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THERMAL MECHANICAL PROCESSING OF Al-Li ALLOY 2020 TO ACHIEVE FINE GRAIN SIZE

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Aluminum lithium alloys are attractive as airframe materials because of their low density and high modulus of elasticity. However, these alloys suffer from poor fracture toughness and low ductility which limit their applicability. It is believed that the large constitutive particles and grain size exhibited by alloys such as 2020 aluminum are responsible for their low ductility and fracture toughness. Intermediate thermal mechanical processing (ITMT) involving heat treatment, cold work, and recrystallization was employed to refine the grain size of 2020 aluminum lithium plate. The grain size was successfully reduced from 400μm to 10um. Future work will concentrate on the superplastic formability and fracture toughness of ITMT 2020 plate and new aluminum lithium alloys.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

INTRODUCTION

OBJECTIVES

This paper reports on the progress of an intermediate thermal mechanical processing (ITMT) study of aluminum lithium alloys to refine grain size for improved ductility and fracture toughness.

BACKGROUND

The first commercially available aluminum lithium aircraft alloy was designated 2020 by the Aluminum Association. 2020 had a nominal composition of 4.45 wt.% Cu, 1.2 wt.% Li, 0.51 wt.% Mn, and and 0.21 wt. % Cd. The alloy had mechanical properties of UTS 75ksi, YS 70ksi, and elongation 2%. This alloy was employed successfully as wing skin material on the A5 Vigilante; however, due to low fracture toughness, the alloy's production was discontinued in 1969 when the Vigilante's mission changed to one requiring damage tolerance.

Air frame manufacturers have recently focused a great deal of research and development effort on the exploitation of aluminum lithium alloys. (1,2,3) Aluminum lithium alloys have attractive properties with many exhibiting a 10% reduction in density and a 10% increase in modulus of elasticity over conventional high strength aluminum alloys. With the use of rapidly solidified powder (RSP) alloys, the specific modulus is increased 30% over that of 7075-T6. (4) In addition to their excellent mechanical properties, recent work indicates that many aluminum lithium alloys are superplastically formable. (1,5,6) Thus, aircraft weight can be significantly reduced; the manufacturing and servicing cost can also be reduced by superplastically forming complex components. However, despite their attractive properties, aluminum lithium alloys suffer from poor ductility (< 5% Elongation) and poor fracture toughness (< 20 ksi (in). (4)

The current demand for aircraft alloys with high specific properties has renewed interest in Al-Li alloy development and thermal mechanical processing to improve ductility and toughness. Improved thermal mechanical processes are being investigated to enhance these properties. (8,9,10) Thermal mechanical processing theory developed for 7000 series alloys is being applied to aluminum lithium alloys. Fundamentally, there are three types of thermal mechanical treatments used during the processing of aluminum alloys: (1) Primary thermal mechanical treatment (PTMT) which is used to eliminate casting inhomogeneities, (2) Intermediate thermal mechanical treatment (ITMT) which follows PTMT and is used to refine grain and subgrain structure, and (3) Final thermal mechanical treatment (FTMT) used to control precipitate morphology and distribution. ITMT has been used successfully to improve fracture toughness, ductility, and to induce superplasticity in 7000 series alloys. The basic process consists of aging to coarsen precipitates, cold/warm deformation, and recrystallization to refine the grain structure. (11,12,13) The present work seeks to extend the work of Starke and Lin (14) on the ITMT of aluminum lithium alloys and explore the role of heat treatment and cold deformation.

EXPERIMENTAL PROCEDURE

The ITMT consisted of a heat treatment, cold work, and recrystallization. The initial heat treatment was used to vary the amount and types of second phase precipitates present in the microstructure. Cold rolling was used to impart energy to promote recrystallization. Recrystallization was accomplished by annealing the cold rolled 2020 aluminum plate in a salt bath.

HEAT TREATMENT

Five types of thermal treatments were examined:

Type	Treatment
1.	SHT, 940°F, 2 min.; CWQ
2.	SHT, 940°F, 1 hr.; CWQ
3.	SHT, 940°F, 20 min.; CWQ; Age at 662°F, 2 hrs.
4.	SHT, 940°F, 1 hr.; CWQ; Age at 662°F, 2 hrs.
5.	SHT, 940°F, 2 hr.; FC to 775°F, 5 hrs.; FC to 400°F, 16 hrs

FC —Furnace cool
SHT —Solution Heat Treatment
CWQ—Cold Water Quench

SELECTION OF THERMAL TREATMENTS

Specimens were treated according to the above schedule and examined metallographically in the unetched and the etched condition. This enabled the selection of two treatments producing extremes in microstructure: (1) type 2, maximum solute in solution, and (2) type 5, minimum solute in solution. These heat treatments were used in the balance of the study.

COLD ROLLING

Six 2.5 inch × 6 inch × 0.875 inch thick plates of 2020 aluminum were cold rolled. Half of the material was put in the type 2 condition and the other half was put in the type 5 condition. The plates were rolled on a Stanet rolling mill using 6 inch diameter rolls. The percent reduction in areas (%RA) taken were 20%, 40%, and until cracking was observed.

RECRYSTALLIZATION

Samples from the rolled plate were cut into 1 inch by 1 inch specimens. The specimens were recrystallized in a low temperature salt bath operating at temperatures ranging from 840°F to 980°F. Two recrystallization experiments were performed: (1) isochronal recrystallization for 10,000s (2.78 hrs.) at 840, 900, 940, and 980°F, (2) isothermal recrystallization at 940°F for 10s, 100s, 1000s (16.7 min.), and 10,000s (2.78 hrs.). Hardness measurements were made prior to and after recrystallization. Hardness measurements were made on a Rockwell Hardness Tester using the R_A scale.

METALLOGRAPHY

The annealed and recrystallized samples were mounted, polished, and etched using Keller's Re je for microstructural analysis. Photomicrographs were taken on a Bausch and Lomb metallograph at several magnifications. Grain size was measured in the longitudinal and transverse directions of the plate. A line intercept technique was employed using a minimum of 50 grain boundary-line intercepts per sample.

EXPERIMENTAL RESULTS

THERMAL TREATMENTS

The microstructures of the samples heat treated in the five different manners were examined metallographically in the etched and unetched conditions. In the unetched condition, all the specimens had large dark constituent particles. These particles were more numerous in the type 5 treated material than in the other types of heat treated specimens. Figures 1a and 1b show the microstructure resulting from the type 5 and 2 treatments.

In the etched condition, types 1 and 2 heat treated material exhibited similar microstructures as did types 3 and 4. All the microstructures had elongated grains typical of rolled aluminum alloys, however, types 3 and 4 had coarse precipitates and wide precipitate free zones which highlighted the grain boundaries. The type 5 heat treatment resulted in a microstructure characterized by extremely coarse precipitates, wide precipitate free zones, and a classic example of a Widmanstätten pattern composed of coarse T_1 platelets. (Fig. 2 and 3)

ISOCHRONAL RECRYSTALLIZATION

Samples were recrystallized at 840, 900, 940, and 980°F for 10,000s (2.78 hrs). No recrystallization was observed in specimens treated at 840°F. The recrystallized grain sizes for the various processing conditions are reported in Table I. The longitudinal grain size prior to thermal mechanical processing was measured as between 532 and 571 microns and the transverse grain size as between 424 and 434 microns.

With increased amounts of cold rolling, the grain size is observed to decrease regardless of recrystallization temperature. Figures 4, 5, and 6 illustrate the effect of cold rolling on grain size at 900, 940, and 980°F. Increasing the amount of cold work to greater than 40% RA had little influence on grain dimensions. The finest grain sizes were achieved when the material was rolled until cracking was observed and recrystallized between 900 and 940°F. Cracking was observed at RA of greater then 49%. Longitudinal grain sizes were measured at between 10 and 14 microns.

The effect of processing parameters: heat treatment, % cold work, and recrystallization on the final longitudinal and transverse grain size is illustrated in Figure 7. The grain size on the material recrystallized at 900°F is 19% smaller than that recrystallized at 980°F. Increasing the amount of cold work from 20 to 49% RA, decreases the average grain dimension by 57%. Material put in the super-saturated solid solution condition by a type 2 heat treatment has a grain size 8% greater than the overaged material-type 5 treated.

ISOTHERMAL RECRYSTALLIZATION

Type 2 and 5 heat treated specimens cold rolled 40% were recrystallized at 940°F. The recrystallization time was varied from 10s to 10,000s (2.78 hrs). Microstructural analysis indicates that 100% recrystallization had occurred after 10,000s (2.78 hrs). Figures 8 and 9. The overaged samples show fine nuclei formation at 10s; however, the super saturated solid solutionitized material does not. It is worth noting that even after only 10s, the coarse overaged microstructure exhibited by the type 5 treated material had completely dissolved. Also, the recrystallized grains of the type 5 treated material appear more equiaxed than the type 2 treated specimens.

Hardness measurements were made immediately after cold rolling and recrystallization. This data is presented in Table II. After cold rolling, the type 2 material had hardness a value 42% greater on the Rockwell A scale than the type 5 material. Hardness values drop off precipitously during the first 10s of recrystallization and then level off. Hardness is observed to increase slightly with extended times at temperature.

DISCUSSION

The 2020 aluminum plate was successfully ITMT processed to a fine equiaxed grain structure of about 10 microns in size. The controlling process parameters are % cold work, initial microstructure, and recrystallization temperature. The final grain size is most dramatically affected by the % cold rolling followed by recrystallization temperature and starting microstructure.

Cold rolling imparts energy to the aluminum plates. During recrystallization, this stored energy is released and the result is the nucleation and growth of new grains. Thus, it appears reasonable that the more cold work imparted to the material, the greater the number of initiation sites. Cold work increases the internal energy of a material up to a point; then, the amount of stored energy remains essentially constant. Figures 4, 5, and 6 show how cold work affects grain size and how grain size is relatively uneffected by cold rolling past 40% reduction in area.

The final grain dimension is also affected by the recrystallization temperature used. At 840°F, no recrystallization was observed; however, at 900°F and above recrystallization took place. This confirms the findings of Starke and Lin(14) which indicated that there was a temperature minimum which must be exceeded in order for recrystallization to occur. Recrystallization is predicated upon nucleating new grains by the appropriate release of stored energy. This points to two important factors: heating rate, and microstructure. Slow heating allows for the gradual dissipation of this energy; rapid heating releases the energy quickly permitting its utilization. Furthermore, at lower temperatures the precipitates have not dissolved fully and hence retard grain growth.

Increasing the recrystallization temperature from 900 to 980°F resulted in a larger grain size. This may be attributable to grain growth. The energy for grain growth, unlike recrystallization, is exponentially related to temperature. At these temperatures, only thermally stable precipitates help restrain unwanted grain growth.

The recrystallized grain size of the overaged material in which coarse precipitates were evident at 100x was finer than the recrystallized grain size of the solutionitized material. This may be the result of an increased amount of stored energy during rolling. The precipitates inhibit dislocation motion and act as heterogeneous nucleation sites during recrystallization.

CONCLUSIONS

1. An ITMT has been developed to reduce the grain size of 2020-T6 plate from over 400μm to 10μm.

2. Minimum grain size is obtained by cold rolling 40-50% and recrystallizing at 900-940°F for 10,000s (2.78 hrs).

3. 2020 plate can not be recrystallized below 840°F.

4. 2020 can not be cold rolled more than 49% without causing cracking.

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Table I
Grain Size (um) of 2020 Aluminum After Recrystallizating for 10,000s(hrs)

Recrystallization Temperature(°F)	% Reduction in Area 0	20	40	49
I. Supersaturated Solid Solution				
A. Transverse Grain Size				
900	434	33	19	8
940	434	34	29	8
980	434	38	29	18
B. Longitudinal Grain Size				
900	571	54	21	11
940	571	74	45	9
980	571	66	50	22
II. Overaged				
A. Transverse Grain Size				
900	424	30	26	11
940	424	27	25	10
980	424	31	27	16
B. Longitudinal Grain Size				
900	532	43	31	15
940	532	64	45	13
980	532	57	37	16

Table II.

Hardness(RA) of 2020 Recrystallized at 940°F

% Reduction in area	After Rolling	Annealing Time(s) 10	100	1,000	10,000
I. Super Saturated Solid Solution					
20	41	26	28	28	24
40	45	27	26	26	25
49	--	36	30	28	26
II. Overaged					
20	19.5	13.5	17	17	22
40	30	26	15	21	20
58	--	13	18	27	28

a

b

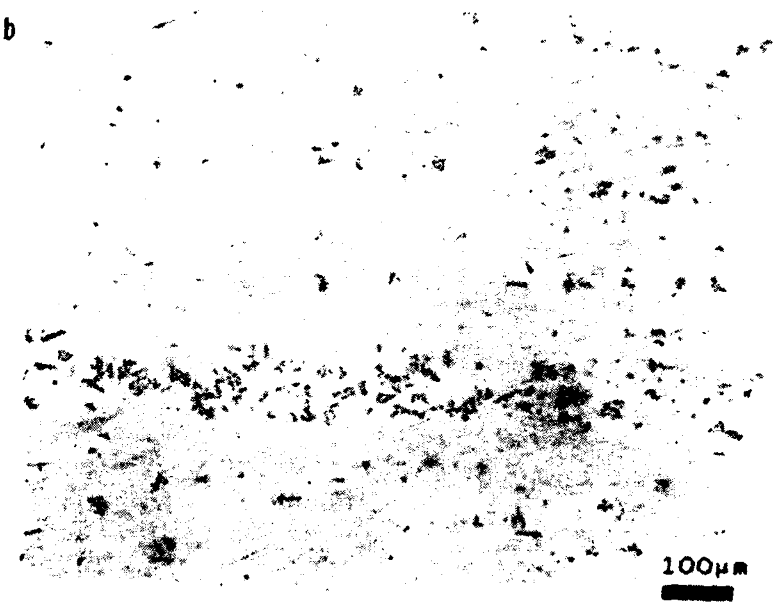

Figure 1. Unetched microstructures of 2020: a) heat solution heat treated at 959°F for one hour and CWQ; b) solution heat treated at 959°F for two hours; 775°F for five hours; and 400°F for 16 hours.

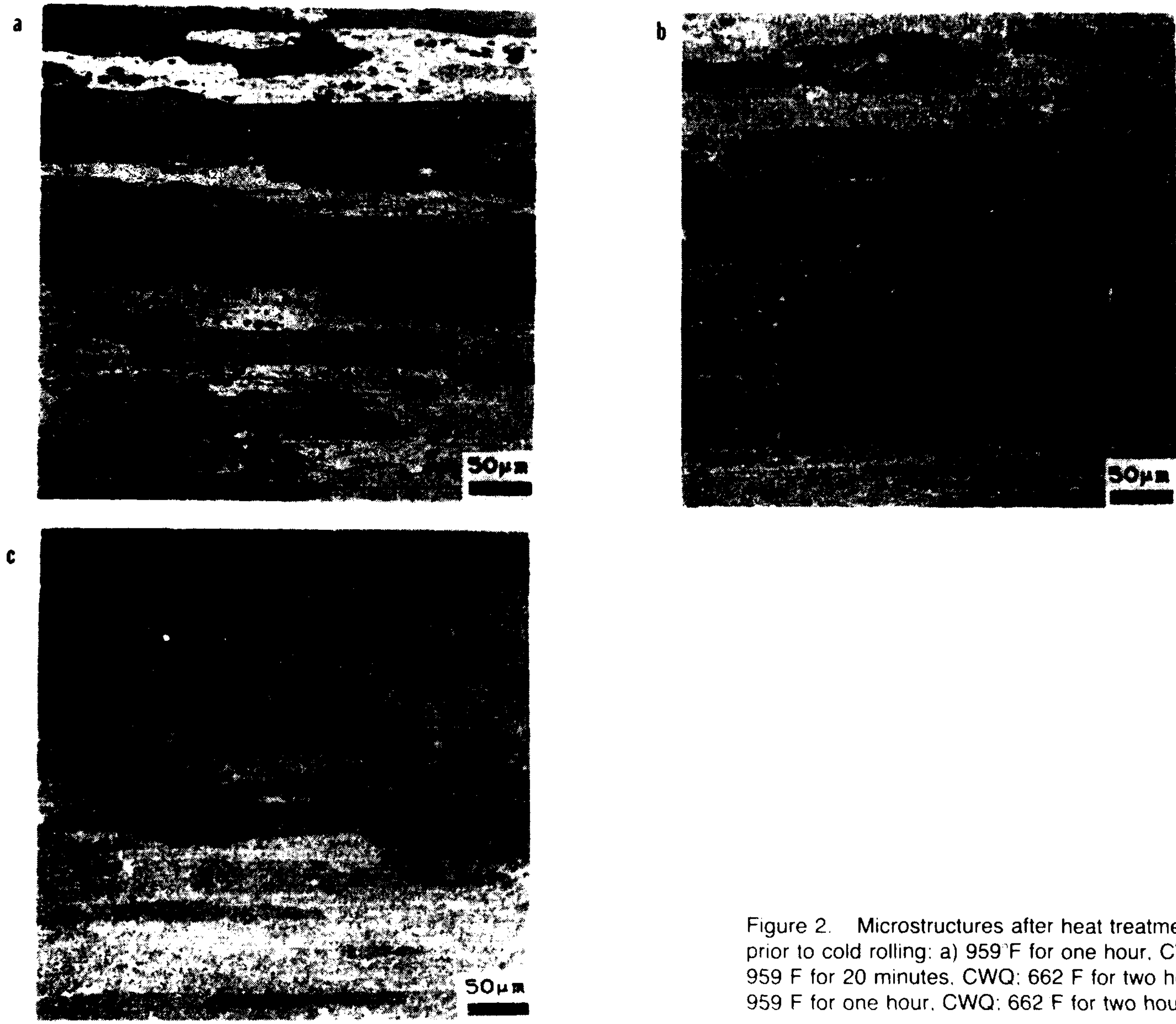

Figure 2. Microstructures after heat treatment and prior to cold rolling: a) 959°F for one hour, CWQ; b) 959 F for 20 minutes, CWQ; 662 F for two hours; c) 959 F for one hour, CWQ; 662 F for two hours.

a

b

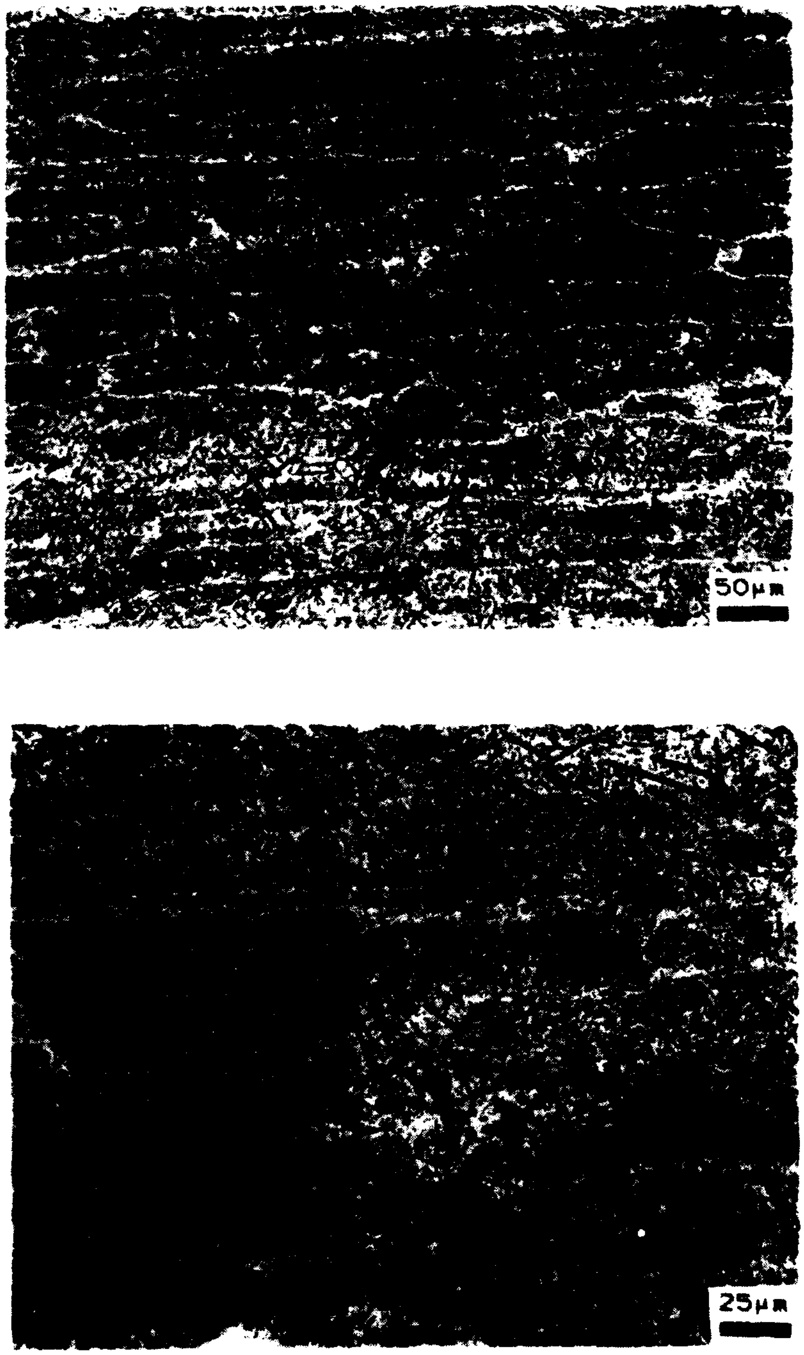

Figure 3. Microstructure of 2020 after heat treatment and prior to cold rolling: 959°F for two hours; 775°F for five hours; 400°F for 16 hours.

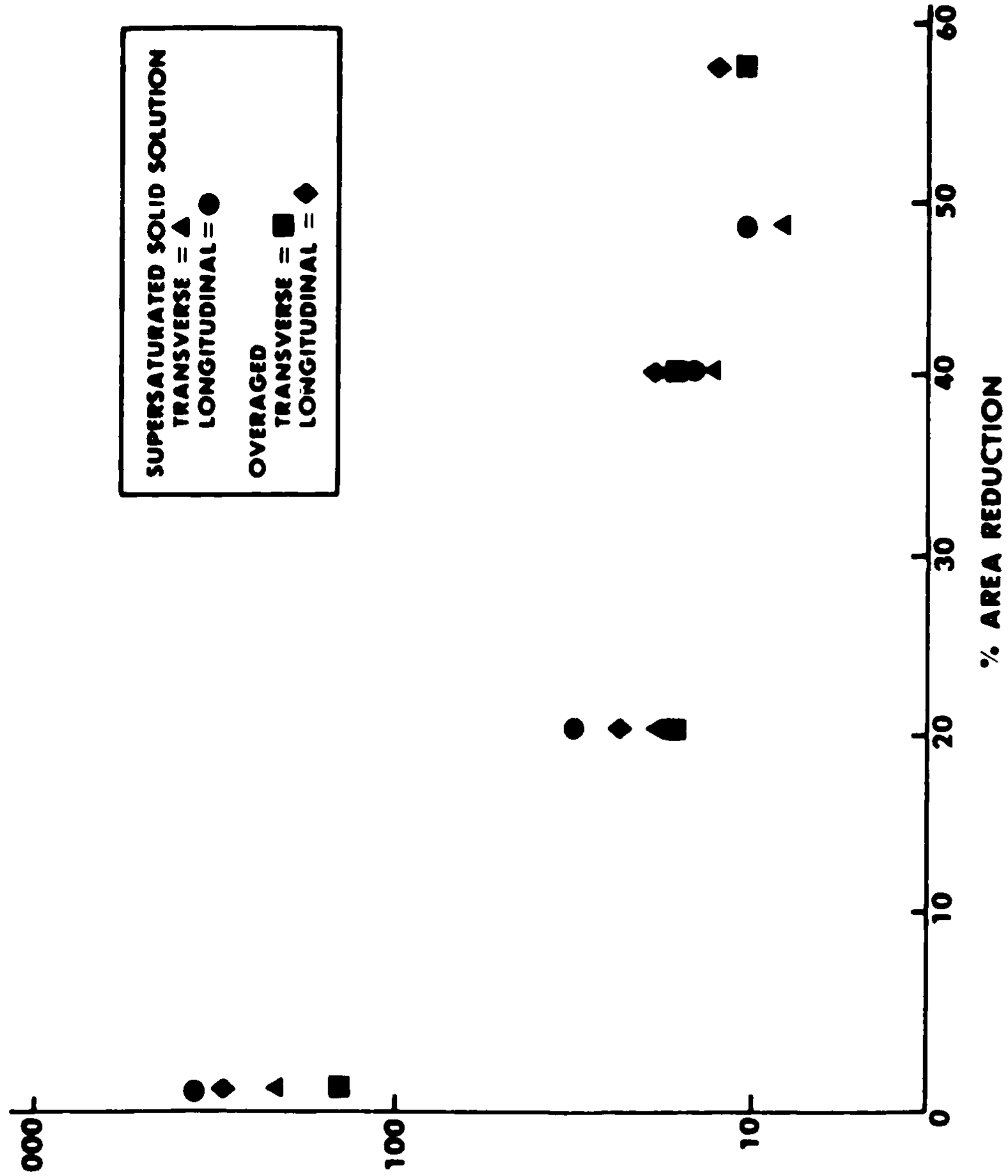

Figure 4. Grain size of 2020 aluminum recrystallized at 900°F for 10,000 s.

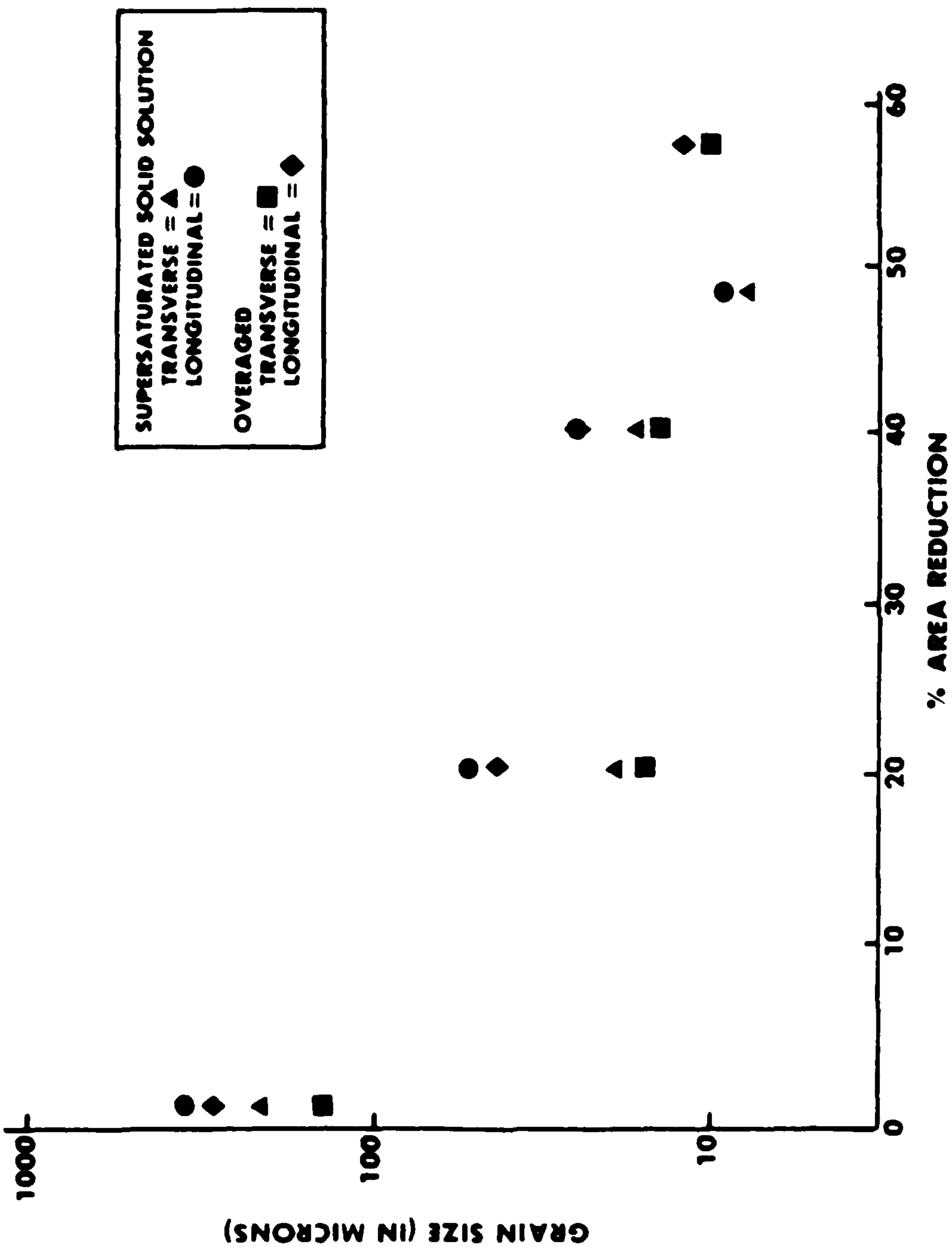

Figure 5. Grain size of 2020 aluminum recrystallized at 940°F for 10,000 s.

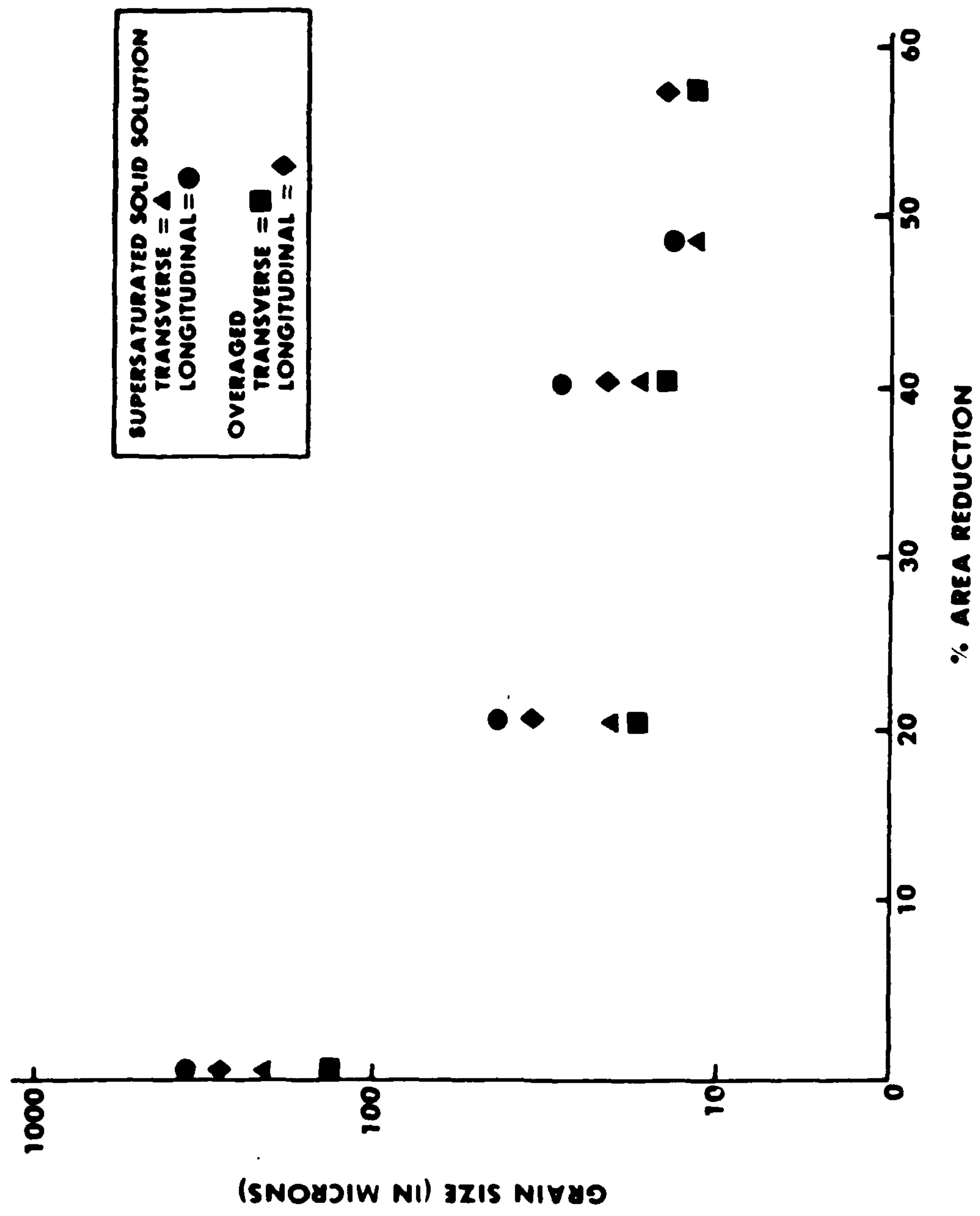

Figure 6. Grain size of 2020 aluminum recrystallized at 980°F for 10,000 s.

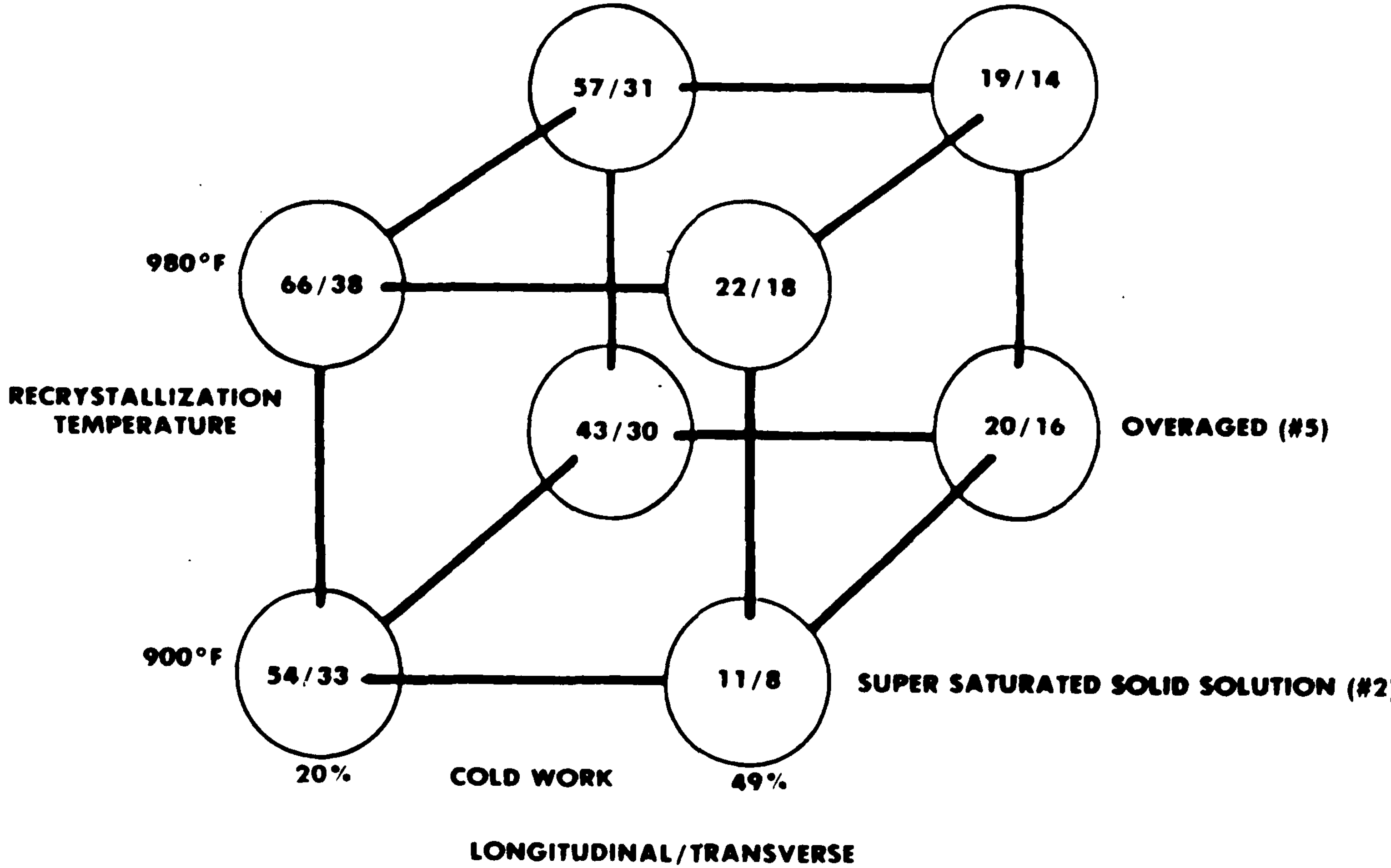

Figure 7 Recrystallized grain size of 2020 aluminum plate as a function of processing parameters: recrystallization temperature, cold work, and heat treatment.

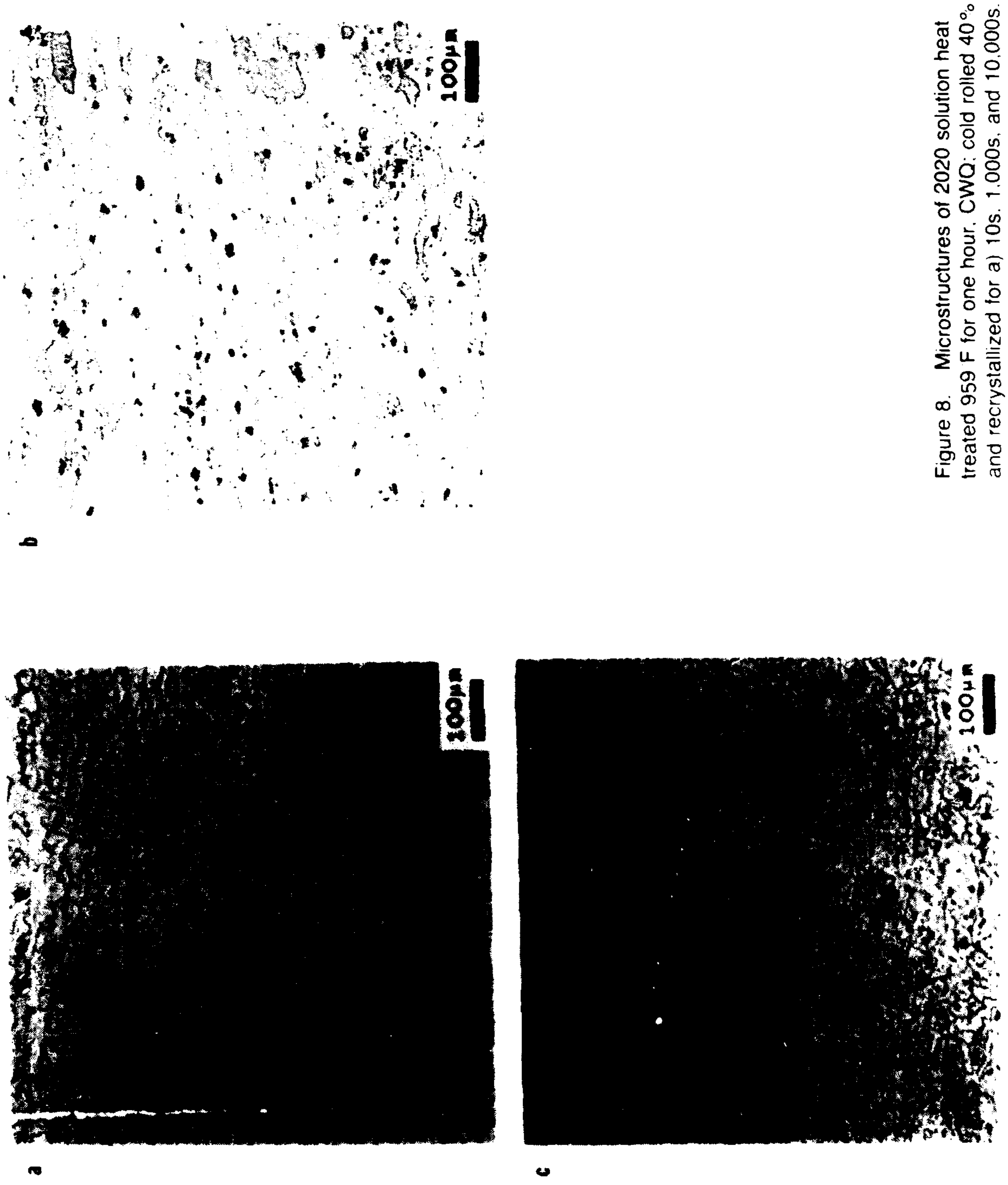

Figure 8. Microstructures of 2020 solution heat treated 959 F for one hour, CWQ; cold rolled 40% and recrystallized for a) 10s, 1,000s, and 10,000s.

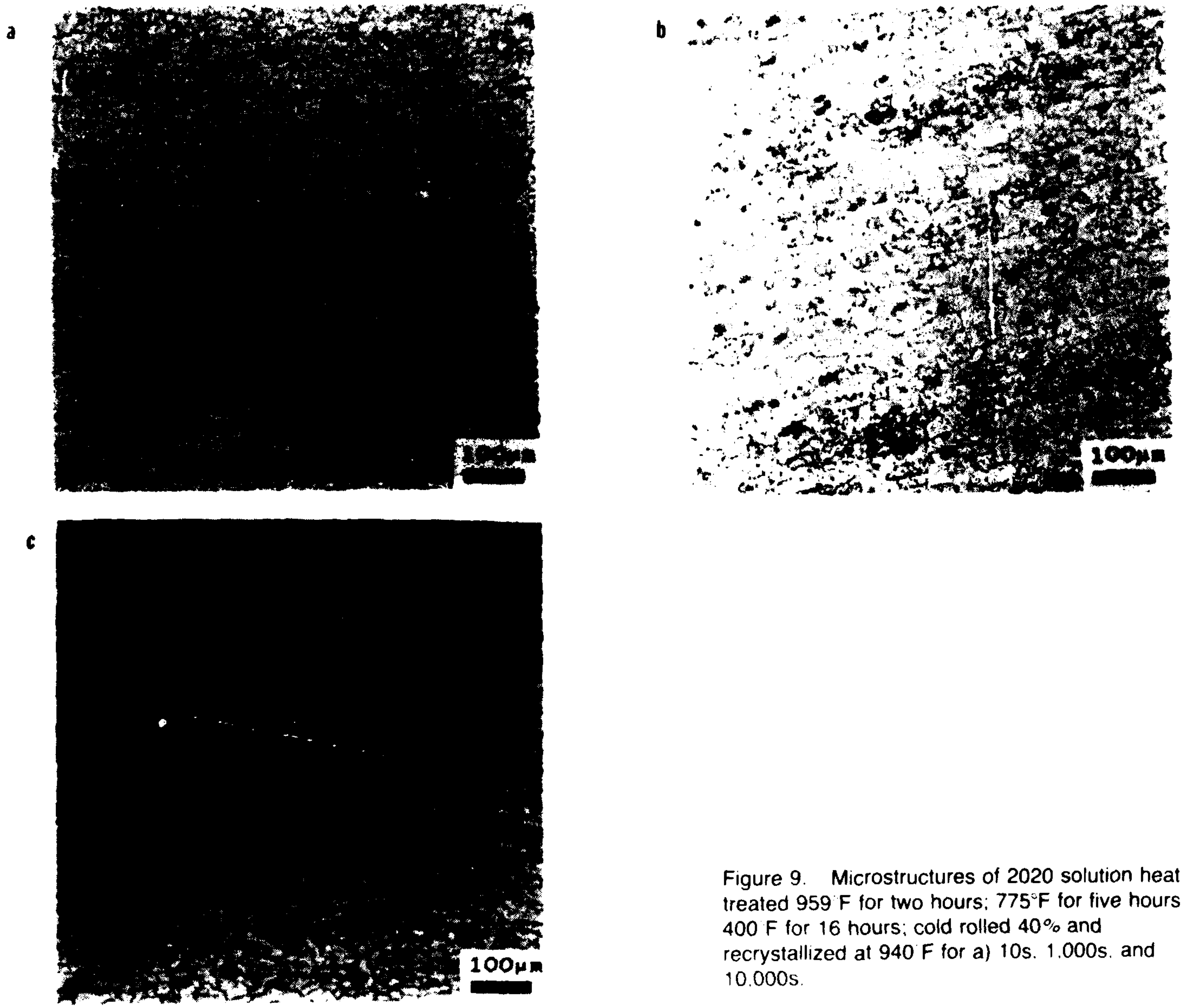

Figure 9. Microstructures of 2020 solution heat treated 959°F for two hours; 775°F for five hours 400°F for 16 hours; cold rolled 40% and recrystallized at 940°F for a) 10s, 1,000s, and 10,000s.

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