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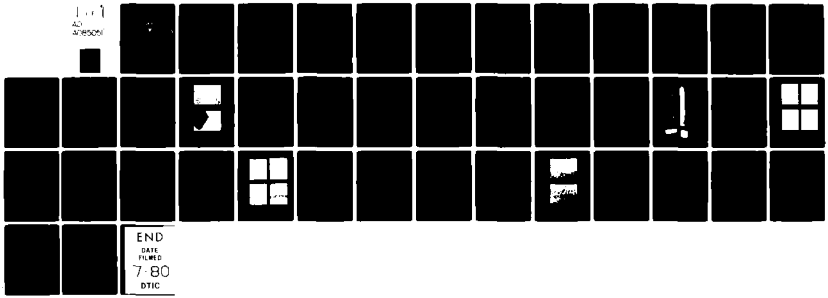

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THESIS

AN INVESTIGATION INTO THE INFLUENCE OF THERMOMECHANICAL PROCESSING ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF HIGH-STRENGTH ALUMINUM-MAGNESIUM ALLOYS

by

William Goodwin Speed

December 1979

Thesis Advisor: T.R. McNelley

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#20 - ABSTRACT - Continued

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A

AN INVESTIGATION INTO THE INFLUENCE OF THERMOMECHANICAL PROCESSING ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF HIGH-STRENGTH ALUMINUM-MAGNESIUM ALLOYS

by

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ABSTRACT

Microstructures and mechanical properties resulting from thermomechanical processing of high-Magnesium (Mg) content Aluminum-Magnesium(Al-Mg) alloys were investigated in this research. Warm rolling processes, intended to refine both grain size and second phase Al_3Mg_2 (β) Beta particle size, were conducted for alloy compositions of 10.2 weight ~~percent~~ % Mg, 10.2 weight ~~percent~~ % Mg plus 0.5 weight ~~percent~~ % copper (Cu) and 12.1 weight ~~percent~~ % Mg. Solution treatment, hot upset forging, resolutioning and rapid cooling provided initial microstructural homogenization. Subsequent warm rolling was employed to refine the microstructure. The effect of warm rolling parameters on β Beta particle size and distribution was of particular concern. By warm rolling an alloy containing 10.2 ~~percent~~ % Mg plus 0.5 ~~percent~~ % Cu at 250°C, an ultimate tensile strength of 565 MPa (82000 psi), with 11.5 ~~percent~~ % elongation, was achieved with the added advantage of a strength to density ratio higher than present equivalent-strength alloys, such as 7075-T6.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

The Aluminum-Magnesium (Al-Mg) alloy system, particularly for compositions between 8.0 and 14.0 percent Magnesium (Mg), can be processed by warm rolling to obtain mechanical properties equivalent to or superior than those of currently available Al-base alloys [Ref. 1-4]. The approach taken in this research was stimulated by Bly, Sherby and Young's [Ref. 5] warm rolling of hyper-eutectoid steels. For the Al-Mg system, the ability to refine and uniformly disperse second phase Al_3Mg_2 (β) particles in an α solid solution matrix is central to the success of the warm rolling process. An additional benefit would be the improved strength-to-weight ratios realized by use of Mg, the only commonly used alloying addition to Al which reduces the mass density of the resulting alloy. This is of particular interest, for example, in the transportation industry where reduced weight means improved fuel efficiency. Such an interest in this area of improvement has prompted the Naval Air Systems Command to fund this ongoing research.

A. BACKGROUND

Sherby's [Ref. 5] work led to the examination of the use of thermomechanical treatments, including warm rolling, on Al-Mg alloys. The phase diagram for Al-Mg, Figure 1, illustrates that this system has an intermetallic second phase, Al_3Mg_2(β). This phase is relatively hard when compared to

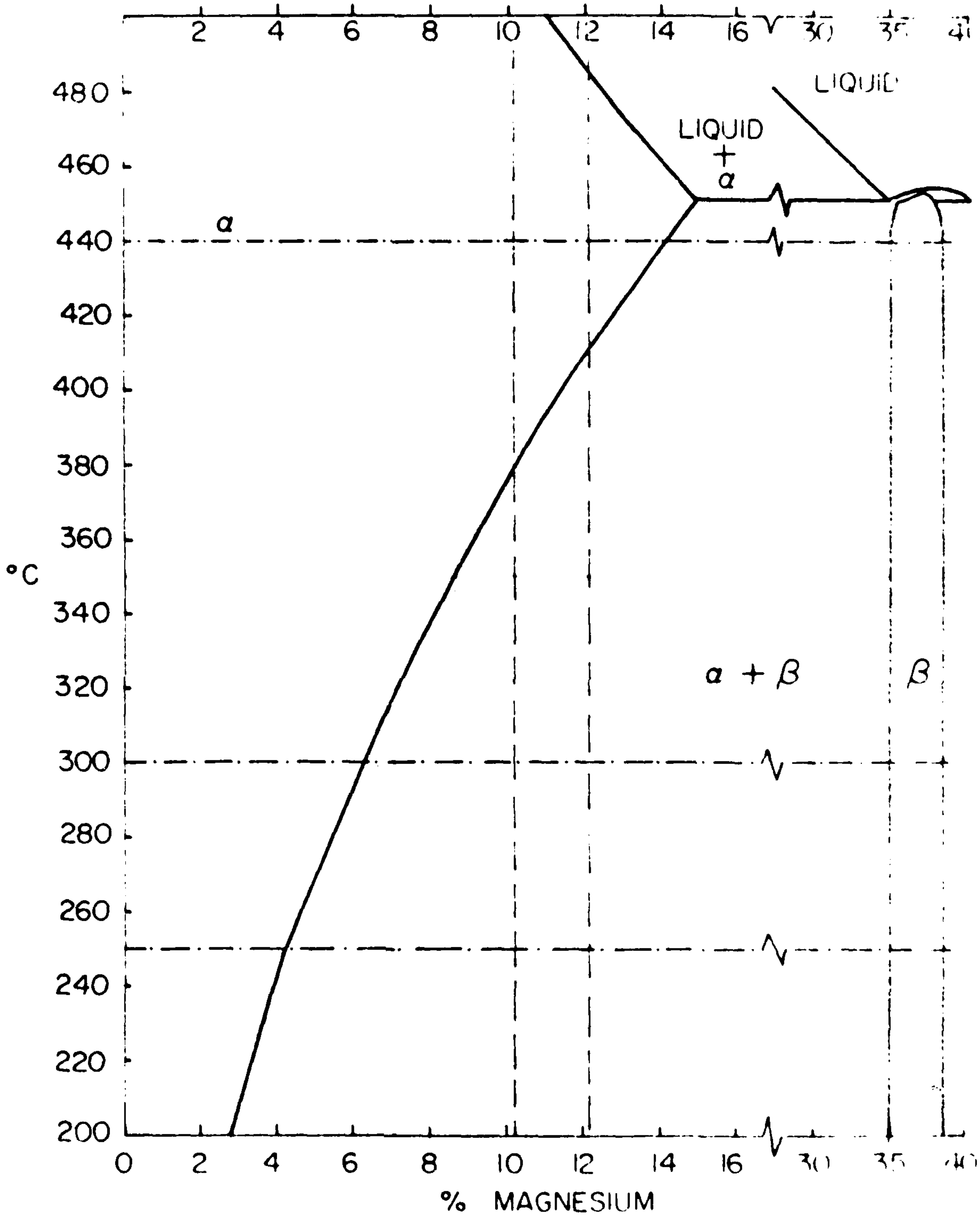


FIGURE 1. A Partial Aluminum-Magnesium Phase Diagram. Compositions and processing temperatures for materials studied during this research are indicated.

the α solid solution, and it is brittle. Nonetheless, if dispersed uniformly as fine particles in an α matrix, the β may be used to provide strengthening. It does this by refining and stabilizing the grain structure of the α matrix as well as by stabilizing the dislocation substructures developed during deformation processing.

In thermomechanical processing, grain size refinement occurs by recrystallization, either statically, by annealing after rolling, or dynamically, during rolling at elevated temperatures. Even though grain size refinement can strengthen metals in many instances, the focus of this research, was on the degree of β precipitation and refinement, resulting from various rolling schedules, for the Al-Mg alloy compositions examined.

B. PREVIOUS RESEARCH ON ALUMINUM-MAGNESIUM ALLOYS

Ness [Ref. 1] studied an 18 percent Mg alloy which he prepared by casting. By slowly warm rolling it, he was able to produce a fine dispersion of submicron-sized β particles in an α matrix. This material had compressive strength in excess of 654 MPa (95000 psi).

Bingay [Ref. 2] and Glover [Ref. 3] continued this work, but with commercially produced alloy castings. In Bingay's [Ref. 2] and Glover's [Ref. 3] work hot upset forging was only used on Al-Mg alloys with Mg content above the maximum solubility of Mg in Al, 15%, Figure 1. This was necessary to break up β particles which could not be idssolved during solution treatment.

Bingay's [Ref. 2] work focused on 15.0 and 19.0 percent Mg alloys. He investigated the effect of upset forging parameters on microstructure and concluded that such processing would work only on lower Mg-content alloys where the alloy could be initially solution treated, dissolving all of the β particles. Future study on precipitation from solid solution while warm working was suggested by Bingay [Ref. 2].

Glover [Ref. 3] also processed 15.0 and 19.0 percent Mg alloys. Rolling of these materials was not possible so he shifted to a 7.0 percent Mg alloy which was readily rolled. His warm rolled Al-Mg alloy was only two-thirds the strength of Ness's [Ref. 1], but more importantly he demonstrated that a relatively rapid warm rolling process could be performed on a high Mg-content Al-Mg alloy.

Grandon [Ref. 4] worked with 7.0 to 10.2 percent Mg alloys. He concentrated his research on the warm rolling of solution-treated material. He did this in order to determine the warm rolling parameters which would produce the most refined β precipitate and α matrix grain structure. His work provided extensive data on the effects of rolling temperature and reduction schedule on the strength and ductility of his Al-Mg alloys. Grandon [Ref. 4] used solution treatment at 440 °C as his initial processing step. He did not use the forging operation as it was thought unnecessary in light of the large deformations used in subsequent warm rolling. He observed a banded microstructure with a non-uniform distribution of β in the 10.2 percent Mg alloy. However, a much more uniform distribution of β resulted from this same processing in a 10.2 percent Mg plus 0.5 percent Cu alloy. He also observed that, for the 7.0 percent Mg alloy, recrystallization occurred when the material was slowly rolled but not when rapidly rolled. He suggested forging in addition to solution annealing for the initial homogenization of Al-Mg alloys and that a more detailed examination of conditions leading to recrystallization and homogenization of β distribution during warm rolling was required. He also suggested that the beneficial effects of additional alloying elements, such as Cu [Ref. 6], needed closer examination. Grandon's processing achieved at maximum ultimate tensile strength of 606 MPa (88000 psi).

C. PURPOSE OF THESIS

This study has extended the investigation of the 10.2 percent Mg alloys examined by Grandon [Ref. 4] and began the investigation of a 12.1 percent Mg alloy. Also, the initial processing steps examined by Bingay [Ref. 2], Glover [Ref. 3] and Grandon [Ref. 4], namely solution treatment, upset forging and resolution treatment were combined to constitute an initial series of thermomechanical treatments of the as-cast material. The purpose of these initial treatments is to refine and homogenize the as-cast microstructure prior to warm rolling.

II. EXPERIMENTAL PROCEDURE

Materials, processes and processing equipment used during this research are described in this section. Metallographic specimen preparation and mechanical testing equipment are also described.

A. MATERIALS

Table I lists the identification and compositions for the materials used in this research. All material used was obtained from Alcoa, Alcoa Technical Center, Alcoa Center, Pennsylvania. Specimens were cut from direct-chill cast ingots and were machined to two typical dimensions: 30.5 x 30.5 x 76.2 mm (1.2 x 1.2 x 3.0 ins.) and 30.5 x 30.5 x 88.9 mm (1.2 x 1.2 x 3.5 ins.).

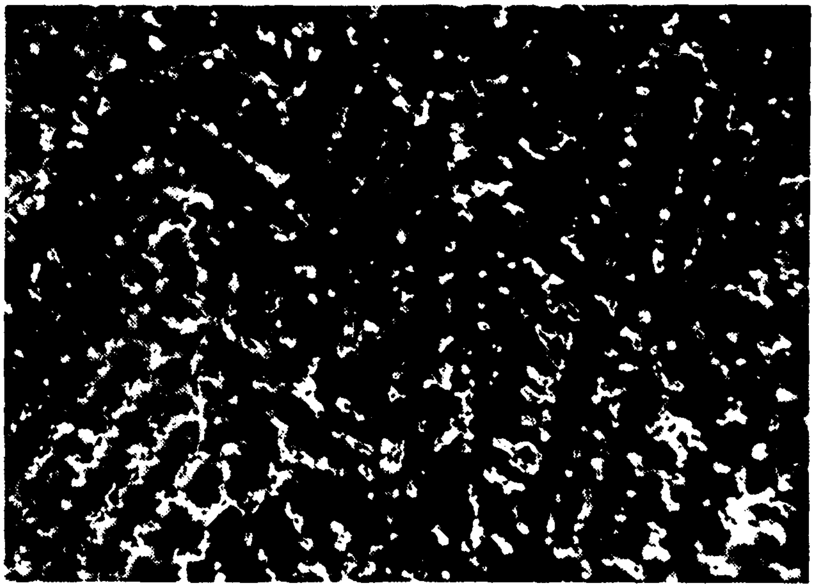
A typical as-cast microstructure is seen in Figure 2a.

Table I

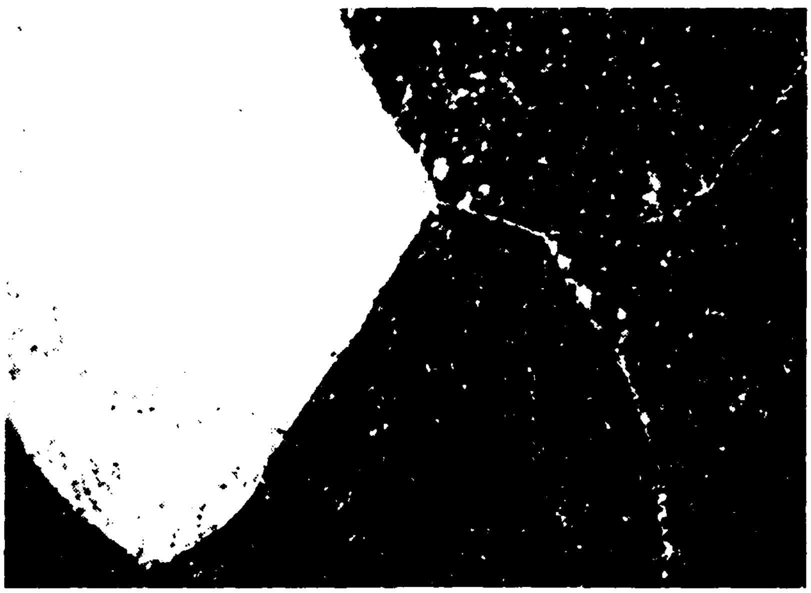
Identification and Composition of Alloys Used in This Research

Identification (Series)	Composition (Weight Percent)			Density (Lb/in^3)
	Mg	Cu	Al	
51X	10.2	-	Balance[1]	.09259
54X	10.2	0.5	Balance	.09260
52X	12.1	-	Balance	.09238

[1]All alloys contained less than 0.010 weight percent residual elements.



a) As-cast microstructure, with directional grain structure and extremely coarse second phase (β) particles



b) Hot upset forged and resolutioned microstructure, with equiaxed grain structure and signficantly more refined β particles

FIGURE 2. Typical As-Cast (a) and Hot Upset Forged and Resolutioned (b) Microstructures. These micrographs are for 52X Series (12.1 Percent Mg) taken at 200X.

B. SOLUTION TREATMENT AND FORGING

Each specimen was solution treated at 440°C for at least 20 hours in a Lindberg Hevi-Duty Box furnace. Grandon [Ref. 4] found that the non-equilibrium β phase of the as-cast material was completely dissolved by this process.

Immediately following solution treatment the specimen was upset forged at 440°C by compressing it between heated platens affixed toa Baldwin-Tate-Emery testing machine of 2780 N (60000 lbs) capacity. Typical reduction was from 76mm (3 in) to 25mm (1 in) in height. Temperature control was maintained by insulating the platens and specimen with Fiberglas ® insulation. The specimen temperature was monitored by a Copper-Constantin thermocouple in contact with the specimen. Temperature was recorded by a Newport Digital Thermometer. Forging commenced when 440°C was reached. Maintaining 440°C during forging was considered necessary to retain a single phase α solid solution.

Immediately after forging, the specimen was returned to the furnace for solution heat treatment (at 440°C) for at least 3 additional hours allowing for grain growth of the α phase and solutioning at the β phase. Subsequently the specimen was air cooled, which proved fast to retain most Mg in solid solution. At this point, the solutioning, upset forging, resolutioning and air cooling procedure produced a uniform, equiaxed grain structure, with some fine β particles dispersed within the grain and at grain boundaries, Figure 2b.

C. ROLLING SCHEDULES

Table II contains a complete, detailed listing of rolling schedules used for each specimen. The rolling reduction was typically 1 mm (0.04 in) per pass using a Fenn Rolling Mill equipped with 108 mm (4.25 in) diameter rolls. The reduction per pass was held at 1 mm or less due to power limitations of the rolling mill. For the purposes of this thesis, rolling schedules have been categorized as isothermal or non-isothermal.

1. Isothermal Rolling

This process is characterized by maintaining the specimen at a single temperature throughout the rolling schedule. Specimen temperature was held close to the rolling temperature by quickly returning the specimen to a holding furnace for 10 minutes after each rolling pass. For some specimens, one hour intermediate anneals at the rolling temperature, were scheduled between rolling stages. As can be seen in Table II, specimens 5110, 549 and 527 were isothermally rolled with periodic, one hour intermediate anneals. Specimens 5112, 5441 and 5442 were also rolled isothermally but did not undergo intermediate anneals.

2. Non-Isothermal Rolling

This process was characterized by an initial reduction at a low temperature, for example, room temperature; then, the rolling temperature would be raised. Warm rolling to completion would be done at this higher temperature. Warm rolled specimens were heated in a Blue M electric furnace,

Table II

Table of Thermomechanical Processes and Mechanical Testing Results

Table Key

ST:	Solution treated
AN:	Annealed
xxx/xx:	Temperature (°C)/Time (hrs)
CR:	Cold rolled
WR:	Warm rolled with a 10 minute anneal between each pass
UF:	Upset forged
xx/xx/xx:	Approximate reduction per pass (in[1])/Number of Passes/Temperature (°C)
AC:	Air cooled
OQ:	Oil quenched
WQ:	Water quenched

A. <u>10.2 Percent Mg Alloy (51x Series)</u>

Sample Designation	Process	Ultimate Tensile Strength (psi)[2]	0.2% Offset Yield Strength (psi)[2]	Elongation, percent	Hardness, R_B
511	ST 440/24 AC UF 2.0/1/420 ST 440/3 WQ CR .04/6/20 AN 300/1 WR .08/3/300 AN 300/1 WR .08/3/300 AN 300/1 WR .04/2/300 AN 300/.08 AC	66,100	52,500	2.0	80.0
5110	ST 440/24 AC UF 2.0/1/440 ST 440/3 AC WR .04/3/300 AN 300/1 WR .04/8/300 AN 300/1 WR .04/18/300 AC	69,300	56,700	3.3	81.0

5111	ST 440/24 AC	68,700	58,100	3.3	78
	UF 2.0/1/440				
	ST 440/3 AC				
	WR .04/6/250				
	AN 250/1				
	WR .04/6/250				
	AN 300/1				
	WR .04/6/300				
	AN 300/1				
	WR .04/5/300 AC				
5112	ST 440/24 AC	68,700	56,700	8.7	79.0
	UF 2.0/1/440				
	ST 440/3 AC				
	WR .04/8/300 OQ				
	WR .04/17/300 AC				

B. <u>10.2 Percent Mg plus 0.5 Percent Cu Alloy (54x Series)</u>

548	ST 440/24 AC	67,300	54,900	3.3	82.0
	UF 2.5/1/440				
	ST 440/3 AC				
	CR .04/6120				
	AN 300/1				
	WR .04/3/300				
	AN 300/1				
	WR .04/3/300				
	AN 300/1				
	WR .04/5/300				
	AN 300/1				
	WR .04/5/300 AC				
549	ST 440/24 AC	73,200	64,400	3.3	80.0
	UF 2.5/1/400				
	ST 440/3 AC				
	WR .04/6/300				
	AN 300/1				
	WR .04/17/300 AC				
5441	ST 440/24 AC	82,000	65,000	11.5	82.0
	UF 2.0/1/440				
	ST 440/3 AC				
	WR .04/23/250 OQ				
5442	ST 440/24/AC	-	-	-	83.5
	UF 2.0/1/440				
	ST 440/3 AC				
	WR .04/20/200 AC	Specimen failed on 20th pass.			

C. <u>12.1 Percent Mg Alloy (52x Series)</u>

527	ST 440/24 AC UF 2.0/1/440 ST 440/3 AC WR .04/6/300 AN 300/1 WR .04/8/300 WR .02/9/300 AC	61,000	47,400	2.0[3]	79.0
5210	ST 440/24 AC UF 2.5/1/440 ST 440/3 AC CR .02/12/20 AN 300/1 WR .04/2/300 AN 300/1 WR .04/3/300 AN 300/1 WR .04/3/300 AN 300/1 WR .04/4/300 AN 300/1 WR .04/3/300 WR .02/7/300	62,900	47,400	2.0[3]	80.0

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[1] 1.0 in. = 2.54 mm

[2] 1.0 psi = 0.00689 MPa

[3] Based upon original gage length ℓ_o = 1.0 ins., all other specimens ℓ_o = 1.5 ins. Gage length to width ratio ℓ_o/W = 4:1, all other specimens ℓ_o/W = 6:1.

Stable Glow Type, Model No. 8655F-3, located near the rolling mill. As can be seen in Table II, specimens 511, 5111, 548 and 5210 underwent non-isothermal, "roll up" schedules.

D. METALLOGRAPHY

Standard preparation methods were employed to produce specimens for metallographic study. The etching process, used to determine β phase distribution and size, employed dilute (50 percent) fluoroboric acid (Barker's Reagent) as the electrolyte in a quick, two or three second, electrolytic etch. Micrographs were made with cross polarizers in a Bausch and Lomb Balplan optical microscope. Micrographs were taken on the plane transverse to rolling direction.

E. MECHANICAL PROPERTIES TESTING

Hardness testing was accomplished on a Rockwell Hardness Tester, Mode 1-JR, using a 100 Kg Load and a 1/16 inch Ball Penetrator set on the 'B' scale. Hardness testing was conducted after the specimens had been rolled and cooled. Tests were conducted on the rolled surface only.

Tensile testing was performed on an Instron Universal testing instrument, Model TTD, with crosshead speed of 1.27 mm (0.05 in.) per minute and an Autographic Chart speed of 50.8 mm (2.0 in.) per minute. Tensile specimens were made from strips taken from completed rolling specimens with the long axis parallel to the rolling direction. The strips were machined to 19 mm (0.75 in.) width, either 102 mm (4.0 in.) or 114 mm (4.5 in.) in length and were typically 2.5 mm (.1 in.)

thick. The gage region was milled to 6.35 ± .13 mm (.250 ± .005 in.) width as required by ASTM [Ref. 7] for subsized tensile specimens. Figure 3 depicts the stages of processing that a typical specimen underwent.

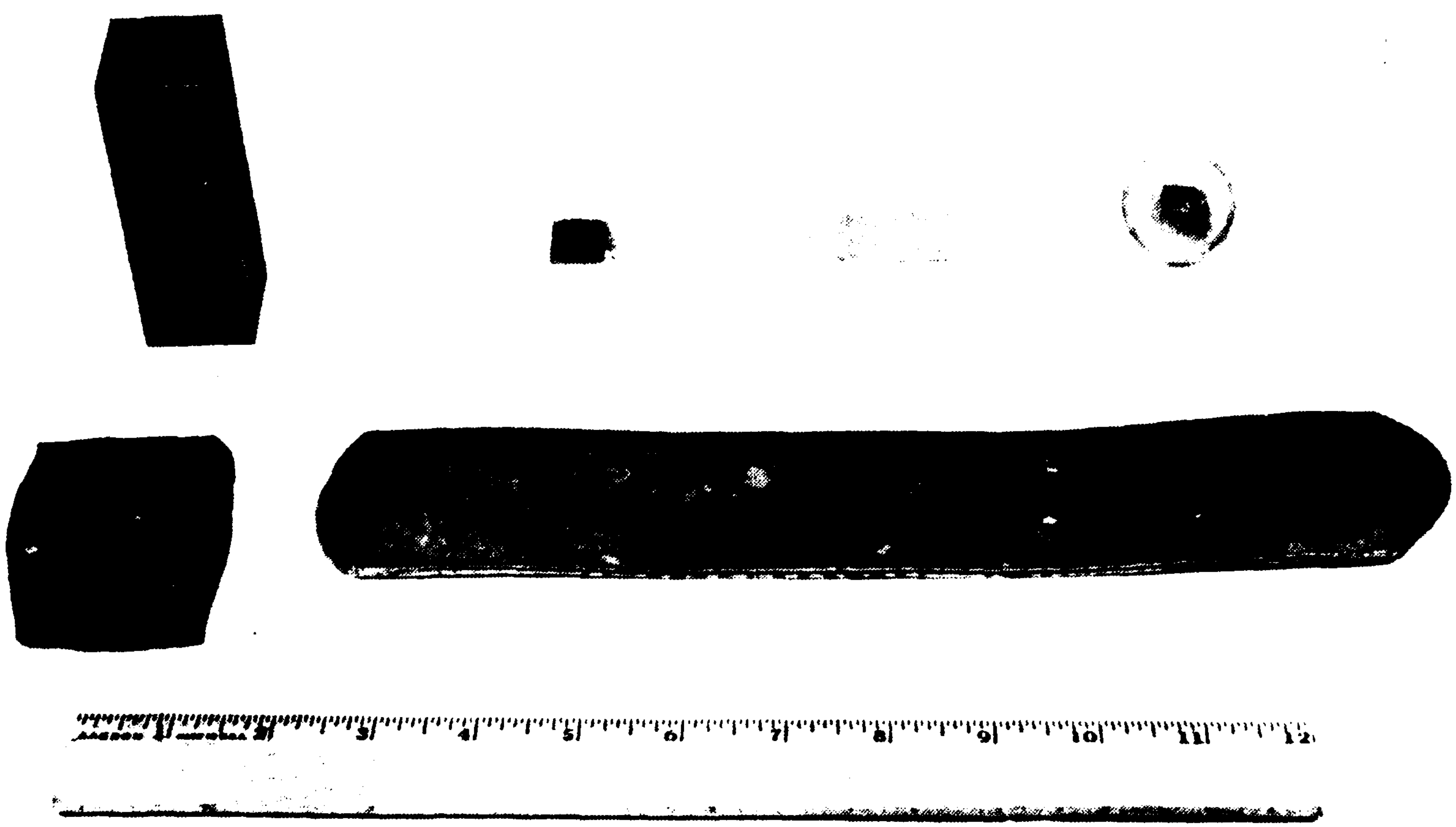


FIGURE 3. Photograph of Typical Specimen and Its Subsequent Deformation Resulting from Upset Forging and Warm Rolling. The tensile test sample and mounted metallographic sample are also shown.

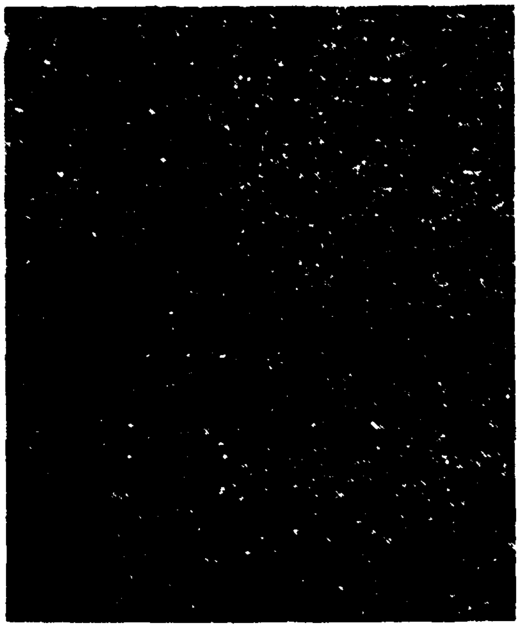
III. EXPERIMENTAL RESULTS

The rolling schedules described in Table II were designed to investigate several variables. The Mg-content of the alloy, in conjunction with rolling temperature, determines the equilibrium β content of the alloy. Initial cold rolling creates stored energy to promote recrystallization during subsequent warm rolling. Also, following Grandon's [Ref. 4] observation of recrystallization in a 7.0 percent Mg alloy, one hour intermediate anneals were introduced to increase time at temperature, again to promote recrystallization. Lastly, the influence of Cu as a minor addition was to be investigated. Results are presented below for each alloy composition examined and the effects of process variations on each alloy.

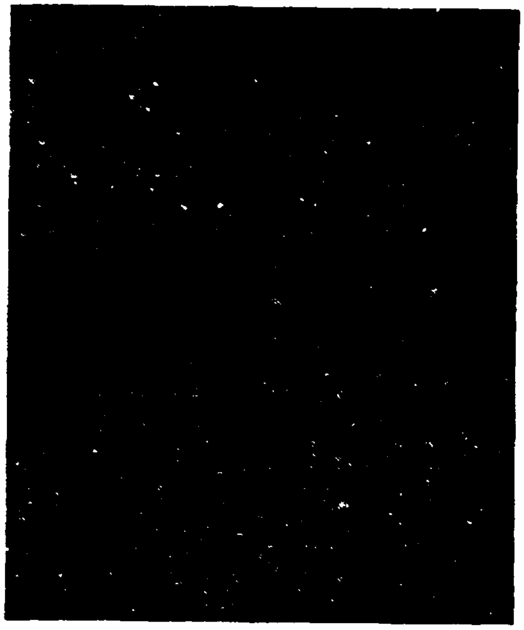
A. 10.2 PERCENT Mg ALLOY (51X SERIES)

1. 511 Specimen

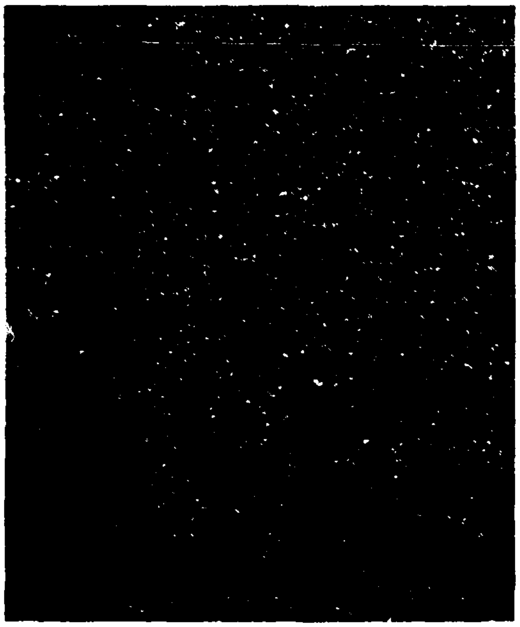
The non-isothermal rolling schedule (Table II) for specimen 511 evaluated the effect of initial cold rolling at 20°C with subsequent warm rolling and intermediate anneals (three) at 300°C on β particle refinement and distribution. Final warm rolling at 300°C was done to encourage recrystallization. Mg additions to Al lower the stacking fault energy which may promote recrystallization during rolling at a temperature lower than normally expected for aluminum. The goal of this process schedule



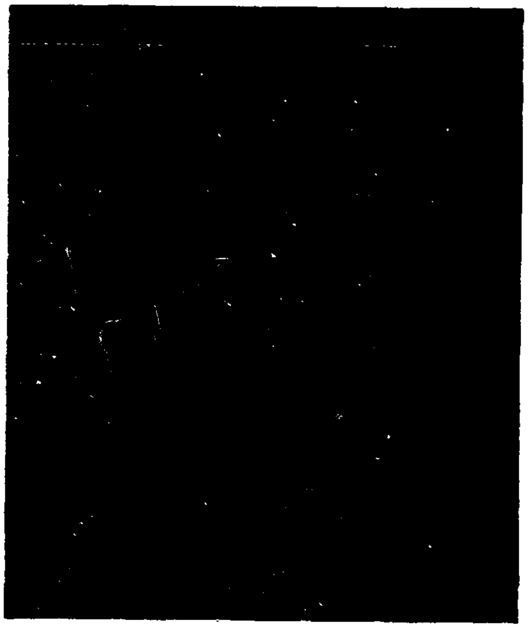
a) Specimen 511



b) Specimen 5110



c) Specimen 5111



d) Specimen 5112

FIGURE 4. Photomicrographs of β Distribution in Warm Rolled 10.2 Percent Mg Alloy Specimens (51X Series). Specimen 5112 did not undergo any long intermediate anneals. Micrographs were taken at 200X.

was to obtain a fine, uniform dispersion of β particles and to refine the grain structure. As can be seen in Figure 4a, a very homogeneous dispersion of the β was achieved. However, the β is also relatively coarse. The tensile mechanical properties were relatively poor in that the elongation at fracture is only 2 percent (Fig. 5). The fracture surface of this sample was flat and perpendicular to the tensile axis, indicating brittle behavior of the material.

2. 5110 Specimen

A determination of the effects of isothermal warm rolling, without initial cold rolling, on the resulting microstructure was the intent of the rolling schedule (Table II) for specimen 5110. Emphasis was placed on continuous warm rolling through the final 60 percent of reduction. This specimen underwent two intermediate anneals prior to the final 60 percent reduction. The result was again a homogeneous dispersion of β particles though now with some apparent directionality (Fig. 4b). The β is slightly finer than in the 511 specimen and this gives a slightly stronger and more ductile material (Fig. 5). The fracture surface was still typical of a brittle material and was like that of specimen 511.

3. 5111 Specimen

The 5111 specimen's non-isothermal rolling schedule (Table II) was intended to determine the effects

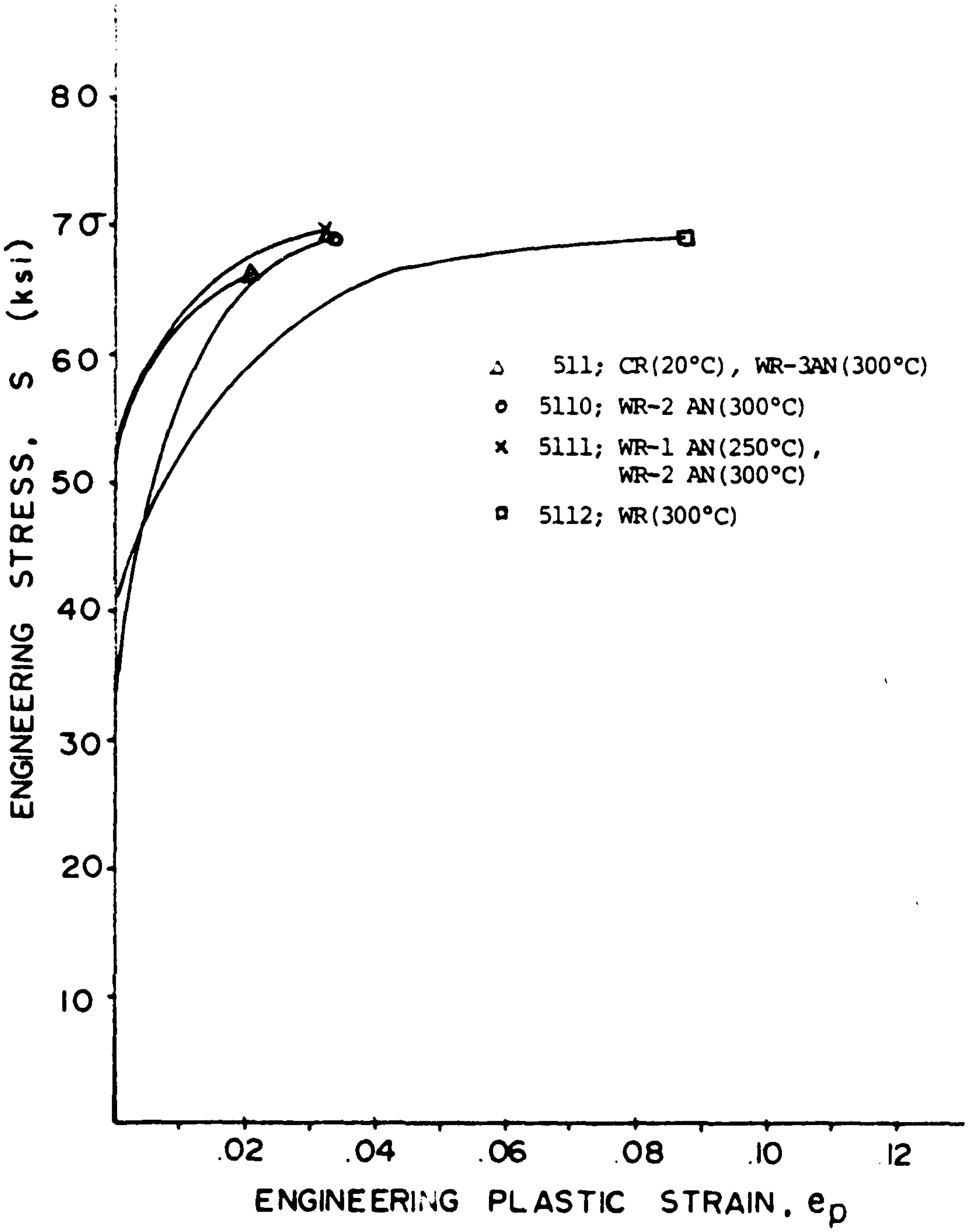


FIGURE 5. Engineering Stress-Strain Curves for the 10.2 Percent Mg Alloy (51X Series). The dramatic increase in ductility for specimen 5112 was due to a significant reduction in β precipitation over that of the others.

that a warm roll-up process would have on β distribution and growth. Rolling at 250°C was expected to further refine β particles that remained from the initial upset forging and resolution treatment while encouraging some recrystallization. Further recrystallization was expected to occur during subsequent warm rolling and intermediate anneals conducted at 300°C. The result was again a homogeneous but somewhat directional dispersion of β (Fig. 4c). Specimen 5111's lower total time at 300°C has improved its microstructure by minimizing β growth, though at a sacrifice in homogeneity of β dispersion. The reduced amount of β as compared to specimen 511 provided a slight increase in properties (Fig. 5), although the fracture mode was again brittle.

4. <u>5112 Specimen</u>

The rolling schedule for specimen 5112 (Table II) was isothermal without any intermediate anneals. As can be seen in Figure 4d, an important result was a significant decrease in the amount and degree of refinement of β precipitated during warm rolling. The β dispersion is the least homogeneous of this series. It is clear that annealing treatments at 300°C lead to a more homogeneous β dispersion but result in excessive β growth. The ultimate strength of specimen 5112 is similar to that of preceding specimens in this series. But ducility is increased fourfold. Furthermore, the fracture is a slant type of fracture indicative of a ductile fracture mode.

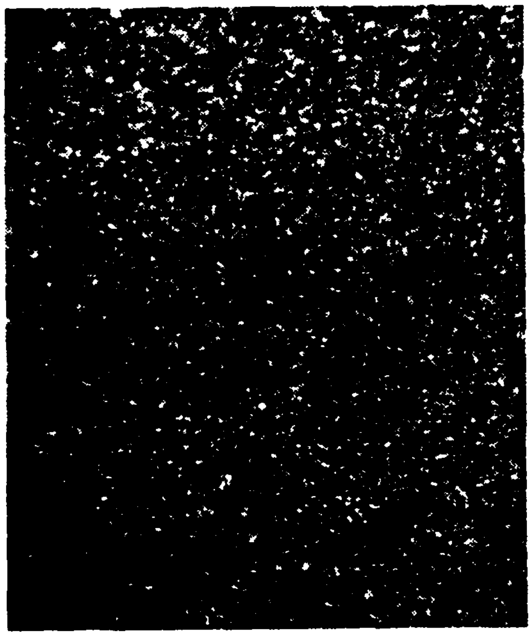
B. 10.2 PERCENT Mg PLUS 0.5 PERCENT Cu (54X SERIES)

1. 548 Specimen

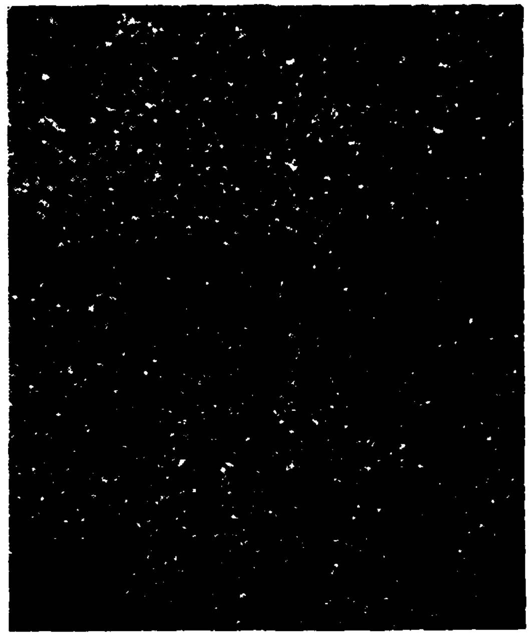
The cold roll, warm roll non-isothermal rolling schedule for specimen 548, which contained a small amount of Cu, was intended to provide a microstructural comparison with specimen 511, which was similarly processed but did not contain Cu (Table II). The resulting microstructure was a very homogeneous dispersion of coarse β (Fig. 6a). There was no noticeable difference between β distribution and size when compared to specimen 511 (Fig. 4a). Some refinement was expected. However, based on the studies done of alloy effects upon β by Polmear and Sargan [Ref. 6] it was not achieved with this particular rolling schedule. The coarse β kept strength and ductility (Fig. 7) low but the ductility was slightly better than that for specimen 511. The improved ductility is attributed to a more refined grain structure due to the presence of Cu. The fracture surface was, however, flat and typical of brittle failures.

2. 549 Specimen

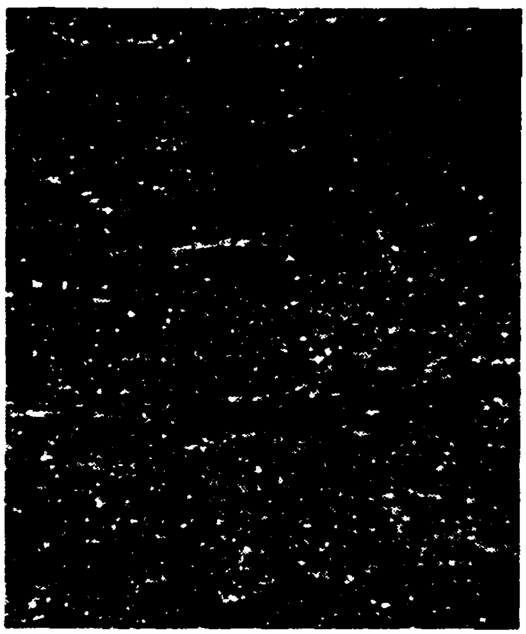
The rolling schedule (Table II) proposed for specimen 549 was intended to determine the β distribution that would result from an isothermal process at 300°C with only one intermediate anneal. The resulting microstructure (Fig. 6b) differs very little from that of specimen 548 (Fig. 6a). There is a barely discernible reduction in the amount of β dispersed homogeneously through the microstructure.



a) specimen 548



b) specimen 549



c) specimen 5441

d) specimen 5442

FIGURE 6. Photomicrographs of β Distribution in Warm Rolled 10.2 Percent Mg Plus 0.5 Percent Cu Alloy (54X Series). Specimen 5441 did not undergo any long intermediate anneals and was oil quenched upon completion of rolling. Micrographs were taken at 200X.

This may account for the improvement in strength (Fig. 7). The fracture surface was characteristic of the brittle type.

3. 5441 Specimen

The process schedule for specimen 5441 was selected to examine isothermal warm rolling without a long intermediate anneal (Table II) in order to compare properties and microstructures with that of specimen 5112. Additionally it was decided to lower the rolling temperature to 250°C in order to extend the knowledge of β precipitation characteristics at lower temperatures. Previously, it was felt that rolling below 300°C would result in failure during rolling due to increase material strength and strain hardening. However, based on the knowledge gained from previous specimens concerning the relation between amount of precipitate and total time at the annealing temperature, it was felt that a 54X series specimen could be rolled to completion below 300°C without long intermediate anneals. It is evident that diffusion is rapid and thus recovery likely even at these low temperatures. To further control precipitation an oil quench was performed after the final rolling pass.

The resulting microstructure, seen in Fig. 6c, displayed a directional dispersion of mostly fine, particulate β. There was less β present than in specimens 548 or 549, even with a 50°C lower rolling temperature. This

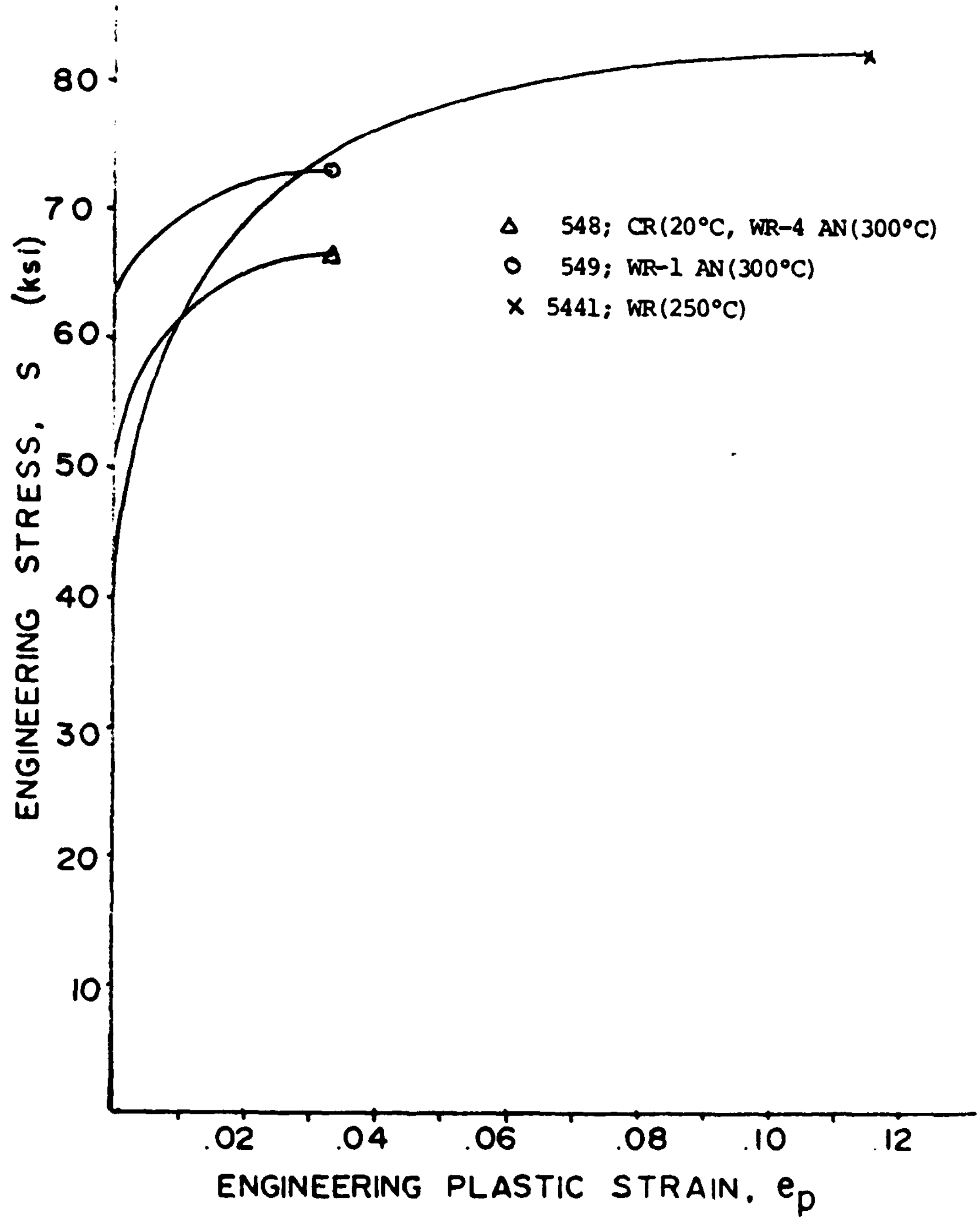


FIGURE 7. Engineering Strain Curves for 10.2 Percent Mg Plus 0.5 Percent Cu Alloy Specimens (54X Series). The dramatic increase in ductility as well as an improvement in strength was due to a significant reduction in size and amount of β precipitation over that of the others.

suggests that the long intermediate anneals must be eliminated in order to minimize β growth during precipitation and that the forging step hels most when rolling at temperatures lower than 300°C.

The tensile test results were significantly better in both ductility and strength than other specimens in the 54X series (see Fig. 7). In fact, they were the best results obtained during this study for any series. The fracture mode was ductile; that is, of the slant type.

4. 5442 Specimen

The results from the rolling schedule used for specimen 5441 prompted a similar attempt for specimen 5442, namely, isothermal warm rolling, but at 200°C, and with no intermediate anneals (Table II). The specimen failed in the rolling mill during the twentieth pass. It was removed and air cooled. Its microstructure had large amounts of very fine β particles, uniformly dispersed throughout large, elongated grains (Fig. 6d). Although tensile data was not obtainable, the Rockwell "B" hardness of this specimen was the highest of all specimens examined which indicates a high strength.

C. 12.1 PERCENT MAGNESIUM (52X SERIES)

1. 527 Specimen

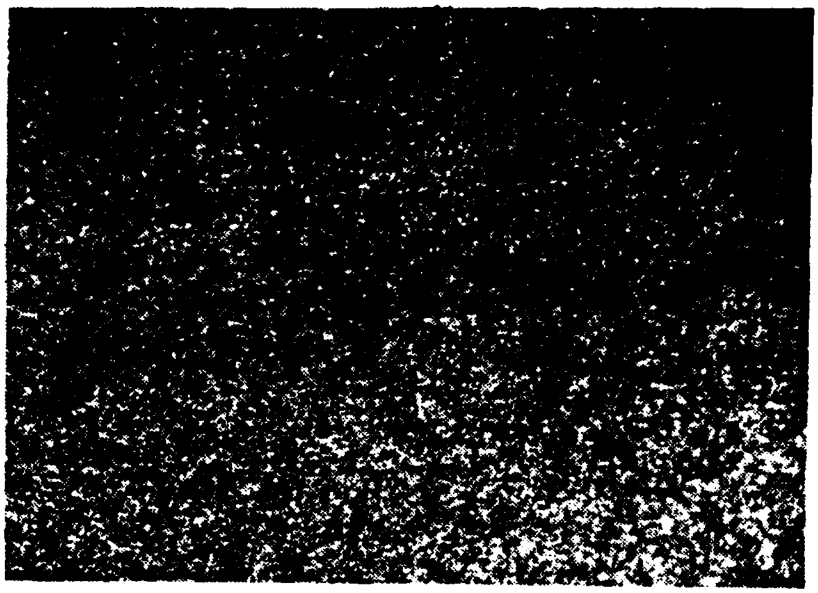
The rolling schedule for specimen 527 was intended to determine if this higher Mg series could be isothermally rolled at 300°C (Table II). The specimen was rolled to completion, undergoing only one intermediate anneal. It was found necessary to reduce amount of reduction per pass by half in order to prevent fracture of the specimen during rolling. A large amount of β precipitation occurred, as can be seen in Fig. 8a. The microstructure was a very homogeneous dispersion of coarse β particles.

This produced a medium strength, but very brittle material (Fig. 9). The fracture surface was flat, typical of brittle fracture.

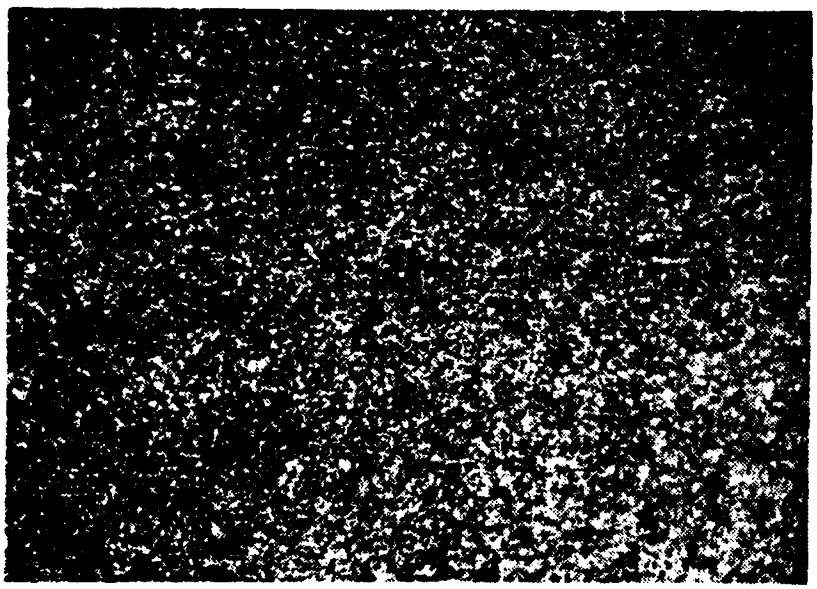
2. 5210 Specimen

Non-isothermal rolling with five intermediate anneals (Table II) was expected to provide some microstructural comparisons between specimens 5210 and 527. The comparison would be between schedules which included five and one intermediate anneals, respectively.

The result for specimen 5210 (Fig. 8b) was essentially the same as seen in the micrograph for specimen 527 (Fig. 8a). The 12.1 percent Mg alloy microstructures were dominated by β precipitation at 300°C, despite large differences in total annealing time. This suggests rolling with conditions wherein considerably finer β can be produced, i.e. at lower temperatures. The tensile date were similar to that of specimen 527 (Fig. 9). Fracture was again brittle.



a) specimen 527



b) specimen 5210

FIGURE 8. Photomicrographs of β Distribution in Warm Rolled 12.1 Percent Mg Alloy Specimens (52X Series). Variation in the total time at annealing temperature (300°C), produced no difference in β Distribution. Micrographs were taken at 200X.

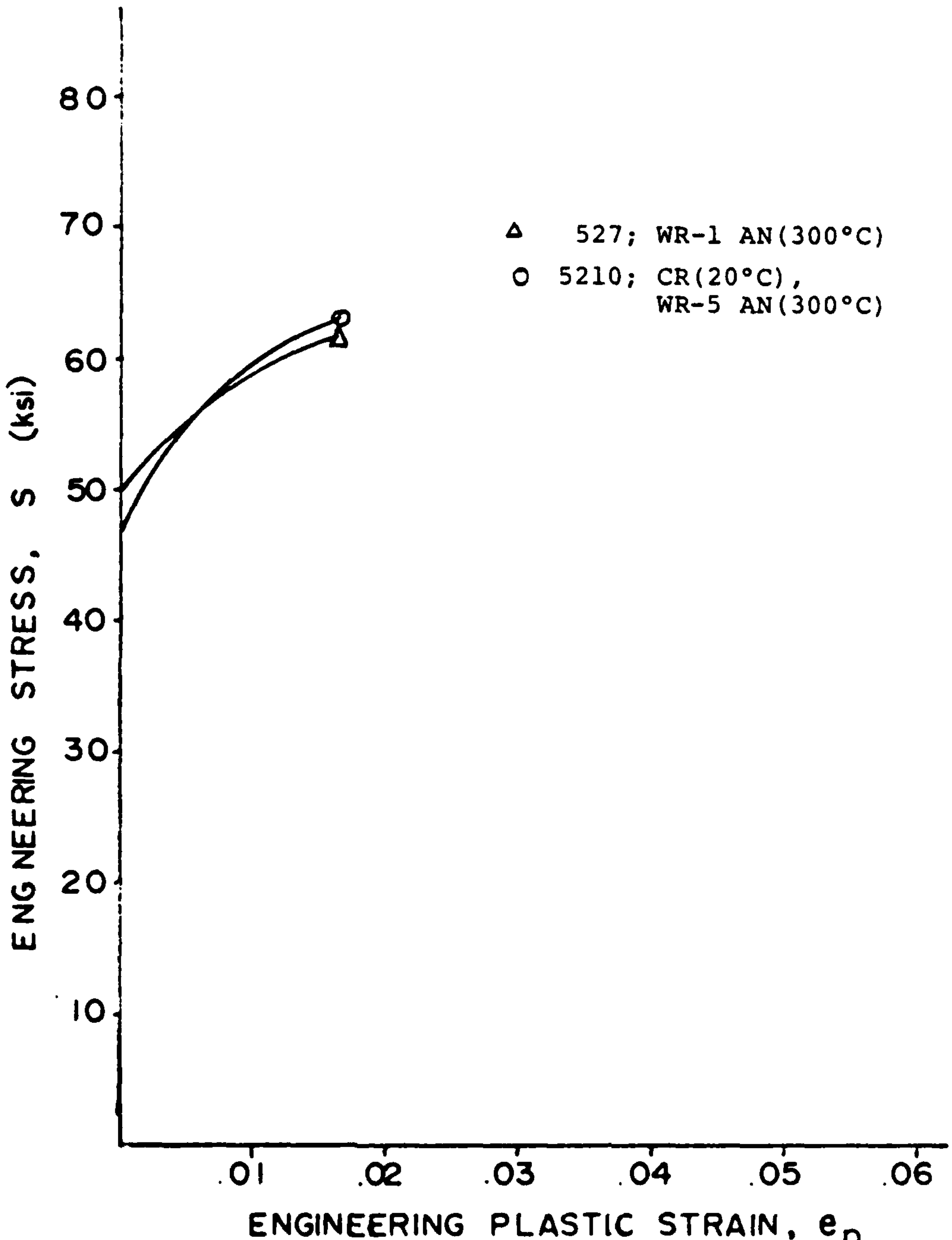


FIGURE 9. Engineering Stress-Strain Curves for 12.1 Percent Mg Alloy Specimens (52X Series). Large amounts of coarse β particles characterized the microstructures of both specimens.

IV. SUMMARY AND RECOMMENDATIONS

A. SUMMARY

1. The addition of the hot upset forging process, followed by a resolution treatment, provides an initially more homogeneous, equiaxed grain structure in comparison to the initial processing used by Grandon [Ref. 4]. Subsequent warm rolling of a 10.2 percent Mg alloy, without intermediate annealing treatments, indicates some improvement in the distribution of the β relative to that achieved by Grandon [Ref. 4]. Use of intermediate anneals during warm rolling leads to increased precipitation and coarsening of the β, but also a very homogeneous distribution of it. This coarsened β leads to poor ductility in the as-rolled product.

2. Little insight into recrystallization in the 10.2 percent Mg alloy was gained in this study. Processing procedures introduced to study recrystallization, such as initial cold rolling with intermediate anneals during warm rolling, also influenced β precipitation. The extensive β precipitation that occurred masked any recrystallization which might have taken place. Transmission electron microscopy would be required to examine this question.

3. Grandon [Ref. 4] noted a large effect of the addition of 0.5 percent Cu to a 10.2 percent Mg alloy. This alloy possessed a much finer and more homogeneous

dispersion of the β when warm rolled after solution treating. In this study, similar though less pronounced microstructural effects were observed. Here the Cu-containing alloy was initially hot upset forged before warm rolling. Intermediate anneals employed during warm rolling led to coarsening of the β and poor ductility as in the alloy not containing Cu. In material not given the intermediate anneals during rolling, the β distribution became less homogeneous, as in the material with no Cu addition, but the precipitated β was finer. This suggests that Cu does have some refining effect at this stage. In comparing the combined effects of hot upset forging and the Cu addition, it appears that the refining effect of Cu is greatest in the early stages of processing, and this may be a result of a homogenizing effect of Cu in the original casting. As processing proceeds, and in particular, as time at the warm-rolling temperature is increased, the effectiveness of Cu as a microstructural refiner is decreased.

4. An important result of this study is the processing of the 10.2 percent Mg plus 0.5 percent Cu alloy, by warm rolling at 250°C, to an ultimate tensile strength of 565 MPa (82000 psi) with 11 percent elongation to fracture. The fracture was of the slant type in the gage thickness tested (2.5 mm (0.1 in.)), indicative of a ductile fracture mode. These results compare favorably with the mechanical

properties of aluminum alloy 7075-T6, and with the advantage of a higher strength-to-weight ratio.

B. RECOMMENDATIONS

Recommendations for future research in this area are:

1. Determination of δ precipitation and growth kinetics and of the recrystallization characteristics of these alloys. In particular, the influence of Mg-content and other alloy additions must be considered.

2. Investigation of warm rolling at still lower temperature than employed to date in these studies (i.e., in the temperature range 200°C to 300°C).

3. Incorporation of fatigue, elevated temperature and stress-corrosion studies to provide a broader range of physical property characteristics for these alloys.

LIST OF REFERENCES

1. Ness, F. G., Jr., High Strength to Weight Aluminum-18 Percent Magnesium Alloy Through Thermal Mechanical Processing, M.S. Thesis, Naval Postgraduate School, Monterey, California, December 1976.

2. Bingay, C. P., Microstructural Response of Aluminum-Magnesium Alloys to Thermomechanical Processing, M.S. Thesis, Naval Postgraduate School, Monterey, California, December 1977.

3. Glover, T. L., Effects of Thermo-Mechanical Processing on Aluminum-Magnesium Alloys Containing High Weight Percentage Magnesium, M.S. Thesis, Naval Postgraduate School, Monterey, California, December 1977.

4. Grandon, R. A., High Strength Aluminum-Magnesium Alloys; Thermomechanical Processing, Microstructure and Tensile Mechanical Properties, M.S. Thesis, Naval Postgraduate School, Monterey, California, March 1979.

5. Bly, D. L., Snerby, O.D., and Young, C. M., "Influence of Thermal Mechanical Treatments on the Mechanical Properties of Finely Spheroidized Eutectic Composition Steel," Materials Science and Engineering, V. 12, 1973.

6. 1979 Annual Book of ASTM Standards, V. 10, American Society for Testing and Materials, 1979.

7. Polmear, I. J., and Sargant, K. R., "Enhanced Age-Hardening in Aluminum-Magnesium Alloys," Nature, V. 200, 1963.

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