GPO PRICE $ _____

CFSTI PRICE(S) $ _____

Hard copy (HC) _____ $3.00

Microfiche (MF) _____ .50

ff 653 July 65

FACILITY FORM 602

N66 27077
(ACCESSION NUMBER) _____ (THRU)

53
(PAGES)

CR- 64249
(NASA CR OR TMX OR AD NUMBER)

/
(CODE)

/7
(CATEGORY)

Alexandria Division

AMERICAN MACHINE & FOUNDRY COMPANY

DEVELOPMENT OF
LIGHT WEIGHT MAGNESIUM ALLOYS
FOR LOW TEMPERATURE APPLICATIONS

Annual Progress Report
June 19, 1964 through June 18, 1965
Contract No. NAS 8-11168
DCN-1-4-50-01030-01(IF)

July 15, 1965

H. W. Leavenworth, Jr.
H. F. Develin
L. R. Mullen
G. DiGiovanni
Dr. F. J. Dunkerley
Dr. E. P. Flint

AMERICAN MACHINE & FOUNDRY COMPANY
MATERIALS DEPARTMENT
ALEXANDRIA DIVISION
1025 NORTH ROYAL STREET
ALEXANDRIA, VIRGINIA

GEORGE C. MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS & SPACE ADMINISTRATION
HUNTSVILLE, ALABAMA

ACKNOWLEDGEMENT

ABSTRACT

$2\eta\mid 0\eta\eta$

Forty magnesium alloys were melted and cast in a permanent mold. Of these, nineteen were successfully hot worked and tested at ambient and cryogenic temperatures. The nineteen successful alloys included fourteen modified alloys whose compositions were altered during the course of the program to achieve improved wrought properties.

As expected, wide ranges of strength and ductility values were obtained which depended upon the composition of the alloys, the hot working temperature, and the heat treatment. The tensile strength of alloy II-4 (72 Mg - 1 Zr - 3 Th - 7 Li - 6 Zn - 5 Cd - 6 Ag) varied from 51,000 psi to approximately 40,000 psi and the percent elongation varied from 11% to 40% at ambient temperature depending upon the wrought structure. The maximum ductility of this alloy at cryogenic temperatures was a respectable 7.8%, but well below the established goals of the program.

An elongation of 14% at cryogenic temperatures was obtained for alloy IA8 (76.5 Mg - 1 Zr - 3 Th - 9 Li - 4 Zn - 2 Al - 4 Ag - 0.5 Mn) with a corresponding tensile strength of 41,300 psi and a yield strength of 39,000 psi. The strength and ductility of this alloy are discussed in detail and recommendations for increasing its mechanical properties by variations in melting and casting techniques are presented.

In general, the results of the testing program showed that the amount, distribution, and size of the β (bcc) phase in the two phase, $\alpha + \beta$ alloys was the most significant factor in determining the ductility of the alloys. Small additions of Zn, Ag, Cd and Li did not significantly affect the properties of a basic Mg - 1 Zr - 3 Th alloy. Increasing the lithium to 7% and raising the silver and cadmium content to 4% and 10%, respectively, while the zinc content remained at 2% did not increase the strength but lowered the ductility. Increasing the zinc content to 6%, with 6% Ag and 5% Cd, increased the strength by 60% with good ambient temperature ductility, but increasing the zinc content to 6% in a 12% lithium alloy resulted in poor ductility. Eliminating cadmium and reducing the thorium content of these alloys to $1\frac{1}{2}$% improved the low temperature ductility without affecting its stability.

The 9% lithium alloys were characterized by excellent ductility even at cryogenic temperatures. Eliminating cadmium and reducing the zinc content to a maximum of 4% was accredited for the improved ductility.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

The results of work performed under Phases I, II and III of Contract No. NAS 8-11168 for the period from June 19, 1964 through June 18, 1965 are described below in this Annual Report.

A. PROGRAM PLANNING

A chart reflecting the entire program schedule and planning is shown in Figure 1. No changes were made in program planning since Monthly Progress Report No. 8. The most notable change from the original schedule was to extend the cryogenic testing to June 15, 1965 in order to include additional alloys in the testing program.

B. TECHNICAL REVIEW OF WORK ACCOMPLISHED DURING THE PERIOD FROM JUNE 19, 1964 THROUGH JUNE 18, 1965

Introduction

The purpose of this program has been to develop light weight, wrought magnesium alloys for applications requiring high strength, high ductility and low notch sensitivity at cryogenic temperatures. Specifically, the ultimate goal was to develop an alloy with a tensile strength of 45,000 psi, a yield strength of 35,000 psi and with 20% elongation at temperatures from -423°F (-253°C) to room temperature (68°F); contractual goals call for these minimum properties over the entire range, except that at the low limit the elongation may decrease to 15%. In addition, the weldability of the developed alloys shall equal or exceed that of the AZ31B magnesium alloy.

The program has consisted of three phases: Phase I included a comprehensive literature search and analysis as well as the preparation of one-pound heats of selected alloys for preliminary screening examinations; Phase II consisted of preparation of ten pound heats of several of the compositions shown to be promising in Phase I. After processing into suitable wrought forms, the mechanical properties of the alloys were tested at -452°F, -320°F and +68°F; finally, Phase III consisted of recrystallization and grain growth studies, welding tests, metallographic, and electron microscopy examinations of the most promising alloy.

Most of the program was devoted to Phase II; ten pound melts of each of nine alloys for each of the three basic systems were prepared, processed, and tested. All alloys were selected according to a statistical plan in order to cover as wide a range of strength and ductility values as possible. Each alloy system represented one statistical matrix and the nine alloys represented components of the matrix. A few alloys represented alloying compositions of known mechanical properties, but these were included to complete the statistical design. The three matrices

are shown below:

MATRIX I

Basic Alloy - Pure Mg

	0.05 Li	0.2 Li	1.0 Li
.25 Mn	1 3 Al 6 Zn	2 8.5 Al 3 Zn	3 12 Al 1 Zn
.75 Mn	4 12 Al 3 Zn	5 3 Al 1 Zn	6 8.5 Al 6 Zn
1.5 Mn	7 8.5 Al 1 Zn	8 12 Al 6 Zn	9 3 Al 3 Zn

MATRIX II

Basic Alloy - Mg + 1 Zr + 3 Th

	5 Cd	10 Cd	20 Cd
2 Zn	1 2 Ag 2 Li	2 4 Ag 7 Li	3 6 Ag 12 Li
6 Zn	4 6 Ag 7 Li	5 2 Ag 12 Li	6 4 Ag 2 Li
12 Zn	7 4 Ag 12 Li	8 6 Ag 2 Li	9 2 Ag 7 Li

MATRIX III

Basic Alloy - Mg + 1 Zr

	0 Nd	1.5 Nd	3 Nd
0 Th	1 2 Zn 2 Ag	2 6 Zn 4 Ag	3 9 Zn 6 Ag
3 Th	4 9 Zn 4 Ag	5 2 Zn 6 Ag	6 6 Zn 2 Ag
5 Th	7 6 Zn 6 Ag	8 9 Zn 2 Ag	9 2 Zn 4 Ag

The nine alloys of Matrix I have a hcp structure; the small addition of lithium was chosen to reduce the c/a ratio[1] rather than to transform the matrix to a bcc structure. The tendency for magnesium-aluminum alloys containing high percentages of lithium to over age rapidly at low temperatures prompted the selection of alloys with conservative lithium additions for the first matrix; higher lithium additions were reserved for the second matrix. Magnanese was selected for additions as high as 1.5% because of its solid solution strengthening effect, even though its limited solubility and tendency to segregate to the bottom of the lower density magnesium-rich Mg - Al - Zn liquid was recognized as a problem. A chill casting technique from a pouring temperature above 1500°F to retain the maximum amount of mangenese in solution was employed. The solid solution strengthening effects of aluminum and zinc were assumed to be additive and were utilized to the fullest. In actual commercial practice, alloys containing more than 10% Al are rarely cast because of the danger of incipient or eutectic melting at grain boundaries. Matrix I contains three alloys with aluminum contents of 12%, the maximum limitations of solid solubility, so that the effect of aluminum would not be masked by other alloying effects in the statistical matrix.

Zinc in excess of 2% has been found to produce alloys susceptible to heat treatment for maximum strength, although ductility usually decreases rapidly as the zinc content is further increased. Matrix I was designed to contain three alloys with less than 2% zinc with three alloys containing a maximum of 6% zinc. The properties of binary alloys containing 6% zinc in the fully heat treated condition do not approach those of magnesium aluminum alloys and the emphasis in Matrix I was placed on aluminum rather than zinc. No nucleant grain refiner was added to Matrix I because of the presence of aluminum. Grain refining was to be accomplished by chill casting and subsequent forging and rolling.

Nucleant grain refining was studied in Matrix II. Zirconium (1 wt. %) was added to each melt and several modifications were made with silicon as a grain refiner. Each melt also contained 3 wt. % thorium for structural stability, a property often overlooked in magnesium lithium alloys. Several modifications of these alloys were made in order to study the effect of thorium separately. The primary purpose of Matrix II was to study the effect of lithium on the strength and ductility of magnesium alloys containing a variety of strengthening elements. Cadmium was added for solid solution strengthening, as was silver. The favorable size factor

---

1. R. S. Rusk, Trans. AIME, 188, 1460 (1950).

of both these elements enhances solid solution strengthening, but the electro-negativity of the latter element restricts its maximum solid solubility. Matrix II contains alloys with as much as 20 wt. % cadmium and 6 wt. % silver.

Zinc was added to the Matrix II alloys in rather large quantities in order to study the effect of lithium-zinc compounds on the ductility of magnesium alloys. Alloys 7, 8 and 9 contain 12% zinc with 12%, 2% and 7% lithium, respectively.

Matrix III contains zinc and silver additions for strengthening and the thorium content varied from 0% to 5%. The system is inherently fine grained and strong, but lacks ductility and weldability. Thorium and neodymium were added to overcome the adverse ductility effects by forming ductile intermetallic phases. One of the functions of the Matrix III alloys was to study a technique to significantly increase the ductility of magnesium alloys without adding lithium.

Melting Procedure

All the alloys were melted in Hevi-Duty Electric Furnaces which were mounted on frames for easy tilting and direct pouring. One of the melting crucibles used for alloy preparation is shown in Figure 2. The crucibles were continuously flushed with purified argon and additions made to the melt through the large port shown on the top of the crucible.

Two small openings are also shown on the crucible top; one was made to accommodate a thermocouple well to which a stirring paddle was also attached; the other port was used to admit the argon. The pouring spout is shown in front of the crucible with a removable cap. After all additions were made and the melt thoroughly stirred, the cap was removed and the metal was either teemed into a hot ladle or directly into the mold. Pouring shanks, not shown in Figure 2, were fitted to the crucible to facilitate pouring of the more oxygen sensitive melts without ladling.

All the alloys were cast in the cast iron permanent mold, which was designed to facilitate producing oxide free cast rolling stock. The design of the mold is shown in Figure 3 and an open view of the mold is shown in Figure 4. The size of the vents shown in Figure 4 was continuously increased until the cavity could be completely filled.

The ingate system was developed by trial and error starting from minimum ingates to the final openings required to produce a sound casting. One side gate was added to feed hot metal to the riser for the sluggish melts, but this gate was blocked off for most of the alloys.

The most important factor in obtaining good magnesium casting was the elimination of turbulence in the flowing metal to minimize the formation of oxide inclusions. This was accomplished partly by avoiding "squirting" through the ingate and by choking the metal in the sprue; the final sprue-to-runner-to-ingate ratio ultimately developed was 1/1/8.* Any dross that did form during pouring was trapped in the sump by a tin plated perforated metal cylinder. Fluffed steel wool was also placed inside the cylinders to cushion the liquid metal and to eliminate turbulence.

For alloys containing from 7% to 12% lithium, double screening was necessary to keep the metal clean. This was accomplished by using concentric perforated cylinders with fluffed steel wool inserted between the cylinders for additional screening.

Five insulating and/or fluidity promoting mold coatings were evaluated during the course of the program, including acetylene or lamp black, Dycoat 140, Dycoat 140 + Dycoat 11, Dycoat 140 + Ep. 2210, and Dycoat 140 + acetylene soot. Acetylene acted as a good lubricant but the coating had to be repaired after each use. Dycoat 140 was a white, tenacious coating with excellent insulating properties. However, this coating reacted with the high lithium alloys and had to be protected by Dycoat 11, a graphite coating with excellent lubricating properties. This combination gave excellent insulating and lubricating properties, requiring little additional attention when properly applied. Ep. 2210 was finely divided carbon which proved to be messy and difficult to apply. Dycoat 140 with a final coating of acetylene soot gave good castability, but the outer coating had to be constantly repaired. All coatings were applied to a hot, 500°F mold; the temperature being measured by a surface pyrometer.

While the mold was being prepared, empty crucibles were heated to the temperature range 1350° to 1400°F. After reaching equilibrium, eighty percent of the pure magnesium was added to the crucible and the top was tightly secured. After the initial charge melted, the remaining pure magnesium was added to the melt by lowering it through the alloying port shown in Figure 2. Additional alloying elements were added in sequence through the same port with the grain refiner and lithium added last. Following established melting practice, the melt was slowly "puddled" after the zirconium additions and thoroughly stirred after the lithium additions were made. Lithium was added as a Mg + 47% Li master alloy, developed by the Foote Mineral Company at the request of AMF project personnel. The use of a master alloy insured thorough mixing and complete lithium recovery.

---

*This ratio is not corrected for the restriction offered by the screen which had a 40% opening.

After the melt was thoroughly stirred, the pouring spout was opened and the crucible removed from the furnace so that a portion of the metal could be poured into a fracture mold. (See Figure 5.) The crucible was returned to the furnace and the pouring spout closed while the fracture casting was examined for grain refining. If the proper texture was obtained, the pouring spout was again opened and the crucible was removed from the furnace and the metal quietly poured into the sprue as shown in Figure 6. Argon was continuously fed into the crucible through a flexible line to keep the metal from oxidizing. After solidification, the mold was opened and the casting removed and stored for subsequent heat treatment and hot working. A typical casting is shown in Figure 7.

Metallography of Matrix I As-Cast Structures

Metallographic analysis of the cast alloys of Matrix I shown in Figures 8 through 16, proved the as-cast alloys to be cored. In nearly all of the alloys, the grain boundaries contained thick envelopes composed of alternate layers of a eutectic type structure in conjunction with a continuous, multiple component, brittle phase. The matrix material itself appeared to be soft and ductile, with numerous brittle inclusions embedded in the individual grains.

For the purposes of this report the microstructures of the individual alloys were developed by appropriate metallography to better illustrate one or more of the salient microstructural characteristics of the entire matrix. For example, Alloy I-1, Figure 8, shows coring and some brittle intergranular phase. Alloys I-2 and I-3, Figures 9 and 10, have been prepared to best illustrate the large amounts of eutectic type structure found in the grain boundaries of these as-cast alloys. Alloy I-4, Figure 11, has been prepared to illustrate coring and the presence of a continuous brittle phase. Figure 12, Alloy I-5, primarily illustrates coring. Figure 13, Alloy II-6, shows large amounts of eutectic type structure and brittle phase. Figure 14, Alloy I-7, illustrates the numerous brittle phases forming a continuous envelope in the grain boundaries. Figure 15, Alloy I-8, shows coring, intergranular brittle phases, and a eutectic type structure with brittle inclusions in the grain boundaries.

Metallography of Matrix II As-Cast Structures

As a result of metallographic analysis of the Matrix II alloys, three basic types of microstructures were discovered. Solution heat treatment was used on some of the alloys to accentuate these basic microstructural differences. Alloys II-4, as shown in Figure 19, and the modified II-4 alloys, Figures 24-28, consist of a somewhat brittle matrix material along with amounts of discontinuous ductile phases in the grain boundaries. The

12% lithium alloys, II-3, II-5 and II-7, as shown in Figures 18, 19 and 22 after solution heat treatment, are very nearly single phase alloys with a larger grain size than the two phase alloys. The high cadmium-high zinc II-6 and II-8 alloys, Figures 21 and 23, exhibited a continuous brittle grain boundary precipitate. After solution heat treatment, one of the grain boundary precipitates, undoubtedly the Cd-Zn eutectic, melted leaving voids in the grain boundaries.

Metallography of Matrix III As-Cast Structures

Metallographic analysis of the as-cast alloys of Matrix III proved the alloys to be cored and to have an almost continuous brittle intergranular phase which exhibited brittle behavior, as shown in Figures 29 through 38. Several of the alloys were also found to have brittle phases embedded in the individual grains. The microstructure of Alloy III-3, shown in Figure 31, was preferentially prepared to illustrate the brittle inclusions found in the individual grains. Figures 36 and 37 of Alloys III-8 and III-9 show the microstructure preferentially prepared to best illustrate the multi-phase brittle intergranular envelope characteristic of the as-cast alloys of this matrix while photographs of Alloys III-1, III-7 and III-10 as shown in Figures 29, 35 and 38, were selected to illustrate coring.

Hot Working Procedure

The castings were homogenized for 48 hours at $800^\circ F$ prior to hot working. Total reductions of 87% to 97% were made on the most promising alloys at temperatures from $600^\circ F$ to $720^\circ F$, depending upon the desired structure. All of the Matrix I and Matrix III alloys showed signs of cracking after reductions of 10% to 15% and were discarded as being too brittle to meet the requirements of the program. All of the Matrix 1A alloys hot worked without difficulty and the first four alloys of Matrix II were easily hot worked. Alloys 5 and 6 of Matrix II showed slight cracking in the early stage of rolling, but Alloy II-5 was successfully rolled to 1/8" sheet in spite of the difficulties with the initial reductions. The high cadmium alloys, II-6 and II-9, were difficult to hot work and could not be successfully rolled into sheet. Alloys II-7 and II-8 cracked severely on the first pass because of the formation of brittle intermetallic compounds and possible incipient melting in the grain boundaries (see Figures 22 and 23). All the modifications of Alloy II-4 were easily rolled to sheet form. The castings were heated in a 56% KCl-LiCl eutectic salt solution which formed a film on the surface of the castings and acted as a lubricant during subsequent hot working. The film also acted as an insulator to prevent the castings from cooling below the hot working temperature. After hot working, excess salt was removed from the rolled sheet to prevent moisture pickup and ensuing saline corrosion.

Mechanical Properties

     After hot working, the rolled sheet was sectioned and machined into six inch flat tensile specimens. The specimens were subsequently heat treated at a variety of temperatures or tested in the as-rolled condition. The composition of the alloys that were successfully hot worked and tested are given in Table I:

TABLE I

COMPOSITION OF ALLOYS THAT WERE
SUCCESSFULLY HOT WORKED

Alloy No.	Composition, wt.%							
	Mg	Grain Refiner	Th	Li	Zn	Mn	Al	Ag
1A1	81.75	1 Si	3	9	1	$\frac{1}{4}$	0	4
1A2	79.50	1 Si	3	9	1	$\frac{1}{2}$	4	2
1A3	82.00	1 Si	3	9	1	1	2	1
1A4	80.75	1 Si	3	9	2	$\frac{1}{4}$	2	2
1A5	83.50	1 Si	3	9	2	$\frac{1}{2}$	0	1
1A6	76.00	1 Zr	3	9	2	1	4	4
1A8	76.5	1 Zr	3	9	4	$\frac{1}{2}$	2	4

	Mg	Zr	Th	Li	Zn	Cd	Ag
II 1	85	1	3	2	2	5	2
II 2	73	1	3	7	2	10	4
II 3	56	1	3	12	2	20	6
II 4	72	1	3	7	6	5	6
II 5	66	1	3	12	6	10	2
II 10	69	1	6	7	6	5	6
II 11	66	1 Si	3	12	6	10	2
II 4A	78.5	1	$1\frac{1}{2}$	7	6	0	6
II 4B	73.5	1	$1\frac{1}{2}$	7	6	5	6
II 4C	72.5	1	$2\frac{1}{2}$	7	6	5	6
II 4D	77.0	1	3	7	7	0	6
II 4E	74.5	1	3	7	6	$2\frac{1}{2}$	6

All tensile specimens were tested in a 20,000 pound capacity Instron Universal Testing Machine. Figure 39 shows two views of a Cryogenic Research Co., Model TC-20000 Tensile Cryostat that was used to test the magnesium specimens in cryogenic fluids. The rigid transfer line shown in Figure 39 did not operate well with liquid helium because of constant breakage of the vacuum jacket seals that insulated the inner transfer tube, and in some cases the lowest temperature that could be obtained was -423°F. This transfer line was ultimately replaced by a 100 liter capacity flexible connection of more modern design that allowed us to reach -452°F.

The testing program was initiated by testing Alloys II-1, II-2, and II-4 at ambient temperature. Fracture analysis of the broken tensile specimens revealed that rupturing started at minute oxide impurities. All of these alloys were melted under a "gettered" inert argon atmosphere and cast in the permanent mold with the steel wool and perforated screen in place as previously indicated. These minute particles were removed from subsequent melts by using the double screening technique described in the Melting Procedure. These results illustrated the importance of a good mold design and showed that magnesium alloys cannot be cast directly into an open mold if optimum strength and ductility are to be obtained.

Most of the testing in the early phase of the program was done on Alloy II-4. A wide variation in mechanical properties was obtained for this alloy in the as-rolled condition as shown in Table II. The ductility at 68°F varied from 11% to 40% and the tensile strength varied from 40,000 to 51,000 psi (considering only the alloys cast with the improved double screening technique). The actual chemical composition of these alloys varied somewhat as follows: Mg - 0.5 Zr - 2.2 Th - 5.9 Zn - 5.1 Cd - 5.35 Ag - 7.2 Li for the alloy with 16% elongation and Mg - 0.05 Zr - 1.8 Th - 6.3 Zn - 5.3 Cd - 8.7 Li for the alloy with 40% elongation. Good recovery was obtained for the most readily oxidized alloying elements, thorium and lithium. The fine, as-cast grain structure of these alloys was attributed to chill casting rather than to nucleant grain refining because of the low zirconium recovery.

Most of the variation in the as-rolled properties was attributed to their microstructure, as shown in Figures 40 through 43. The microstructure of specimens with high elongation values has a very fine, needle-like second phase [bcc β phase] randomly dispersed through the hcp matrix, whereas this phase is longer and oriented in the direction of rolling in those specimens of moderate elongation. The specimens with random orientation of the β phase, i.e., those that show high ductility, were hot worked at a lower temperature where the second phase did

not tend to agglomerate.

In an effort to study the effect of wrought structure on the low temperature ductility of Alloy II-4, duplicate castings were hot worked at 600°F and 720°F; both castings rolled successfully without difficulty. Rolling at 600°F elongated the β needles of the as-cast structure (shown in Figure 19) in a preferred direction giving the appearance of a cold-worked structure as shown in Figure 44. Rolling at 720°F resulted in the structure shown in Figure 45, which shows a random distribution of a fine β phase and a preferred orientation of coarser β needles. As expected from the microstructure, Alloy II-4 hot worked at 600°F showed low values of elongation at 68°F regardless of the post hot working heat treatment. At -320°F the elongation of this alloy was only 3.0%. The II-4 alloy that was hot worked at 720°F had a greater ductility at -320°F, but the values of 6.4% to 7.8% were not as high as expected. Evidently a slightly higher lithium content is required, in addition to a fine microstructure, for optimum ductility. The strength and ductility of alloys containing 9% lithium was studied later in the program as a supplement to the Matrix I alloys and the results are discussed in the section entitled Modification of Matrix I Alloys.

Heat treating studies were performed to further stabilize the mechanical properties of Alloy II-4. Tensile specimens were heat treated at a variety of temperatures to determine the optimum solution heating and aging conditions. Figure 46 shows that the strength of the as-rolled material falls off drastically with a low temperature anneal (210°F) but increases with increasing temperature until 600°F is reached. The ductility, on the other hand, continues to decrease with increasing temperature. Above 600°F, the ductile β phase agglomerated, the matrix recrystallized, and considerable grain growth occurred. In view of these results, a solution heat treating temperature of 600°F was considered to be optimum and the time at this temperature was obtained by the survey summarized in Figure 47. Again a maximum in the tensile strength of the alloy occurred, but the elongation dropped continuously with time. A compromise was made between strength and ductility and a time of one hour at 600°F was chosen as the optimum solution heat treatment; the aging time at 200°F following the heat treatment at 600°F was then varied as shown in Figure 48. This group of alloys started with an ultimate strength of 47,300 psi, a yield strength of 43,700 psi and an elongation of 5%. Aging for one hour at 200°F reduced the tensile strength to 40,800 psi, the yield strength to 37,400 psi, and increased the elongation to 22%. Upon testing in tension at cryogenic temperatures, the ductility of the II-4 alloy decreased to 3% in the as-rolled condition. Optimizing the heat treatment and carefully controlling the wrought structure caused the elongation to improve to 7.8% at -320°F or about one-half the desired ductility.

Tensile specimens of alloy II-4 were cut and joined by a butt-type weld but oxides were formed at the start and end of each weld. Flat sheet specimens were similarly welded and then machined into tensile specimens with the welded joint location at the center of the gage area. These specimens appeared good from a macroscopic examination, but low ductility (about 2%) and low tensile strength values were obtained (32,400 to 39,600 psi) during subsequent tensile testing. Microstructural examinations revealed that the poor weld efficiency was not caused by the crystallographic structure of the weld but by small oxide entrapment in the weld zone. This oxide entrapment resulted from using insufficient argon cover gas during the welding operation. A vacuum dry box was modified to develop procedures for inert gas welding of the magnesium alloys. Ultimately the alloys will be welded successfully without using the dry box.

In order to study the separate effects of the minor strengthening elements Cd and Th the cadmium content of alloy II-4 was varied from 0% to 5% and the thorium content was varied from $1\frac{1}{2}$ to 3%. All of these alloys showed an increase in strength and a decrease in ductility at cryogenic temperatures. The 0Cd-3Th alloy was heat treated to obtain an elongation of 42.2% at 68°F, but the ductility decreased to 3.5% at -320°F. The 0Cd-$1\frac{1}{2}$Th alloy showed the most promise for cryogenic applications. The elongation of this alloy at 68°F was a moderate 17 to 18%, but at -320°F and -452°F the elongation was 8.5% and 7.0% respectively. The tensile and yield strength at -452°F was 50,000 psi and 45,300 psi respectively.

The as-cast structure of Alloy II-4 modified with 1.5% Th and 0% Cd is shown in Figure 25. Note the precipitation of fine particles in the white β phase. These particles remained in the elongated β phase after hot working, as shown in Figure 49 when the total time of preheating and reheating between passes was fifty minutes. When the total time at temperature (720°F) during hot working was 140 minutes, the precipitate in the β phase completely dissolved and all evidence of coring was also eliminated as shown in Figure 50. The ambient temperature tensile strength of the former specimen was 39,800 psi with an elongation of 17.3%. Dissolving the precipitate in the β phase with a longer heating time lowered the strength to 31,500 psi without significantly increasing the ductility, indicating that the amount and distribution of the β phase had a more predominant effect on ductility than the actual composition within the β phase. Note too, that the precipitates dissolved slowly at 720°F, a most essential characteristic of a stable alloy.

The distribution of the β phase in the as-cast structure of the 1.5% Th-5% Cd alloy, shown in Figure 24, is similar to the structure of the regular II-4 alloy, Figure 19, but the amount of precipitate in the matrix has been greatly reduced. The as-hot worked structure of the alloy, Figure 51, shows more of the finer β phase than the original II-4 alloy that was hot

worked at 720°F, Figure 45, but has a coarser structure than the II-4 alloy that exhibited 40.6% elongation (Figure 40). The elongation of the 1½% Th-5% Cd modified alloy was 5.5% in the as-rolled condition and 27% after heat treatment. At -320°F the elongation dropped to only 5% indicating that cadmium is detrimental to the low temperature ductility of the alloy.

The as-cast structure of the 2.5% Th-5% Cd alloy is shown in Figure 28. Unfortunately, no tests could be made on this alloy because the casting cracked during hot rolling at 600°F. On the premise that cracking was caused by the experimental procedure rather than by the composition of the alloy, this alloy should not be eliminated from further consideration in future research.

The as-cast structure of the 3% Th-0% Cd alloy is shown in Figure 26. This composition exhibits a typical dispersion of β phase with a large amount of particle precipitate in the matrix. This precipitate completely dissolved in 70 minutes at a hot working temperature of 720°F, as shown in Figure 52. The hot worked structure of this alloy exhibits a high degree of preferred orientation with very little of the randomly dispersed small needle-like phase. This alloy had only moderate strength and ductility in the wrought condition, but it could be heat treated to obtain an elongation of 42.2% at 68°F while the strength remained essentially the same. At cryogenic temperatures, the elongation was a low 3.5% proving that elimination of the cadmium does not, per se, improve the low temperature ductility. Further, the wrought structure of this alloy indicates that its properties are highly directional.

The as-cast structure of the 3% Th-2.5% Cd alloy is shown in Figure 27 and the wrought structure is shown in Figure 53. A great deal of the β phase redissolved during hot working, which consisted of sixty minutes of preheating at 720°F and a total of thirty minutes (at five minute intervals) between passes. The tip of the needles dissolved first, leaving the β phase with a shorter and more ellipsoidal appearance. The total amount of β also appears to be less, indicating that the terminal solid solubility of lithium is a function of temperature, contrary to the most recently published binary magnesium-lithium phase diagram. As expected from the appearance of the wrought microstructure, the low temperature ductility of this alloy was found to be only 4.5% at -320°F.

The rest of the alloys in Matrix II did not warrant an extensive development effort. Alloy II-1 had adequate ductility but the strength was low. The properties of this alloy were similar to the well known commercial alloy HK31. Since all of the Matrix II alloys contained 1% Zr and 3% Th, it must be concluded that small additions of Zn, Ag, Cd and Li do not significantly affect the properties of the basic alloy. Increasing the lithuim content

to 7% and the silver and cadmium contents to 4% and 10% respectively, while keeping the zinc at 2% (Alloy II-2), did not increase the strength but lowered the ductility to 17.5% at 68°F. These results signify that silver and cadmium are not efficient strengthening elements.

Increasing the zinc content from 2% to 6% (Alloy II-4 and II-5) increased the strength more than 60% to 42,000 psi. The ambient temperature ductility of Alloy II-4 (containing 7% Li) remained high, but the ductility of Alloy II-5 (containing 12% Li) was only 2% because of the formation of brittle lithium-zinc compounds in the grain boundaries (See Figure 20). Increasing the lithium content from 7%, which produced a two phase $\alpha + \beta$ structure, to 12% and an all bcc β structure did not increase the ductility as expected. Significantly the difference in the silver and cadmium contents of Alloy II-4 and II-5 did not distinguishably affect their strength. None of the original Matrix II alloys completely achieved the property goals of the program at cryogenic temperatures. Eliminating cadmium and reducing the thorium content of Alloy II-4 improved the ductility and careful control of the β phase in the wrought structure increased the ductility still further; however, low temperature brittleness was still evident. The results obtained from testing the Matrix II alloys indicated that the optimum lithium content lies between 7% and 12% and that the amount and orientation of the ductile β phase must be carefully controlled to minimize ensuing fracture cracks.

Modification of Matrix I Alloys

Since none of the original Matrix I alloys were ductile, seven extra-curricular modifications were made. These alloys were designated as Matrix IA alloys and all contained 9% lithium and, similar to the original Matrix II alloys, contained 3% Th and 1% of a grain refiner. Silicon was added to Alloys IA1 through IA5 and zirconium was added to alloys IA6 and IA8. Neither of these nucleant grain refiners proved effective for these high lithium alloys regardless of the aluminum content as shown in Figures 52 through 56. Hexachlorobenzene grain refining may have been effective but time did not permit an evaluation of this compound during the present program.

Manganese was added to the melt in the form of a dusting flux, but was evidently not effective as a solid solution strengthener because of the moderate ultimate tensile strengths obtained for the whole series of alloys. The results indicate that the effect of manganese should be studied with manganese additions made in the form of a master alloy hardener.

The entire alloy system of Matrix IA was characterized by excellent ductility even at cryogenic temperatures. For example, one specimen of Alloy IA8 showed 14% elongation at -320°F with a tensile strength of 41,300 psi. These specimens exhibited local necking which, in many cases, occurred outside the two-inch gage markings, but within the necked down area of the specimen; as a result, a wide scatter of the reported ductility data

-13-

was obtained. If a $2\frac{1}{8}$" gage length was used, the elongation would have measured 18%. All elongation values in Table II are given as a percentage within two inches and therefore must be considered the low limit of the inherent ductility of the Matrix IA alloys.

Alloy IA4 showed an elongation of 45.3% when tested at 68°F in the as-rolled condition with only a moderate strength of 24,300 psi. Reducing the silver content to 1% and eliminating aluminum resulted in a slight decrease in strength with practically no loss in ambient temperature ductility as shown by the results of testing Alloy IA5. Heat treating this alloy raised the yield strength but did not affect the ultimate tensile strength or the elongation. At cryogenic temperatures, the tensile strength of this alloy was somewhat lower than the desired strength goal of 45,000 psi

The higher alloyed specimens of the 9% Li series, Alloy IA6 and IA8, showed an increase in strength over Alloy IA4 and IA5 as well as excellent ductility, but were surprisingly weaker than Alloy IA3 which contained a comparatively low alloying content. However, the sixty percent increase in strength for Alloy IA8 at -320°F coupled with its good ductility indicates that this alloy should be considered for further development.

The greatest improvement of this nominal composition probably can be achieved by modifying the melting and casting technique. These alloys were difficult to cast with the present mold design and dross was entrapped in the casting resulting in less than optimum properties. The castability of this type of alloy, however, can be increased by increasing the cross sectional area of the sump to provide a greater screening area, while maintaining a sprue area which will choke the liquid alloy during pouring. This is good magnesium melting practice because this way, air is not aspirated into the molten stream and the liquid alloy flows quietly into the mold cavity.

The wrought microstructures of Alloy IA6 and IA8 are shown in Figure 57 and 58 respectively. The photomicrostructures show that the alloys are almost totally β phase similar to the 12% lithium Alloys II-3, II-5 and II-7; however, these alloys are ductile whereas the latter alloys are extremely brittle. The elimination of cadmium and the reduction of zinc was believed to be primarily responsible for this improvement.

Electron Microscopy

Electron photomicrographs of a heat treated II-4 alloy were obtained. Five electron micrographs are shown in Figure 59. The dark area in the picture is β (bcc) and the large white area is the α matrix. A spherical precipitate can be seen in the β phase which evidently does not embrittle the alloy because this specimen had good ductility (18.3%) at ambient temperature.

-14-

C. STATEMENT OF MAN HOURS EXPENDED

A total of 4100 man hours was expended during the course of the program.

D. ANTICIPATED WORK FOR THE PERIOD FROM JUNE 19, 1965 THROUGH MARCH 20, 1966

The program will continue with primary emphasis placed upon improving the strength and ductility of magnesium alloys at cryogenic temperatures through alloying and hot working techniques. The weldability of the alloys will be improved by devising methods for full protection of the molten metal from oxidation during welding and fifty pound ingots of the most promising alloys will be cast and rolled into sheet for final testing and evaluation. Part of the evaluation program will include applying existing coatings to the alloys and determining the susceptibility of the composite coating and magnesium alloy to corrosion.

TABLE II

SUMMARY OF MECHANICAL PROPERTY DATA

Alloy	U.T. psi	Y.S. 0.2% Offset psi	El. % in 2"	Hardness Re	Testing Temp. °F	S.H.T. °F	Aging Time Mins.	Aging Temp. °F	Remarks
II 1	26,400	10,000	22	78	68	-	-	-	As Rolled
II 1	25,200	16,600	12	70	68	-	-	-	As Rolled
II 2	27,770	10,900	17.5	83	68	-	-	-	As Rolled
II 4	46,560	29,470	-	83	68	-	-	-	As Rolled
II 4	45,450	28,000	10 ·	83	68	-	-	-	As Rolled
II 4	42,770	27,000	11	83	68	-	-	-	As Rolled
II 4	51,050	44,890	16	95	68	-	-	-	As Rolled (Improved Screening During Casting)
II 4	40,000	33,333	40.6	90	68	-	-	-	As Rolled (Improved Screening During Casting)
II 4	46,870	40,000	15.8	91	68	-	-	-	As Rolled (Improved Screening During Casting)
II 4	41,000	39,900	11.4	88	68	-	-	-	As Rolled (Improved Screening During Casting)
II 4	40,000	33,120	19	86	68	-	-	-	As Rolled (Improved Screening During Casting)
II 4	48,600	47,500	12	89	68	-	-	-	As Rolled (Improved Screening During Casting)
II 4	49,500	48,000	11	93	68	-	-	-	As Rolled (Improved Screening During Casting)
II 4	49,900	37,300	1.0	92	-320	-	-	-	As Rolled (Average of Two Specimens: Improved Screening During Casting)
II 4	54,800	44,500	4.5	94	-320	-	-	-	As Rolled (Improved Screening During Casting)
II 4	55,000	50,600	3	92	-320	-	-	-	As Rolled (Improved Screening During Casting)
II 4	53,700	43,200	4	85	-320	-	-	-	As Rolled
II 4	37,190	-	13.3	84	68	-	-	-	Rolled-SHT 1 hr. at 210°F
II 4	38,000	30,500	10.5	84	68	-	-	-	Rolled-SHT 1 hr. at 210°F
II 4	41,600	-	5.0	89	68	-	-	-	Rolled-SHT 1 hr. at 410°F
II 4	45,400	-	4.0	94	68	-	-	-	Rolled-SHT 1 hr. at 500°F
II 4	47,300	43,700	5	96	68	-	-	-	Rolled-SHT 1 hr. at 600°F
II 4	44,100	41,000	6.3	-	68	-	-	-	Rolled-SHT 1 hr. at 600°F, Aged 15 mins. at 200°F
II 4	42,770	-	4.3	-	68	-	-	-	Rolled-SHT 1 hr. at 600°F, Aged 30 mins. at 200°F
II 4	41,210	38,000	18.3	-	68	-	-	-	Rolled-SHT 1 hr. at 600°F, Aged 45 mins. at 200°F
II 4	38,120	29,000	6.25	80	68	-	-	-	Rolled-SHT 2½ hrs. at 600°F, Aged 60 mins. at 200°F
II 4	36,510	33,700	26	88	68	-	-	-	Rolled-SHT ½ hr. at 600°F, Aged 60 mins. at 200°F
II 4	36,050	33,600	28.1	87	68	-	-	-	Rolled-SHT ½ hr. at 600°F, Aged 60 mins. at 200°F
II 4	44,790	39,600	9.4	-	68	600	60	200	
II 4	39,300	33,400	14.9	-	68	600	120	200	
II 4	43,000	42,500	3	102	68	700	-	-	As Quenched
II 4	41,200	40,200	3	99	68	700	-	-	As Quenched
II 4	44,000	-	1.1	98	68	800	-	-	As Quenched
II 4	37,900	37,900	0	80	68	700	180	300	
II 4	36,800	36,800	0	82	68	600	60	200	Notched
II 4	39,800	39,800	0	91	68	600	60	200	Notched
II 4	36,500	36,500	0	90	68	600	60	200	Notched
II 4	38,900	38,900	0	84	68	600	60	200	Notched
II 4	40,000	40,000	0	79	68	600	60	200	Notched
II 4	32,400	32,400	0	92	68	600	60	200	Welded
II 4	36,600	35,000	1.3	92	68	600	60	200	Welded
II 4	39,600	39,600	1.7	91	68	600	60	200	Welded
II 4	46,500	43,300	9.3	89	68	650	60	200	Hot Worked at 600°F
II 4	45,100	39,100	10.0	83	68	600	90	200	Hot Worked at 600°F
II 4	48,600	37,200	3.5	88	68	600	75	200	Hot Worked at 600°F
II 4	58,400	46,800	3.0	91	-320	650	60	200	Hot Worked at 600°F
II 4	52,500	44,000	7.8	86	-320	650	60	200	Hot Worked at 720°F
II 4	52,500	42,000	6.5	85	-320	650	60	200	Hot Worked at 720°F
II 4	51,900	41,500	6.4	85	-320	650	60	200	Hot Worked at 720°F

TABLE II
(Continued)
SUMMARY OF MECHANICAL PROPERTY DATA

Alloy	U.T. psi	Y.S. 0.2% Offset psi	El. % in 2"	Hardness Re	Testing Temp. °F	S.H.T. °F	Aging Time Mins.	Aging Temp. °F	Remarks
1A1	25,100	24,000	28.4	64	68	-	-	-	As Rolled, Coarse Grained
1A1	25,100	24,000	-	67	68	-	-	-	Unable to obtain accurate elongation
1A1	25,000	24,000	27	66	68	-	-	-	As Rolled
1A1	26,260	25,100	30	69	68	-	-	-	As Rolled
1A3	38,200	33,600	11.8	76	68	850	180	200	Coarse Grained
1A3	37,700	33,200	13.3	71	68	650	30	200	Coarse Grained
1A3	36,800	32,400	11.5	80	68	650	180	200	Coarse Grained
1A3	37,700	33,800	13.3	79	68	650	30	200	Coarse Grained
1A3	36,800	31,600	11.5	80	68	650	180	200	Coarse Grained
1A3	33,333	30,000	22.5	78	68	-	-	-	As Rolled
1A3	38,500	33,500	4	74	68	-	-	-	As Rolled
1A3	45,000	37,000	5	-	-320	-	-	-	As Rolled
1A3	32,800	32,800	0.7	68	68	600	60	200	Notched (Dross in Gage Area)
1A3	33,000	33,000	0.5	66	68	600	60	200	Notched (Dross in Gage Area)
1A4	24,300	23,600	45.3	67	68	-	-	-	As Rolled
1A4	24,500	23,800	25.7	70	68	-	-	-	As Rolled
1A5	20,200	16,100	40	67	68	-	-	-	As Rolled
1A5	20,200	16,200	30	68	68	-	-	-	As Rolled
1A5	20,200	16,000	40	69	68	-	-	-	
1A5	20,200	16,000	30	-	68	-	-	-	
1A5	20,900	18,400	40	-	68	850	30	200	Coarse Grained
1A5	20,200	17,800	30	-	68	850	30	200	Coarse Grained
1A5	30,000	20,300	8.8	65	-320	850	30	200	
1A5	31,000	19,300	10.5	68	-320	850	30	200	
1A5	31,600	20,300	11.5	65	-320	850	30	200	
1A5	41,380	32,000	11.2	66	-320	-	-	-	As Rolled-local necking-dross
1A5	32,151	25,000	14	67	-320	-	-	-	As Rolled-local necking-dross
1A5	47,100	38,600	13.5	66	-452	850	30	200	Coarse Grained
1A6	28,200	25,000	30.8	79	68	-	-	-	As Rolled, Coarse Grained
1A6	24,700	21,800	50	74	68	850	30	200	Coarse Grained
1A6	25,800	23,000	15	76	68	850	30	200	Coarse Grained
1A6	39,100	-	9.7	76	-320	850	30	200	Coarse Grained
1A6	40,000	28,000	9.2	75	-320	850	30	200	Coarse Grained
1A6	66,200	43,300	10	76	-452	850	30	200	
The Following Alloys are Alloy II 4 with Variations in the Cadmium and Thorium Content									
0Cd-3 Th	37,800	34,000	20.7	84	68	-	-	-	As Rolled
0Cd-3 Th	34,500	30,200	42.2	80	68	650	60	200	
0Cd-3 Th	51,700	48,200	3.5	88	-320	650	60	200	
0Cd-3 Th	64,300	59,100	2.5	86	-452	650	60	200	
0Cd-1½Th	40,200	35,600	17	84	68	-	-	-	As Rolled
0Cd-1½Th	39,800	35,300	17.3	83	68	650	60	200	
0Cd-1½Th	31,500	27,900	18.4	82	68	650	60	200	
0Cd-1½Th	48,200	43,700	8.5	87	-320	650	60	200	
0Cd-1½Th	50,000	45,300	7	80	-452	650	60	200	
0Cd-1½Th	51,300	50,000	4.5	82	-320	650	60	200	
0Cd-1½Th	65,000	60,200	2.5	86	-452	650	60	200	
5Cd-1½Th	40,200	39,200	5.5	92	68	-	-	-	As Rolled
5Cd-1½Th	37,600	32,900	27	85	68	650	60	200	
5Cd-1½Th	48,300	44,100	5	85	-320	650	60	200	
II 5	42,500	40,000	1.3	76	68	-	-	-	As Rolled
II 5	48,800	45,900	2.25	-	-320	-	-	-	As Rolled
II 5	21,300	21,300	0	80	68	800	-	-	
II 10*	48,888	44,444	4	85	68	-	-	-	As Rolled
II 10	47,440	41,000	6	86	68	-	-	-	As Rolled
II 10	47,000	42,000	6.8	84	-320	-	-	-	As Rolled
II 10	42,500	41,000	2.7	83	68	-	-	-	As Rolled
II 10	38,500	38,000	2	84	68	-	-	-	As Rolled
II 10	39,500	39,000	2	83	68	-	-	-	As Rolled
II 10	38,000	36,600	2.5	85	68	-	-	-	As Rolled
II 10	40,800	39,400	2	86	68	-	-	-	As Rolled

*II 10: 75 Mg - 1 Zr - 6 Th - 5 Zn - 4 Cd - 5 Ag - 5 Li

TABLE II
(Continued)
SUMMARY OF MECHANICAL PROPERTY DATA

Alloy	U.T. psi	Y.S. 0.2% Offset psi	El. % in 2"	Hardness Re	Testing Temp. °F	S.H.T. °F	Aging Time Mins.	Aging Temp. °F	Remarks
II 11**	43,400	41,400	3.1	68	68	-	-	-	As Rolled, Coarse Grained
II 11	40,000	40,000	0.6	69	68	-	-	-	As Rolled, Coarse Grained
II 11	42,300	42,300	1.4	68	68	-	-	-	As Rolled, Coarse Grained
II 11	41,700	40,700	3	70	68	-	-	-	As Rolled, Coarse Grained
II 11	39,100	39,100	1.2	67	68	-	-	-	As Rolled, Coarse Grained
II 11	42,600	40,000	3.1	68	68	-	-	-	As Rolled, Coarse Grained
II 11	38,000	38,000	0	70	68	-	-	-	As Rolled, Coarse Grained
II 11	40,800	37,800	3	71	68	-	-	-	As Rolled, Coarse Grained
II 11	43,000	40,000	1.5	68	68	-	-	-	As Rolled, Coarse Grained
II 11	40,000	38,000	2.2	70	68	-	-	-	As Rolled, Coarse Grained
II 11	43,000	38,000	4.6	69	68	-	-	-	As Rolled, Coarse Grained
II 11	42,300	42,000	1.0	70	68	-	-	-	As Rolled, Coarse Grained
1A8	26,800	24,500	35.3	80	68	-	-	-	As Rolled, Coarse Grained
1A8	25,400	22,500	49	76	68	850	30	200	Coarse Grained
1A8	26,200	23,300	54.5	78	68	600	30	200	Coarse Grained
1A8	41,600	30,400	9.9	76	-320	850	30	200	Coarse Grained
1A8	44,900	34,600	8.2	74	-320	850	30	200	Coarse Grained
1A8	41,300	39,000	14.0	76	-320	850	30	200	Coarse Grained
1A8	42,000	31,100	8.5	74	-320	850	30	200	Coarse Grained
1A8	40,000	30,000	10.8	75	-320	850	30	200	Coarse Grained
1A8	51,500	43,000	5	74	-452	850	30	200	Notched

**II 11 : 66 Mg - 1 Si - 3 Th - 6 Zn - 10 Cd - 2 Ag - 12 Li

PHASE	TASK	1964 Jun	Jul	Aug	Sep	Oct	Nov	Dec	1965 Jan	Feb	Mar	Apr	May	Jun
I	Preparation of Equipment		▬											
I	Literature Search			▬	▬									
I	Preparation of One Pound Ingots						▬	▬						
I	Development of Metal Working Techniques				▬	▬	▬							
I	Heat Treating Studies				▬	▬	▬	▬						
I	Screening & Welding Tests						▬	▬	▬	▬				
II	Preparation of Pilot Lots Ingots						▬	▬	▬	▬				
II	Preparation of Testing Equipment						▬	▬						
II	Preparation of Test Specimens					▬	▬	▬						
II	Cryogenic Testing, Welding & Evaluation							➤	▬	▬	▬	▬	▬	▬
III	Recrystallization & Grain Growth							▬	▬	▬	▬	▬		
III	Heat Treatment - Metallography									▬	▬	▬	▬	
III	Weld Fabrication - Joint Efficiency											▬	▬	
III	Electron Microscopy & X-Ray Diffraction									▬	▬	▬	▬	

REPORTING

	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
MONTHLY			X	X	X	X	X	X	X	X	X	X	
QUARTERLY					X			X			X		
FINAL													X

CODE: ➤ CRYOGENIC LIQUID REQUIRED AT THIS TIME

Figure 1. Task Schedule

Figure 2   Melting Crucible and Top Showing Entrance Port for Adding
              Alloying Elements to the Melt

ESTIMATED MACHINING TIME 34 HOURS

AMERICAN MACHINE & FOUNDRY CO.
SIGHT LIGHT DIVISION
DEEP RIVER, CONNECTICUT

MATERIAL SPEC.

CAST IRON

TITLE
PERMANENT CASTING MOLD

WELD HINGE TO THIS END

OPTIONAL ADD AT A LATER DATE

OPTIONAL

WELD LATCH TO THIS END

Figure 3. Design of Permanent Casting Mold showing initial dimensions of the sprue and runner. A bottom ingate was added after trial castings. Note: The side tapers are exagerated in the drawing for illustration.

-21-

Figure 4. Opened View of Cast Iron Permanent Mold Showing An Enlarged Runner And The Final Ingate Design. The Side Gate Was Blocked Off For Most Of The Melts.

SECTION A'-A'
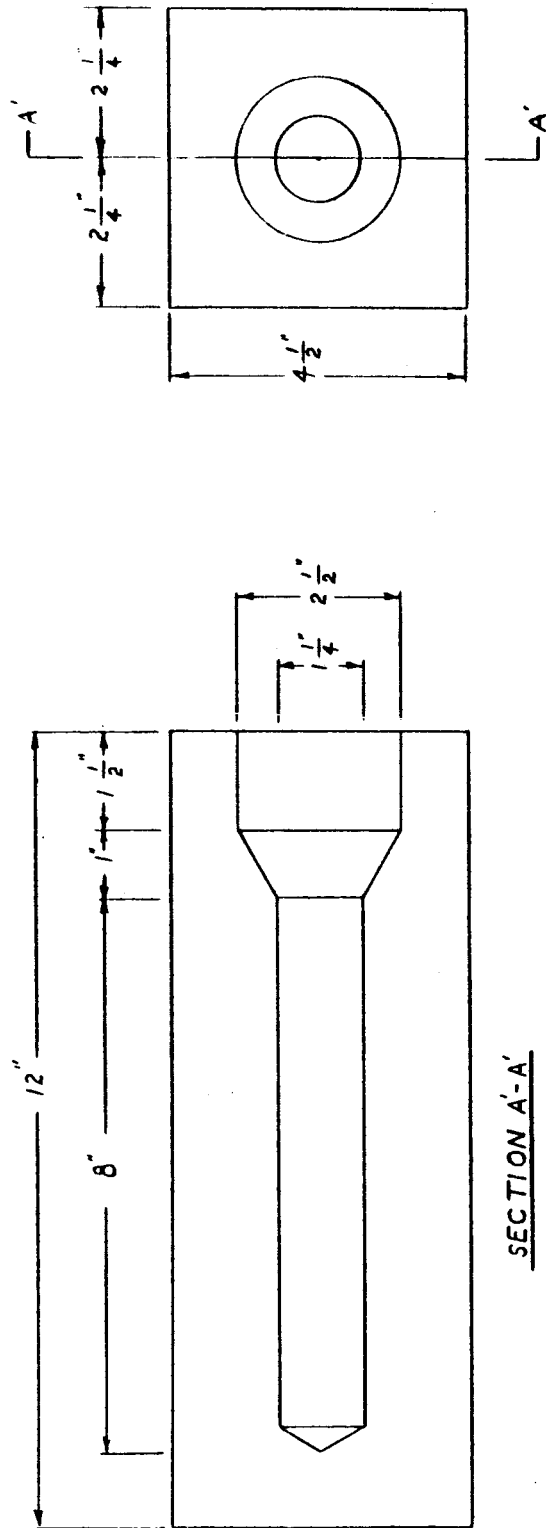
Figure 5. Fracture Mold – Used For Texture And
As Cast Grain Size Studies

Figure 6. Melting and Casting of Magnesium Alloys At the AMF Research Foundry. The Metal is being poured directly into the Sprue of a cast iron permanent mold. The Crucible is tightly sealed and purified argon protects the liquid metal from oxidation.
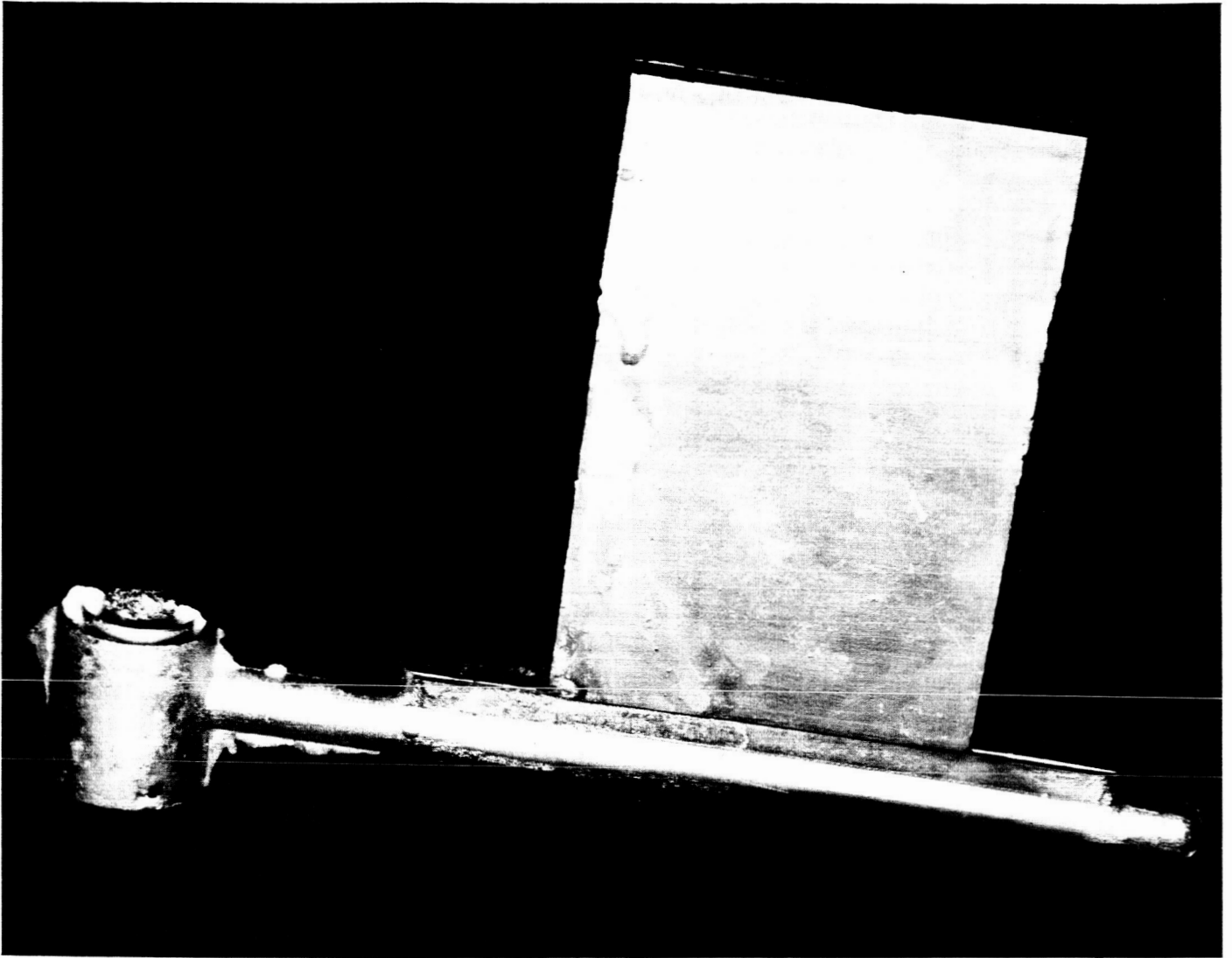
Figure 7.   Typical Permanent Mold Casting Showing The Gating, Runner, and Sump.
Note the excellent castability of this alloy as shown by the sharp edges
and absence of shrinkage in the ingot.

Alloy I-1, As Cast   250X
Figure 8

Alloy I-2, As Cast   250X
Figure 9

Alloy I-3, As Cast   250X
Figure 10
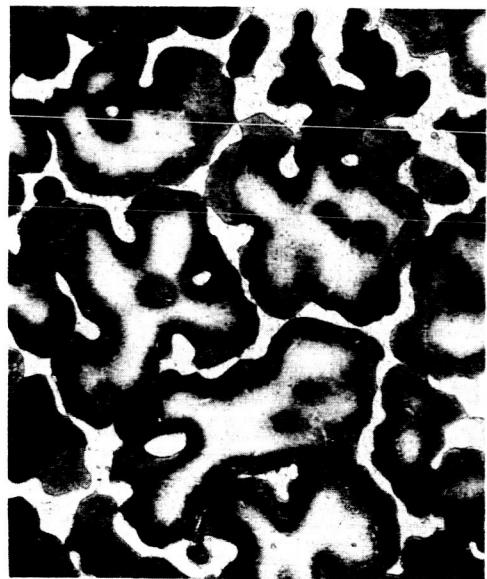
Alloy I-4, As Cast   250X
Figure 11

Alloy I-5, As Cast   250X
Figure 12
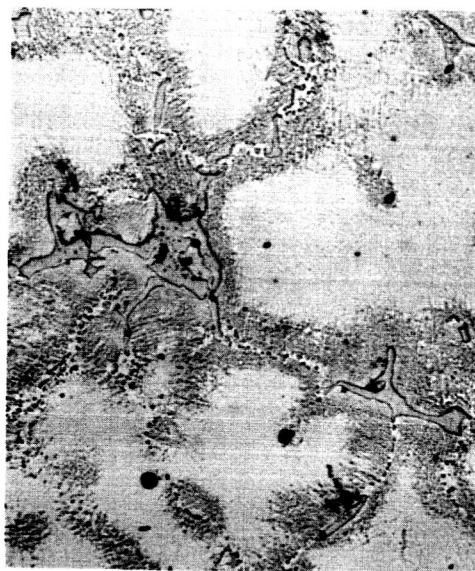
Alloy I-6, As Cast   250X
Figure 13

Alloy I-7, As Cast   250X
Figure 14
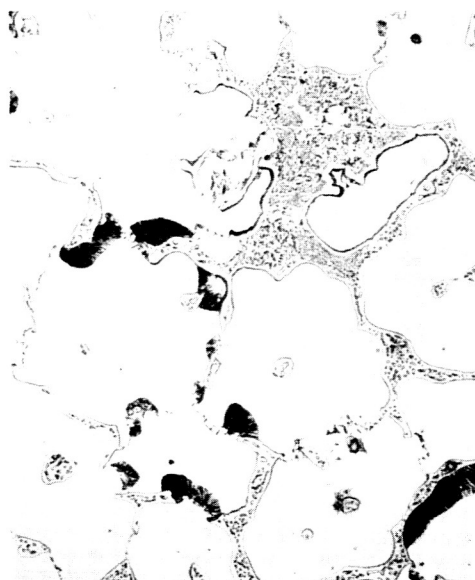
Alloy I-8, As Cast   250X
Figure 15
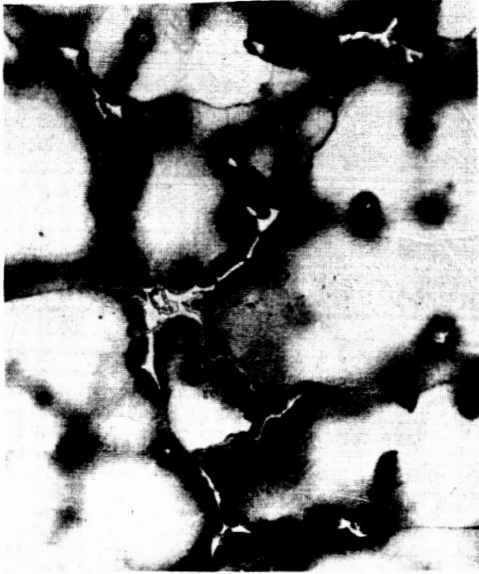
Alloy I-9, As Cast   250X
Figure 16
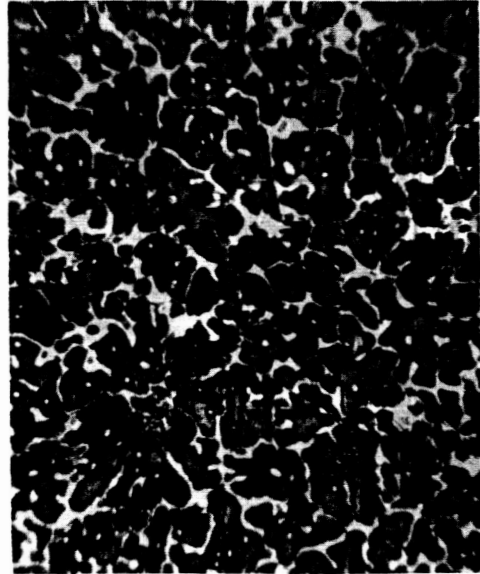
Alloy II-2, As Cast   100X
Figure 17
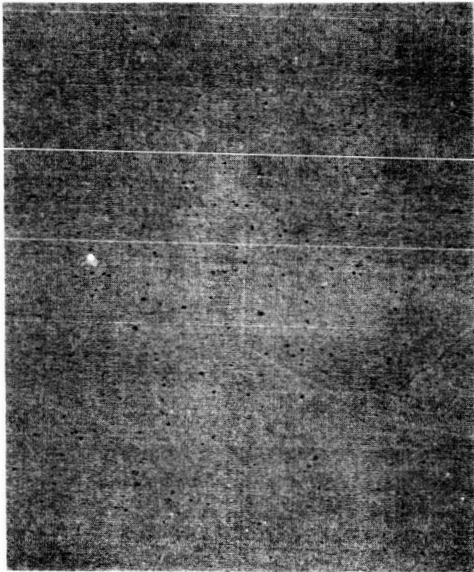
Alloy II-3, Solution Heat
Treated   100X
Figure 18
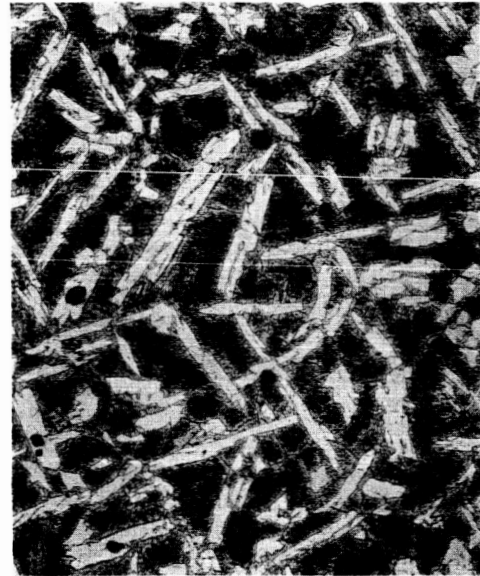
Alloy II-4, As Cast   75X

Figure 19
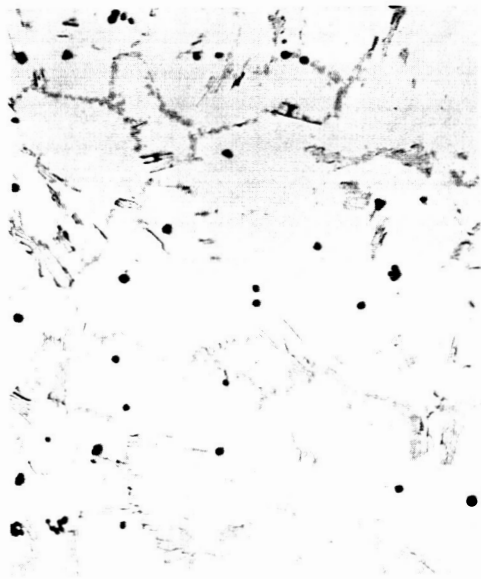
Alloy II-5, Solution Heat
Treated   100X
                Figure 20
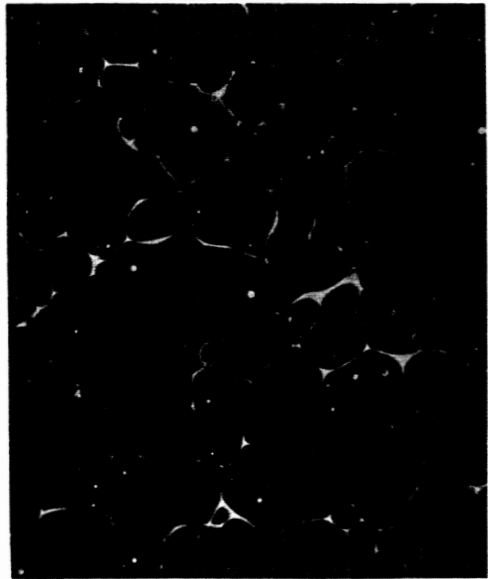
Alloy II-6, Solution Heat
Treated   100X
                Figure 21
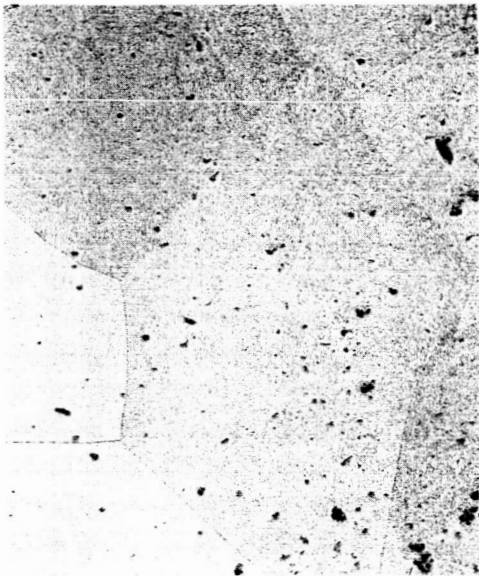
Alloy II-7, Solution Heat
Treated   100X
                Figure 22
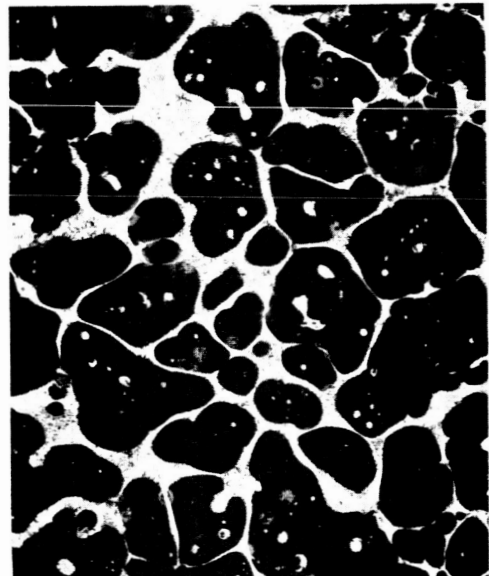
Alloy II-8, Solution Heat
Treated   100X
                Figure 23

29
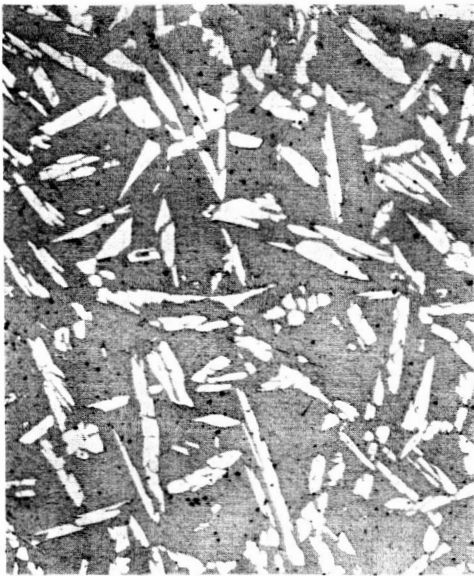
Alloy II-4, Modified, As
Cast, $1\frac{1}{2}$ Th, 5 Cd   75X
Figure 24
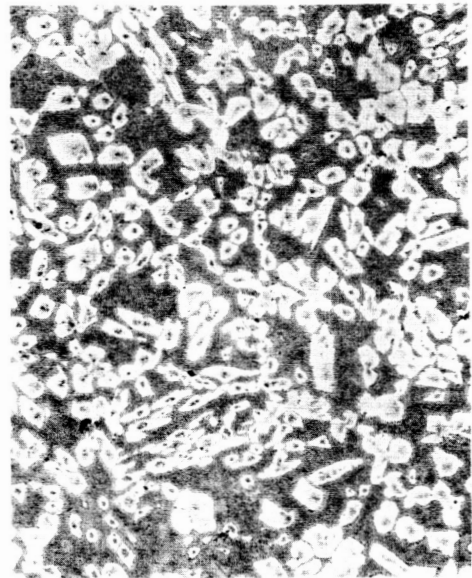
Alloy II-4, Modified, As
Cast, $1\frac{1}{2}$ Th, 0 Cd   75X
Figure 25

Alloy II-4, Modified, As
Cast, 3 Th, 0 Cd   75X
Figure 26
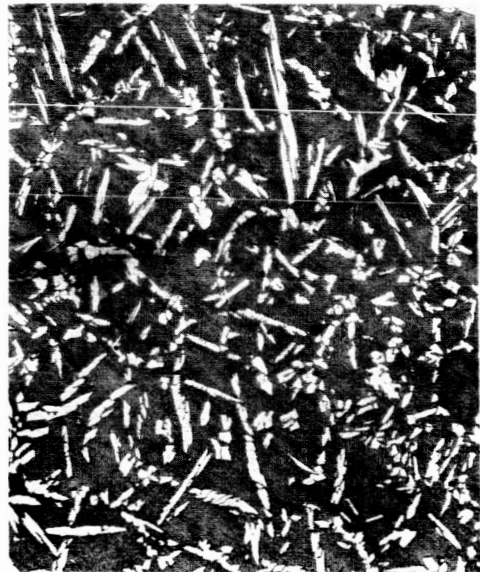
Alloy II-4, Modified, As
Cast, 3 Th, $2\frac{1}{2}$ Cd   75X
Figure 27

Alloy II-4, Modified, As
Cast, 2½ Th, 5 Cd   75X
Figure 28
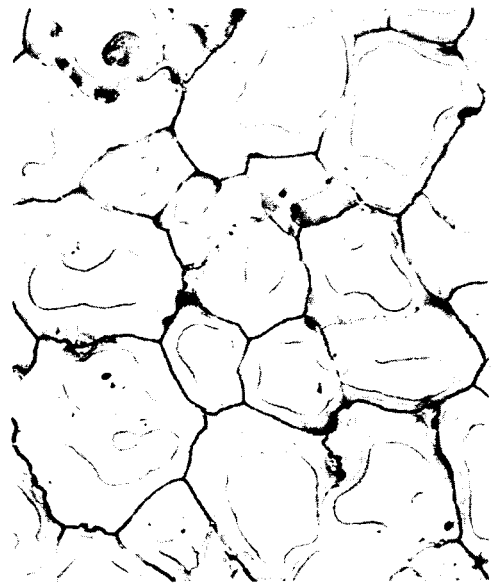
Alloy III-1, As Cast   250X

Figure 29
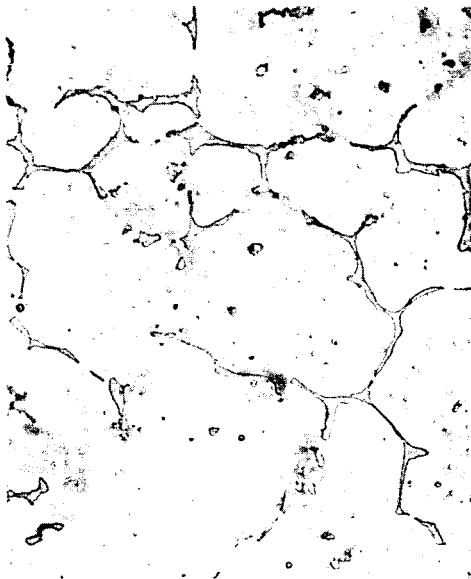
Alloy III-2, As Cast   250X
Figure 30
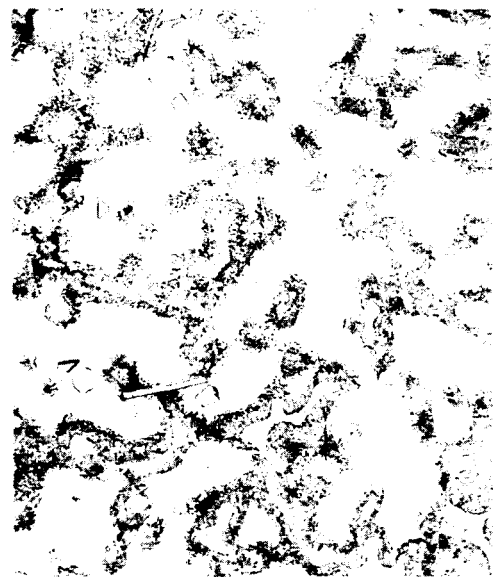
Alloy III-3, As Cast   100X
Figure 31
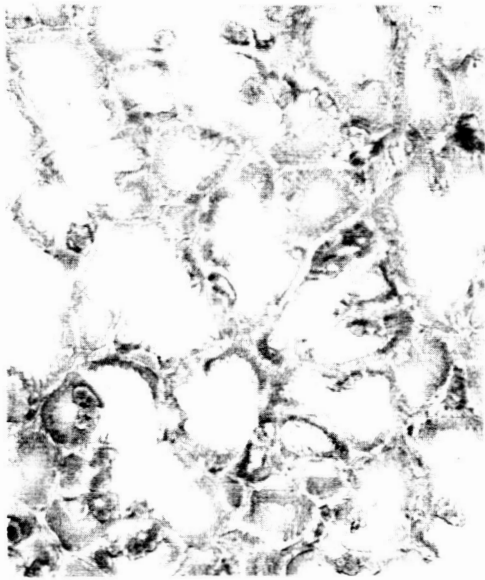
Alloy III-4, As Cast   250X
Figure 32
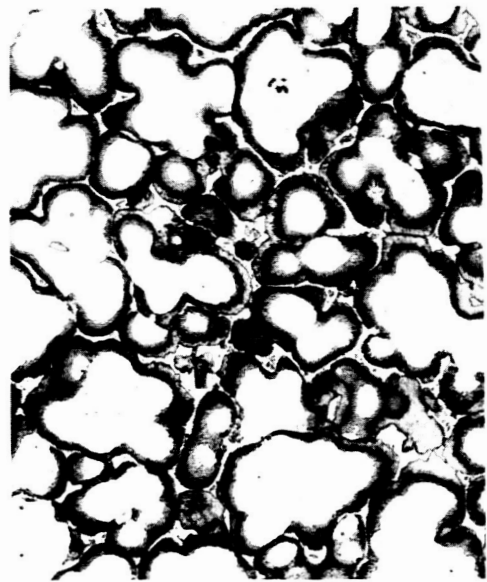
Alloy III-5, As Cast   250X
Figure 33
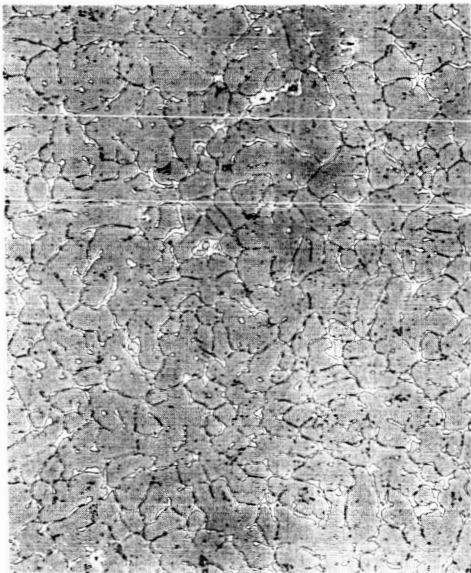
Alloy III-6, As Cast   100X
Figure 34

Alloy III-7, As Cast   250X
Figure 35
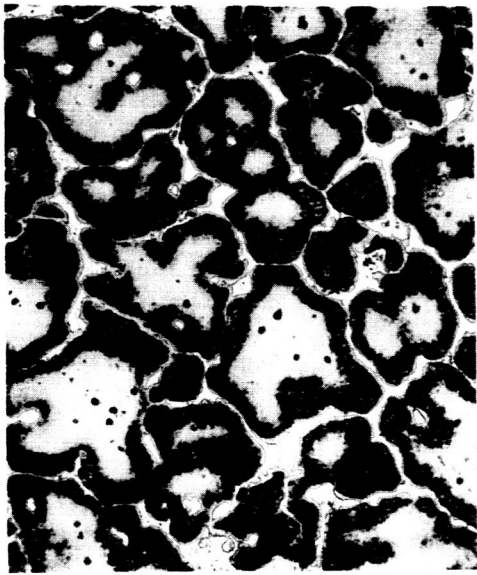
Alloy III-8, As Cast   250X
Figure 36
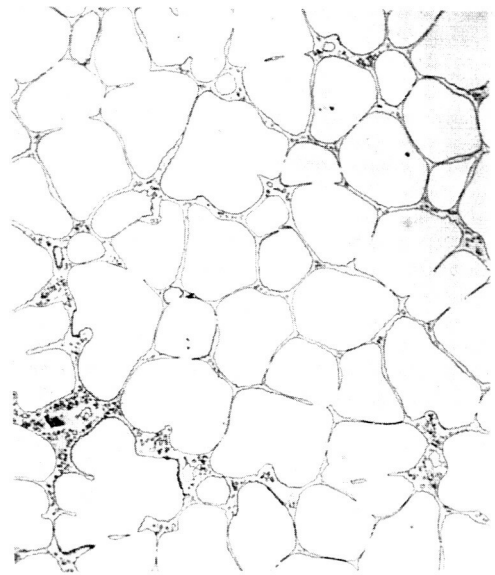
Alloy III-9, As Cast   250X
Figure 37
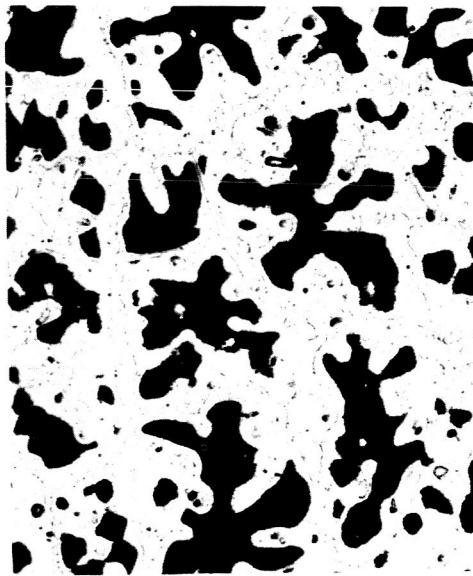
Alloy III-10, As Cast 250X
Figure 38
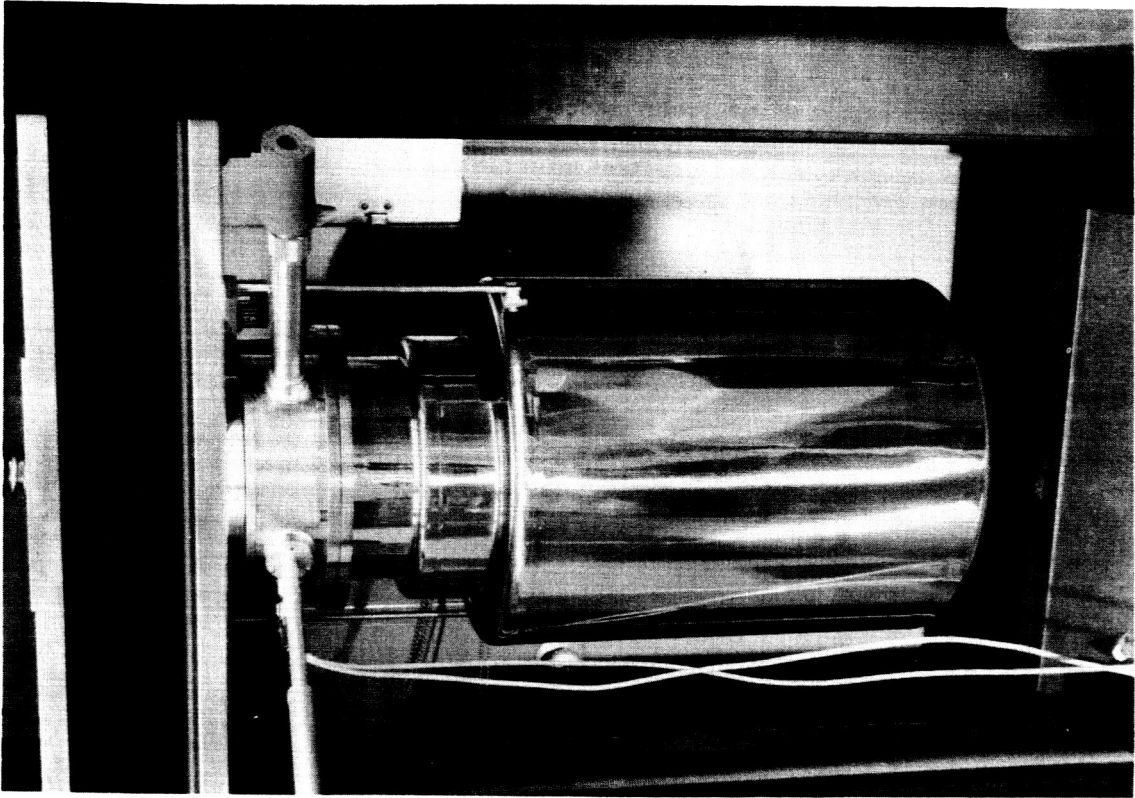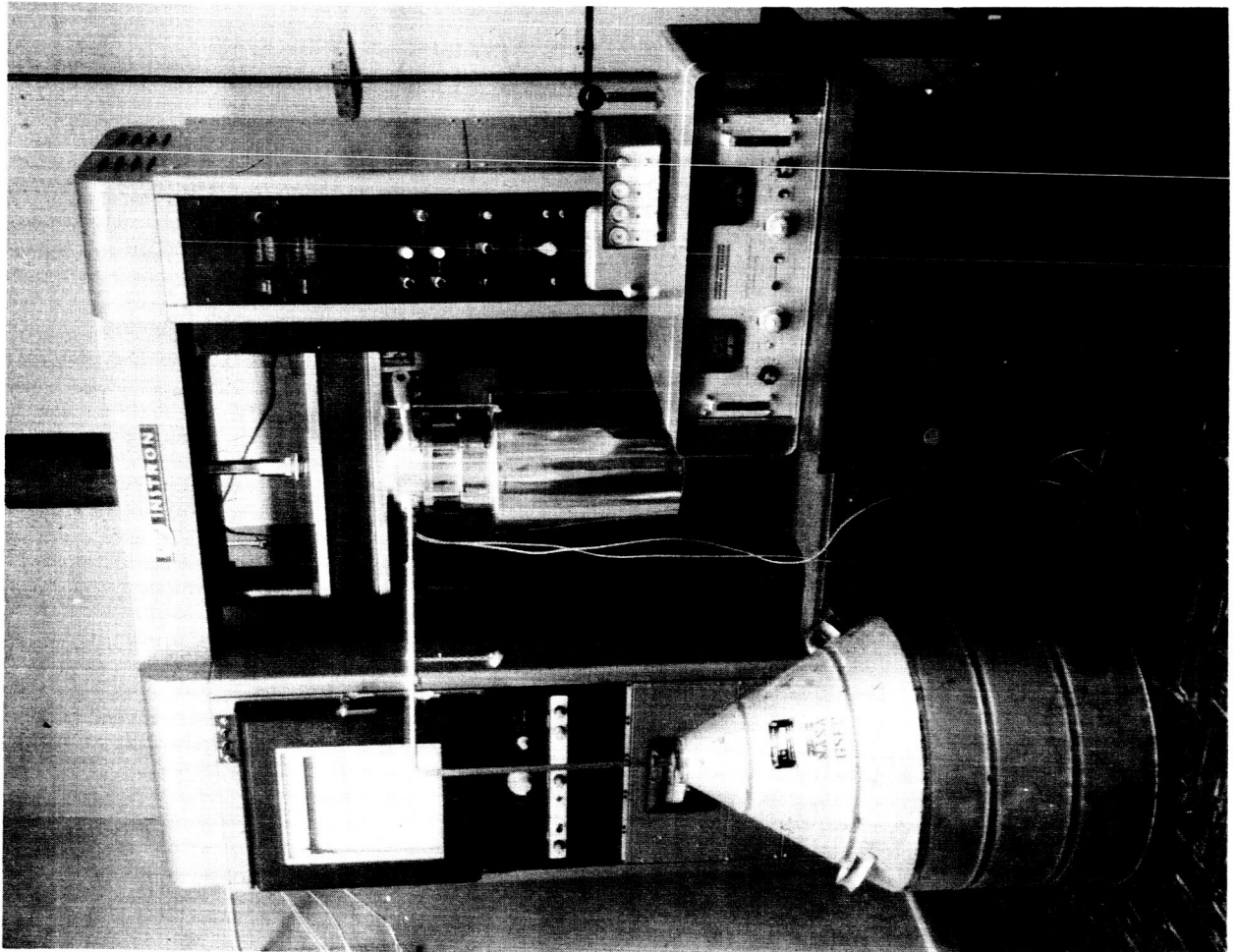
Figure 39   Cryogenic Research Co., Model TC-20000 Tensile Cryostat

34
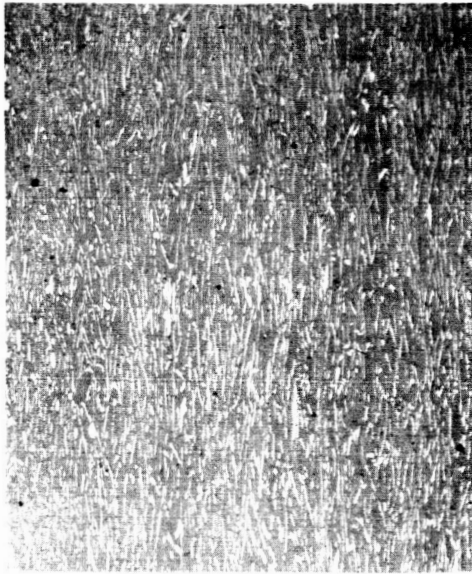
Alloy II-4, Photomicrograph,
Exhibited 40.6% Elongation
75X

Figure 40
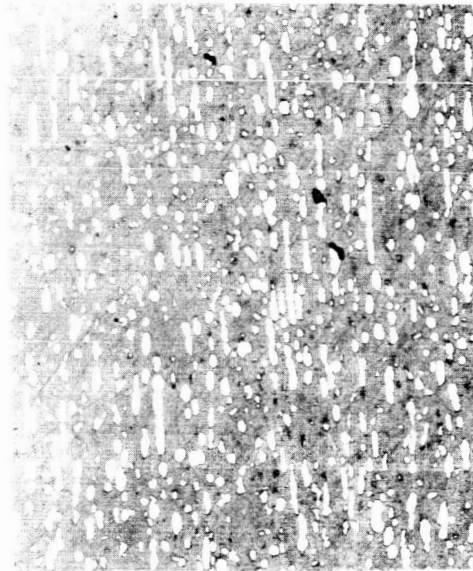
Alloy II-4, Photomicrograph,
Exhibited 26% Elongation
75X

Figure 41

35
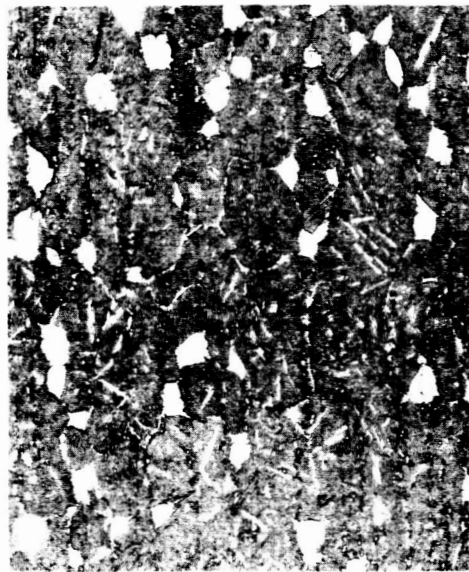
Alloy II-4, Photomicrograph,
Exhibited 16% Elongation
100X
Figure 42
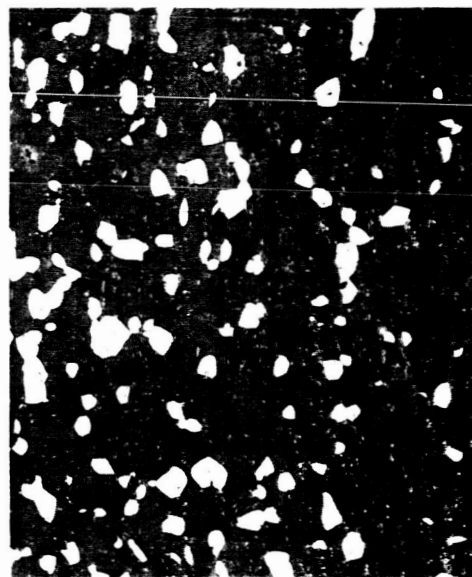
Alloy II-4, Photomicrograph,
Exhibited 3% Elongation
75X
Figure 43

Alloy II-4, Hot Worked at
600°F   75X
    Figure 44
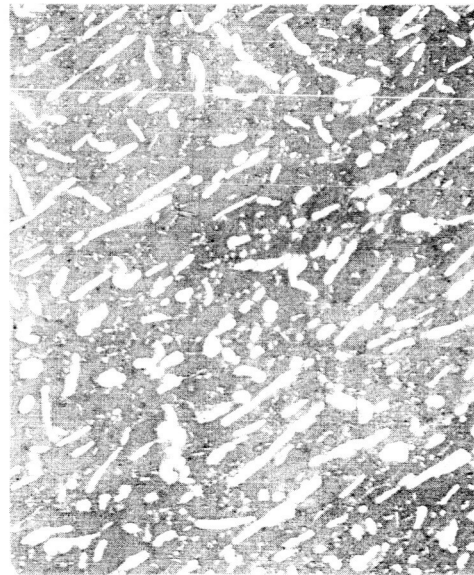
Alloy II-4, Hot Worked at
720°F   75X
    Figure 45

37
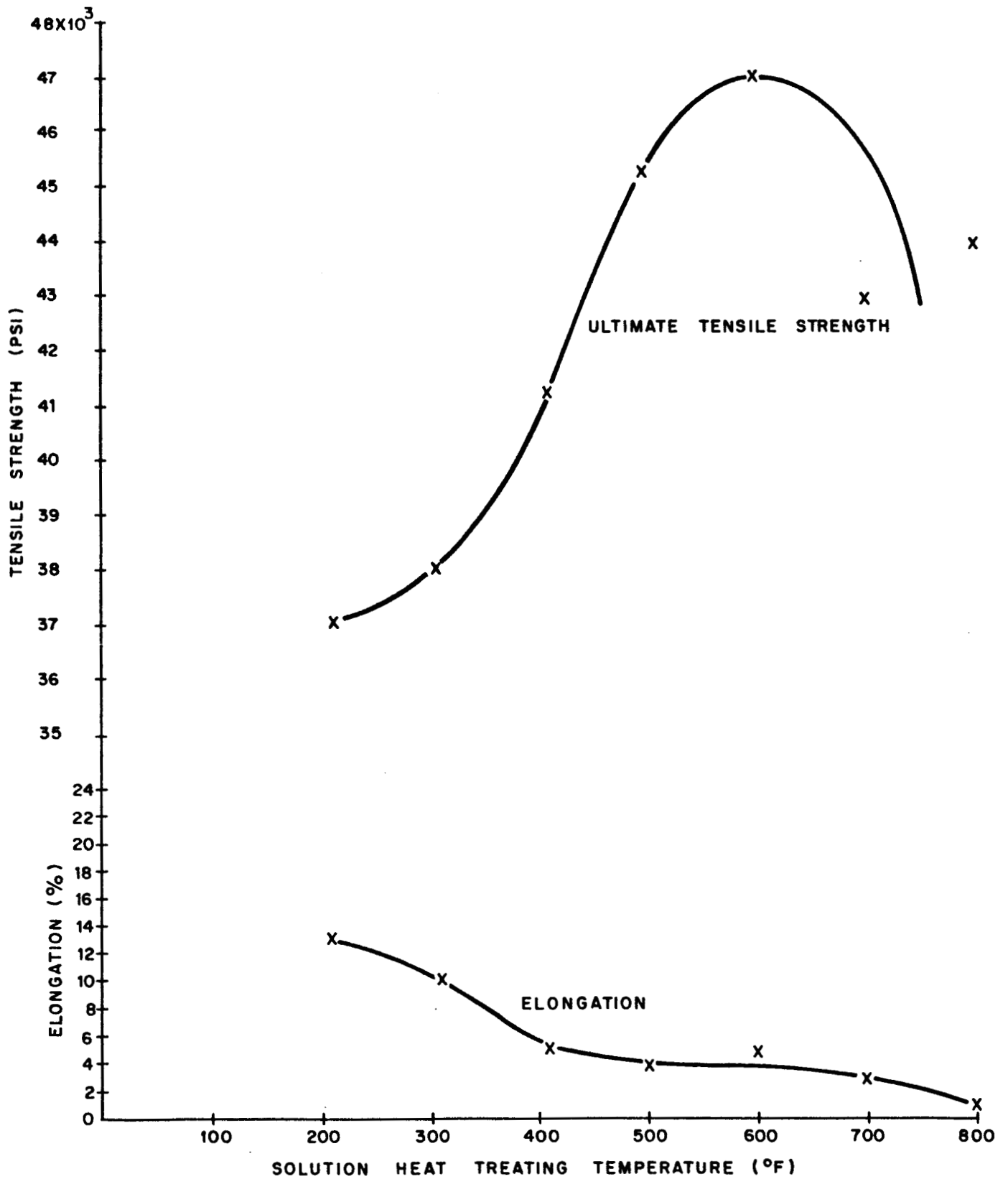
Figure 46. The effect of post hot working heat treatment (for one hour at various temperatures) on the strength and ductility of of Alloy II 4.
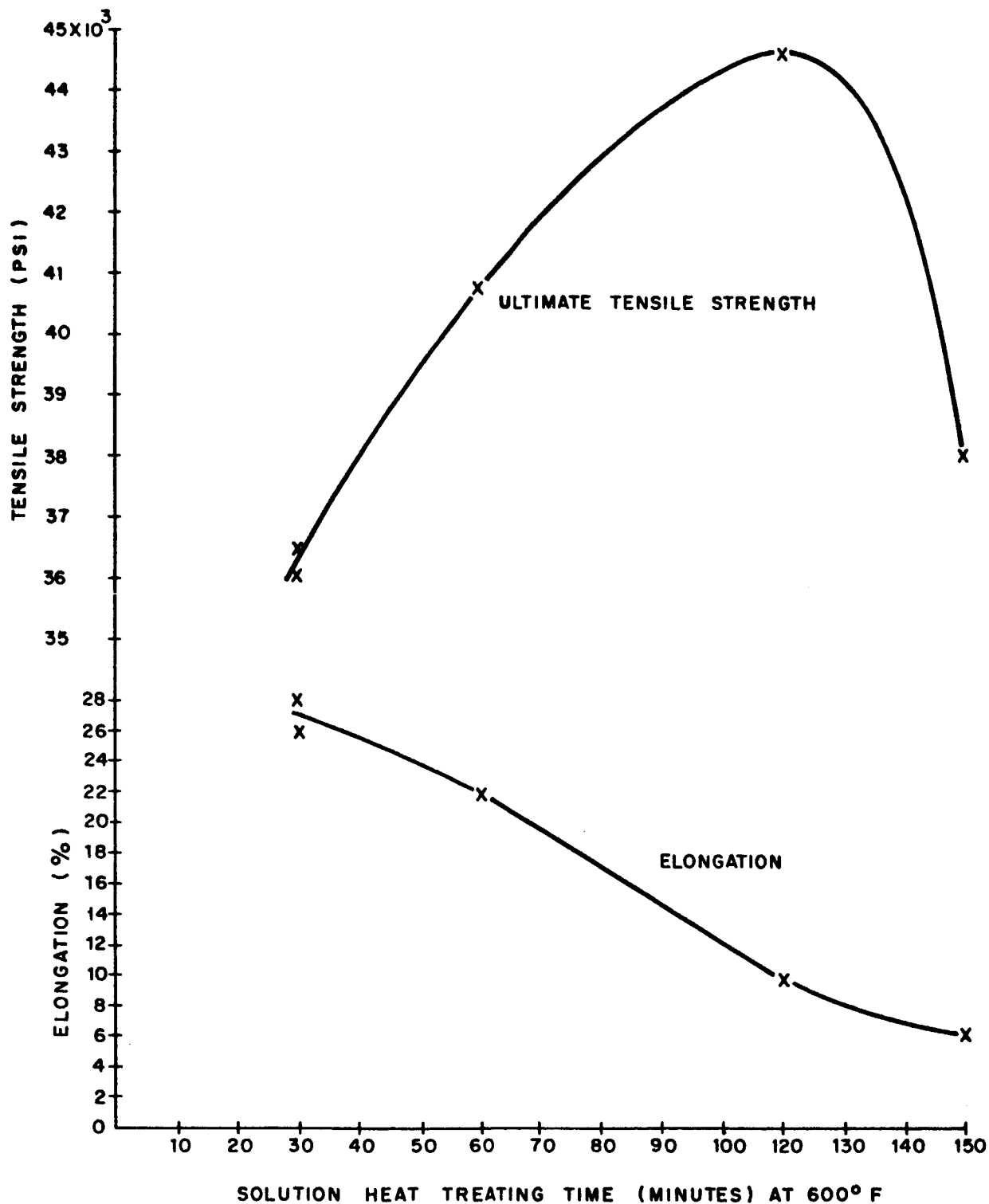
Figure 47. The effect of post hot working heat treating time at 600°F on the strength and ductility of Alloy II 4.
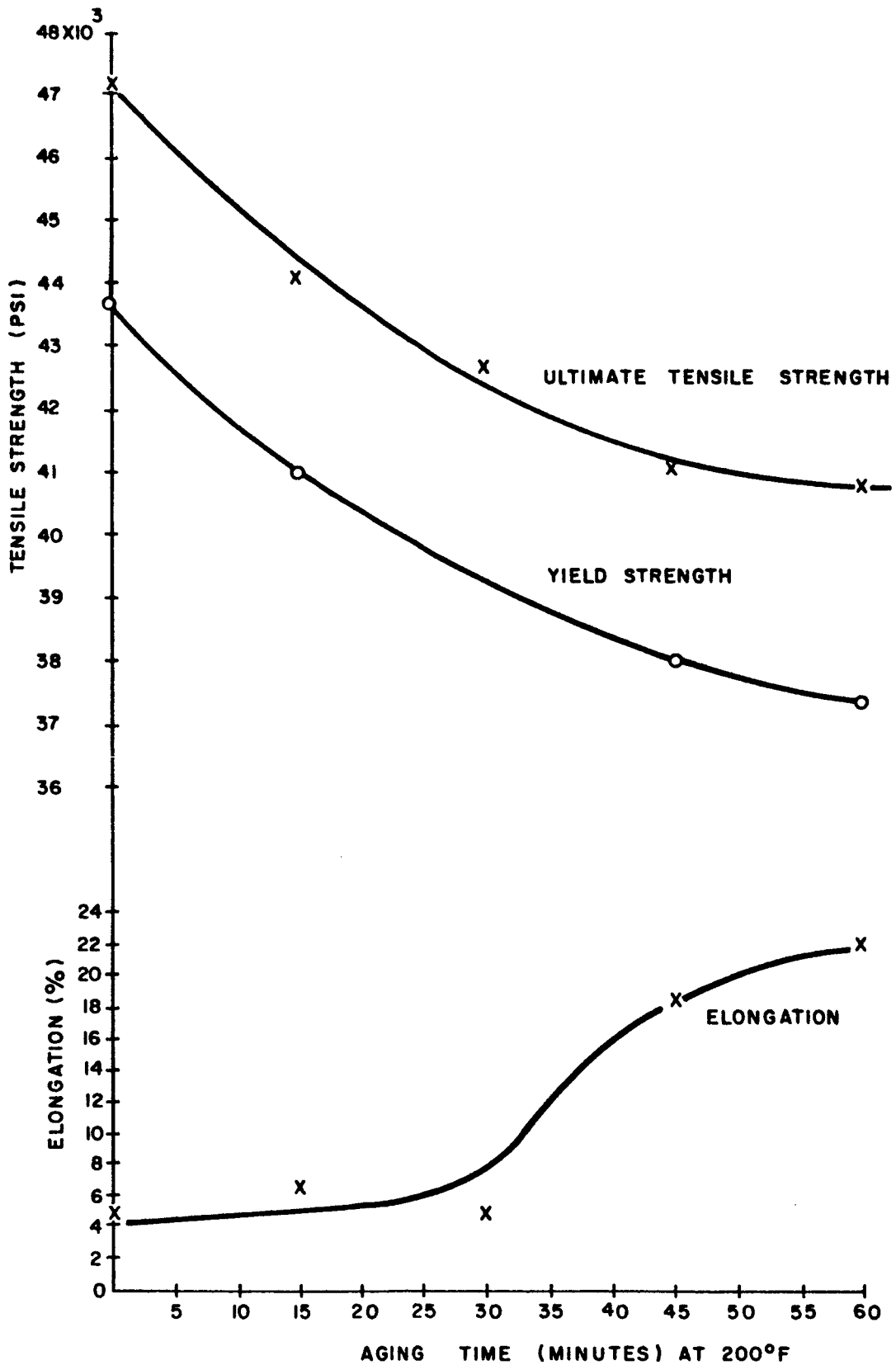
Figure 48. The effect of solution heat treating for 1 hours at
600°F and aging for various times at 200°F on the
strength and ductility of Alloy II 4.

Alloy II-4, Modified, As
Rolled, $1\frac{1}{2}$ Th, 0 Cd, 50
Minutes at Temperature
Tensile Strength 38,800 psi
Elongation 17.3%   75X
Figure 49
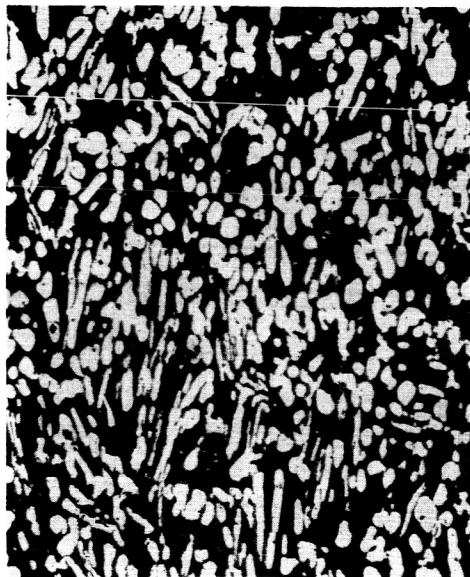
Alloy II-4, Modified, As
Rolled, $1\frac{1}{2}$ Th, 0 Cd, 140
Minutes at Temperature
Tensile Strength 31,500 psi
Elongation 18.4%   75X
Figure 50
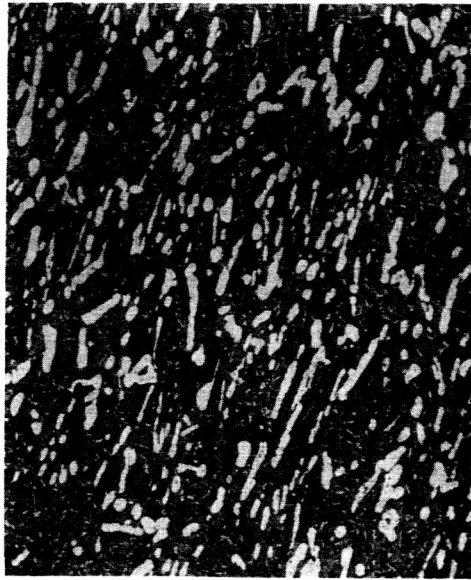
Alloy II-4, Modified, As
Rolled, $1\frac{1}{2}$ Th, 5 Cd   75X
Figure 51
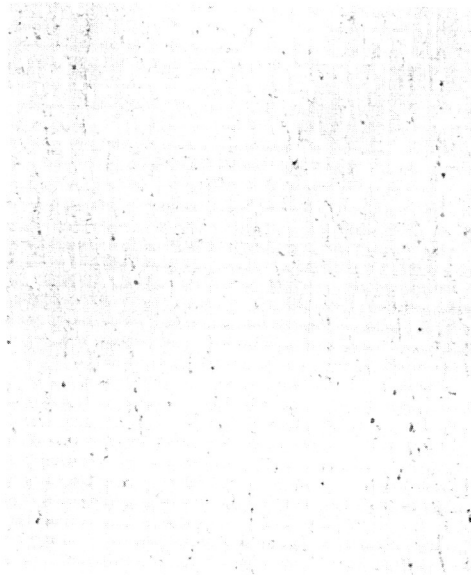
Alloy II-4, Modified, As
Rolled, 3 Th, 0 Cd   75X
Figure 52
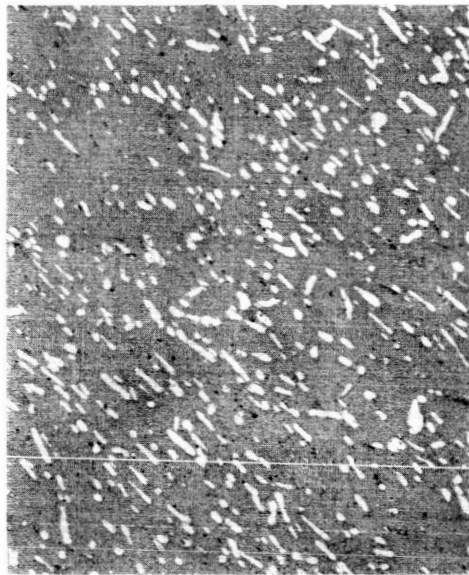
Alloy II-4, Modified, As
Rolled, 3 Th, $2\frac{1}{2}$ Cd   75X
Figure 53
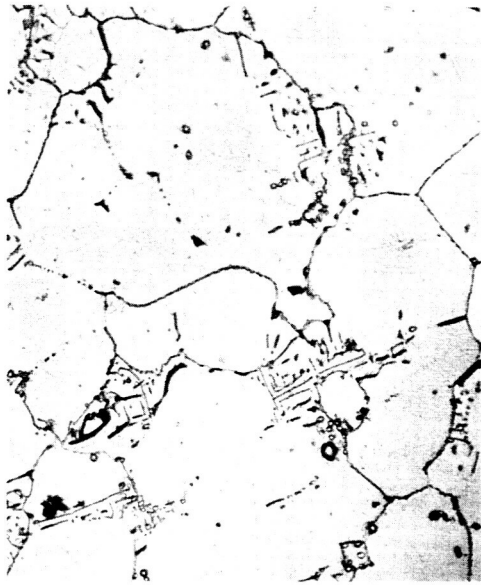
Alloy IA-5, As Cast   250X
Figure 54
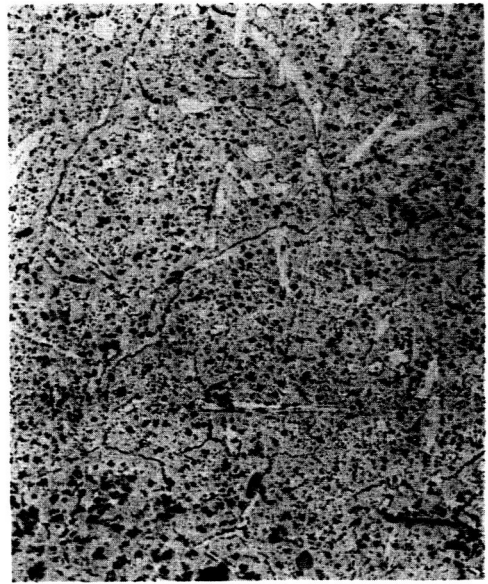
Alloy IA-6, As Cast   75X
Figure 55

Alloy IA-8, As Cast   75X
Figure 56
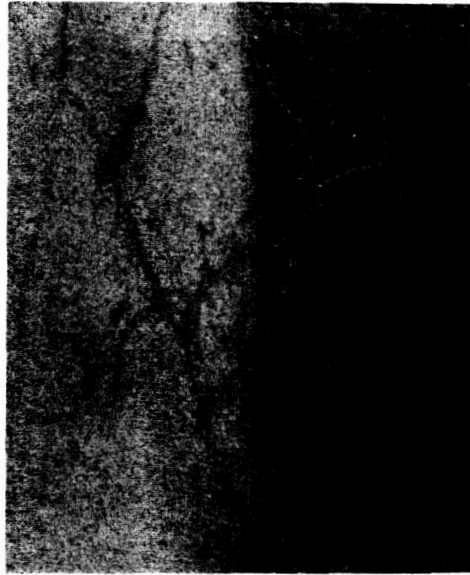
Alloy IA-6, Hot Worked at
720°F   75X

Figure 57

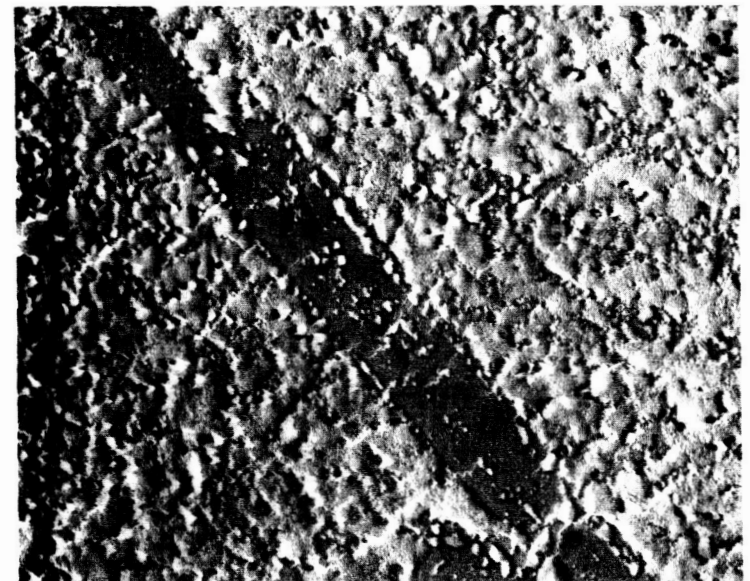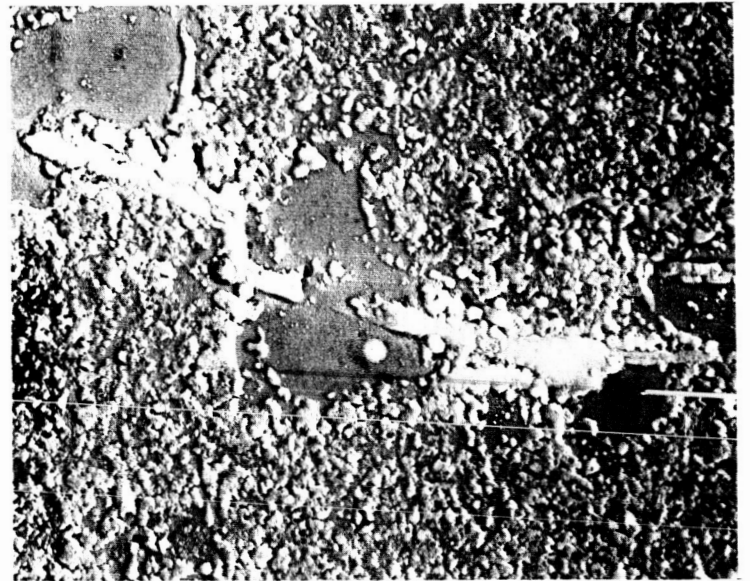Alloy IA-8, Hot Worked at
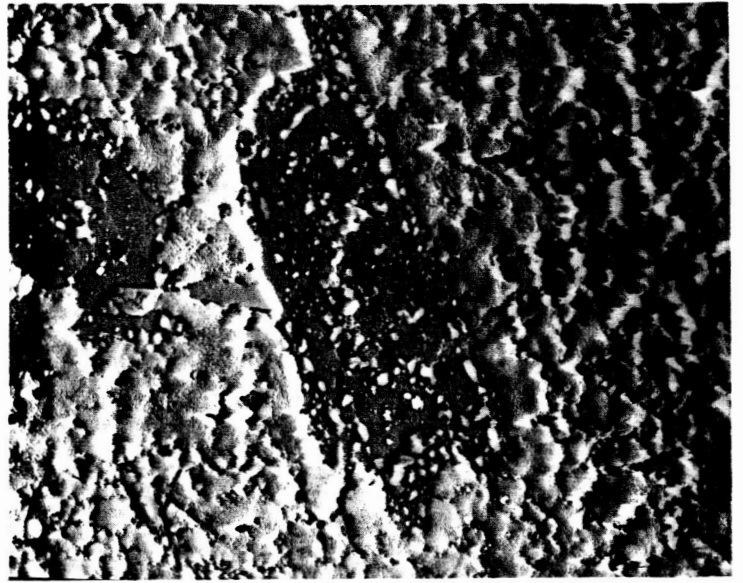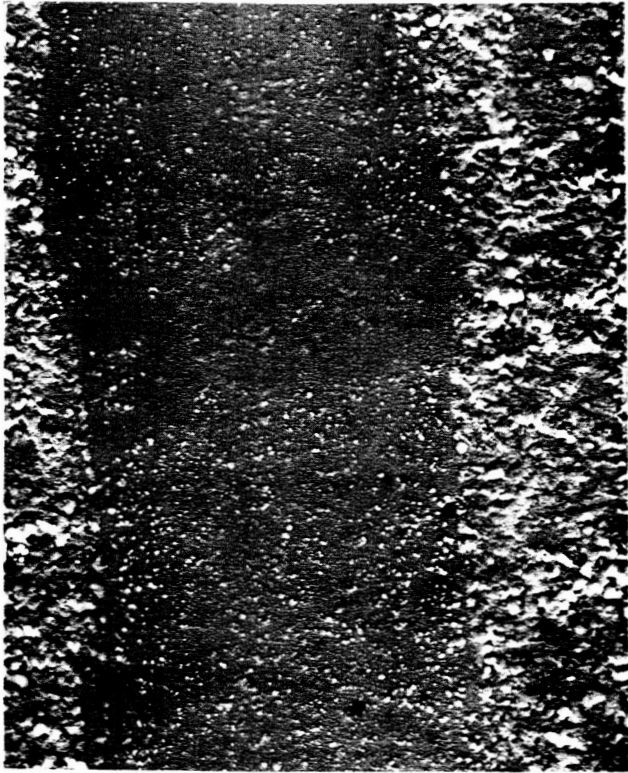720°F   75X

Figure 58

45

Figure 59
Electron Photomicrographs of Alloy II 4
at 4300 X Magnification

46