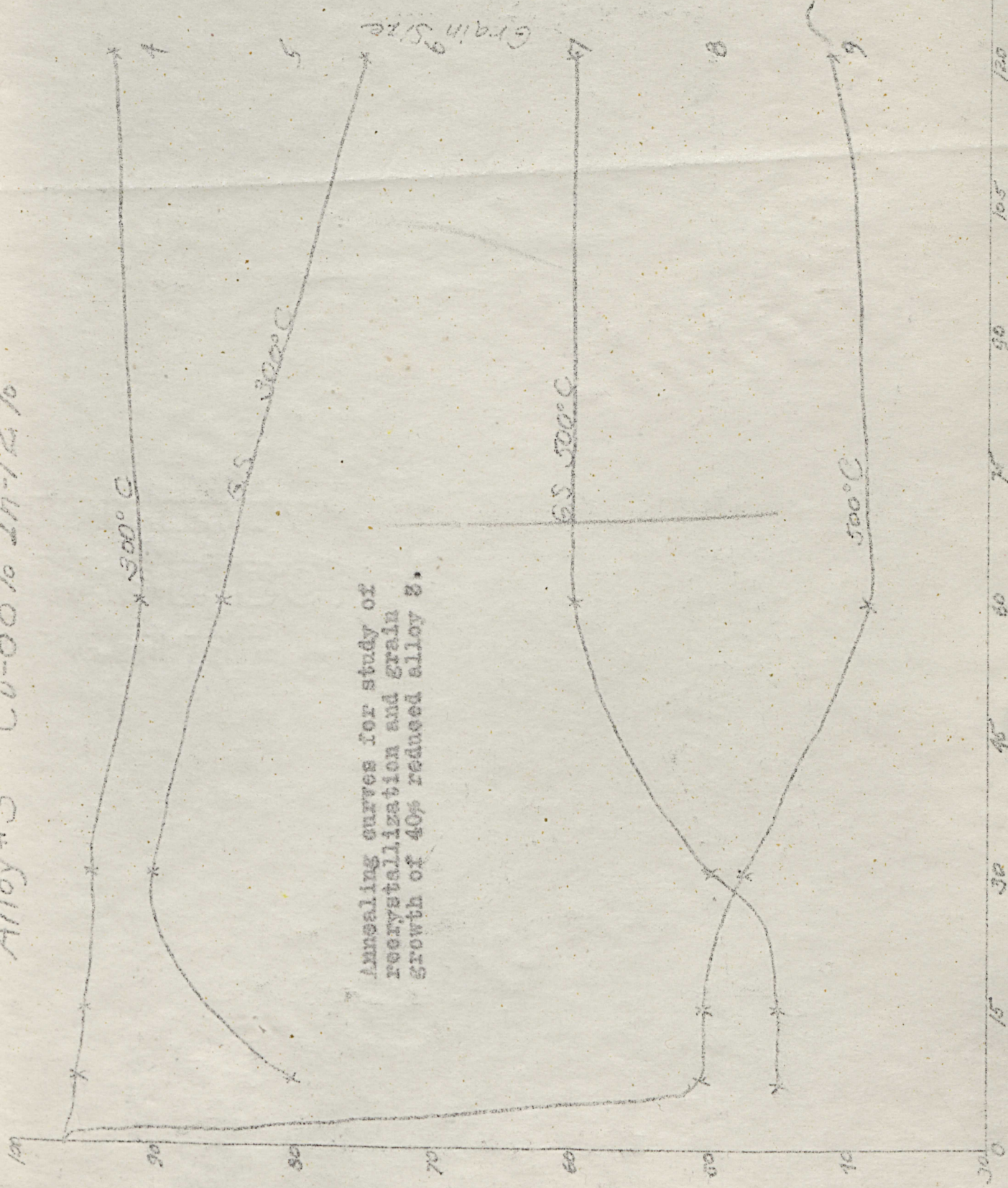
Annealing Time (in minutes)
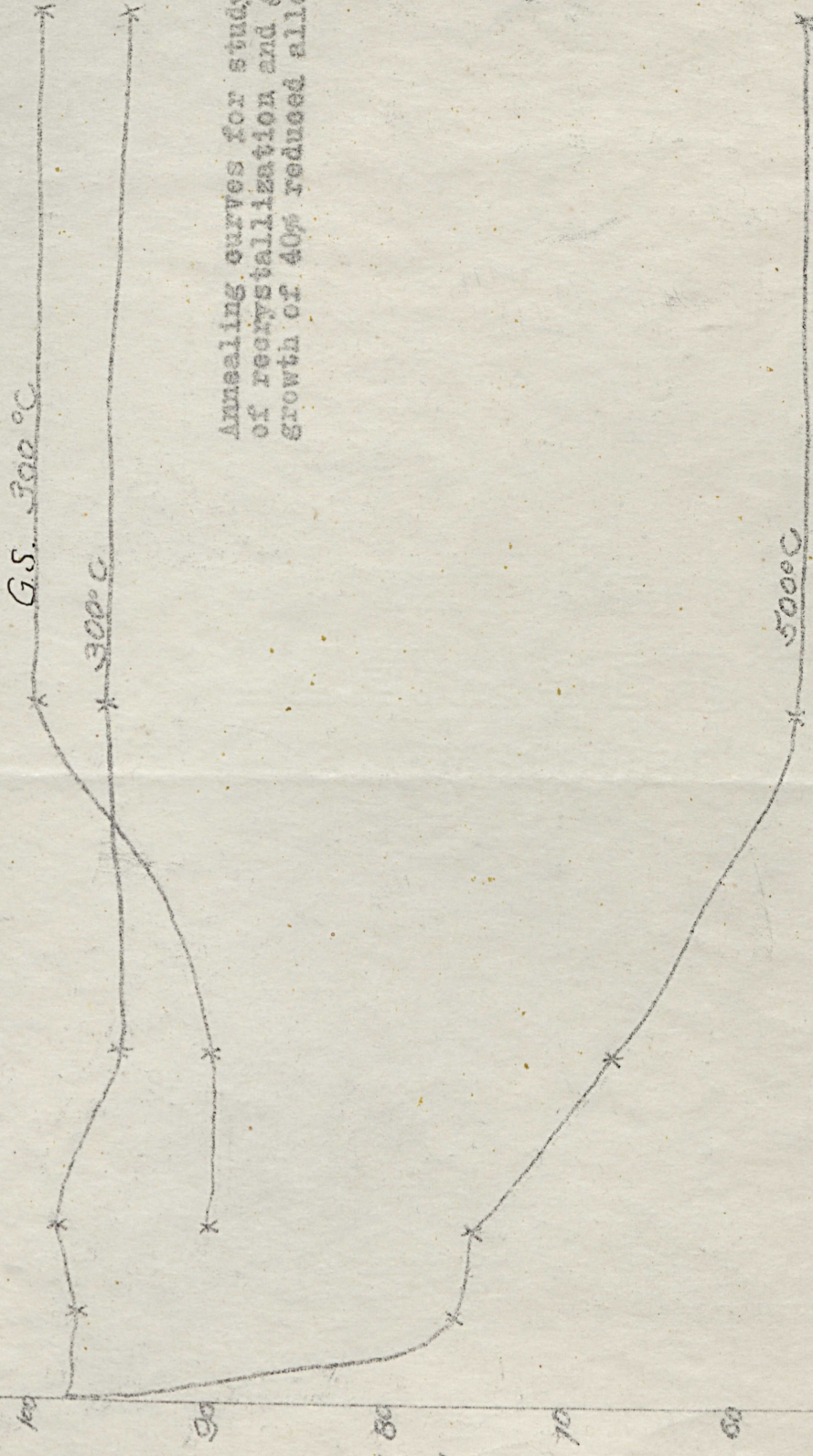
Alloy #2 Cu 85% In 15%

G.S. 300 °C

300° C

500°C

Grain Size

Rockwell B

Annealing Time

Annealing curves for study of recrystallization and grain growth of 40% reduced alloy 2.

Alloy #3 Cu-88% Zn-12%
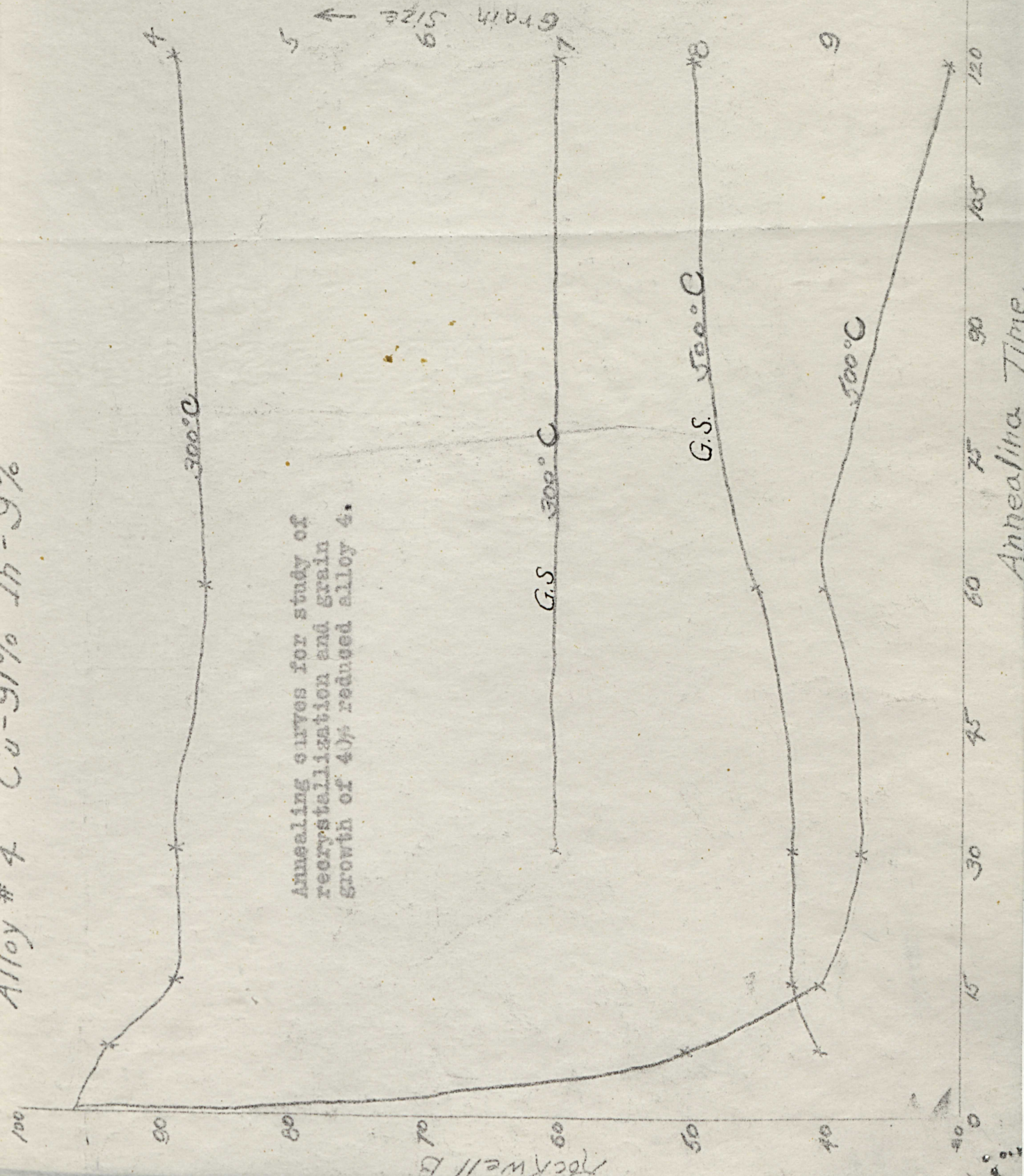
Annealing curves for study of recrystallization and grain growth of 40% reduced alloy 3.
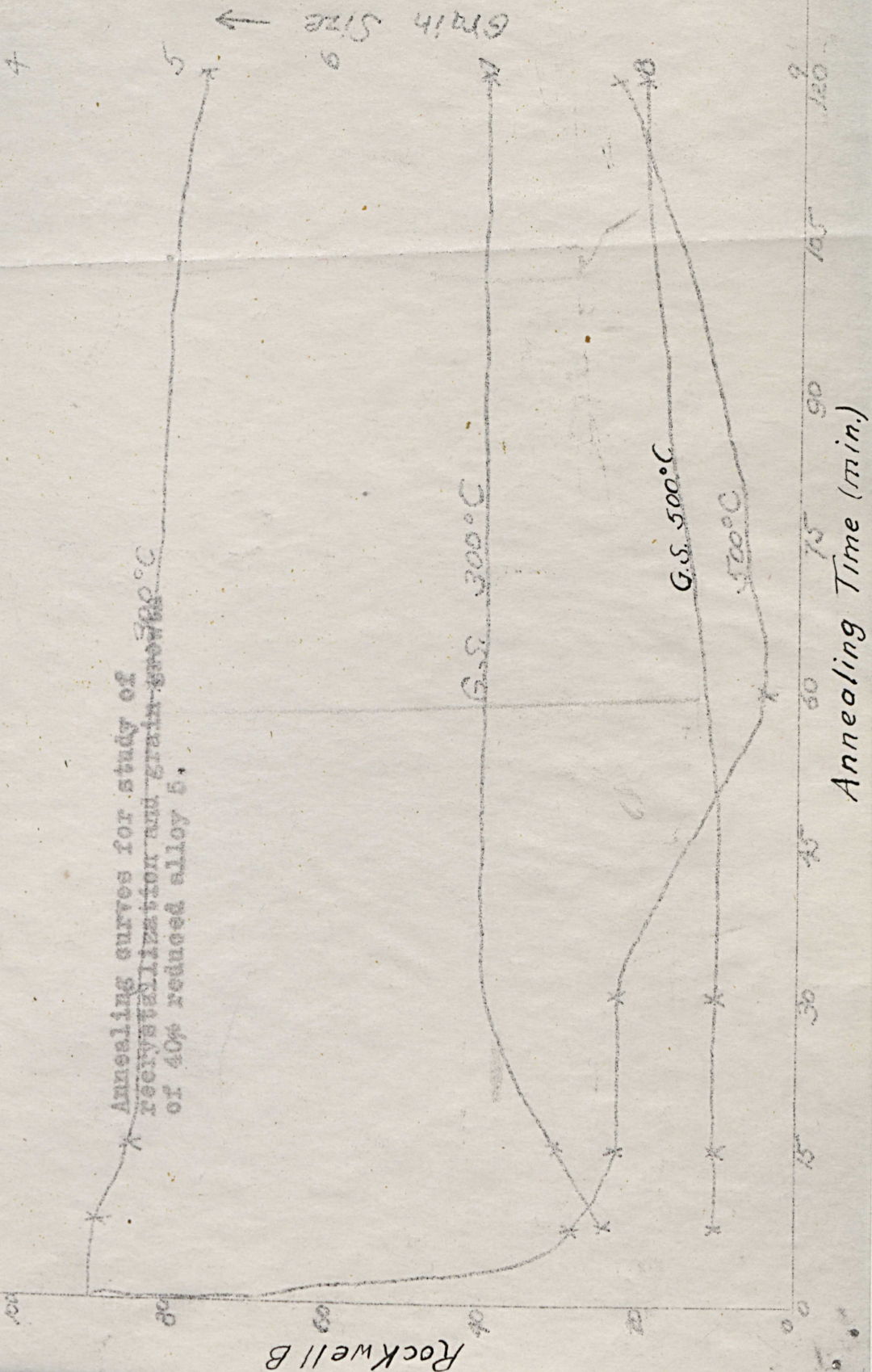
Annealing Time (min)

Annealing curves for study of
recrystallization and grain
growth of 40% reduced alloy 4.

Alloy # 4   Cu-91% In-9%

Alloy #5 Cu 94% In 6%

Annealing curves for study of
recrystallization and grain growth at 300°C
of 40% reduced alloy 5.

Grain Size ←

G.S. 300°C

G.S. 500°C

500°C

Rockwell B

Annealing Time (min)

15 30 45 60 75 90 105 120

0 20 40 60 80 100

4 5 6 7 8

Alloy #6 Cu 97% In 3%

Annealing curves for study of
recrystallization and grain
growth of 40% reduced alloy 6.

Grain Size

Rockwell B

Annealing Time (min)
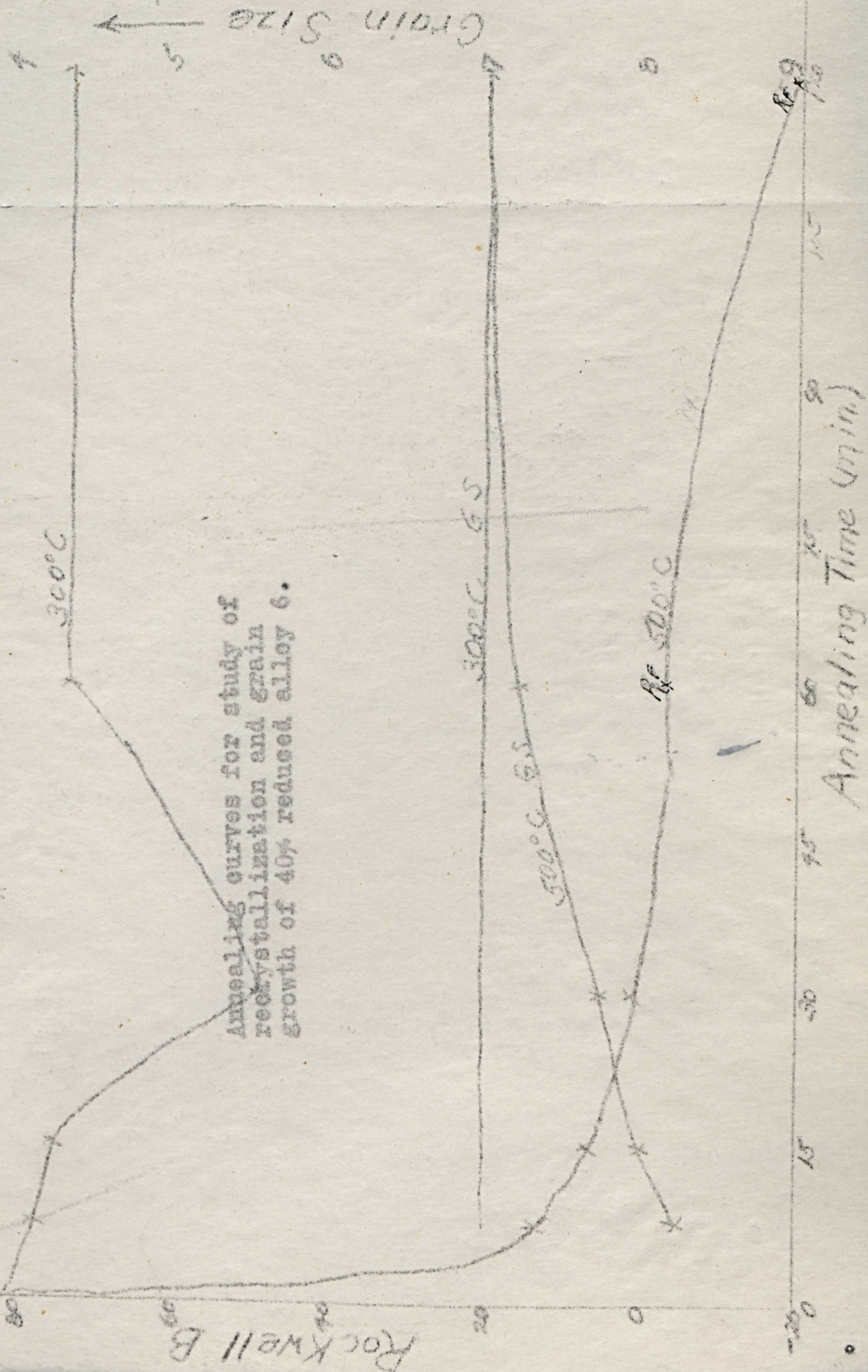
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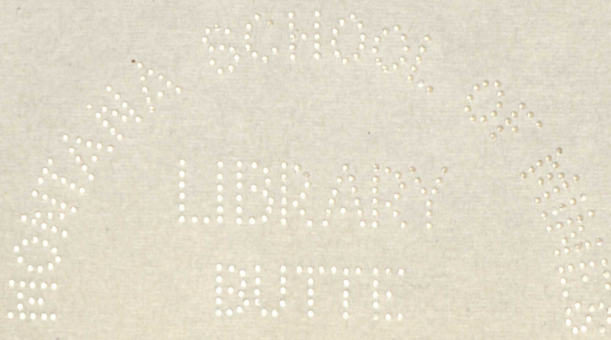
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