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ANN ARBOR, MICH.

ABNORMAL GRAIN GROWTH IN NICKEL-BASE
HEAT-RESISTANT ALLOYS

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Report 51

to

THE NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

May 11, 1956

Project 1478-10

engn

UMR 6587

SUMMARY

A laboratory study was carried out to establish the basic causes of abnormal grain growth in air- and vacuum-melted Waspaloy, Inconel "X"-550 and Nimonic 80A. All of the results indicated that small reductions of essentially strain free metal were the basic cause of abnormal grain growth. Between reductions of 0.4 and 5.0 percent in most cases, there was a narrow range of reductions responsible for abnormal growth. In a few special cases the responsible reductions were as low as 0.1 percent and as high as 9.7 percent.

The prevention of abnormal grain growth clearly requires avoidance of small critical reductions. The main problem is to anticipate and avoid conditions leading to critical deformation. Insuring that all parts of a metal piece receive more than 5 to 10 percent reduction will prevent it. Non-uniform metal flow during hot working operations is probably the major source of abnormal grain growth. Any small reduction, particularly if it includes a strain gradient so that the critical reduction will definitely be present, is a common source. Strains arising from thermal stresses during rapid cooling can develop susceptibility. Removal of strain by recrystallization during working followed by a small further reduction can, in certain cases, induce abnormal grain growth in the presence of large reductions.

The phenomena of abnormal grain growth is remarkably independent of temperature of working and of heating temperatures. If the heating temperature and time are sufficient for abnormal grain growth, higher temperatures increase the grain size only slightly. Prior history of the alloys before critical straining also has relatively little effect, provided the prior treatment reduces strain below the critical amount. Certain conditions of working or heating seemed to minimize abnormal grain growth. These, however, do not appear dependable for controlling

abnormal grain growth due to the probability that their effectiveness is dependent on prior history.

The influence of alloy composition seems to be mainly in variation of the excess phases which restrict grain growth. A somewhat smaller grain size in vacuum-melted than in air-melted Waspaloy was apparently due to more grain growth restrainers resulting from a higher carbon content. Inconel "X"-550 did not undergo abnormal grain growth at 1950°F as did Waspaloy and Nimonic 80A alloys. At 2150°F, the normal solution temperature for Inconel "X"-550, it did occur. Apparently the more stable columbium compounds in Inconel "X"-550 restrained grain growth to a higher temperature than the less stable growth restrainers in the other alloys.

INTRODUCTION

A study of the causes of abnormally large grains forming in nickel-base heat-resistant alloys during hot-working or subsequent final solution treatment was carried out. The alloys investigated were Waspaloy and Inconel "X"-550. Vacuum-melted Waspaloy, reputed to be less susceptible to grain growth, as well as air-melted material, were included in the investigation. A limited amount of data for Nimonic 80A is included from another investigation (ref. 1). One previous report (ref. 2) presented preliminary results for a similar study of S-816 alloy.

The objective of the investigation was to establish the fundamental principles governing the formation of abnormally large grains during hot working and final heat treatment in heat-resistant alloys of the types used in the gas turbines of jet engines. For purposes of this investigation, any grains larger than ASTM number 1 were considered abnormally large. Furthermore, the investigation was mainly limited to normal conditions of heating for hot working and for heat treatment, it having been well established that the abnormal grain growth of interest occurred under these conditions. However, a few experiments involving temperatures higher than normal were included.

The presence of abnormally large grains has been associated with poor properties in heat-resistant alloys, particularly low fatigue strength and brittleness under creep-rupture conditions. The consequent necessary grain size control is a recurring problem in making forgings and other hot-worked products from the heat-resistant alloys used in aircraft gas turbines. In practice, procedures for hot working are eventually developed which eliminate or minimize grain size problems. Those developed have generally been empirical and have not defined the basic principles involved. The data included in this report for Nimonic 80A alloy, for instance, represent experiments carried out to help clarify a production problem of grain size control in an alloy which has been extensively used.

The general procedure of the investigation was to carry out controlled laboratory experiments on samples of bar stock to find conditions of heating and hot working which resulted in abnormal grain growth. Like the previous results for S-816 alloy (ref. 2), this investigation did not disclose any conditions for abnormal grain growth other than by small amounts of critical deformation. The investigation does, however, define many conditions which lead to such critical deformation which are not as obvious as simple small amounts of deformation during hot working.

The investigation was carried out by the Engineering Research Institute of The University of Michigan under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics. The members of the NACA Subcommittee on Power Plant Materials assisted in the planning of the experimental program, particularly by defining conditions of working where grain growth problems had been troublesome.

PROCEDURES

The general procedures used to establish conditions leading to abnormal grain growth were as follows:

1. Commercially produced bar stock was used for experimental materials. The only exception was small commercially produced ingots of vacuum-melted Waspaloy rolled to bar stock at the University.

2. Most of the as-received bar stock was not suitable for experimental research due to uneven grain growth or to the presence of susceptibility to abnormal grain growth during reheating to hot-working or solution treating temperatures. Accordingly, most stock was given an "equalizing treatment" designed to produce a uniform reasonably fine grained material for experimental purposes. This treatment usually consisted of:

- (a) A fairly heavy reduction by rolling.

- (b) A heat treatment of one hour at the usual solution treating temperature for the alloy.

The cooling rate after the equalizing heat treatment was either air cooling or oil quenching. Water quenching made all of the alloys susceptible to abnormal grain growth on the surface of the bars. In some cases even air cooling developed some susceptibility to such growth. An equalizing heat treatment was, however, necessary. Otherwise, the initial uneven grain growth characteristics could mask the influence of the experimental conditions used to obtain abnormal grain growth.

The conditions of equalizing treatment were sometimes deliberately varied, or the treatments omitted, to study the influence of such factors on abnormal grain growth characteristics.

3. Repeated heating and cooling was used to study the abnormal grain growth induced by thermal stresses alone. Water quenching, oil quenching and air cooling were used to vary the cooling rate and resultant thermal stresses.

4. The influence of amount and temperature of working was studied by rolling tapered specimens to flat bars between open rolls in a rolling mill. The tapered specimens were usually machined from the equalized stock. Two types of specimens (fig. 1) were used to give reductions ranging from zero to about 15 or 29 percent. The specimens were placed in a furnace at the temperature selected for rolling and held in the furnace one half hour before rolling. In most cases, only one pass through the rolls was used. The specimens were air cooled from the rolling operation.

A few experiments were carried out using tensile specimens to obtain uniform reduction to study the comparative effects of uniform strain and the strain gradients from the tapered specimens.

5. The rolled specimens were heated to the usual solution treating temperatures for the usual times for grain growth to occur. In some cases, the specimens were cut into two pieces parallel to the direction of rolling before solution treatment. One half was examined in the as-rolled condition and the other after solution treatment.

6. The specimens were then carefully measured and the reduction in cross-sectional area computed. The specimens were sectioned and examined microscopically for grain size along the lengths of the rolled bars.

7. The grain size rating system used was that established by the American Society for Testing Materials (ref. 3). It was necessary to extend this system to larger sizes than number 0 through the notation (-1) to (-5) grain size. The actual grain sizes involved were as follows:

<u>ASTM Grain Size Number</u>	<u>Grains per sq. in. of Image at X100D</u>	<u>Approximate Diameter of Grains (inch)</u>
8	128	.0009
7	64	.0012
6	32	.0018
5	16	.0025
4	8	.0035
3	4	.005
2	2	.007
1	1	.010
0	0.5	.014
(-1)	0.25	.020
(-2)	0.125	.028
(-3)	0.0625	.040
(-4)	0.0312	.056
(-5)	0.0156	.080

In reporting grain sizes, the range is given in the tables of data. The graphical presentations are generally limited to the maximum size.

EXPERIMENTAL MATERIALS

The experiments were carried out on bar stock commercially produced from air-melted heats, with the exception of the vacuum-melted Waspaloy. The information furnished by the suppliers of the test materials is given in the following sections.

Waspaloy

The air-melted material was supplied gratis by the Allegheny Ludlum Steel Corporation as 1 inch square bar stock made from a 9 inch ingot from Heat 43638. The vacuum-melted material was supplied gratis by the Utica Drop Forge and Tool Corporation as a 2-inch diameter ingot from Heat 3-259. The chemical analyses, in weight percent, supplied by the producers were as follows:

<u>C</u>	<u>Mn</u>	<u>Si</u>	<u>Cr</u>	<u>Ni</u>	<u>Co</u>	<u>Mo</u>	<u>Ti</u>	<u>Al</u>	<u>Fe</u>	<u>Cu</u>	<u>S</u>	<u>P</u>
<u>Heat No. 43638</u>												
0.03	1.14	0.63	18.8	bal.	13.7	3.15	2.56	1.43	1.18	0.11	0.015	0.016
<u>Heat No. 3-259</u>												
0.08	0.27	0.57	19.8	bal.	13.8	3.90	3.17	1.15	0.69	<.10	0.005	

The small ingots of vacuum-melted stock were hot rolled at 1950°F to 3/4 and 1/2 inch bars at The University of Michigan.

Inconel "X"-550 Alloy

The stock was furnished gratis by The International Nickel Company as hot-rolled 2-1/4 inch by 1-1/16 inch flat bars from Heat Y7180X. The only other information supplied was the following report of chemical composition on a weight percent basis:

<u>C</u>	<u>Mn</u>	<u>Fe</u>	<u>S</u>	<u>Si</u>	<u>Cu</u>	<u>Ni</u>	<u>Cr</u>	<u>Al</u>	<u>Ti</u>	<u>Ta + Cb</u>
0.05	0.73	6.59	0.007	0.28	0.03	72.63	14.97	1.16	2.50	1.03

Nimonic 80A Alloy

This material was in the form of 1/2 inch hot-rolled centerless ground bar stock which had been purchased by the Continental Aviation and Engineering Corporation from commercial air-melted Heat 5331B made by The International Nickel Company.

The following report of chemical composition on a weight percent basis was supplied:

<u>C</u>	<u>Mn</u>	<u>Fe</u>	<u>S</u>	<u>Si</u>	<u>Cu</u>	<u>Ni</u>	<u>Cr</u>	<u>Al</u>	<u>Ti</u>
0.05	0.55	0.59	0.007	0.34	0.05	Bal.	20.5	0.98	2.20

FACTORS INFLUENCING GRAIN GROWTH

A number of factors influenced observed grain growth characteristics in the experimental materials. Because these were fairly complicated, consideration of the following discussion of some of these factors will help in understanding the results of the studies:

1. The experimental materials in the as-received condition had been hot-worked to bar stock under unknown conditions. In some cases the grain sizes were initially mixed. The grain growth characteristics when reheated to normal

hot-working or solution treating temperature indicated susceptibility to abnormal or uneven grain growth in most cases. Usually this tendency varied along the bar stock lengths.

2. These varied and uncertain prior history effects were minimized in most experiments by an "equalizing treatment". This was a fairly heavy reduction by rolling combined with a heat treatment for one hour at the normal solution temperature. This gave a uniform grain structure in material with uniform response to subsequent experimental variables. The cooling rate from the heat treatment had to be restricted to air or oil quenching to avoid susceptibility to abnormal grain growth on the surface during subsequent reheating.

It should be recognized that there are certain important considerations involved in these equalizing treatments:

(a) The best way to avoid uneven or abnormal grain growth during any subsequent heating is to introduce more than a minimum amount of uniform work into the stock. As discussed later, this should be a reduction larger than at least 5 percent. Material given such reductions would, however, be unsuitable for the experimental program because the initial reduction would mask the experimental variables to be studied.

(b) The equalizing treatments do not make the material independent of prior history. The actual grain size is influenced by the prior working and heating conditions. It can be postulated that if the prior working results in a material which undergoes recrystallization and grain growth to uniform reasonably fine grain size, it is then in a condition suitable for study of abnormal grain growth. The recrystallization reduces prior strain hardening to a minimum. As far as is known, some other sequence of treatments could have resulted in a different initial grain structure. This, however, would alter the results of the experiments only in detail.

(c) The heat treatment step probably did not attain the equilibrium grain size for the temperature of heating. Secondly, the degree of solution of excess phases was probably variable. Thirdly, the cooling from the heat treatment introduced a small strain in the surface of the metal. However, by air cooling or oil quenching, this was kept below the critical amount required for abnormal grain growth.

3. The equalized material when reheated for working might or might not have undergone further alteration of grain structure as a result of the additional heating before working actually started.

4. When the tapered specimens were rolled, a range of conditions were set up in the specimens:

(a) A zone of no reduction where any change should have been only that induced by reheating.

(b) A zone of increasing amounts of strain resulting from the increasing reduction.

(c) If the temperature of reduction was too low for any recrystallization for the range of reductions, the whole length of the specimen was strain hardened. This was dependent on the amount and temperature of reduction and the opportunity for recovery during cooling.

(d) If the temperature of working was sufficiently high for recrystallization during working, there was a zone of increasing strain hardening followed by a zone at the larger reductions where strain hardening had been reduced by the recrystallization. In general, the zone of cold-worked material decreased with increasing temperature of reduction. The zone of recrystallization was reduced in strain hardening in proportion to the degree of completeness of recrystallization. In general, this increased with both temperature and amount of reduction.

(e) The air cooling from working introduced some surface strain from the thermal stresses.

5. When the tapered specimens were reheated for solution treatment, the reaction was characterized by zones as follows:

(a) A zone of no or very small reduction where the grain growth was mainly dependent on the further growth to be expected from unstrained material. Presumably the machining of the tapered specimen removed any surface metal strained during cooling from the equalizing treatment. Consequently, only the air cool from the working temperature was involved.

(b) A zone, covering reductions generally in the order of 0.4 to 5.0 percent, which was critically strained, resulting in a few grains growing to abnormal sizes.

(c) A zone of higher reductions where deformation resulted in more grains growing in competition to prevent abnormal final grain size.

(d) At still larger reductions recrystallization definitely occurred in the more severely strainhardened metal during reheating unless it occurred during working. In the latter case grain growth occurred. Many of the specimens showed partial recrystallization at the heavier reductions. Presumably recrystallization occurred during reheating in those locations where it did not occur during rolling. The zones of recrystallization presumably underwent grain growth.

EXPERIMENTAL RESULTS

Grain growth data were obtained for Waspaloy and Inconel "X"-550. In addition, data are reported for experiments on Nimonic 80A material from another investigation. The major experimental conditions studied were induction of abnormal grain growth by repeated heating and cooling and by deformation by rolling.

In the experiments involving rolling, tapered specimens were rolled to flats. In the regions of small reductions causing abnormal grain growth, as discussed in subsequent sections, the grain growth was remarkably uniform across the entire section of the specimens. The line of demarkation at the smallest reduction causing such growth was very sharp. The recrystallization and grain growth was also uniform on a macroscopic scale across the bar section. Recrystallization during working or after solution treatment, however, was often banded.

Air- and Vacuum-Melted Waspaloy

Grain growth experiments were carried out on bar stock from both air- and vacuum-melted heats. A number of experiments were carried out on the bar stock to establish grain growth characteristics and to develop initial treatments which would provide a reasonably uniform and fine initial grain size.

In the as-received condition, the air-melted stock was fine grained on the outside with a mixed grain size in the center (fig. 2). This material developed a non-uniform grain size when heated to 1950°F (fig. 3). Using higher temperatures than 1950°F reduced the variation in grain size and did not cause large grains to form (fig. 3). It was considered, however, that it would be best to further reduce the bar stock by rolling before heat treatment to obtain a uniform fine grain size with the normal treatment at 1950°F. A reduction of 70 percent from 1950°F followed by a treatment of one hour at 1950°F was applied to material used for the repeated heating and cooling experiments. This gave a grain size of 4 to 6 (fig. 3). A similar grain size was obtained by a reduction of 50 percent from 1950°F (fig. 4) and this treatment was used for all the deformation experiments except when prior treatment was deliberately varied. Figure 4 shows that rolling at 1950°F to a reduction of 50 percent resulted in partial recrystallization to very fine grains. However, this material had a uniform grain size of 4 to 6 after heating 1 hour at 1950°F (fig. 4).

The vacuum-melted stock as originally rolled had a grain size of 5 to 8 (fig. 5). Heating to 1950°F for one hour gave a grain size of 4 to 7 (fig. 5). The latter condition was used for all of the grain growth experiments.

Induction of Abnormal Grain Growth by Repeated Heating and Cooling

The experiments conducted and the resulting grain sizes are summarized by figures 6 through 9. The observed grain growth characteristics were:

1. Air cooling did not induce abnormal grain growth in air-melted stock. There was a gradual increase in grain size during four reheats so that the final grain size was 2 to 4 with few random number 0 grains (fig. 6). Vacuum-melted stock was also free from abnormal grain growth as a result of repeated heating and air cooling. The normal grain growth was less than for the air-melted stock, final grain size being 3 to 6 (fig. 8).

It should be noted that one 4 hour cycle gave nearly the same grain sizes as 4 cycles of one hour duration (figs. 6 and 8).

2. Water quenching between reheats did induce abnormal grain growth starting at the surface in both air- and vacuum-melted stock. The air-melted stock developed larger grains and a larger percentage of abnormal grains (figs. 6 and 8). Figures 7 and 9 show typical microstructures.

Again it should be noted that a 4 hour reheat to 1950°F developed just about as much abnormal grain growth as 4 cycles of one hour at 1950°F (fig. 8).

3. Air-melted material initially water quenched from 1950°F but air cooled during four subsequent cycles to 1950°F underwent nearly the same abnormal grain growth as material water quenched during each cycle. The initial water quench appeared to be the critical factor controlling abnormal grain growth (fig. 6).

4. Oil quenching did not induce significant abnormal grain growth in air-melted stock. The largest grains formed were number 0 in size (fig. 6).

The experiments indicate that:

1. For the sizes and shapes studied, air cooling or oil quenching did not induce abnormal grain growth during subsequent reheating. Water quenching did induce abnormal grain growth in both air- and vacuum-melted materials during subsequent reheating.

2. The governing factor in the abnormal grain growth was time of heating at the solution temperature and not the number of times the materials were reheated and quenched. One water quench was just as effective as four.

3. The vacuum-melted material did not develop quite as large grains as the air-melted stock.

Induction of Abnormal Grain Growth by Deformation

All of the experiments were designed to establish the conditions which lead to abnormal grain growth during a standard final solution treatment of 4 hours at 1950°F. Therefore, all grain size ratings are based on material which had been solution treated after subjection to various initial treatments possibly influencing grain growth.

The main result was that grains larger than number 1 were induced in material which had been reduced between 0.4 and 5.0 percent. A limited number of special conditions resulted in abnormal grains when reductions were as small as 0.1 percent or as large as 9.7 percent. In these limited cases, abnormal grain growth did not occur over this entire range of reductions; but rather did occur over some narrow reduction within this range.

There was a very sharp increase to grain sizes of (-3) to (-4) at the lower side of this range in reductions, usually for reduction between 0.4 and 1 percent. The grain size then diminished so that for most cases when the reduction was 5 percent, the maximum grain size was number 1 or less.

The following additional features of the results can also be generalized:

1. The range of reduction for abnormal grain growth was independent of temperature of reduction.

2. Vacuum-melted stock underwent abnormal grain growth after the small critical reductions in the same manner as the air-melted stock. The maximum grain size was, however, less for the vacuum-melted material; the usual differential being about two sizes smaller for the vacuum-melted material.
3. Working above the solution temperature of 1950°F generally reduced maximum grain size in the area of abnormal grain growth in air-melted stock.
4. A number of conditions of working and heat treatment prior to critical reductions were found to have little effect on the tendency for abnormal grain growth.
5. Uniform reductions more than the critical amount prior to a critical reduction did not completely suppress the abnormal grain growth.
6. Uniform critical reduction in a tensile machine also induced abnormal grain growth.
7. A very steep strain gradient from working tended to suppress maximum grain size, apparently by restricting the amount of metal subject to abnormal grain growth.
8. A limited number of experiments were not successful in inducing abnormal grain growth as a result of partial recrystallization during working.

The details of the data which led to these summarized results are discussed in the following sections.

Effect of amount and temperature of reduction. - Abnormal grain growth was induced at some small reduction in all specimens of air-melted stock regardless of the temperature of rolling (See table I and fig. 10). The reductions inducing this grain growth were between 0.7 and 3.0 percent. The maximum grain size in this region of reductions was (-3) to (-4) except for rolling at 2000° and 2100°F when it was (-2). The grain size was less than number 1 for all reductions larger than 1.8 to 5 percent depending on the rolling temperature. Typical microstructures along a tapered specimen are shown in figure 11.

The rolling temperature had very little effect on that portion of the specimens which was not reduced, except when the rolling temperature was 80° or 2100°F. The maximum grain sizes shown by figure 10 were remarkably similar for reductions larger than the critical amount for all temperatures of rolling. Apparently, the varying degrees of recrystallization during rolling at 1800° to 2100°F did not greatly alter the final grain size from that induced by strain hardening at lower temperatures of rolling.

Vacuum-melted stock responded similarly to the air-melted stock (table II and fig. 12) except that the maximum grain size was (-2). The overall grain size was also finer. There also was no difference in maximum grain size in the critically reduced section between samples rolled at 2100°F and lower temperatures. Typical microstructures are shown in figure 13.

It will be noted that the change in grain size in the critical section was the same for both air- and vacuum-melted material. Although this suggests change in grain size as a controlling factor in grain growth from critical reduction, it was not borne out by subsequent studies.

Influence of prior history on abnormal grain growth. - A number of details in the treatments prior to rolling as tapered specimens were varied. The more important results were:

1. Omission of the heat treatment at 1950°F after a reduction of 50 percent at 1950°F did not completely eliminate the susceptibility to abnormal grain growth from critical reduction although it greatly reduced maximum grain size (table I and fig. 14). This was true for specimens rolled both at room temperature and 1600°F. The only difference for the two cases was the rather high reduction of 6 to 10 percent for abnormal growth when rolled at 1600°F. It had been expected that there would be no tendency for abnormal growth from critical reduction after this heavy initial reduction.

The results of the preceding section showed that a reduction of more than 5 percent at any temperature restricted the grain size to less than number 1. It was presumed that superimposing any further amount of reduction would not alter the tendency to produce fine grains during solution treatment. Data presented later for specimens strained uniformly in tension tend to show that the amount of deformation and not strain gradients is the controlling factor in critical deformation for abnormal grain growth. This then suggests that the superimposing of a strain gradient on material strained past the critical amount was not responsible for retention of some tendency for abnormal grain growth.

It is important to recognize in considering these possibilities that, as reduced 50 percent at 1950°F, the metal was not susceptible to abnormal grain growth. It does, however, seem apparent that further reduction at some lower temperature can induce abnormal grain growth. It is highly probable that this susceptibility arises from partial simultaneous recrystallization leaving areas of essentially strain free material which can be subsequently critically strained.

2. Air cooling from the 1950°F treatment instead of oil quenching did not substantially alter the maximum grain growth caused by critical reduction at 80°F (fig. 14) or 1900°F (fig. 15). Grain growth was, however, less for the air cooled material when it was rolled at 2100°F (fig. 15) for reasons which do not seem explainable from the available information.

3. It was noted that the grain growth after solution treatment was considerably greater in that part of the tapered specimens which received no reduction when the rolling was carried out at room temperature (figs. 12 and 14). Apparently, the half hour of heating for rolling at 1400°F or higher restricted general grain growth during the final solution treatment in material which did not receive any further reduction.

4. The inclusion or omission of the equalizing heat treatment at 1950°F before rolling at 2100°F had practically no effect on grain growth. (See table I and

fig. 16) Heating first at 2100°F and then dropping the temperature to 1600°F may have increased the amount of reduction to initiate abnormal grain growth from 0.7 to 2.5 percent.

These results suggest that the tendency for the critical reduction to increase for rolling at 2100°F is due to heating to 2100°F and not to working at that temperature. This was carried over in the specimen cooled to 1600°F before rolling.

5. As-received material reduced 25 percent at 1600° or 1950°F had about the same growth characteristics for maximum grain size (fig. 17) as material reduced 50 percent at 1950°F when all were equalized at 1950°F and oil quenched prior to rolling at 1600°F. This is support for the general conclusion that prior history has relatively little effect on abnormal grain growth unless there is a large reduction without opportunity for substantial recrystallization.

Abnormal grain growth induced by tensile straining. - Uniform critical reduction by limited straining in a tensile machine was used to obtain an indication as to the relative importance of the amount of reduction and a strain gradient. Specimens were stretched: (1) 1 percent at 1400°F; (2) 1 percent at 1600°F; and (3) 2.5 percent at 1600°F. The grain sizes after subsequent solution treatment are given in figure 18.

These results show:

1. The 1 percent elongation at 1400°F developed only a maximum grain size of (-1).
2. The 1 percent elongation at 1600°F gave very nearly the same result as 1 percent reduction by rolling of tapered specimens, the maximum grain size being (-4).
3. An elongation of 2.5 percent at 1600°F strained the gage section more than the critical amount so that abnormal grain growth was restricted to the fillets where the strain was the smaller critical amount.

These data are interpreted to show that the critical strain is the controlling factor and not the strain gradient. The absence of appreciable grain growth after straining 1 percent at 1400°F apparently was due to the strain being below the minimum amount required.

Influence of recrystallization during working. - The apparent confinement of induction of abnormal grain growth to a small critical reduction raised questions as to whether the same condition could be attained by partial recrystallization during working. Since recrystallization leaves a relatively strain free condition, there must be strain gradients between the recrystallized and the unrecrystallized zones.

The method of study selected was to roll tapered specimens so as to obtain reductions from 0 to about 29 percent. This would provide a wider range of recrystallization than was obtained in the bars reduced a maximum of 15 percent. Temperatures of 1850°, 1950° and 2050°F were used to further vary the recrystallization characteristics during rolling. The grain sizes obtained (table I and fig. 19) along with typical microstructures (fig. 20 and 21) indicate the following:

1. The reduction for abnormal grain growth remained approximately the same that had previously been found, 0.4 to 5.8 percent. The maximum grain size, however, was (-1) to (-2) instead of (-3) to (-4). The narrower zone of critical reduction in the bars with the greater taper apparently restricted the maximum grain size. This seemed to be due to an insufficient volume of metal being critically deformed to provide enough material for larger grains.
2. No abnormal grains were found in the regions reduced more than the critical amount in spite of a wide range in degree of recrystallization during rolling.
3. The material reduced more than 10 percent at 1850°F did show grains having a size of 1 to 2 in bands between finer grained areas (fig. 20c). This appeared to be due to grain boundary migration from the few very small recrystallized grains which formed during rolling. These apparently grew preferentially at the expense of surrounding grains.

4. The material reduced over 7 percent at 1950°F underwent extensive partial simultaneous recrystallization (fig. 21 and 22). However, upon subsequent final solution treatment, a uniform fine grained structure was obtained in the regions of the tapered specimen which received the heavier reductions (fig. 21).

These specimens were solution treated at 1975°F in accordance with more recent commercial practice. There is no reason to believe that this increase from 1950°F appreciably affected the abnormal grain growth characteristics.

The investigation of the possible induction of abnormal grain growth through partial recrystallization was too limited to allow definite conclusions. The results, however, point to certain probable fundamentals which suggest that it would be very difficult to induce abnormal grain growth in this manner. Any strain gradients between recrystallized and unrecrystallized areas would be very steep. As discussed in the previous section, this would probably limit the maximum grain size due to the small amount of available metal subject to abnormal grain growth. In addition, there is good reason to believe that the unrecrystallized grains adjacent to recrystallized grains are deformed more than the critical amount for abnormal grain growth. This would result in a very narrow zone or even the absence of critical deformation with little or no tendency for abnormal grain growth.

Influence of rate of heating on abnormal grain growth. - The occurrence of grains with a size of 1 to 2 in the sample rolled at 1850°F to reductions of 10 to 20 percent, as described in the preceding section, suggested the possibility of abnormal grain growth from a few small simultaneously recrystallized grains (fig. 20). If a slow rate of heating was used, the few very small grains which formed during rolling at 1850°F (fig. 20a and 20b) might have an opportunity to grow even larger. Very large grains can be grown in metals when only a few small grains form by recrystallization and are given time enough to grow at a relatively low temperature to large grains at the expense of the surrounding strained metal.

Accordingly, a sample was prepared and taper rolled to include a considerable region of reduction between 10 and 20 percent. When heated from 1400° to 1950°F in three hours, the grain sizes found (table I and fig. 19) were no different than when placed in a furnace at the maximum temperature.

As far as could be ascertained, the slow rate of heating had little effect on the abnormal grain growth at the critically deformed section. It certainly did not increase grain size in this area.

It will be noted, however, that the critical reduction for abnormal grain growth was only 0.1 percent. This low value suggests that the critical reduction or abnormal grain growth is sensitive to heating rate. If so, unrecognized variations in heating rate could account for some of the apparently inexplicable variation in the minimum reduction for abnormal grain growth observed throughout the investigation.

Degree of recrystallization during working. - During the investigation, estimates were made of the amount of recrystallization in as-rolled structures. These are summarized in figure 22. For some reason, the larger reductions gave more recrystallization at 1950° than at 2050°F. A very small amount occurred at 1850°F and none at lower temperatures.

Inconel "X"-550 Alloy

A number of heat treatments were carried out on the as-received stock to establish initial grain growth characteristics. It was subject to uneven grain growth at 1900° and 2000°F and to abnormal grain growth at 2100°F (See fig. 23). The tendency for abnormal grain growth was reduced at 2200°F. Typical microstructures are shown in figure 24.

Induction of Abnormal Grain Growth by Repeated Heating and Cooling

Stock was reduced 64 percent from 2150°F and then reheated as detailed in figure 25. Four and five cycles to 2150°F with air cooling did induce some abnormal grain growth. This growth occurred during the first reheat after an initial water quench and became more extensive during succeeding cycles (fig. 26).

The Inconel "X"-550 material was quite sensitive to abnormal grain growth from the surface if water quenched and reheated to 2150°F. It was far less sensitive when air cooled. However, repeated air cooling or, more probably, increased heating time at 2150°F resulted in some abnormal grain growth. This, together with the experiments carried out on the as-received stock, indicate that abnormal grain growth can occur in 1 to 4 hours of heating at temperatures above 2000° and below 2200°F for either air cooled or water quenched material.

Apparently Inconel "X"-550 was somewhat more susceptible to abnormal grain growth from repeated heating and cooling than Waspaloy. At least, abnormal grain growth was not induced in the latter material by repeated air cooling from its solution temperature.

Induction of Abnormal Grain Growth in Inconel "X"-550 by Deformation

As-received stock was heated for 2 hours at 1900°F, air cooled and machined into tapered specimens having a uniform grain size of 6 to 8. Abnormal grain growth occurred during final solution treatment at 2150°F in regions reduced 2.6 to 10.5 percent during rolling at 1600°, 1800° and 2000°F (table III and fig. 27). There was no abnormal grain growth after rolling at 2200°F. Increasing the temperature of rolling from 1800° to 2000°F reduced the range of reductions subject to grain growth. It will also be noted that there was no tendency for abnormal grain growth in the section of the specimens which received no reduction. Evidently the heat treatment at 1900°F or the removal of surface metal in machining the specimens eliminated the susceptibility to abnormal grain growth at 2150°F originally present in the stock.

Tapered specimens were prepared from stock solution treated 2 hours at 2100°F. The machining removed the surface material which underwent abnormal grain growth during treatment at 2100°F and left material with a uniform grain size of 0 to 5.

The critical reduction for abnormal grain growth in this material was between 0.4 and 1.4 percent. Again, rolling at 2200°F practically eliminated abnormal grain growth. The tendency was also slightly reduced by rolling at 2000°F in comparison to 1600° or 1800°F (fig. 28).

Stock was reduced 50 percent at 1950°F and then machined into tapered specimens. When heated to 2100°F for 0.5 hour and rolled, it was subject to abnormal grain growth for reduction of 4 to 7.8 percent (fig. 29). Figure 30 shows typical microstructures. When the specimen was cooled to 1600°F before rolling, the range of reduction for abnormal grain growth was somewhat higher. This latter material also developed grains as large as (-1) when reduction was very small.

Apparently the recrystallization during working at 1950°F plus that on heating to 2100°F changed the amount of reduction for critical grain growth. Possibly recrystallization and grain growth during heating at 2100°F for rolling left less residual strain from prior history and therefore required more deformation to induce critical strain. Possibly grain size differences were involved in the change in critical deformation.

Nimonic 80A Alloy

The as-received stock had a grain size of 6 to 8. Figure 31 shows the influence of various heating conditions on grain growth in this material. Four hours at 1950°F developed a grain size of 1 to 3. Higher temperatures resulted in larger grains, including abnormal grains.

Experiments were carried out involving various conditions of rolling. Both as-received stock and stock reduced 50 percent at 1950°F followed by a one hour treatment at 1950°F were utilized. The original grain structure for both materials is shown by figure 32. It will be noted that a treatment of one hour at 1950°F resulted in a structure of fairly coarse grains with bands of very fine grains.

Induction of Abnormal Grain Growth by Deformation

In general the Nimonic 80A stock underwent abnormal grain growth in the same manner as the other alloys. One outstanding difference was the tendency for grain sizes of 1 to 0 to develop after large reductions.

Effect of temperature and amount of reduction. - Material which had been reduced 50 percent at 1950°F and then reheated for one hour at 1950°F and air cooled was prepared as tapered specimens and rolled at 1750°, 1850° and 1950°F and reheated under the conditions outlined in table IV and figure 33. Abnormal grain growth to sizes greater than 0 took place for reductions between 0.1 and 8.5 percent when the specimens were reheated by placing in a furnace at 1975°F. The larger grain size was never smaller than 3 and usually was 1 or 0 for the larger reductions. So far as the effect of temperature of reduction was concerned, there were only minor variations of doubtful significance in the maximum size of the grains formed by abnormal growth.

Reworking after prior deformation. - A specimen equalized by a 50 percent reduction at 1950°F followed by a one hour treatment at 1950°F was rolled once as a tapered specimen, reheated to 1950°F for 10 minutes and again passed through the rolls. Due to springback of the rolls the second pass imposed about one percent additional reduction on the specimen. The observed grain sizes after final solution treatment are given in table IV and figure 33. It is important to recognize that the reductions shown are the combined reduction from the two passes. The observed grain sizes are interpreted as follows:

1. During the 10 minute reheat to 1950°F, considerable relief of strain from the original reduction took place. At small total reductions, the combined effect of the relatively small further reduction from the second pass and the initial reduction did not become effective for abnormal grain growth until the point where the total reduction was 1.6 percent.

2. For all total reductions between about 8 percent and about 23 percent, the strain relief from the 10 minute reheat was probably insufficient to bring the residual strain below the critical amount. Therefore, the second pass did not induce abnormal grain growth.

3. For total reductions between 23 and 28 percent, extensive recrystallization occurred during the original pass. This probably left the material essentially strain free. When given the second pass it probably was then critically deformed and became susceptible to the observed abnormal grain growth.

Another specimen with less taper was made from as-received stock and subjected to the same sequence of operations (See table IV and fig. 34). The behavior was very similar to the previously discussed specimen over the comparable range of total reductions.

This second specimen did develop considerably coarser grains in the regions given more than critical reduction than a similar specimen given only one pass. The grain size in this region was similar to that of the first re-rolled specimen discussed. In fact it was similar to that of all the specimens first equalized at 1950°F. This suggests that the common factor of two heatings to 1950°F was responsible for the relatively large grain size for more than critical reduction.

The most important features of the results of these experiments are:

1. Evidence of considerable strain relief in 10 minutes at 1950°F without a cool to room temperature.
2. Further indication that extensive recrystallization during working leaves alloys susceptible to abnormal grain growth from small additional deformation.
3. Repeated heating to 1950°F increases grain size to near abnormally large sizes for non-critically reduced metal.

From a practical viewpoint, the changes in critical reduction were too small to be significant.

Effect of heating rate on abnormal grain growth. - Reducing the heating rate to solution temperature after rolling at 1850°F (fig. 33) practically eliminated abnormal grain growth and restricted grain size for larger reductions. Bringing the specimen up slowly in the furnace from 1400° to 1950°F in comparison to placing the specimen in a furnace at 1950°F could be expected to give considerable strain relief before the temperature was high enough for grain growth. The opportunity for precipitation and agglomeration at the lower temperatures may also have increased grain growth restrainers. Both factors would favor the observed reduction in grain growth.

Slow heating from 1950° to 2300°F after reduction at 1950°F increased grain size for all reductions (fig. 35) in relation to material rapidly heated to 2300°F. In this case, grain growth could occur at all temperatures involved and the increased grain size was probably due to increased time in the grain growth range.

Influence of temperature of solution treatment after reduction at 1950°F. - Several conditions of heating were used after reduction of tapered specimens at 1950°F with the following results (table IV and figure 35):

1. One hour at 2100°F gave the same critical grain growth as 4 hours at 1950°F. The only difference was the larger grain size for the larger reductions with the 2100°F treatment (grain size of 0 as compared to 3 (fig. 34)).
2. One hour at 2200°F gave a maximum grain size of (-1). The maximum grain size varied between (-1) and (0) along the length of the bar. Apparently solution treating at 2200°F erased any effect of critical reduction.
3. One hour at 2250°F was very similiar except that a grain size of (-3) developed for 1.6 percent reduction.
4. One hour at 2300°F was similiar to 2250°F except that the grain sizes along the bar varied between (-1) and (-2).

The most important feature of these results was the relatively little effect of extremely high temperature treatments on abnormal grain growth. Inadvertent high temperatures apparently are not a major factor in abnormal grain growth

provided it can occur at normal heating temperatures. The absence of abnormal grain growth in heating at 2200°F suggests that there are intermediate conditions of strain relief, solution of grain growth restrainers and grain growth characteristics which restrict abnormal grain growth.

DISCUSSION

The investigation provides considerable information regarding the conditions which can cause abnormal grain growth in heat-resistant alloys of the type studied. Many, if not most, of the conditions of working to be avoided for freedom from abnormal grain growth can be specified. The basic mechanisms involved in many of the interrelated variables can also be postulated from the theory of grain growth.

Prevention of Abnormal Grain Growth

All of the results indicate that small amounts of deformation applied to essentially strain free metal are responsible for the development of abnormal grain growth. When such critically strained metal is reheated to the usual hot-working or solution treating temperatures, abnormal grain growth may occur. The main problem in preventing abnormal grain growth seems to be the anticipation and avoidance of the often complex conditions which can induce critical strain. The usual temperatures and time periods of solution treatment are sufficient for abnormal grain growth. Heating conditions for hot working may or may not develop abnormal grains depending on the temperatures and time periods used.

The amount of strain required to induce susceptibility to abnormal grain growth was rather small. In most cases studied, it was a small portion of the reduction in the range between 0.4 and 5.0 percent. Over all the experiments this reduction was as low as 0.1 percent and as high as 9.7 percent. This means that, if the metal is reduced at least 10 percent in all parts during any one working operation, it should

be free from abnormal grain growth; in most cases 5 percent is adequate. The only exception to this rule noted was the case where a small reduction was applied after fairly large amounts of reduction caused recrystallization during working. The recrystallization left the material essentially strain free and the small amount of further straining induced susceptibility. This apparently does not occur when reduction is continued at essentially constant temperature after recrystallization starts if the last pass is heavy. A reheat after such recrystallization followed by a small critical reduction definitely induces susceptibility. Continued reduction with a falling temperature after recrystallization at higher temperatures is a less obvious but important source of critical reduction.

The data clearly showed that susceptibility can be induced by rapid cooling from a high temperature. In this case, the thermal stresses critically deform the surface of the stock. It should be clearly recognized that this is a case where the dimensions of the metal piece together with the cooling rate are combined variables governing the amount of thermally induced strain. Air cooling can induce abnormal growth in some cases. In other shapes, water quenching may be required. If temperature gradients or the restraint to contraction is sufficiently small even water quenching will not critically strain the metal. This source of critical strain is favored by high thermal expansion and low thermal conductivity. It should be noted that cooling rate after a reduction larger than the critical amount will have no effect because the thermally induced strain will be merely superimposed on the strain already present.

These results clearly indicate the principles necessary to avoid abnormal grain growth.

1. Rapid cooling from an essentially strain free condition must be avoided. Thus, if metal is heated under conditions which remove strain from prior working and then cooled rapidly enough to critically deform the surface by thermal stressing, it will undergo abnormal grain growth when reheated to usual solution or hot-working temperatures. This condition could probably be encountered on

cooling from hot working only if the reduction conditions were such that recrystallization to an essentially strain free condition occurred during the working operation. Likewise any section of a part which received no reduction would be susceptible after such cooling.

2. The critical reduction for developing sensitivity to abnormal grain growth is essentially independent of temperature of straining. Thus, if metal is annealed and cold straightened by methods which introduce small strains, those sections of the metal receiving critical deformations will be susceptible.

3. Any reduction should be more than the critical amount. Thus a reheat followed by a small finishing reduction should be avoided if the reheat conditions leave the metal essentially free from strain from prior reduction.

4. In hot working in dies, it is essential that the deformation in all parts of the piece be more than the critical amount. This means that the dies must be designed to insure more than the critical amount of metal movement in every step. Common sources of difficulty include die "hang-up" where the metal does not move; incorrect proportioning of the sequence of dies so that some parts of the piece receive little or no reduction in some steps; and flash preventing dies from closing, thereby restricting metal flow to small amounts in some parts. Trimming of flash from a forging after a reheat without any other reduction is a common source of critical reduction if the reheat relieves prior strain because the operation introduces a strain gradient certain to include critical deformation.

5. Abnormal grain growth can occur during reheats if the time and temperature of reheating are sufficient for the grain growth. Even though initial reductions may be larger than the critical, it can occur during subsequent reductions if reheating relieves prior strain. Repeated steps involving critical strain and grain growth during reheats are almost certainly the cause of extremely large grains sometimes encountered in forging turbine blades. The repeated sequence causes additional growth during each reheat.

6. The possibility of recrystallization during working rendering metal susceptible to abnormal grain growth from an additional small reduction seems to be a fairly important principle. This is probably a common source of fairly large grains (grain sizes of the order of number 0 to (-1)). It probably explains why many successful forging operations for gas turbine blades require limiting the forging blows to one per heat. The first blow at a relatively high temperature induces recrystallization with little or no strain hardening. The temperature falls rapidly and additional blows probably result in small deformations which critically deform the relatively strain free metal. If multiple operations per heat are to be used, care must be exercised to be sure that recrystallization is not followed by small critical reductions at a lower temperature where recrystallization stops.

7. Forging experience indicates that temperature and time of heating and the capacity of hot-working equipment are important practical variables. The reason for this apparently involves several factors. The most important probably is the uniformity of metal flow in a die as influenced by the temperature sensitive flow characteristics of the metal. Time of heating probably governs amount of relief from prior strain and grain growth effects during reheats. Small parts and thin edges cool rapidly in a die and may become so resistant to deformation that the deformation possible with the equipment being used is limited to the critical amount.

8. Inadvertent abnormally high temperatures of heating for hot working or solution treatment appear to be a relatively unimportant feature of abnormal grain growth. The major exception to this appears to be the case where the normal hot-working or solution temperatures and times were too low for abnormal grain growth to occur. In these cases, an abnormally high temperature will permit abnormal grain growth after critical deformation when there would be no evidence of it from normal heating conditions. The size of abnormal grains increases only

slightly with temperature. If abnormal grain growth can occur during normal heating, the increase from abnormally high temperatures is relatively small.

9. These generalities are restricted to the formation of abnormally large grains under conditions which normally do not develop excessively large grains. The investigation did not consider the causes of mixed grain sizes where the largest grains are of the order of 1 or 0. Several instances of this type of grain growth were, however, noted in the experiments. The development of a very few recrystallized small grains during working at a relatively low temperature was one source. Partial recrystallization causing bands of strained and recrystallized small grains was another. In some cases, certain conditions of prior heating caused relatively large grains to form during a subsequent reheat. Excessively high temperatures of heating frequently caused uniformly coarse grains to form.

10. The investigation showed that the degree of reduction and not strain gradients was the major cause of abnormal grain growth. Abnormal grain growth is usually associated with strain gradients only because the critical deformation is usually present in the gradient. The critical deformation range is so small that it can easily be missed in uniform reduction.

11. Working at or slightly above the normal solution temperature cannot be depended on to reduce abnormal grain growth.

Metallurgical and Compositional Effects

The influence of metallurgical variables and compositional effects on abnormal grain growth was not studied in detail. However, certain observations and deductions can be made from the experimental results:

1. The vacuum-melted Waspaloy did not develop as large abnormal grains and tended to be generally finer grained than the air-melted stock. In theory, the vacuum-melted material should have fewer oxides, nitrides and other dispersed phases which act as grain growth restrainers than the air-melted stock. If this were the governing

factor, the temperatures and heating time for grain growth ought to be reduced. This, therefore, can hardly account for the restriction of the abnormal grain growth. The vacuum-melted heat had a carbon content of 0.08 percent while the air-melted heat had only 0.03 percent carbon. This is a sufficient difference so that the larger amount of carbides in the vacuum-melted material should restrict grain growth appreciably more than in the lower carbon air-melted material. While this investigation did not demonstrate that the carbon content was the controlling factor between the air- and vacuum-melted stock, it alone could be responsible for the observed differences.

2. The composition of the alloys was related to the temperatures and time for abnormal grain growth. For the three alloys considered, Nimonic 80A had the least resistance to grain growth. It underwent rapid grain growth at 1950°F. Waspaloy required considerable time for abnormal grain growth at 1950°F. Inconel "X"-550 required a temperature above 2000°F and the growth still required some time at 2150°F.

The comparatively high coarsening temperature for Inconel "X"-550 was probably due to the grain growth restraining effect of columbium compounds. The main difference between the Nimonic 80A and the Waspaloy presumably was the higher titanium and aluminum contents of the latter material. This presumably increased resistance to grain growth.

3. There were many aspects of the details of the observed grain growth variations which seem due to differences in grain growth restraint from dispersed phases. The usual solution temperatures apparently are on the lower side of the temperature range for solution of such phases. The grain growth was relatively slow at the temperatures used. Under such conditions the critical deformation could be expected to be sensitive to the conditions of the grain growth restrainers and possibly the size of the abnormal grains. This seemed to be involved in the

restraint of grain growth by prior heating in the precipitate-agglomeration range of 1400° to 1700°F. It probably was a factor in the variable effect on abnormal grain growth due to working at or above the usual solution temperature.

4. Deformation of multigrained materials is not uniform on a microscopic scale even though it may be on a macroscopic scale. The microscopic flow characteristics probably vary depending on the temperature and method of working. Consequently, it could be expected that the rather narrow range of reductions inducing abnormal grain growth could be sensitive to details of the mechanisms of flow during working. Furthermore, such metallurgical factors as compositional differences, grain size, dispersed phases and degree of solution of dispersed phases could influence flow characteristics and thereby critical deformation details.

5. The size of grains and extent of abnormal grain growth were remarkably insensitive to increased temperatures of heating above the lowest temperature at which it would occur. There were, however, certain intermediate higher temperatures which in some cases restricted abnormal grain growth. The explanation of these effects are not clear from this investigation. There are probably several interrelated effects. Increased temperature should intensify grain growth. On the other hand, very large grains require initiation of growth from only a few centers. Increasing the temperature would increase the number of centers of grain growth and thereby restrict grain growth through competition for surrounding grains. An increase in temperature would also tend to reduce grain growth restrainers by solution and thereby increase the centers nucleated for growth. Some strain relief probably occurs during heating before grain growth starts, thereby influencing critical strain. This could be expected to be variable depending on temperature and heating rate. Possibly this would result in variation in the amount of initial strain required to leave a residual critical strain at the time the metal attained a temperature sufficient for abnormal grain growth.

Strain relief during heating to the higher temperatures of rolling may well be the cause for the general increase in the amount of strain required for critical grain growth.

6. In general it appeared that abnormal grain growth was fairly independent of initial grain size. In those cases where there was an apparent grain size effect, it is probable that variation in grain growth restrainers was the controlling factor.

7. There was considerable variation in the amount of deformation required to initiate abnormal grain growth. The reasons were not clear. Varying strains from cooling were probably a factor. Also, as previously discussed, variation in grain growth restrainers could have been involved. There was also some evidence that it was related to rate of heating to the solution temperature. The most important effect, however, was probably unrecognized variations in the strain from the conditions of manipulation used in the experiments.

Mechanism of Abnormal Grain Growth

There are two basic mechanisms resulting in grain growth: (1) Absorption of surrounding grains by grain boundary migration; and (2) formation of new grains by recrystallization followed by grain boundary migration. Both mechanisms require a difference in energy between grains such that those at a higher energy level are absorbed by those at a lower energy level. In the first case, some factor sets up a condition such that some grains are at a higher energy level than others. It is the common mechanism for growth of larger grains from smaller grains. In the second case, relief of strain due to deformation causes a small new grain to form. This grain then grows at the expense of the surrounding metal which is at a higher energy level by virtue of the strain present. If there are many centers at which the small new grains form in relation to the original grain size, there will be more grains after recrystallization is complete and grain refinement

will have occurred. If there are few centers strained enough to recrystallize, growth of only a few grains will occur resulting in grain coarsening.

The literature does not clearly define whether abnormal grain growth occurs by grain boundary migration of existing grains or by growth of a very few small grains formed by recrystallization. In either case the essential feature would seem to be non-uniformity of strain within the individual original grains. Grain boundary migration would require that a few grains receive very little strain in relation to their neighboring grains. Recrystallization followed by grain growth would require sufficiently large deformations at a very few centers initiating new grains.

Irregardless of this initial mechanism, it can be postulated that the characteristic shape of the grain size versus percent reduction by rolling curves result from the following sequence of conditions:

1. In regions of no reduction or smaller reductions than the critical amount there is not a sufficient contrast in energy levels to make only a few grains grow at the expense of surrounding grains. Grain growth that occurs is the normal uniform growth.
2. The conditions at the critical deformation are discussed above.
3. At somewhat larger amounts of strain than the critical, apparently there are more grains in a condition to absorb their neighbors than at the critical. The increase in the number results in competition for available surrounding grains. The grain size is then restricted because there are not enough grains available for any one to become large.
4. At still larger amounts of strain, normal recrystallization and grain growth most certainly take place. The effects at larger amounts of strain are, however, complicated if simultaneous recrystallization occurs during working. It appeared from the data that there was little difference in the grain size in either case except when a very small amount of recrystallization occurred. Mixed grain

sizes resulted during reheating in this case, apparently by the few initial small grains growing at a faster rate than those which formed by recrystallization. In the experiments conducted, this mechanism did not develop abnormally large grains although it was theoretically possible. The mechanism, however, seemed to be mainly responsible for mixed fine and coarse grains.

In the discussion of methods of avoiding abnormal grain growth it was pointed out that recrystallization followed by critical reduction could be a source of abnormal grain growth under conditions where apparently the requirement of more than critical reduction was being observed. The mechanism involved apparently was no different than for the case of small reduction of initially strain free material, although there might be differences in the temperatures and times required for abnormal grain growth due to unusually small grain size of the recrystallized metal.

The data predominately indicated that the amount of strain and not the strain gradients was the controlling factor. This would be in accordance with the theory involved.

The influence of the presence of abnormally large grains in the structure before working was not studied. Such grains could be present due to lack of refinement from ingot structure or to allowing abnormal growth to occur during prior processing. General experience indicates that it is difficult to break up such isolated large grains. It is doubtful, however, that they would contribute to abnormal grain growth except in the case where large scale critical deformations was superimposed over the large grains. Apparently, where larger than critical deformations are involved, the proper strain gradient does not develop or the amount of critically strained metal between the large grain and surrounding fine grain is so small that no appreciable grain growth occurs.

Since rate of grain growth increases as heat treating temperature increases, abnormal grain growth can occur in less time at the higher than at the normal solution treating temperatures.

Metallurgical variables had relatively little effect on abnormal grain growth. Various prior history effects caused only minor variations so long as the prior history did not include more than critical deformation without an opportunity for strain relief. Grain growth restrainers as influenced by composition and heat treatment had minor effects. There was some evidence that metal flow characteristics as influenced by temperature and metallurgical variables caused minor changes in critical reduction and grain size. Certain heating rates and temperatures apparently can restrict abnormal grain growth.

The major difference between the three alloys studied was the temperature and time periods for abnormal grain growth. Inconel "X"-550 required a higher temperature than the other two alloys. Presumably this was due to the grain growth restraining tendency of the columbium compounds present in the alloy. The vacuum-melted Waspaloy developed smaller grains than the air-melted, possibly due to the grain growth restraint of a higher carbon content.

CONCLUSIONS

Abnormal grain growth was found to occur in Waspaloy, Inconel "X"-550 and Nimonic 80A alloys only when small deformations caused very large grains to grow during subsequent heating. The deformations inducing abnormal growth usually were within a range of reductions of 0.4 to 5.0 percent and were within a range 0.1 to 9.7 percent when all variables were considered. Normal solution temperatures and times are sufficient for the abnormal grain growth.

Abnormal grain growth can be avoided if care is exercised to be sure that all parts of the metal are deformed more than 10 percent in any one working step

before reheating. In most cases a reduction of 5 percent will be sufficient. The only exception to this is the case where large reductions cause recrystallization during working and working is continued under conditions which will critically deform the strain free recrystallized metal.

The main problem in avoiding abnormal grain growth seems to be recognizing and avoiding conditions leading to critical deformation. It can be induced by the thermal stresses of rapid cooling. Non-uniform metal movement during hot working leaving certain sections critically deformed is a major source of critical deformation. Attention must be given to the design and metal flow to avoid critical deformation. Particular care must be taken to avoid small deformations and deformation gradients which are sure to include a critical deformation. Recrystallization during working and reheating can remove the effect of previous deformation so that it is important to obtain more than critical deformation in every hot working operation.

The development of susceptibility to abnormal grain growth was remarkably independent of temperature of working. Deformation at room temperature had the same effect as at hot-working temperatures. Heating temperature had relatively little effect on abnormal grain growth provided the temperature was high enough for it to occur at all. Because it could occur at the normal solution temperatures for the alloys, inadvert excessively high temperatures are not necessary for it to occur. In addition, these temperatures do not cause substantially larger grains to form.

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Table I
Grain Size Data from Rolled Tapered Specimens of Air Melted Waspaloy

Equalizing Treatment of As-Received Stock	Rolling Temp. for Tapered Specimen (°F)	Final Treatment for Grain Growth	Percent Reduction by Rolling and ASTM Grain Size after Final Treatment as Measured along Tapered Specimens		Critical Reduction (percent)	Minimum Reduction to Prevent Abnormal Grains (percent)
			Reduction	Grain Size		
Rolled 50% at 1950°F + 1 hr. at 1950°F, O, O.	80	4 hrs at 1950°F, O, O.	0 0.7 (-2)-2	3.7 6.5 (-2)-3 1-5	8.9 11.3 2-4 3-6	12.4 3-6
ditto	1400	ditto	0 0.8 (-4)-1	3.1 5.5 0-3 2-5	9.0 9.0 3-5 3-6	12.2 3-6
ditto	1600	ditto	0 0.7 (-3)-2	3.2 4.4 0-4 1-5	5.9 8.3 3-7 3-7	12.6 4-7
ditto	1800	ditto	0 0.3 (-4)-0	0.7 1.6 (-1)-3 1-4	4.2 7.2 2-5 3-6	12.8 3-6
ditto	1950	ditto	0 0.3 (-4)-0	1.0 2.0 (-4)-0 0-3	5.0 6.4 2-5 3-5	13.0 4-6
ditto	2000	ditto	0 0.9 (-2)-2	1.8 2.8 1-4 2-4	3.8 4.9 3-4 3-5	10.2 3-5
ditto	2100	ditto	0 1.6 2-5	2.7 3.0 2-5 (-2)-1	3.7 4.9 1-5 2-3	11.0 2-3
1 hr at 1950°F, O, O.	1600	ditto	0 0.6 3-8	1.5 2.2 (-4)-(-2) 1-5	6.2 8.4 2-7 3-8	10.6 4-8
Rolled 25% at 80°F + 1 hr. at 1950°F, O, O.	1600	ditto	0 0.7 5-8	2.0 3.4 (-4)-(-2) 3-5	6.1 8.6 4-7 5-8	11.1 3-8
Rolled 25% at 1600°F + 1 hr. at 1950°F, O, O.	1600	ditto	0 1.3 3-7	2.5 3.5 (-4)-2 0-4	4.9 6.3 2-7 3-7	11.3 4-7
Rolled 25% at 1950°F + 1 hr. at 1950°F, O, O.	1600	ditto	0 0.8 4-7	2.4 2.6 (-4)-1 3-7	5.3 6.8 3-7 4-7	11.7 4-7
Rolled 50% at 1950°F + 1 hr. at 1950°F, A, C.	80	ditto	0 0.4 0-3	1.5 2.7 (-1)-3 1-5	5.8 8.2 2-5 2-6	10.8 3-6
ditto	1900	ditto	0 0.2 4-7	0.6 0.8 3-6 (-4)-1	1.3 2.4 (-1)-2 2-6	3.6 4-8
ditto	2100	ditto	0 1.1 1-5	2.2 3.4 0-2 1-3	4.9 7.2 1-3 1-3	10.6 2-4
Rolled 50% at 1950°F + 1/2 hr. preheat at 1600°F, then trans-ferred to 1600°F furnace for 1/2 hr	2100	ditto	0 0.2 3-6	1.8 2.5 (-2)-2 0-2	4.2 5.2 1-3 2-5	7.2 2-5
Rolled 50% at 1950°F + 1 hr. at 1950°F, A, C.	1850	Slow heated from 1400°F to 1950°F, then held 4 hrs at 1950°F, A, C.	0 0.1 4-6	0.9 2.9 (-1)-1 (-1)-2	4.8 6.1 2-3 2-5	10.3 4-7
ditto	1950	ditto	0 0.4 4-7	1.4 3.6 (-1)-1 0-3	5.6 7.4 3-6 3-6	10.2 3-6
ditto	2050	ditto	0 0.4 1-5	1.4 2.9 (-1)-3 1-3	6.1 6.8 2-5 2-6	9.3 3-6
Rolled 50% at 1950°F	80	4 hrs at 1950°F, O, O.	0 0.4 1-5	0.7 1.0 (-1)-3 (-1)-3	4.8 7.7 1-5 1-5	10.3 2-5
ditto	1600	Slow heated from 1400°F to 1950°F, then held 4 hrs at 1950°F, O, O.	0 1.6 3-6	3.2 4.7 3-5 1-5	6.2 8.4 (-1)-4 1-5	11.5 2-5

Table II
Grain Size Data from Rolled Tapered Specimens of Vacuum Melted Waspaloy

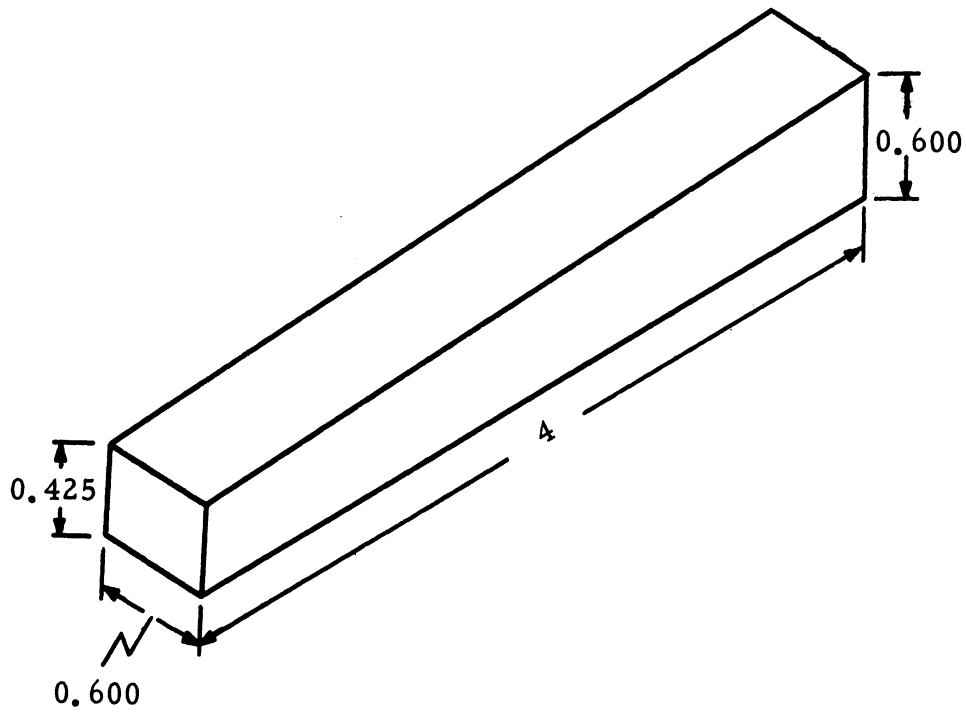
Equalizing Treatment of As-Received Stock	Rolling Temp. for Tapered Specimen (°F)	Final Treatment for Grain Growth	Percent Reduction by Rolling and ASTM Grain Size after Final Treatment as Measured along Tapered Specimens		Critical Reduction (percent)	Minimum Reduction to Prevent Abnormal Grains (percent)
			Reduction	Grain Size		
3/4-inch stock rolled at 1950°F from 2-inch ingot + 1 hr at 1950°F, A, C	1400	4 hrs at 1950°F, O, O.	0 0.1 5-7	0.5 1.2 (-2)-0 2-4	3.8 5.1 3-5 4-6	6.7 5-7
ditto	1600	ditto	0 0.1 5-7	0.5 1.2 (-2)-1 (-1)-1	3.4 5.3 2-4 4-6	8.2 4-7
ditto	1900	ditto	0 0.3 4-7	0.6 0.8 (-2)-(-1) (-2)-3	1.2 1.5 0-2 2-3	5.2 4-6
ditto	2100	ditto	0 0.3 2-5	1.2 2.1 2-5 (-2)-1	4.0 6.2 2-5 3-5	7.6 3-5

Table III
Grain Size Data from Rolled Tapered Specimens of Inconel "X"-550

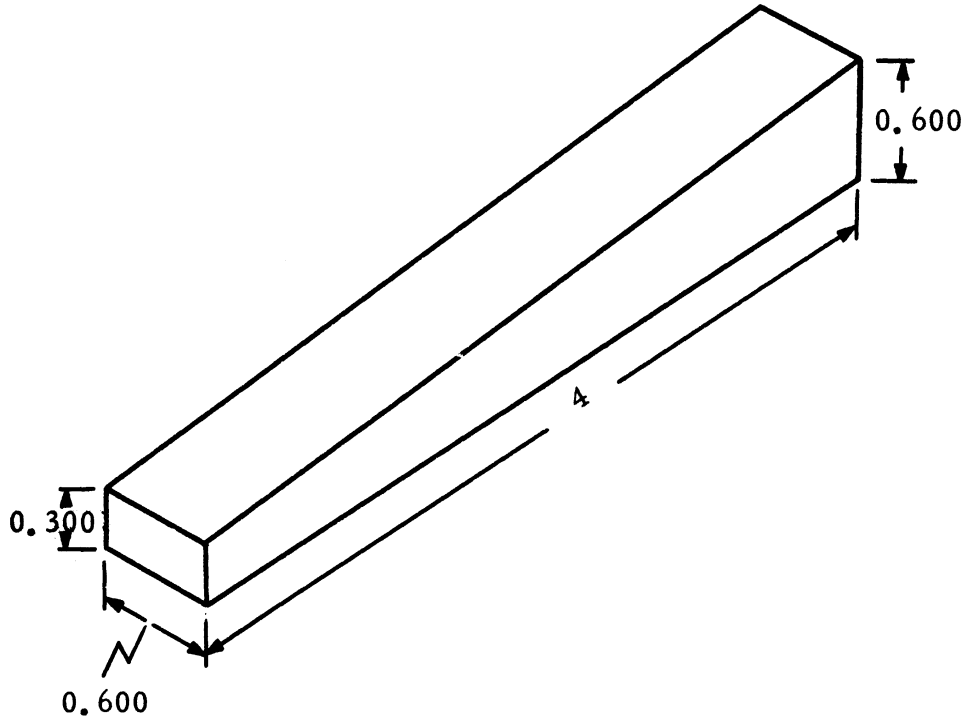
Equalizing Treatment of As-Received Stock	Rolling Temp. for Tapered Specimen (°F)	Final Treatment for Grain Growth	Percent Reduction by Rolling and ASTM Grain Size after Final Treatment as Measured along Tapered Specimens										Critical Reduction (percent)	Minimum Reduction to Prevent Abnormal Grains (percent)			
			Reduction Grain Size	0	1-3	1-3	1-3	2-6	3-4	5-9	8-1	9-2			9-3		
2 hrs at 1900°F, AC	1600	1 hr at 2150°F, AC	Reduction Grain Size	0	2-4	0.4	1.8	1.3	1.3	2.6	3.4	5.9	8.1	9.2	9.3	2.6	8.1
ditto	1800	ditto	Reduction Grain Size	0	2-5	1.4	3.0	4.3	5.7	8.0	10.5	11.1	15.7	2.5	4.3	4.3	10.5
ditto	2000	ditto	Reduction Grain Size	0	1-5	0.5	1.8	3.1	4.4	5.8	7.8	9.3	10.1	2.5	3.1	3.1	5.8
ditto	2200	ditto	Reduction Grain Size	0	1-3	1.3	2.7	4.0	5.4	6.8	8.3	9.7	10.9	2.5	None	0	5.0
2 hrs at 2100°F, AC	1600	ditto	Reduction Grain Size	0	0-3	0.2	1.4	1.8	3.4	5.0	6.7	9.1	11.4	14.4	1.4	5.0	5.0
ditto	1800	ditto	Reduction Grain Size	0	0-3	0.4	2.0	3.6	4.9	6.2	8.1	9.6	10.1	3.6	0.4	4.9	4.9
ditto	2000	ditto	Reduction Grain Size	0	0-3	0.4	2.0	3.6	5.1	6.7	8.2	9.8	11.0	3.6	0.4	3.6	3.6
ditto	2200	ditto	Reduction Grain Size	0	0-3	0.3	2.0	3.7	4.8	6.0	8.2	9.2	11.3	2.5	None	1.2	1.2
Rolled 50% at 1950°F + 1/2 hr preheat at 2100°F + 1/2 hr preheat at 1600°F furnace for 1/2 hr	1600	ditto	Reduction Grain Size	0	1-3	0.1	1.0	2.1	3.3	4.4	5.6	7.5	8.9	2.4	4.4	7.5	7.5
Rolled 50% at 1950°F + 1/2 hr preheat at 2100°F	2100	ditto	Reduction Grain Size	0	1-2	2.0	4.0	5.1	6.2	7.8	9.2	11.1	12.4	1.4	4.0	7.8	7.8

Table IV
Grain Size Data from Rolled Tapered Specimens of Nimonic 80A

Equalizing Treatment of As-Received Stock	Rolling Temp. for Tapered Specimen (°F)	No. of Passes for Grain Growth	Final Treatment for Grain Growth	Percent Reduction by Rolling and ASTM Grain Size after Final Treatment as Measured along Tapered Specimens										Critical Reduction (percent)	Minimum Reduction to Prevent Abnormal Grains (percent)				
				Reduction Grain Size	3-6	3-6	3-6	3-6	4-6	4-6	4-6	4-6	4-6			4-6			
Rolled 50% at 1950°F + 1 hr at 1950°F, AC	1750	1	4 hrs at 1975°F, AC	Reduction Grain Size	0	0.1	1.0	3.6	5.8	7.0	8.2	9.3	10.3	12.5	14.2	26.5	0.1	12.5	
ditto	1850	1	ditto	Reduction Grain Size	0	0.1	1.9	3.9	5.8	7.1	8.4	9.9	11.4	12.6	15.2	26.7	0.1	None	
ditto	1850	1	Slow heated from 1400°F to 1950°F in 3 hrs + 4 hrs at 1950°F, AC	Reduction Grain Size	0	0.7	2.9	5.2	6.6	8.1	9.7	11.3	14.6	22.0	3.6	2.9	5.2	5.2	
ditto	1950	1	4 hrs at 1975°F, AC	Reduction Grain Size	0	0.1	1.0	3.8	5.6	6.8	8.0	9.3	10.6	14.0	16.5	26.8	0.1	26.8	
ditto	1950	2	4 hrs at 1950°F, AC	Reduction Grain Size	4-6	4-6	4-6	4-6	4-6	4-6	4-6	4-6	4-6	4-6	4-6	4-6	4-6	4-6	
None	1950	1	ditto	Reduction Grain Size	2-4	2-4	2-4	2-4	2-4	2-4	2-4	2-4	2-4	2-4	2-4	2-4	2-4	2-4	
ditto	1950	1	ditto	Reduction Grain Size	1-3	1-3	1-3	1-3	1-3	1-3	1-3	1-3	1-3	1-3	1-3	1-3	1-3	1-3	
ditto	1950	2	ditto	Reduction Grain Size	2-4	2-4	2-4	2-4	2-4	2-4	2-4	2-4	2-4	2-4	2-4	2-4	2-4	2-4	
ditto	1950	1	1 hr at 2100°F, AC	Reduction Grain Size	1-3	1-3	1-3	1-3	1-3	1-3	1-3	1-3	1-3	1-3	1-3	1-3	1-3	1-3	
ditto	1950	1	1 hr at 2200°F, AC	Reduction Grain Size	0	0.4	1.5	2.3	4.5	6.6	8.0	9.2	12.5	15.2	18.1	25.6	1.5	None	
ditto	1950	1	1 hr at 2250°F, AC	Reduction Grain Size	0	0.4	1.1	1.6	4.0	6.0	7.6	9.2	12.0	14.0	18.3	24.5	1.6	None	
ditto	1950	1	1 hr at 2300°F, AC	Reduction Grain Size	0-1	0-1	0-1	0-1	0-1	0-1	0-1	0-1	0-1	0-1	0-1	0-1	0-1	0-1	
ditto	1950	1	Slow heated from 1950°F to 2300°F in 1 hr + 4 hr at 2300°F, AC	Reduction Grain Size	0	0.4	0.9	1.0	1.2	3.1	5.0	6.4	7.8	10.5	12.5	17.0	25.0	0-1,2	None

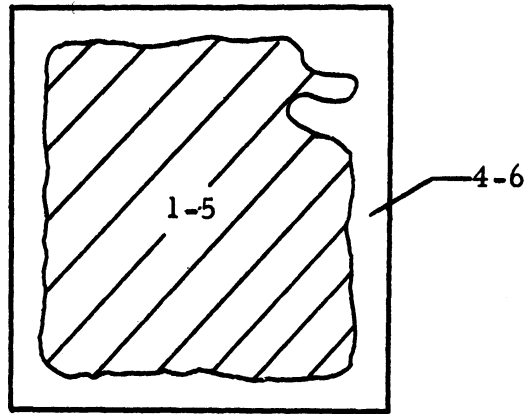


a. Tapered specimen used to obtain approximately 0 to 15 percent reduction.

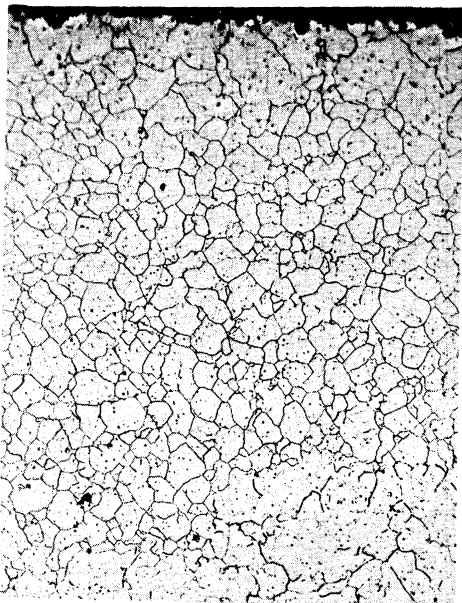


b. Tapered specimen used to obtain approximately 0 to 29 percent reduction.

Figure 1.- Tapered specimens used to obtain range of percent reduction by rolling to flat bars (dimensions in inches).



a. Approximate distribution of grain sizes.



X50D



X50D

b. Microstructure near bar surface.

c. Microstructure in bar center.

Figure 2. - Microstructures and grain sizes of transverse section of as-received air melted Waspaloy bar stock.

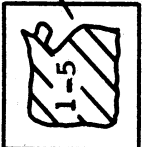
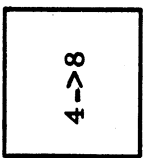
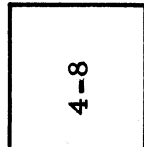
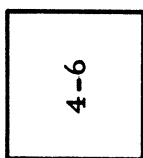
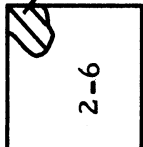
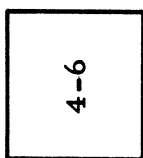
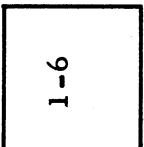

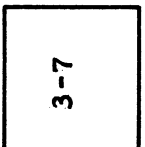
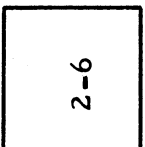
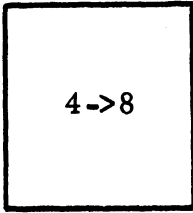
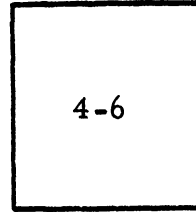
Heat Treatment	Equalizing Treatment of As-Received Stock	
	None	Rolled 70% at 1950°F
1 hour at 1900°F	 1-5 — 4-6	 4->8
1 hour at 1950°F	 4-8	 4-6
1 hour at 1950°F	 2-6 — 0	 4-6
4 hours at 1950°F	 1-6	 3-4
1 hour at 2000°F	 3-7	
1 hour at 2100°F	 2-6	

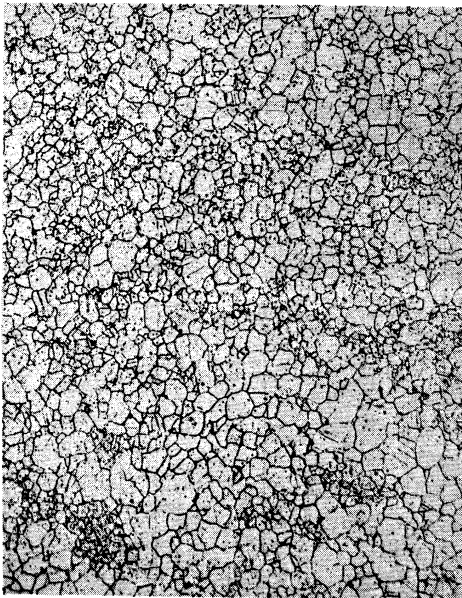
Figure 3.- Effect of heat treating time and temperature upon the grain size of transverse sections of air melted Waspaloy bar stock.



a. Approximate distribution of grain sizes as rolled 50% at 1950°F.

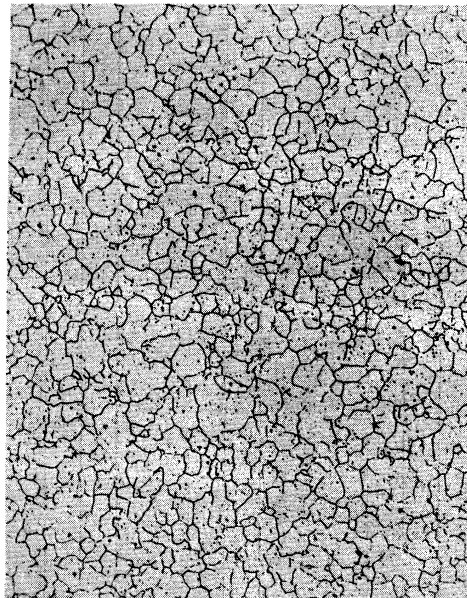


c. Approximate distribution of grain sizes as rolled 50% at 1950°F, + 1 hour at 1950°F, Air Cooled.



X50D

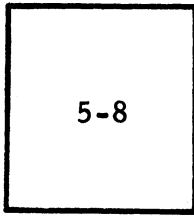
b. Microstructure as rolled 50% at 1950°F.



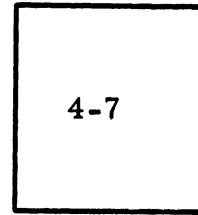
X50D

d. Microstructure as rolled 50% at 1950°F, + 1 hour at 1950°F, Air Cooled.

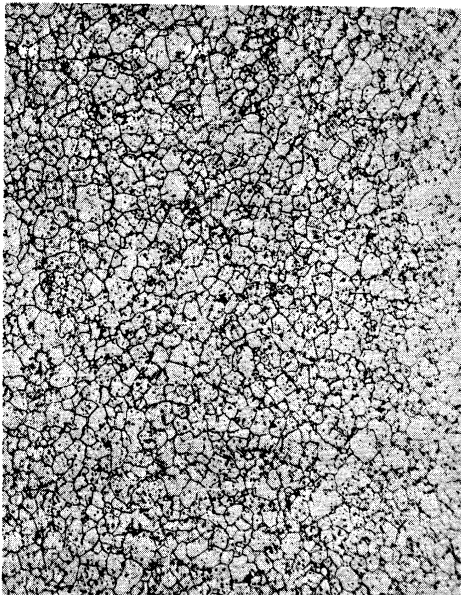
Figure 4. - Microstructures and grain sizes of transverse sections of equalized air melted Waspaloy bar stock.



a. Approximate distribution of grain sizes as rolled.

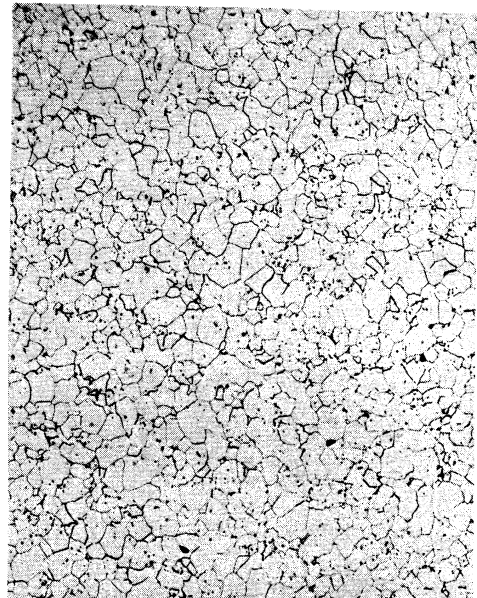


c. Approximate distribution of grain sizes as rolled + 1 hour at 1950°F, Air Cooled.



X50D

b. Microstructure as rolled.



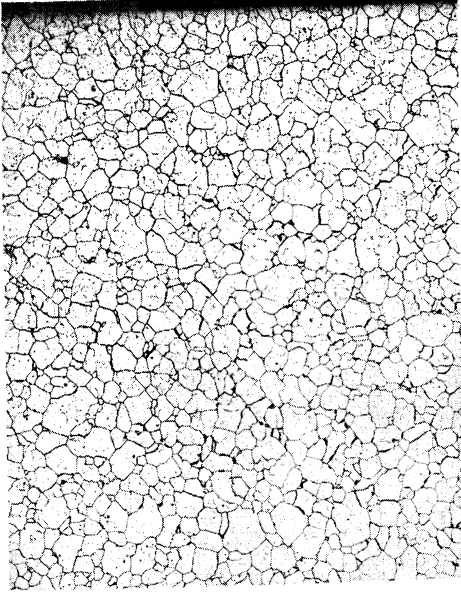
X50D

d. Microstructure as rolled + 1 hour at 1950°F, Air Cooled.

Figure 5. - Microstructures and grain sizes of transverse sections of vacuum melted Waspaloy bar stock.

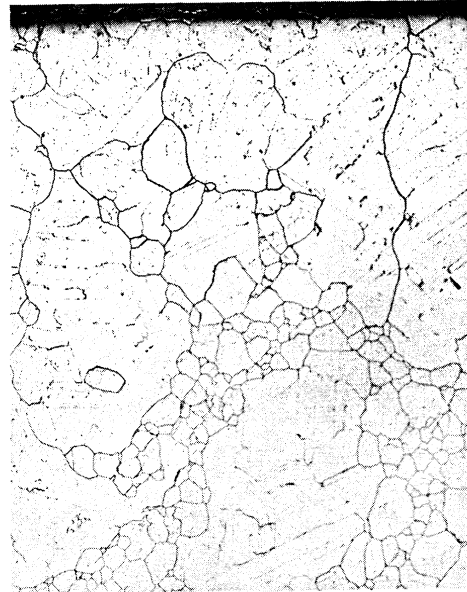
Equalizing Treatment of As-Received Stock			
Rolled 70% at 1950°F		Rolled 25% at 80°F	
Heat Treatment	Cooling Method - Air Cooled	Cooling Method - Water Quenched	Cooling Method - Oil Quenched
	+ 1 hour at 1950°F, air cooled 4-6	+ 1 hour at 1950°F, water quenched 4-6	+ 1 hour at 1950°F, oil quenched 4-8
1 cycle of 1 hour at 1950°F, cooled	4-6 	3-6 	2-8
2 cycles of 1 hour at 1950°F, cooled	3-5 	(-2)-1 	
3 cycles of 1 hour at 1950°F, cooled	3-4 	(-2)-1 	
4 cycles of 1 hour at 1950°F, cooled	2-4 0 	(-3)-1 	
1 cycle at 1950°F, cooled			0-8 3 hrs

Figure 6. - Effect of repeated heating and cooling upon the grain size of transverse sections of air melted Waspaloy bar stock.



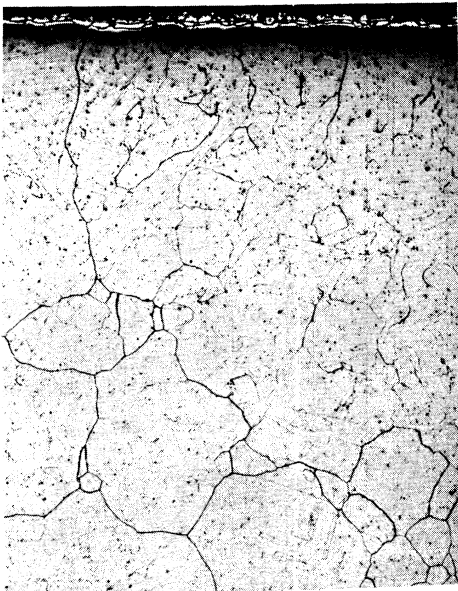
X50D

a. 1 hour at 1950°F, Water Quenched.



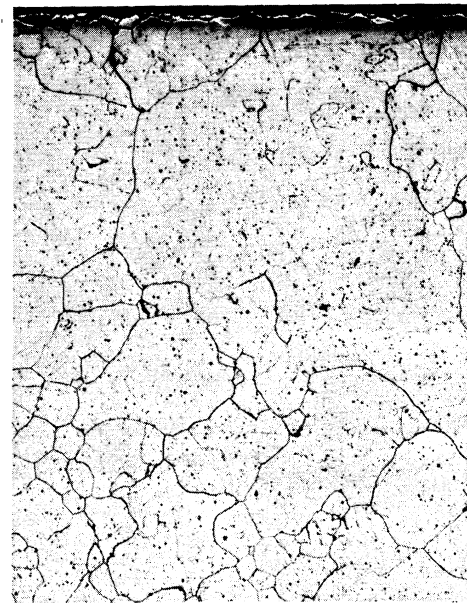
X50D

b. 1 hour at 1950°F, Water Quenched,
+ 2 cycles of 1 hour at 1950°F, Air
Cooled.



X50D

c. 1 hour at 1950°F, Water Quenched,
+ 4 cycles of 1 hour at 1950°F, Air
Cooled.



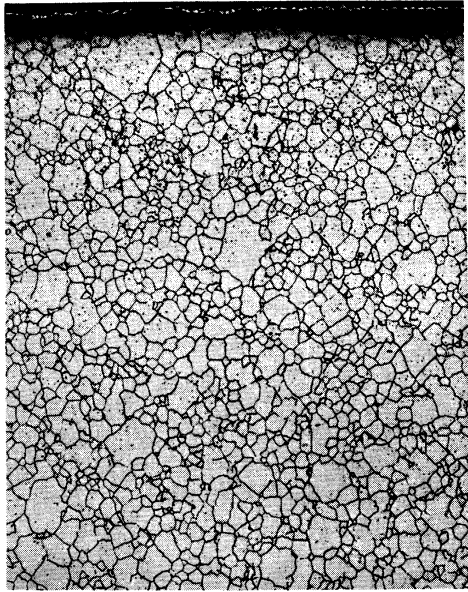
X50D

d. 1 hour at 1950°F, Water Quenched,
+ 1 cycle of 4 hours at 1950°F, Air
Cooled.

Figure 7. - Effect of repeated heating and cooling upon microstructure of air melted Waspaloy which had been equalized by a 70% reduction at 1950°F. (Transverse section at the bar stock surface.)

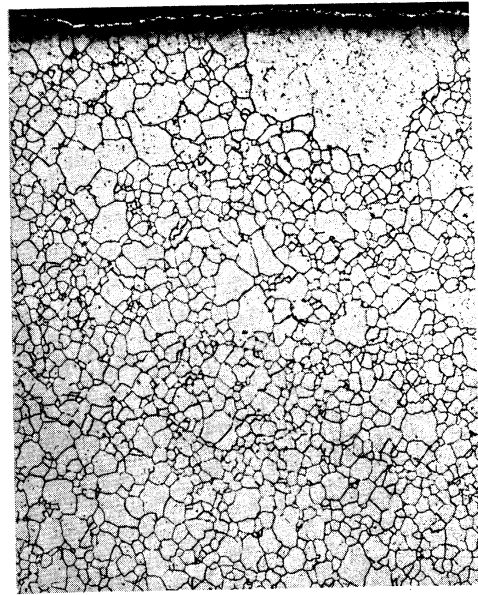
Equalizing Treatment of As-Rolled Stock	
Rolled at 1950°F from 2 inch ingot to 1/2 inch bar stock + 1 hour at 1950°F, water quenched	
Heat Treatment	4-7
	4-7
	Cooling Method - Water Quenched
1 cycle of 1 hour at 1950°F, cooled	4-7
	0-2
	4-7
2 cycles of 1 hour at 1950°F, cooled	4-7
	0-2
	3-6
3 cycles of 1 hour at 1950°F, cooled	4-7
	(-2)-(-1)
	3-6
4 cycles of 1 hour at 1950°F, cooled	3-6
	(-2)-(-1)
	3-6
	Cooling Method - Air Cooled
1 cycle of 4 hours at 1950°F, cooled	3-6
	(-2)-(-1)
	3-6
	Cooling Method - Air Cooled

Figure 8. - Effect of repeated heating and cooling upon the grain size of transverse sections of vacuum melted Waspaloy bar stock.



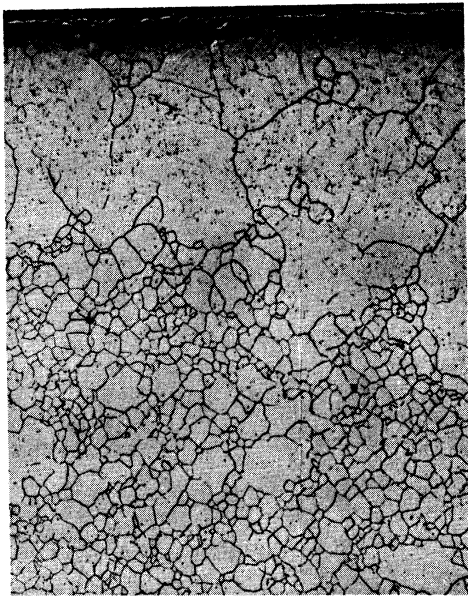
X50D

a. 1 hour at 1950°F, Water Quenched.



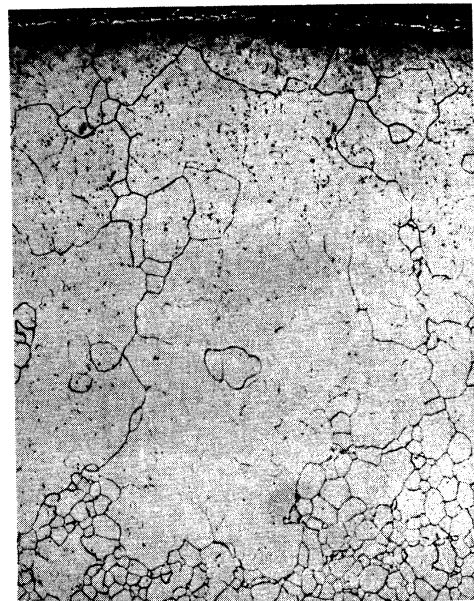
X50D

b. 1 hour at 1950°F, Water Quenched,
+ 1 cycle of 1 hour at 1950°F,
Water Quenched.



X50D

c. 1 hour at 1950°F, Water Quenched,
+ 4 cycles of 1 hour at 1950°F,
Water Quenched.



X50D

d. 1 hour at 1950°F, Water Quenched,
+ 1 cycle of 4 hours at 1950°F, Air
Cooled.

Figure 9. - Effect of repeated heating and cooling upon microstructure of vacuum melted Waspaloy which had been rolled at 1950°F from a 2-inch ingot to 1/2-inch bar stock. (Transverse section at bar stock surface.)

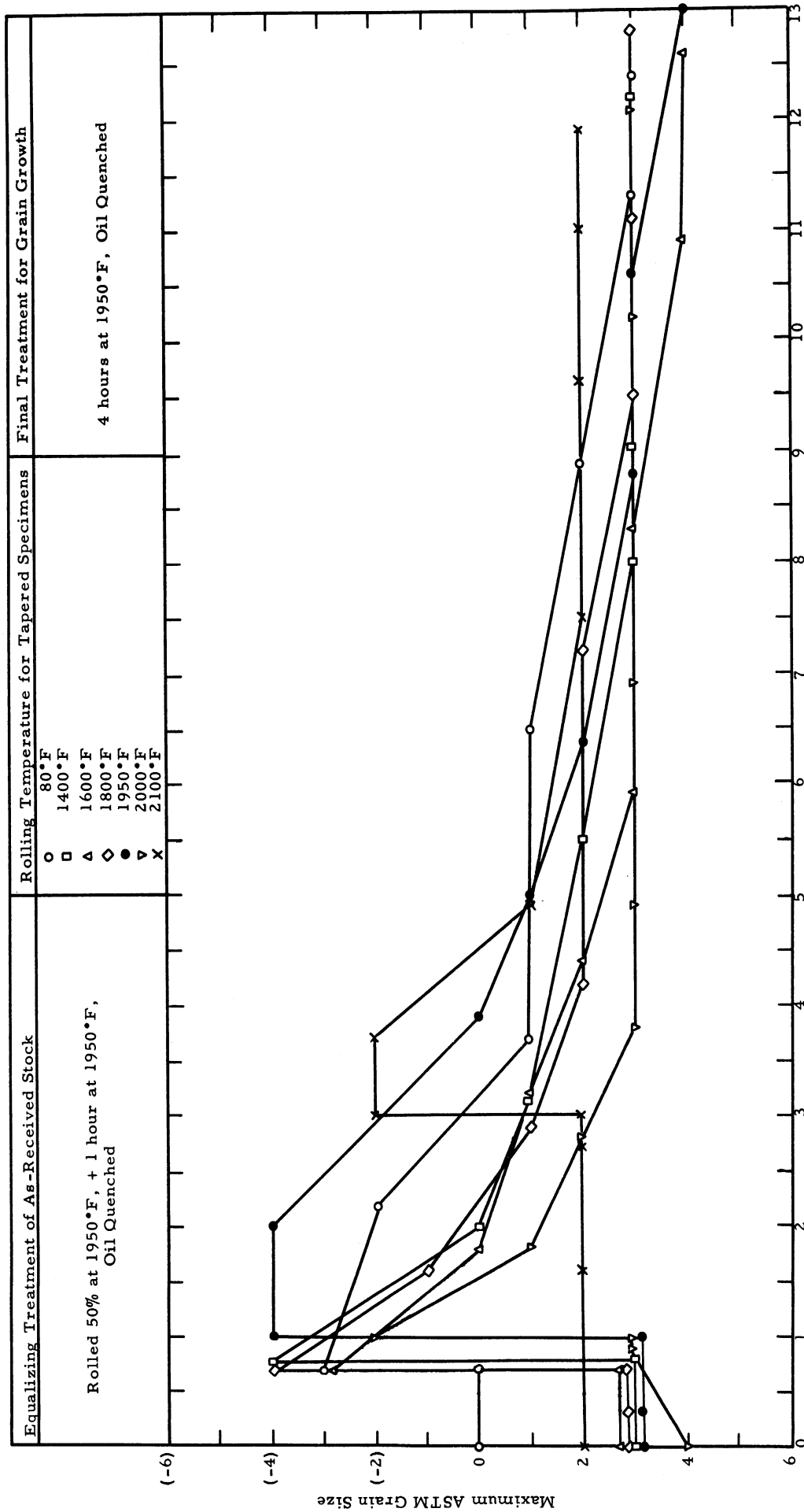
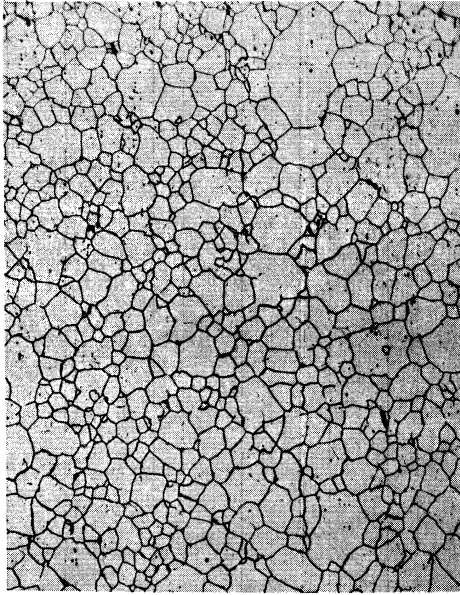
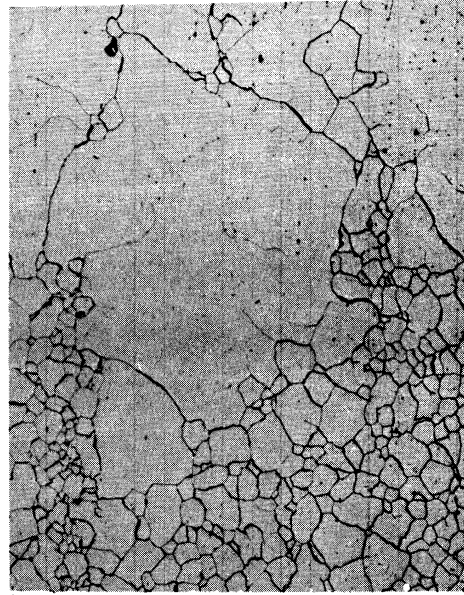


Figure 10. - Effect of rolling temperature and percent reduction upon maximum grain size of air melted Waspalloy after final solution treatment.



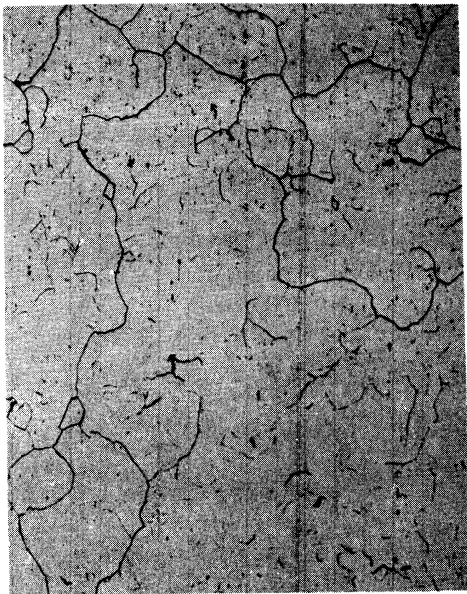
X50D

a. 0 Percent reduction



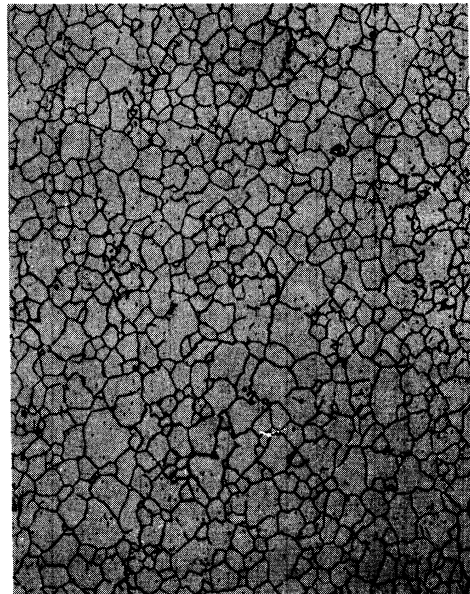
X50D

b. 1.0 Percent reduction



X50D

c. 1.5 Percent reduction



X50D

d. 13.0 Percent reduction

Figure 11. - Effect of percent reduction by rolling at 1950°F upon microstructure of equalized air melted Waspalloy after final solution treatment. The equalizing treatment of the as-received stock was a 50% reduction at 1950°F + 1 hour at 1950°F, oil quenched. Final solution treatment was 4 hours at 1950°F, oil quenched.

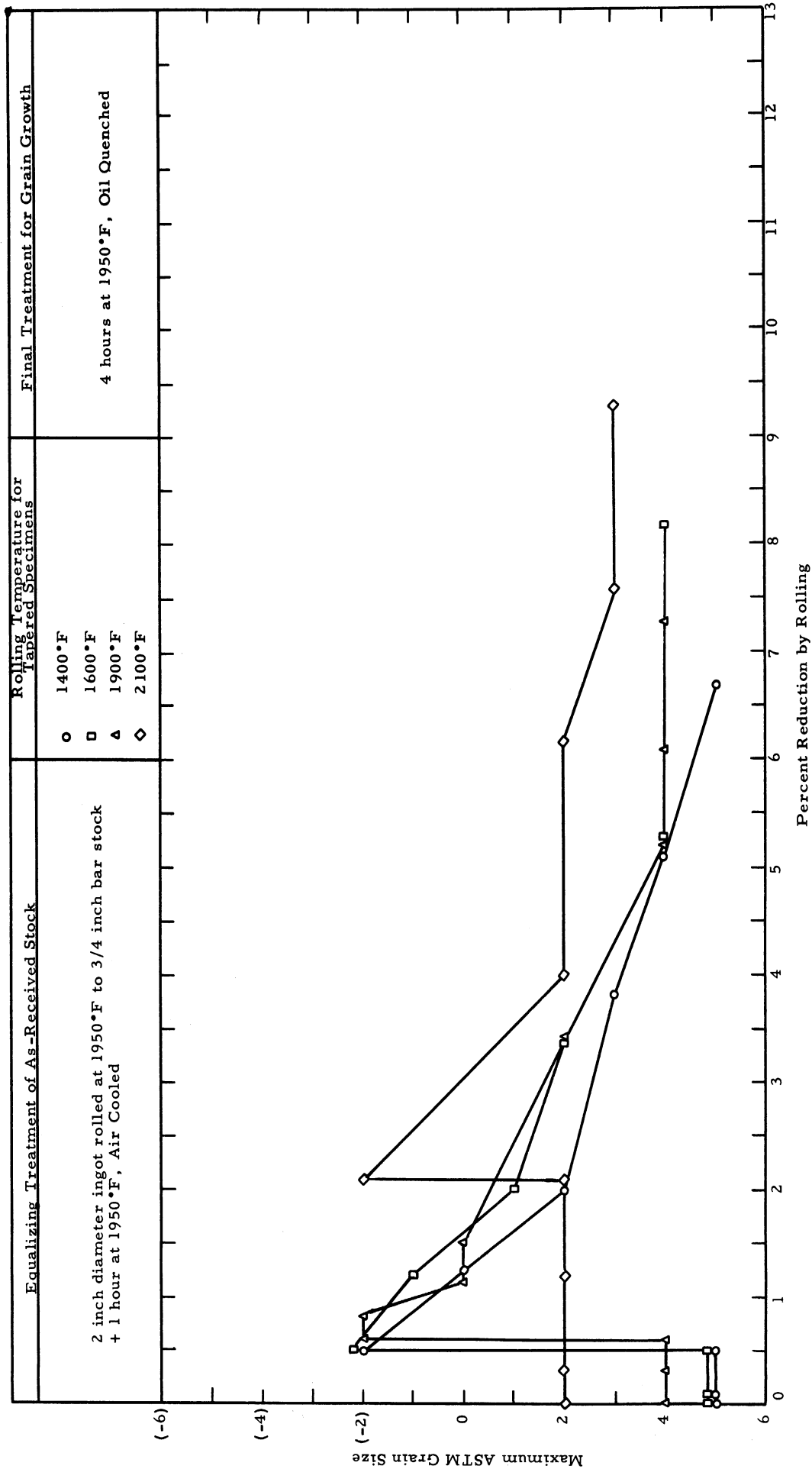
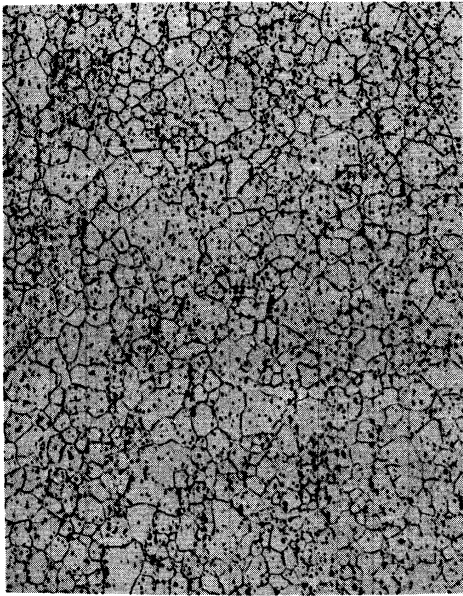
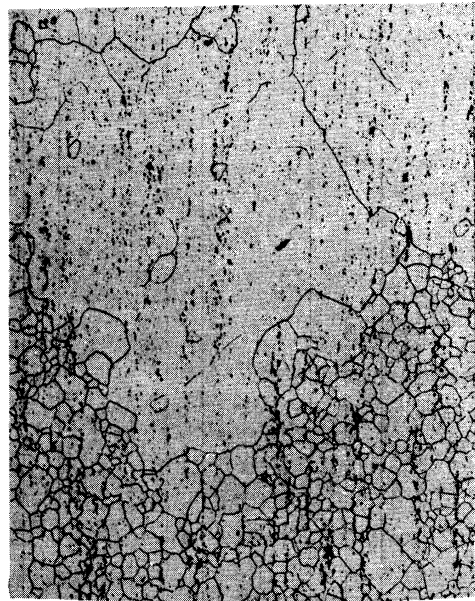


Figure 12. - Effect of rolling temperature and percent reduction upon maximum grain size of vacuum melted Waspalloy after final solution treatment.



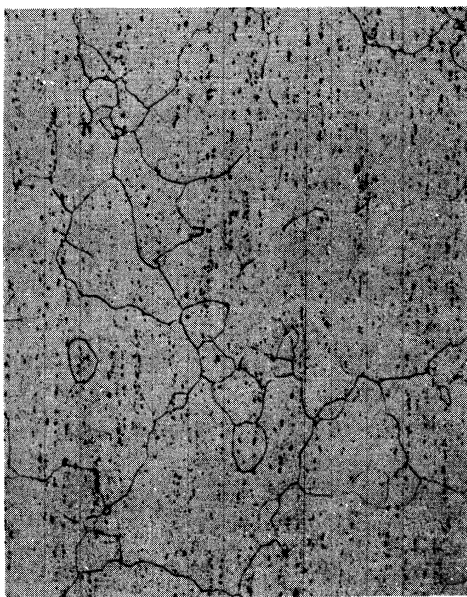
X50D

a. 0 Percent reduction



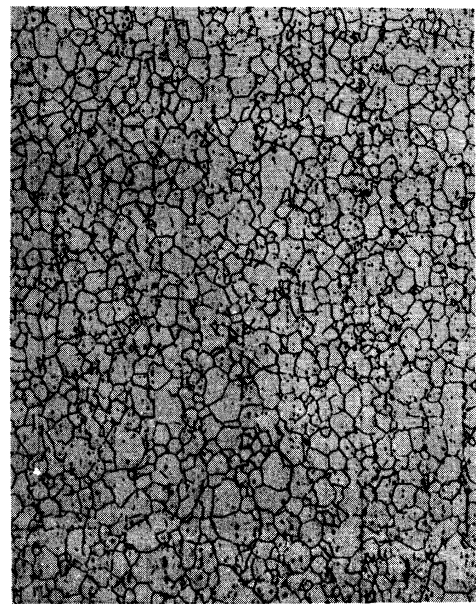
X50D

b. 0.6 Percent reduction



X50D

c. 0.8 Percent reduction



X50D

d. 6.1 Percent reduction

Figure 13. - Effect of percent reduction by rolling at 1900°F upon microstructure of vacuum melted Waspaloy after final solution treatment. The equalizing treatment of the as-rolled stock was 1 hour at 1950°F, air cooled. Final solution treatment was 4 hours at 1950°F, oil quenched.

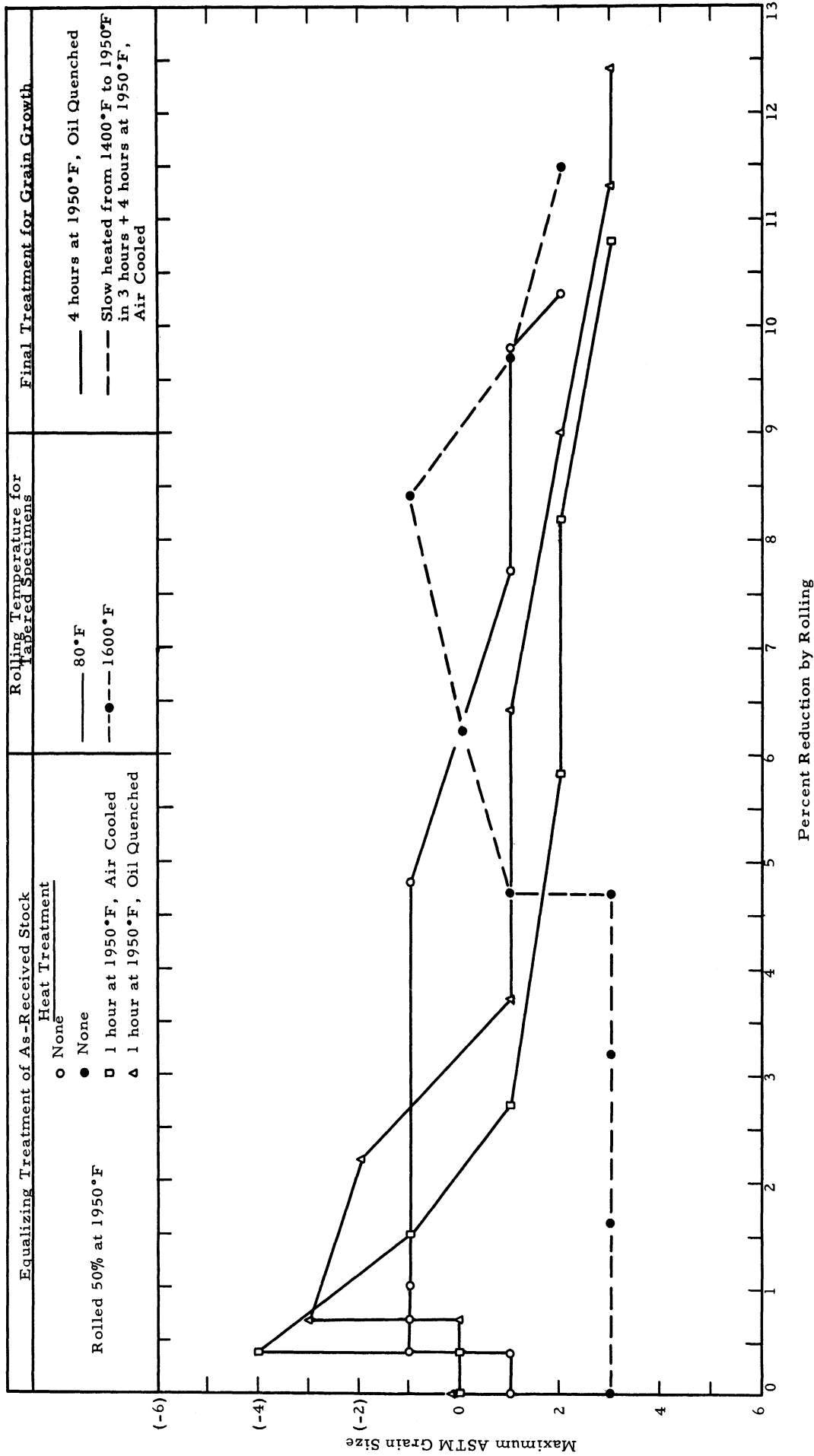


Figure 14. - Effect of equalizing treatment, rolling temperature and percent reduction and heating rate before final solution treatment upon maximum grain size of air melted Waspaloy after final solution treatment.

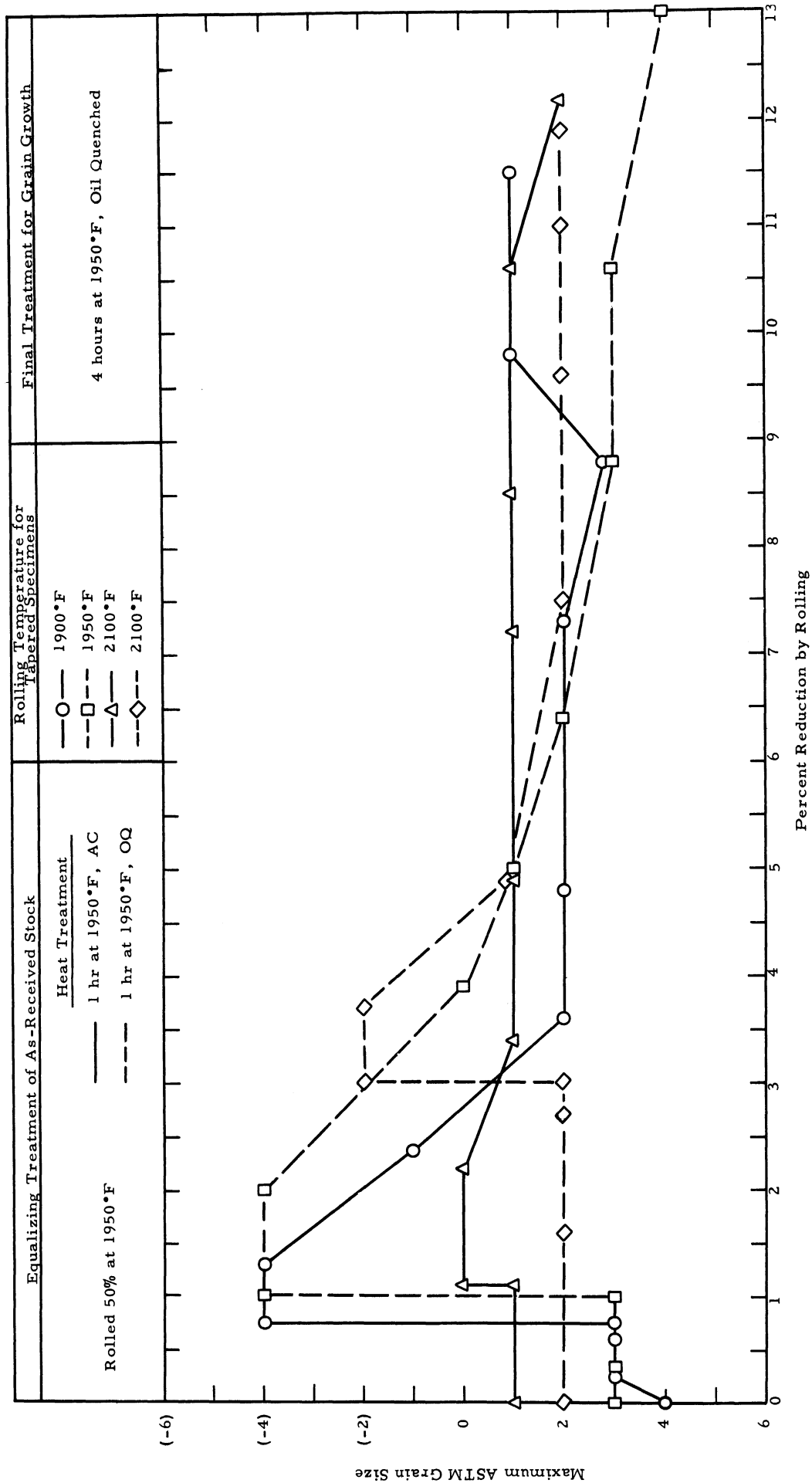


Figure 15. - Effect of equalizing treatment and rolling temperature and percent reduction upon maximum grain size of air melted Waspaloy after final solution treatment.

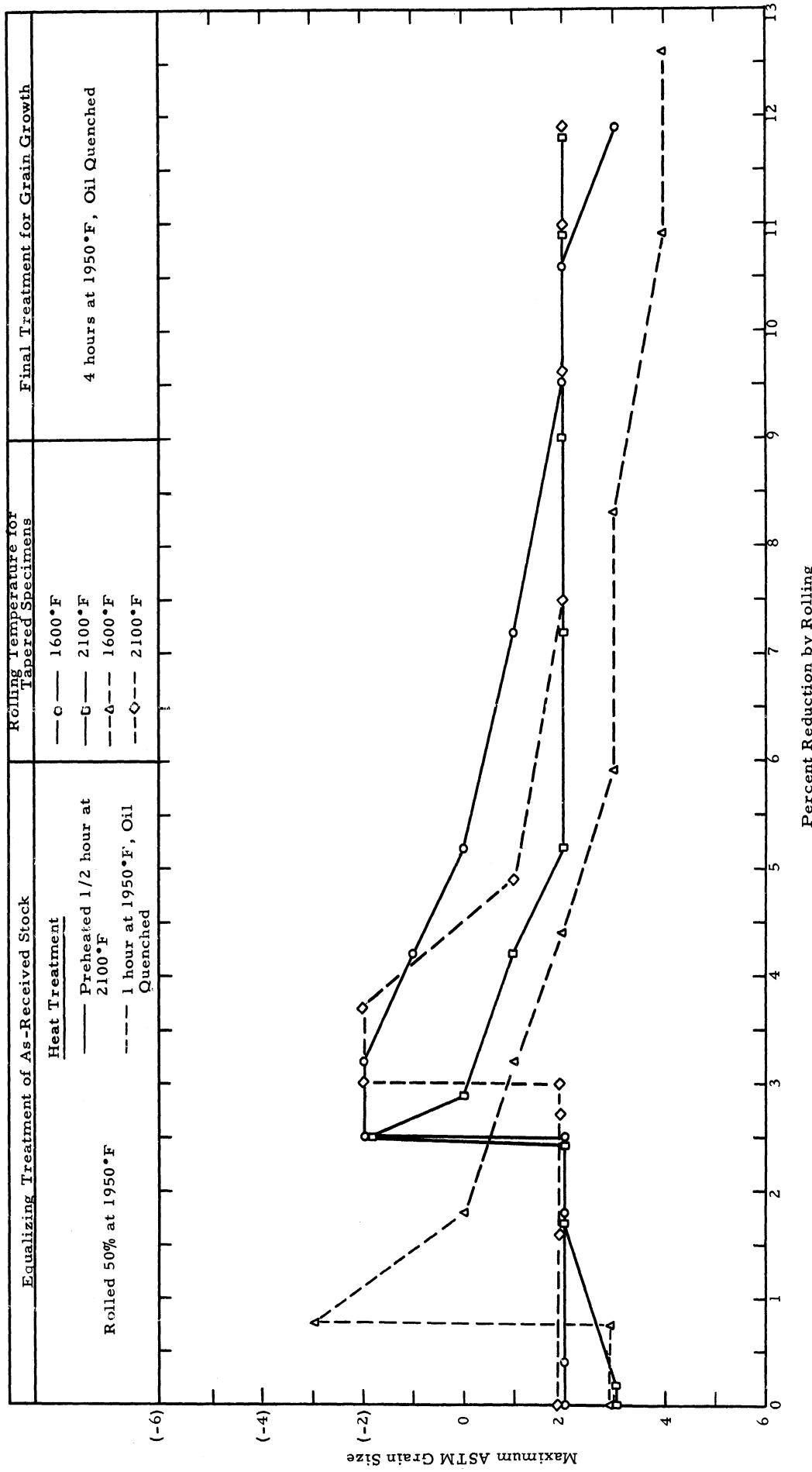


Figure 16.- Effect of equalizing treatment and rolling temperature and percent reduction upon maximum grain size of air melted Waspaloy after final solution treatment.

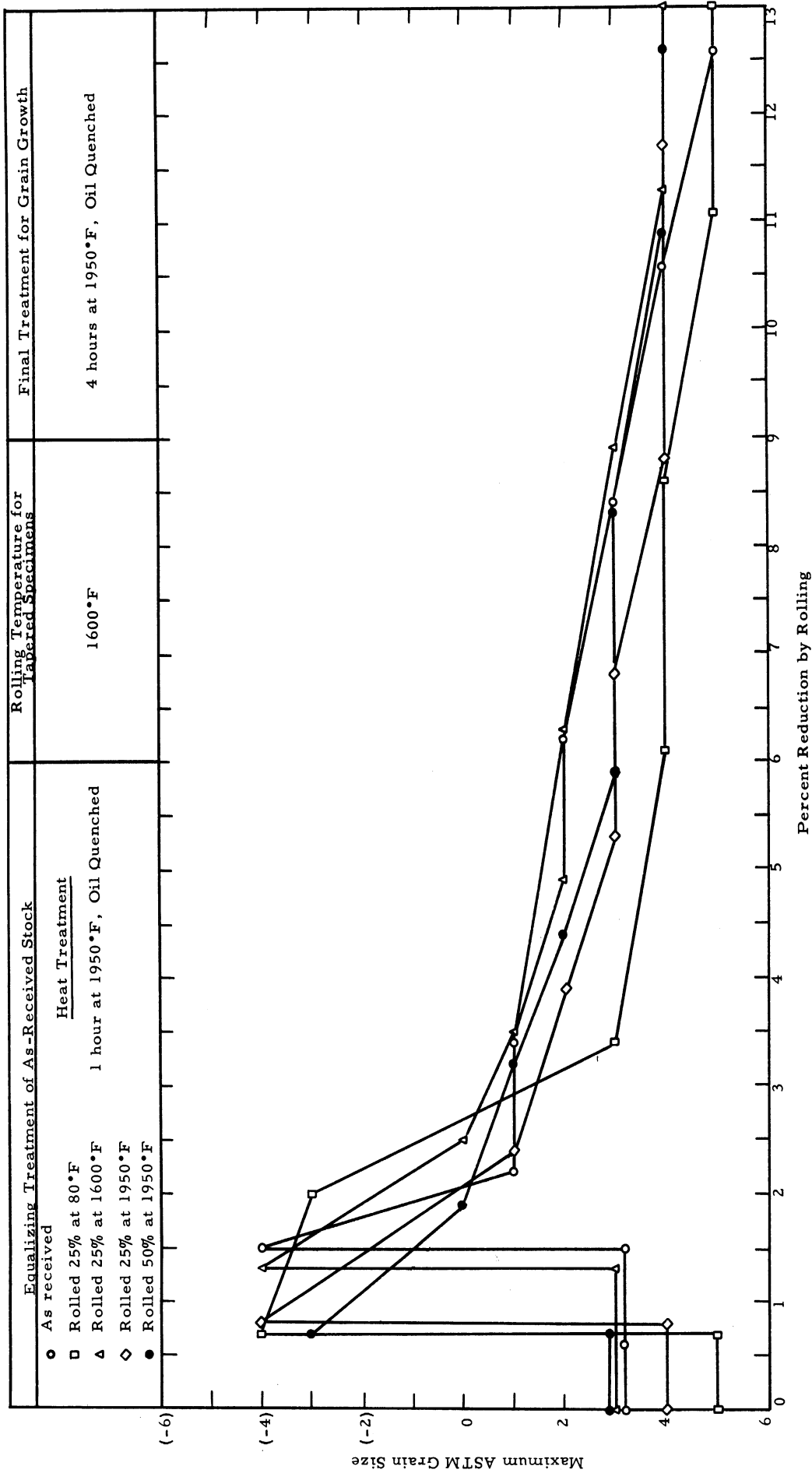
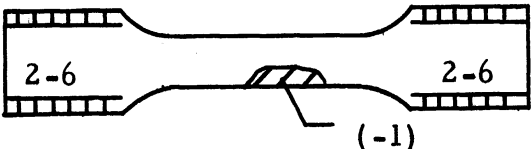
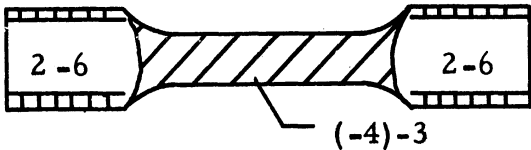
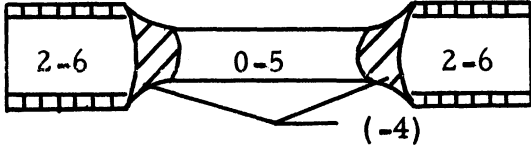


Figure 17. - Effect of equalizing treatment and percent reduction by rolling at 1600°F upon maximum grain size of air melted Waspalloy after final solution treatment.

Equalizing Treatment of As-Received Stock
1 hour at 1950°F, oil quenched, + 25% reduction at 80°F, + 1 hour at 1950°F, oil quenched

Tensile Test Temperature (°F)	Elongation (percent)	Approximate Distribution of Grain Sizes After Final Solution Treatment
1400	1.0	 <p style="text-align: center;">(-1)</p>
1600	1.0	 <p style="text-align: center;">(-4)-3</p>
1600	2.5	 <p style="text-align: center;">(-4)</p>

Final Treatment for Grain Growth
4 hours at 1950°F, oil quenched

Figure 18.- Effect of temperature and percent elongation by tensile testing upon grain size of air melted Waspaloy after final solution treatment.

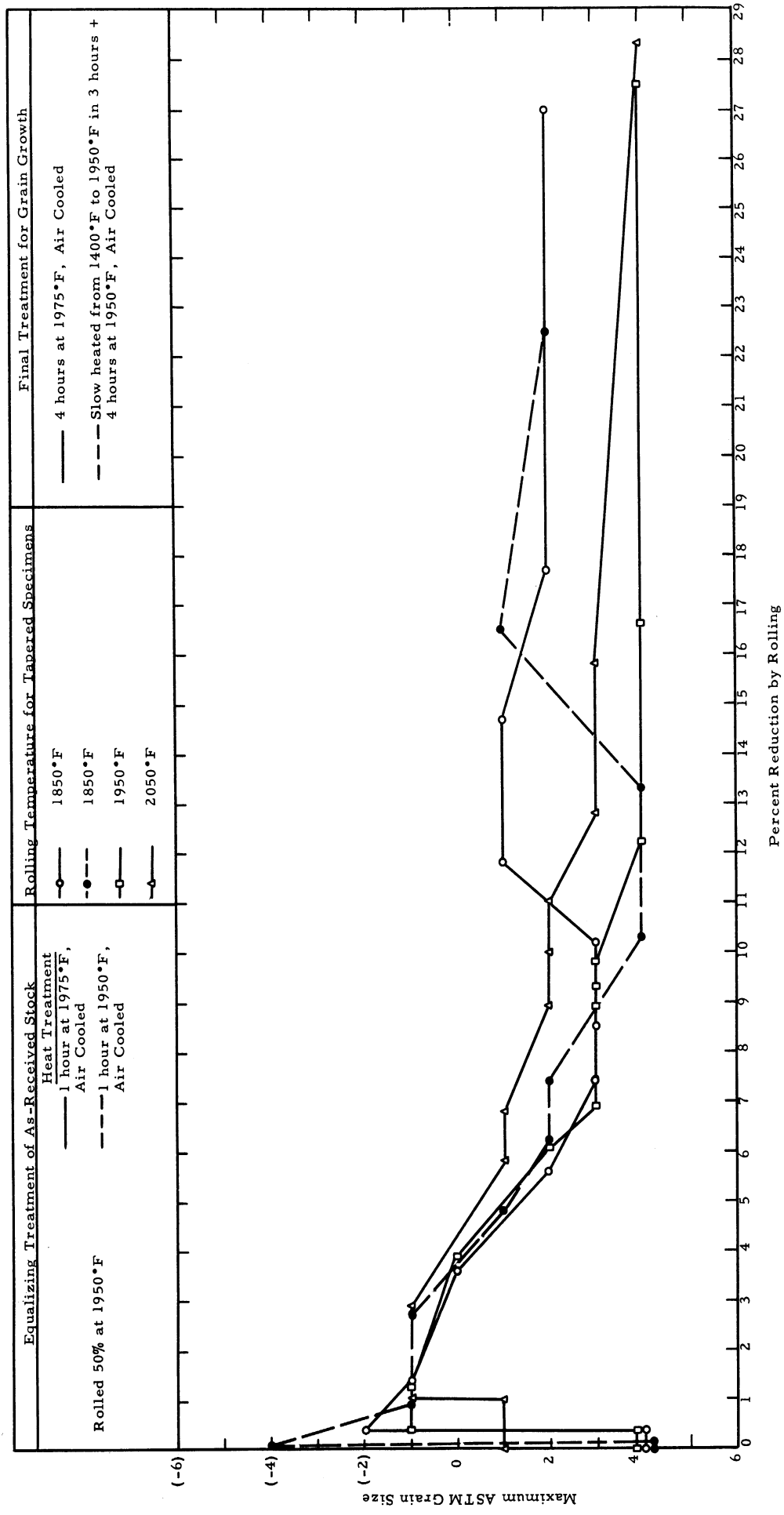
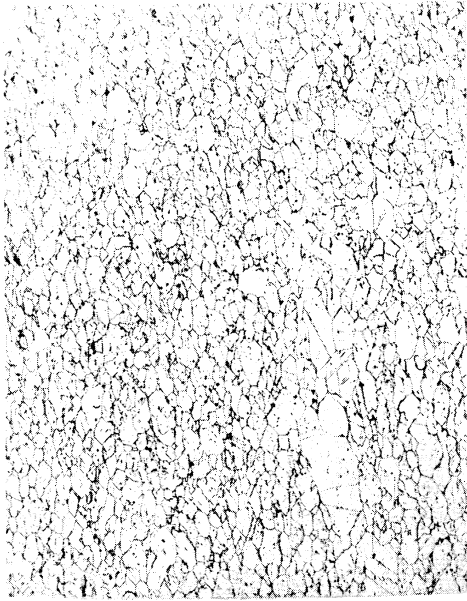


Figure 19. - Effect of rolling temperature and percent reduction upon maximum grain size of air melted Waspaloy after final solution treatment.



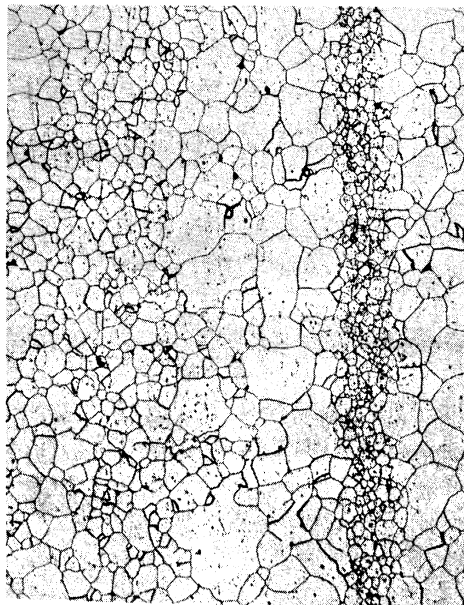
X50D

a. Microstructure as rolled.



X500D

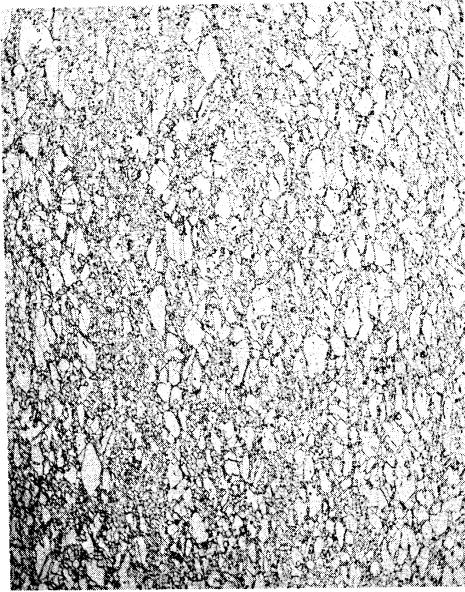
b. Microstructure as rolled.



X50D

c. Microstructure after final solution treatment.

Figure 20. - Effect of partial simultaneous recrystallization during 14 percent reduction by rolling at 1850°F upon grain size of air melted Waspaloy after final solution treatment of 4 hours at 1975°F, air cooled.



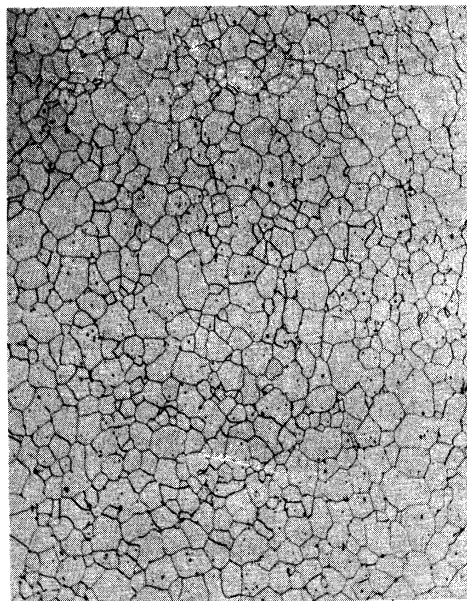
X50D

a. Microstructure as rolled.



X500D

b. Microstructure as rolled.



X50D

c. Microstructure after final solution treatment.

Figure 21. - Effect of partial simultaneous recrystallization during 16 percent reduction by rolling at 1950°F upon grain size of air melted Waspaloy after final solution treatment of 4 hours at 1975°F, air cooled.

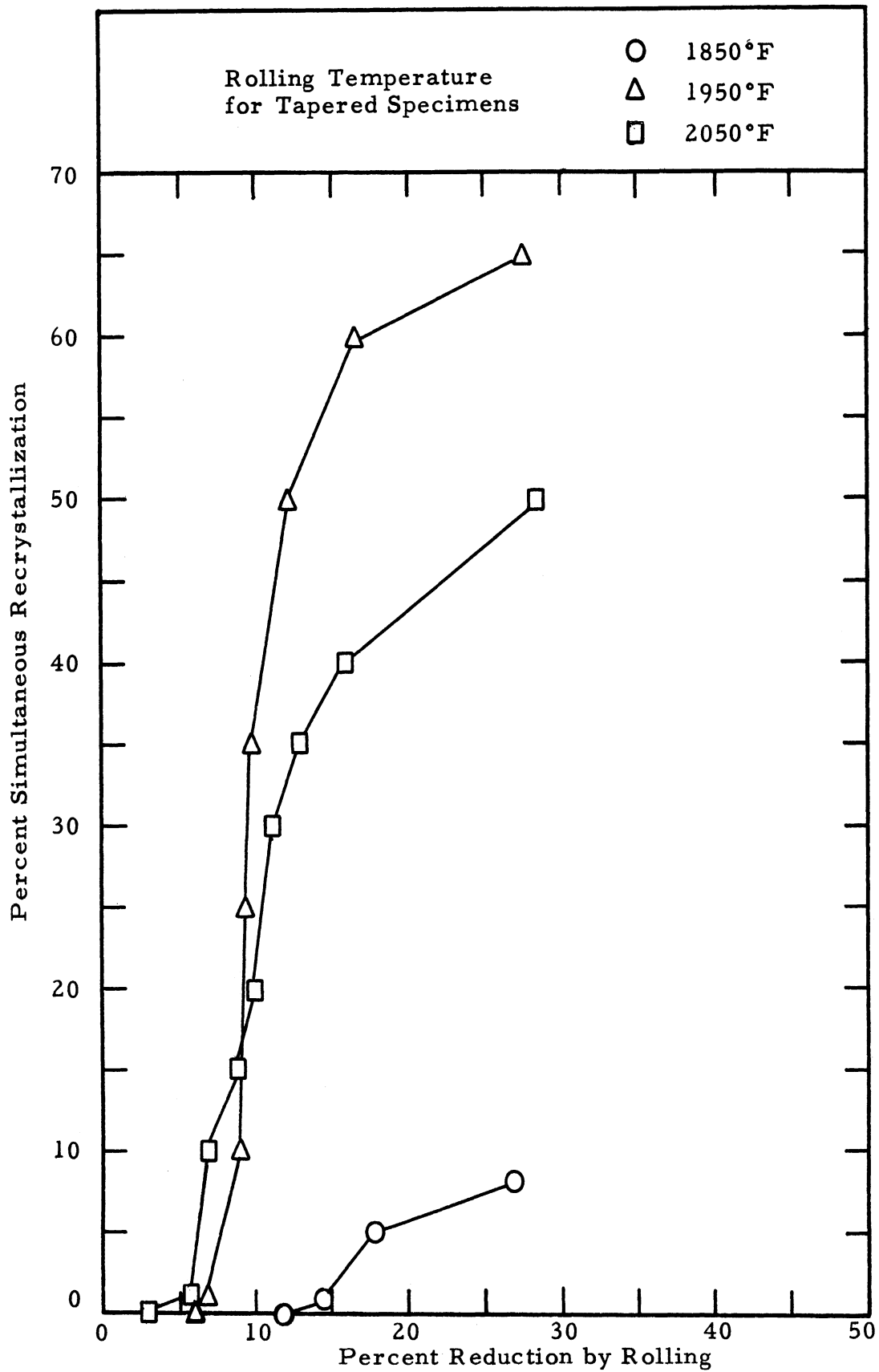
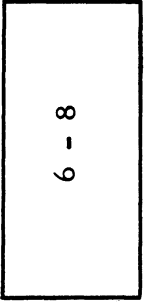


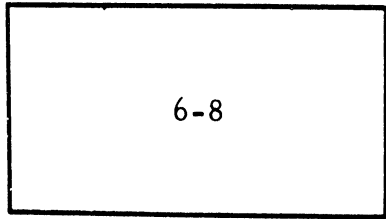
Figure 22. - Effect of percent reduction by rolling upon percent simultaneous recrystallization of air melted Waspaloy.

As-Received

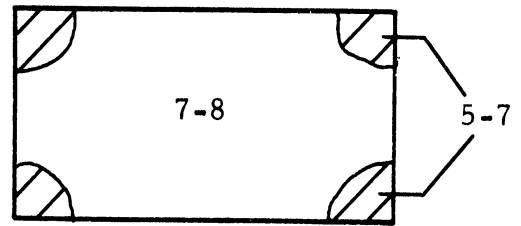


Heat Treating Temperature (°F)	Heat Treating Time (hours)			
	1	4	6	
1900				
2000				
2100				
2200				

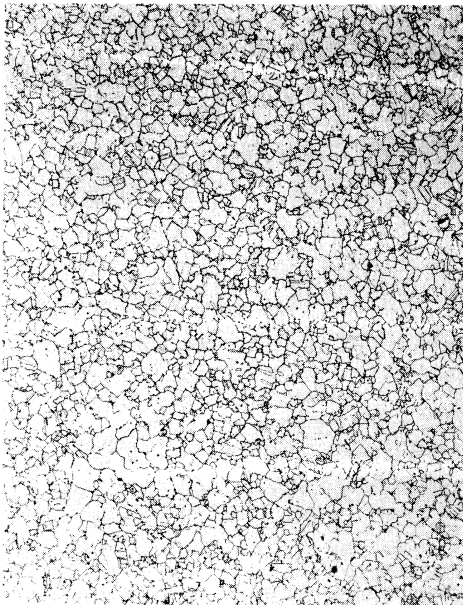
Figure 23.- Effect of heat treating time and temperature upon the grain size of transverse sections of as-received Inconel 'X'-550 bar stock.



a. Approximate distribution of grain sizes, as-received.

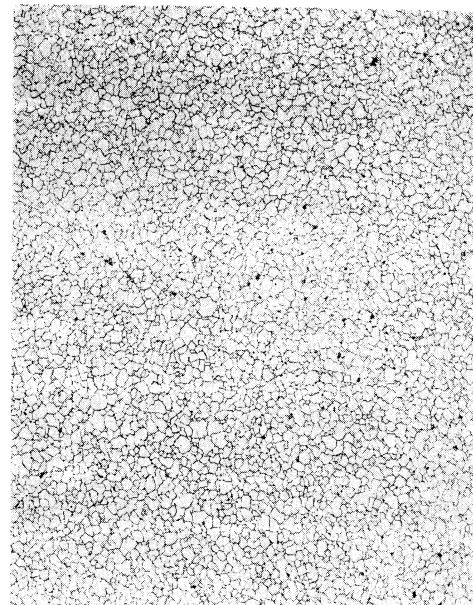


c. Approximate distribution of grain sizes, as-received + 2 hours at 1900°F, Air Cooled.



X50D

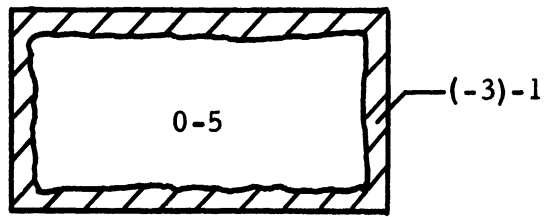
b. Microstructure as-received.



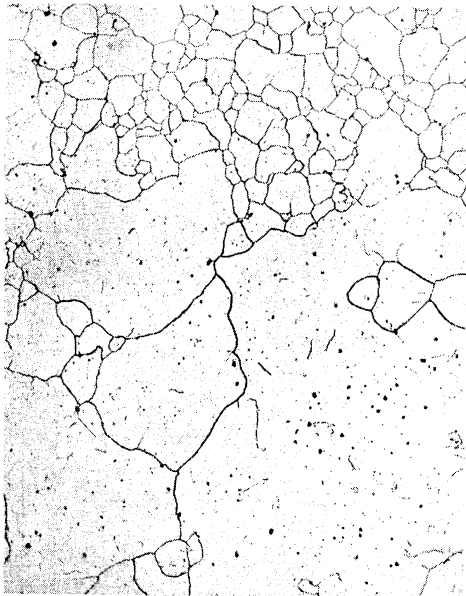
X50D

d. Microstructure as-received + 2 hours at 1900°F, Air Cooled. (Center of bar stock).

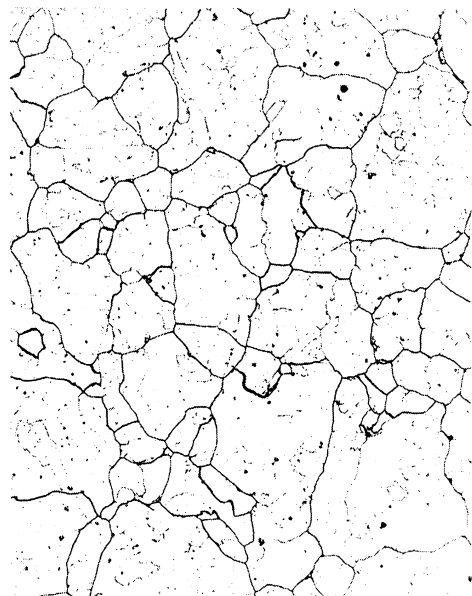
Figure 24. - Microstructure and grain sizes of transverse sections of Inconel "X"-550 bar stock.



- e. Approximate distribution of grain sizes as-received + 2 hours at 2100°F, Air Cooled.



X50D



X50D

- f. Microstructure as-received + 2 hours at 2100°F, Air Cooled. (Junction between fine and coarse grains.)

- g. Microstructure as-received + 2 hours at 2100°F, Air Cooled. (Center of bar stock.)

Figure 24. - (Concluded.)


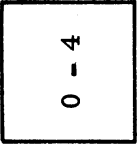
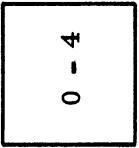
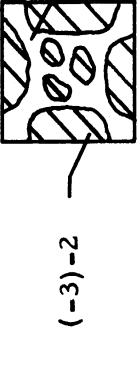
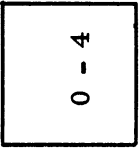
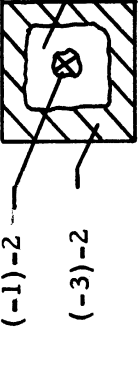
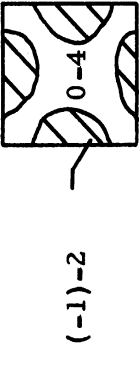
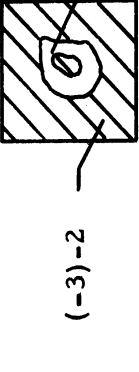
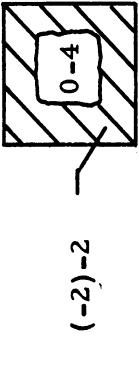
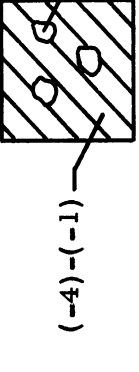
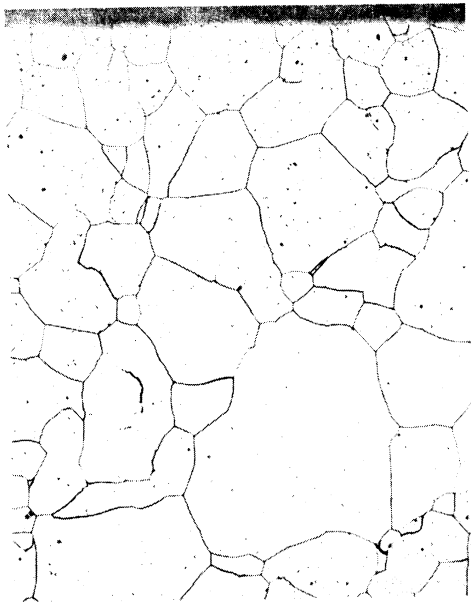
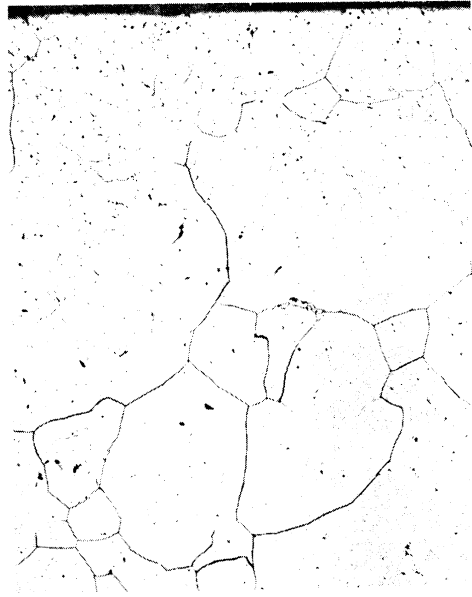
Heat Treatment	Cooling Method	
	Air Cooled	Water Quenched
One cycle of 1 hour at 2150°F, cooled		
Two cycles of 1 hour at 2150°F, cooled		
Three cycles of 1 hour at 2150°F, cooled		
Four cycles of 1 hour at 2150°F, cooled		
Five cycles of 1 hour at 2150°F, cooled		

Figure 25.- Effect of repeated heating and cooling upon the grain size of transverse sections of Inconel "X"-550 bar stock which had been equalized by a 64% reduction at 2150°F.



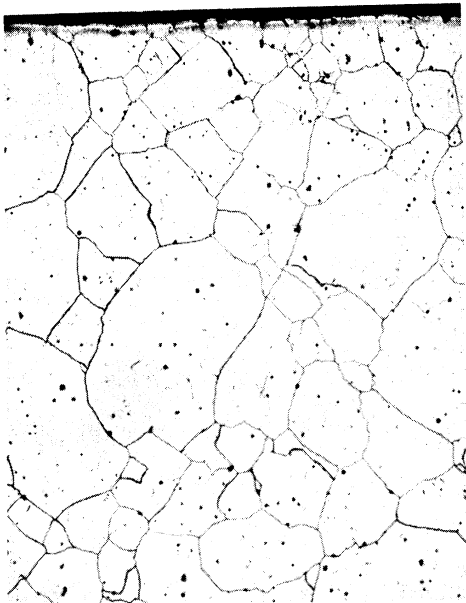
X50D

a. 1 hour at 2150°F, Air Cooled.



X50D

b. 5 cycles of 1 hour at 2150°F, Air Cooled.



X50D

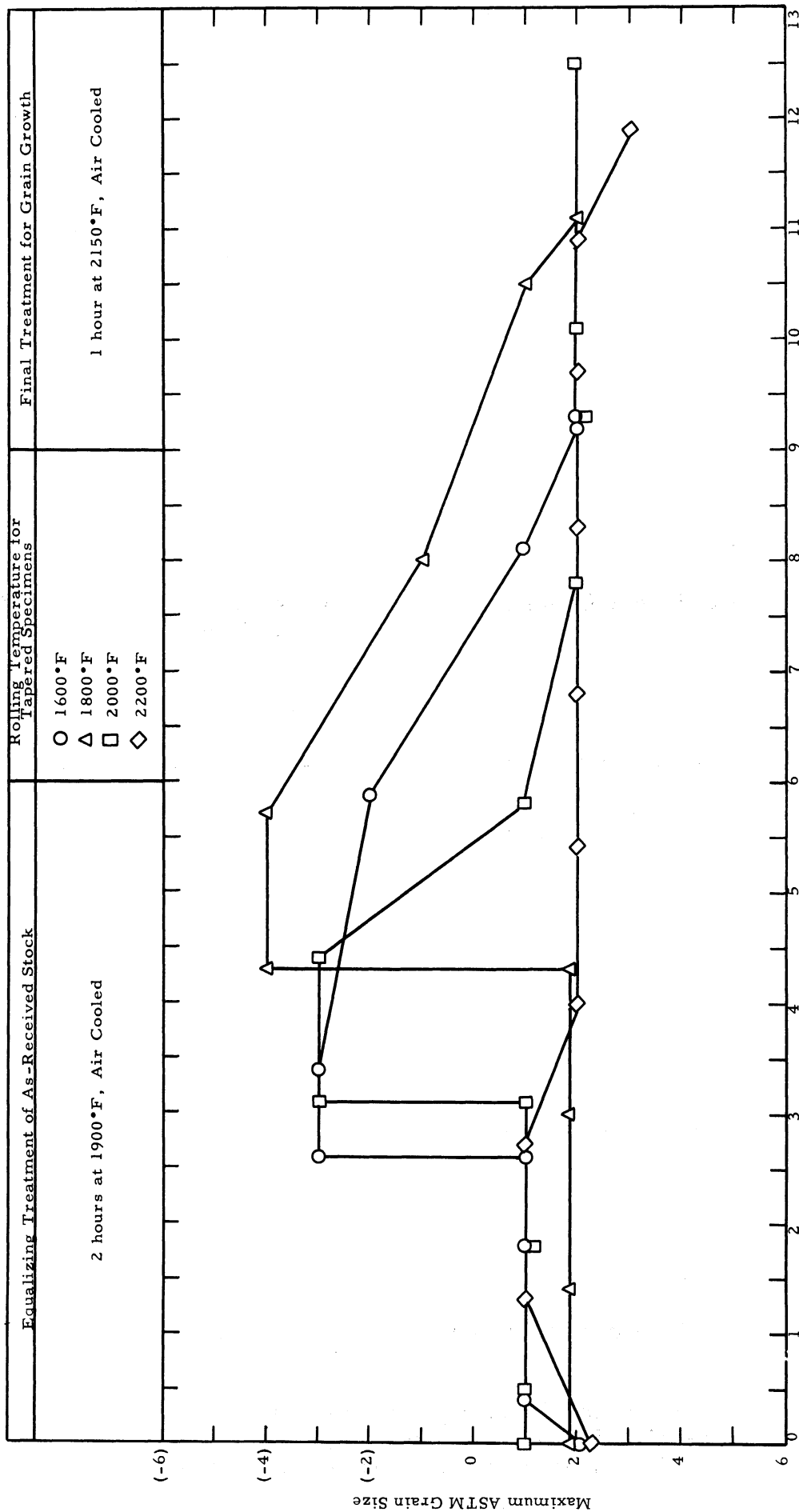
c. 1 hour at 2150°F, Water Quenched.



X50D

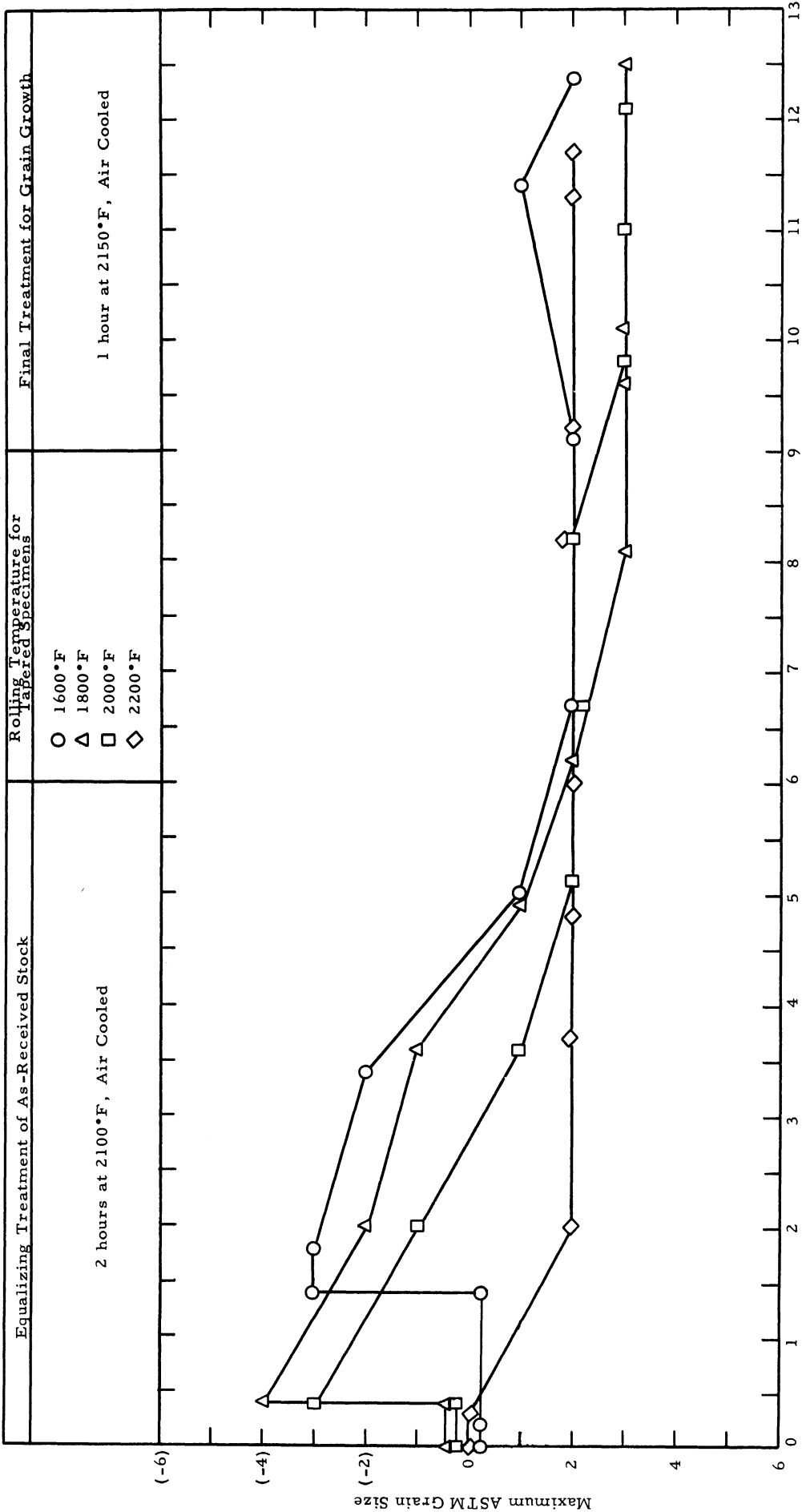
d. 5 cycles of 1 hour at 2150°F, Water Quenched.

Figure 26.- Effect of repeated heating and cooling upon microstructure of Inconel "X"-550 which had been equalized by a 64% reduction at 2150°F. (Transverse section at the bar stock surface.)



Percent Reduction by Rolling

Figure 27. - Effect of rolling temperature and percent reduction upon maximum grain size of Inconel "X"-550 after final solution treatment. Grain size after equalizing treatment was 7-8.



Percent Reduction by Rolling

Figure 28. - Effect of rolling temperature and percent reduction upon maximum grain size of Inconel "X"-550 after final solution treatment. Grain size after equalizing treatment was 0-5.

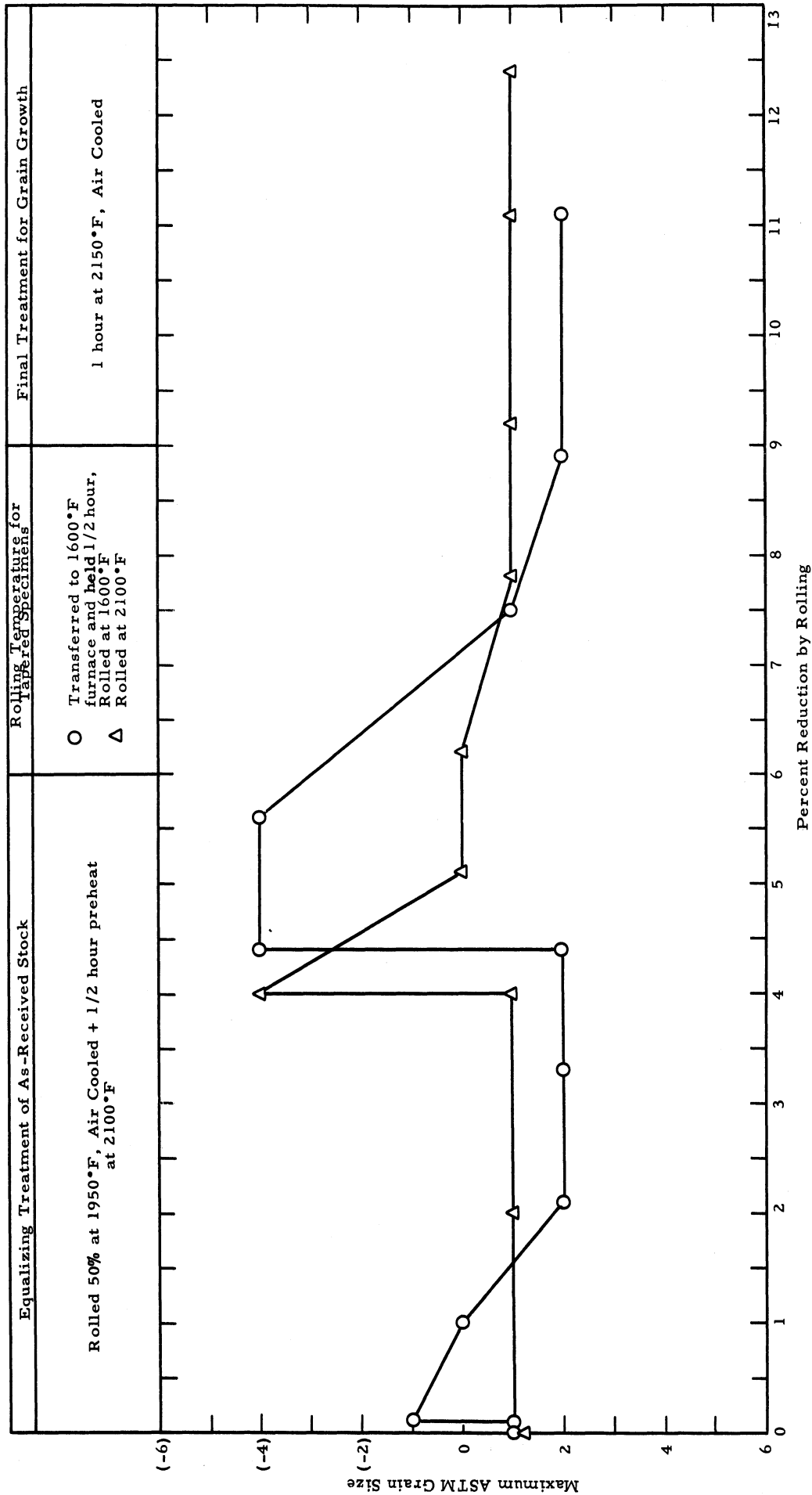
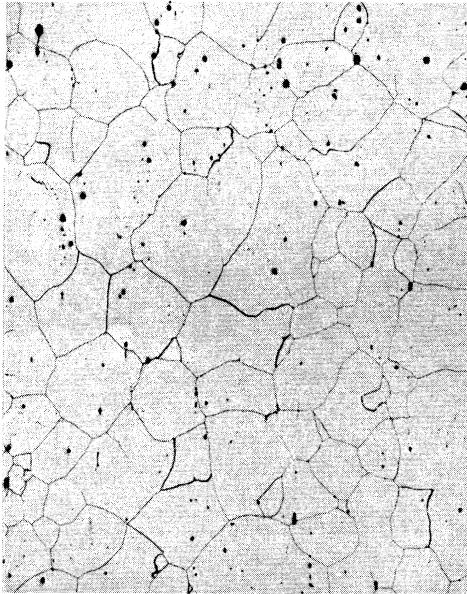
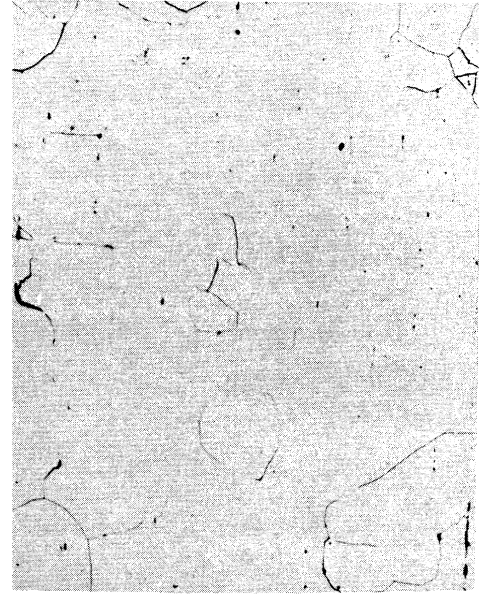


Figure 29. - Effect of rolling temperature and percent reduction upon maximum grain size of Inconel "X"-550 after final solution treatment, Equalizing treatment included rolling at 1950°F and preheat at 2100°F.



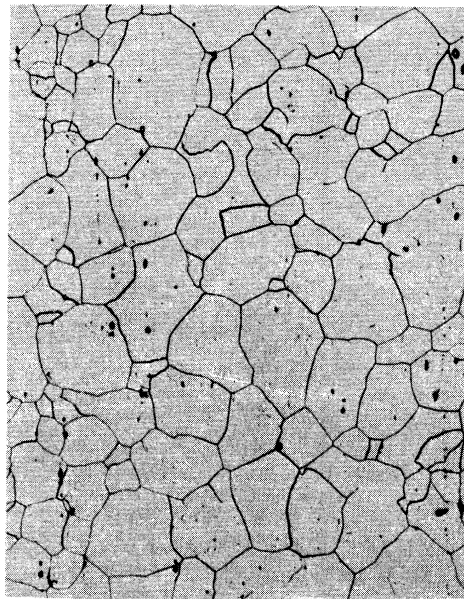
X50D

a. 0 Percent reduction



X50D

b. 4.0 Percent reduction

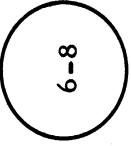


X50D

c. 11.1 Percent reduction

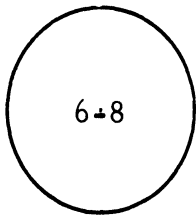
Figure 30. - Effect of percent reduction by rolling at 2100°F upon microstructure of equalized Inconel "X"-550 after final solution treatment. The equalizing treatment of the as-received stock was a 50% reduction at 1950°F + 1/2 hour preheat at 2100°F before rolling. Final solution treatment was 1 hour at 2150°F, Air Cooled.

As-Received

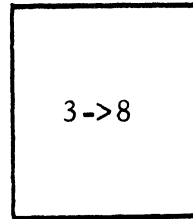


Heat Treating Temperature (°F)	Heat Treating Time (hours)		
	1	4	6
1950			
2100			
2150			
2200			
2300			

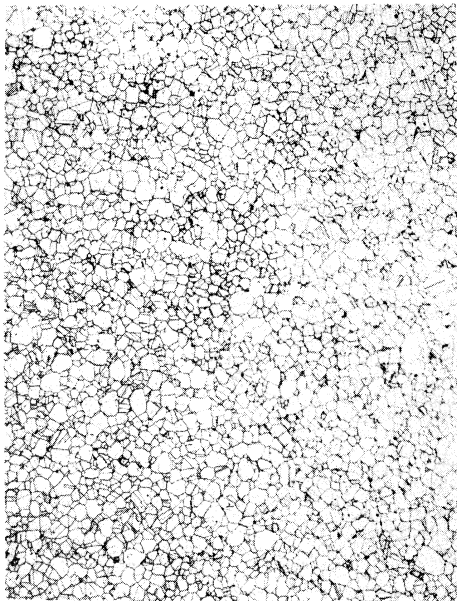
Figure 31.- Effect of heat treating time and temperature upon the grain size of transverse sections of as-received Nimonic 80A bar stock.



a. Approximate distribution of grain sizes as-received.

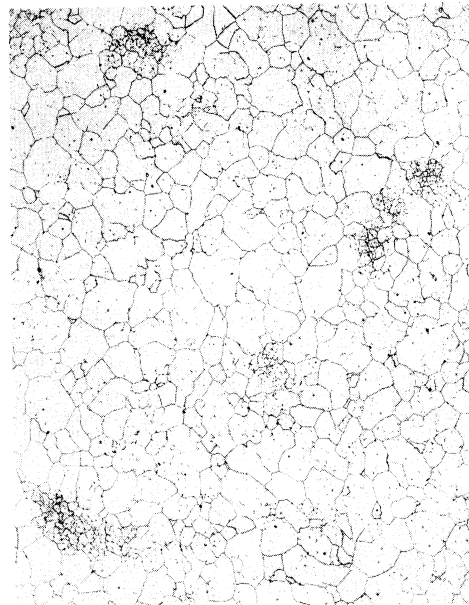


c. Approximate distribution of grain sizes after equalizing with 50% reduction at 1950°F + 1 hour at 1950°F, Air Cooled.



X50D

b. Microstructure as-received.



X50D

d. Microstructure after equalizing with 50% reduction at 1950°F + 1 hour at 1950°F, Air Cooled.

Figure 32. - Microstructures and grain sizes of transverse sections of as-received and equalized Nimonic 80A bar stock.

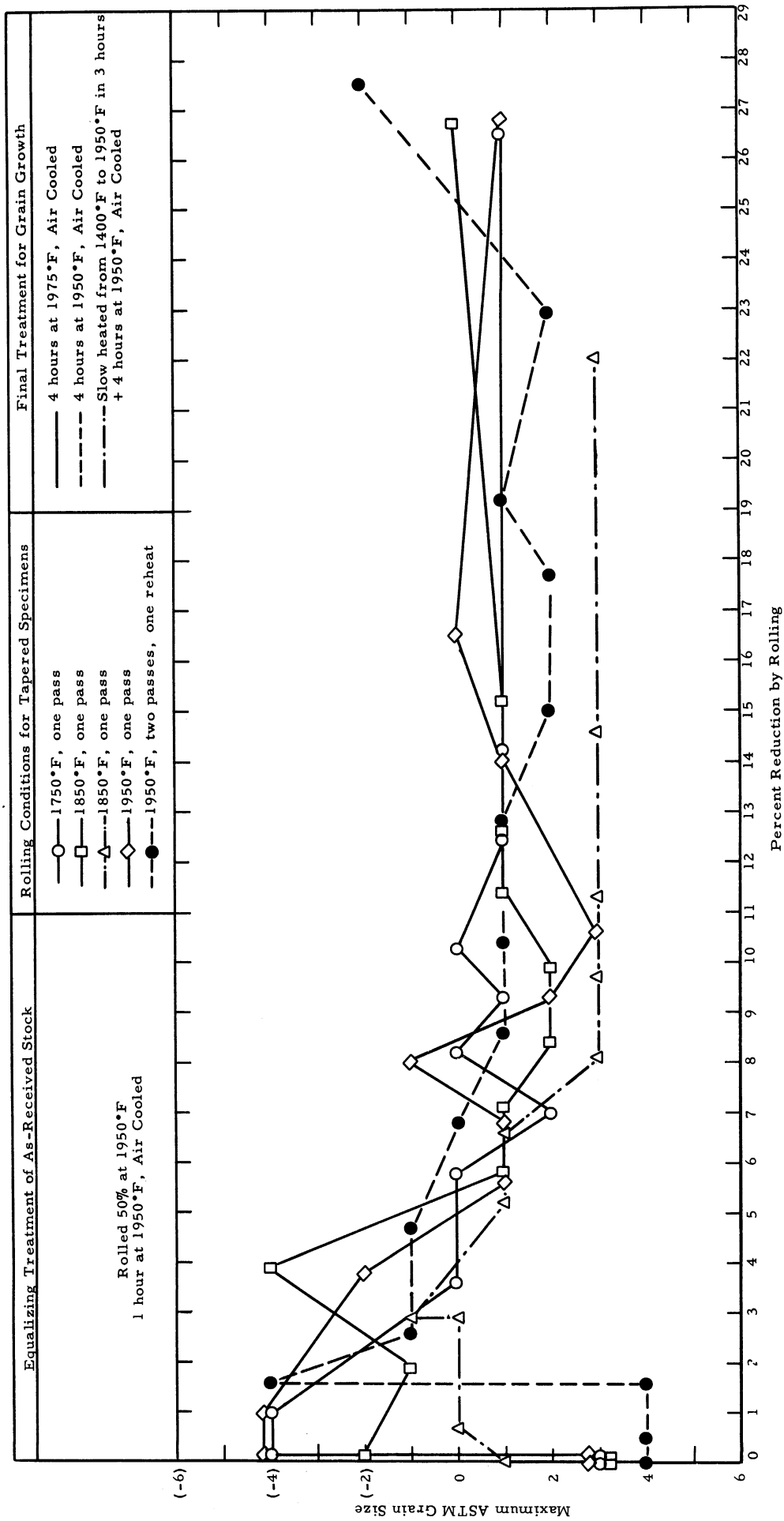


Figure 33. - Effect of temperature and percent reduction by rolling, repeated deformation by rolling and heating rate before final solution treatment upon maximum grain size of Nimonic 80A after final solution treatment.

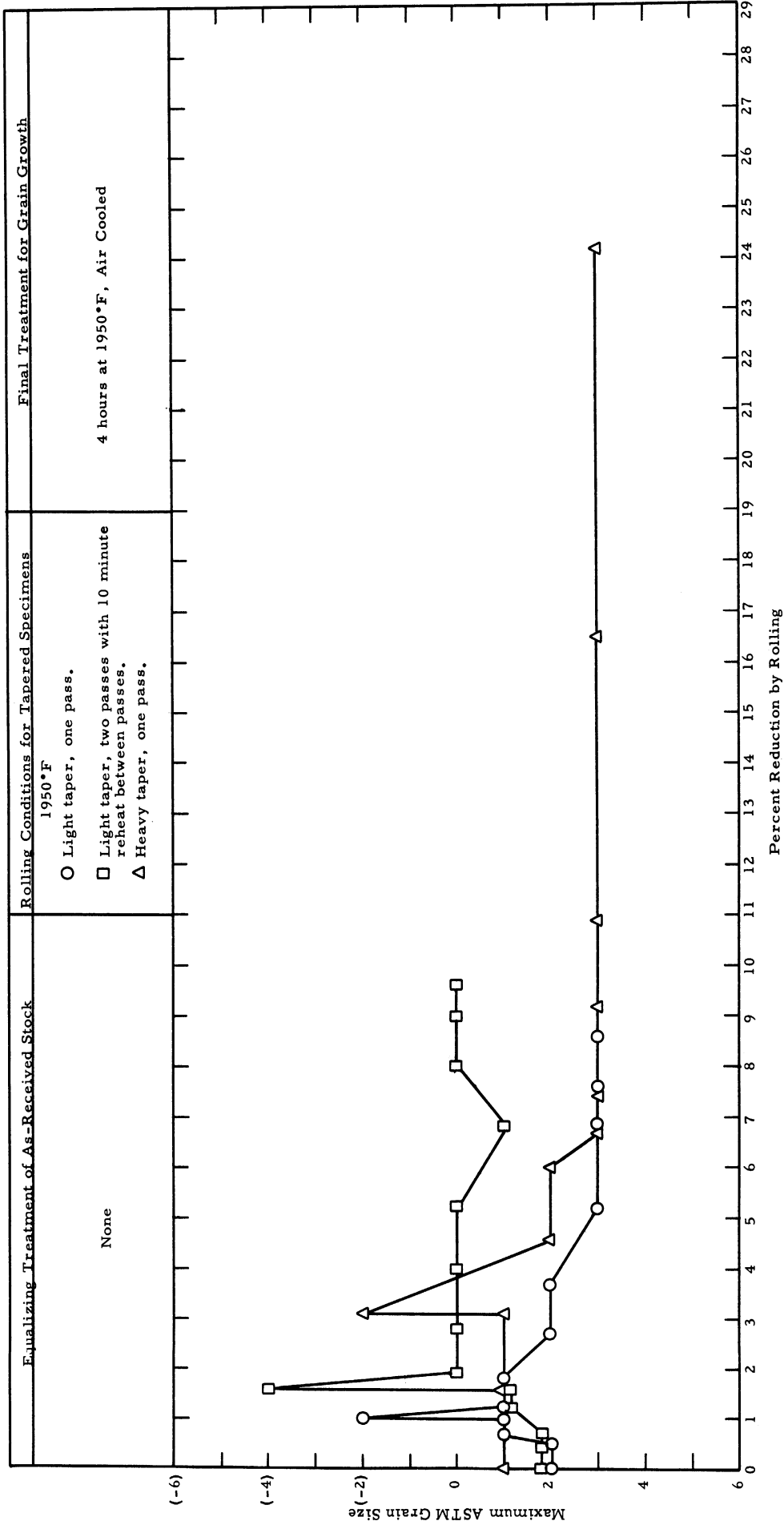


Figure 34. - Effect of degree of taper, repeated deformation and percent reduction by rolling upon maximum grain size of Nimonic 80A after final solution treatment.

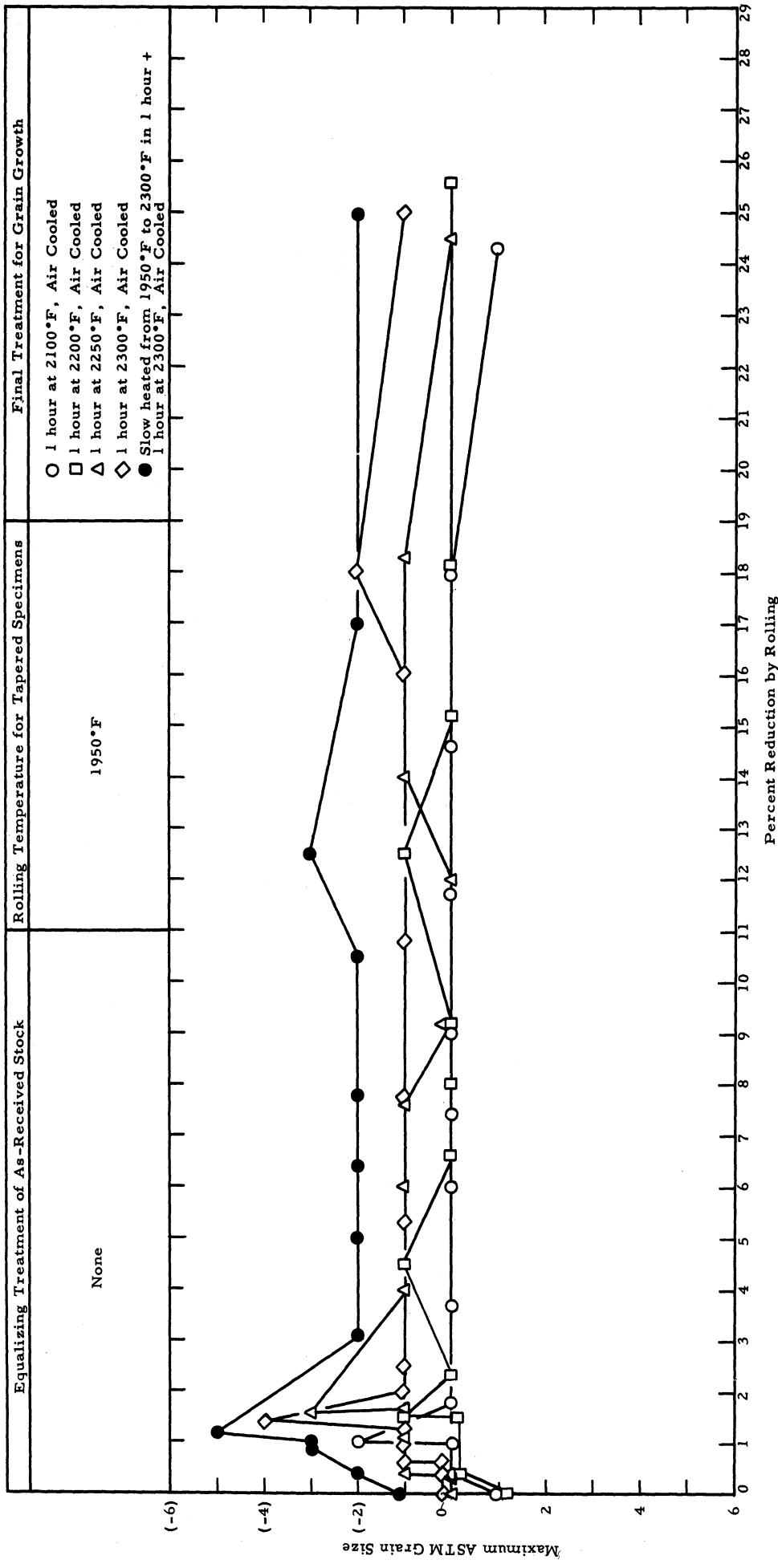


Figure 35. - Effect of final solution treatment and percent reduction by rolling upon maximum grain size of Nimonic 80A.

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