TWELFTH PROGRESS REPORT

TO

MATERIALS LABORATORY

WRIGHT AIR DEVELOPMENT CENTER

ON

FOUR LOW-ALLOY STEELS FOR ROTOR DISKS OF GAS TURBINES

IN JET ENGINES

by

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SUMMARY

This report presents the progress made in an investigation of the high temperature properties of low-alloy steels for use in jet engines. The period covered by the report was from April 1, 1954 to June 30, 1954.

Nearly complete data are presented for survey tests to evaluate the influence of microstructure as controlled by continuous cooling transformation on the high temperature properties of SAE 4340, "17-22A"S, and H-40 steels at temperatures ranging from 700° to 1200°F. The structures studied are those obtained by continuous cooling transformation during the air cooling of 1-inch and simulated 3- and 6-inch diameter bars. Normalizing of 1-inch diameter bars resulted in mixed martensitic-bainitic structures, whereas the slower cooling cycles resulted in predominately bainitic structures for all three steels. It was observed that the microstructures of the simulated 3- and 6-inch bars of "17-22A"S and H-40 steel were considerably coarser than those of the 1-inch bar, but that little or no change was noted for the SAE 4340 steel as a function of heating or cooling rate. In all instances the hardness levels were adjusted by tempering to approximately 300 Brinell.

The incomplete test data tend to show that little variation in creep-rupture properties is obtained for the subject steels as a result of normalizing in section sizes ranging from 1-inch to 6-inch diameter bars. The variations resulting from differences in continuous cooling transformation conditions indicate that the slower cooling cycles, selected to simulate the air cooling of 3- and 6-inch diameter bars, tend to give strength properties equal to or slightly higher than those of a 1-inch diameter normalized bar. However, detailed consideration of such variations has been withheld pending the completion of the testing program.

INTRODUCTION

This report covers the work done during the period between April 1, 1954 and June 30, 1954 on an investigation of the metallurgical factors involved in the use of heat-treatable, low alloy steels at elevated temperatures in jet engines. Contract Number: AF 33(038)13496 (Expenditure Order Number: 605-227 SR-7) and Supplemental Agreement Number: S9(54-1203) (Expenditure Order Number: R 619-11 SR-1z) authorize the work.

The investigation first evaluated the high temperature properties of four low alloy steels in the form of rotor wheels for gas turbines of jet engines. This work has been published as WADC Technical Report 53-277, Part 1.

A concurrent investigation was conducted to determine the relationships between types of microstructure, as controlled by heat treatment, and the properties of the alloys. The properties of such steels at elevated temperatures vary with the types of structure formed by heat treatment. Therefore, the influence of microstructure on high temperature properties was evaluated by survey tests for the temperature range of 700° to 1200°F for structures obtained by isothermal transformations in the pearlitic and bainitic regions as well as those produced by oil-quenching and normalizing of 1-inch rounds.

Three pearlitic and three bainitic structures were studied for the 4340 and "17-22A"S steels, but because of the narrow temperature range in which complete transformation could be obtained in reasonable time periods, only one pearlitic and one bainite structure were studied for the H-40 steel. A technical report entitled "A Survey of the Relations Between Microstructure and Elevated Temperature Properties of Four Low-Alloyed Steels at 700° to 1200°F" covering the results of this portion of the investigation is in preparation and will be published as WADC Technical Report 7 53-277, Part 2.

A third phase of the investigation concerned the properties of structures obtained by continuous cooling transformation at cooling rates approximating those existing during air cooling of sections sizes similar to rotor wheels. The present report presents the results of that portion of the work.

The properties of structures produced by cooling rates simulating those existing in the center of 3- and 6-inch diameter rounds have been survey tested in the temperature range of 700° to 1200°F for the SAE 4340, "17-22A"S, and H-40 steels. It was believed that these cooling rates together with those previously studied, the oil-quenched and normalized 1-inch round bars, cover adequately the range of structures of major interest; that is, from martensite to bainite formed by relatively slow cooling rate. The initial surveys are nearly complete for this report. Future work will involve the completion of the study of the properties of structures obtained by continuous cooling transformation, and the extension to include the effect of variations in austenitizing temperature on high temperature properties. The ultimate objective is to establish the metallurgical principles of heat treatment for producing as nearly optimum properties as possible in such alloys for use at elevated temperatures.

Test Materials

The chemical compositions of the alloys being studied was reported by the manufacturers to be as follows:

Steel	Heat	C	Mn	Si	Cr	Ni	Mo	V	W
4340	19053	0.40	0.70	0.30	0.78	1.75	0.26	--	--
"17-22A"S	10420	0.29	0.61	0.67	1.30	0.18	0.47	0.26	--
H-40	K-2509	0.29	0.48	0.26	3.05	0.49	0.49	0.85	0.55

Procedure

The transformation products obtained by continuous cooling are a function of the cooling rate through the transformation temperature range. Inasmuch as the cooling rates involved in the heat-treatment of parts of large section size are considerably faster than can be obtained easily by controlled furnace cooling, the desired cooling rates may best be obtained by varying the section size being cooled. Since only 3/4- and 1-inch diameter bars were available, the desired cooling cycles were obtained by the retarded cooling of the 3/4- and 1-inch round bars in a cylinder made from a low heat duty fireclay insulating brick. The general procedure was as follows:

1. To establish the cooling cycles for 3- and 6-inch diameter bars, the cooling cycles for 1-inch bars of "17-22A"S steel and 1- and 3-inch diameter bars of plain carbon steel were obtained during air cooling by means of a thermocouple inserted axially to the center of the bar. Cooling curves were not obtained for 6-inch rounds because of the handling difficulties and the capacity of the laboratory furnaces.

2. From the cooling curves obtained for the 1- and 3-inch rounds, the heat transfer coefficient (h) to the surrounding medium, air in this case, was calculated for the conditions existing in the laboratory.[1] From the h value obtained, the cooling curve for a 6-inch round was calculated.

3. Cooling curves were obtained at the center and surface of 1-inch rounds of 4340 and "17-22A"S materials and at the same locations for 3/4-inch rounds of H-40 during cooling in insulating firebrick cylinders estimated to produce cooling cycles similar to the 3- and 6-inch round bars.

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(1) T. F. Russell, "Some Mathematical Considerations on the Heating and Cooling of Steel," First Report of the Alloy Steels Research Committee by a Joint Committee of the Iron and Steel Institute, 1936, page 149.

Through trial and error, the thickness of the firebrick cylinder was adjusted to produce cooling cycles equivalent to the experimentally determined cycle for the 3-inch round and the calculated cycle for the 6-inch round. The actual cooling curves obtained for "17-22A"S during cooling from 1750°F are illustrated in Figure 1, and Figure 2 shows similar curves for H-40 steel cooled from 1950°F. The cooling curves obtained for the 4340 steel, air cooled from 1750°F, were nearly the same as those shown for "17-22A"S, and, therefore, are not illustrated. Figure 3 compares the cooling cycles from 1750°F with those from 1950°F on a semilogarithmic graph.

It was found that since the principal factor controlling the cooling cycle appeared to be the rate of heat transfer across the metal to firebrick interface, the cooling rate at the surface of the enclosed bar was essentially the same as that at the center. This conclusion was confirmed by the uniform microstructure observed throughout the cross-section of the heat-treated bars.

4. After the necessary thickness of firebrick to produce the desired cooling cycle had been determined, a number of specimens were heat-treated by the following procedure:

a. Barstock of 3/4- or 1-inch diameter was enclosed in the firebrick cylinder with a thermocouple attached to the surface of the bar at the midpoint.

b. The assembly was inserted in a furnace at the desired temperature and held until the thermocouple indicated that the specimen had been at temperature for 1 hour.

c. The assembly was removed from the furnace and the test bars allowed to cool to room temperature in the insulating firebrick.

d. Throughout the previous work, all test bars have been tempered to a hardness range of 280 to 320 Brinell when the as-transformed hardness was at a sufficiently high level. In the present phase of the investigation, the same hardness range was employed. Insofar as possible the tempering times and temperatures were the same as or similar to those previously used for the normalized 1-inch bars. However, since the as-normalized hardness of the 4340 steel was only slightly above 300 Brinell and even slight tempering resulted in hardnesses below 300 Brinell, this steel was tested in the as-normalized condition. Table I shows the as-normalized and normalized and tempered hardnesses for all three steels as well as indicating the microstructure obtained and the tempering procedure employed.

5. The general basis for the evaluation of the properties of the structures was the same as previously established for the isothermally transformed structures, which was as follows:

a. Evaluate the properties of the structures for the range of temperatures over which creep and stress-rupture performance would be of most interest. The temperature range was set at 700° to 1100°F for 4340 and at 700° to 1200°F for "17-22A"S and H-40 steels.

b. Evaluate the structure on the basis of the property which is the controlling factor at the temperature of interest. Thus at 700° and 900°F, the criteria of comparison were creep rates and total deformation data. At these temperatures, the stresses causing rupture in reasonable times would be well above the yield strength, and thus service stresses would be limited to those below which rupture would occur. Attempts were made to find a single stress which would evaluate the structures on the basis of time required to obtain one percent total deformation. However, because of the low strength of the 4340 steel at 900°F, approximate 1000-hour rupture data were also obtained.

c. At 1000°F, testing was limited to the 4340 steel, but at 1100°F, all three steels--4340, "17-22A"S, and H-40--were tested. Both creep and rupture properties were considered of interest at these temperatures. Consequently, one test was employed to evaluate the short-time rupture strength, and another to obtain the time for one-percent total deformation.

d. At 1200°F, testing was limited the H-40 and "17-22A"S steels. At this temperature, the property of most interest was considered to be the 100-hour rupture strength, although some 1000-hour data were obtained to permit better correlation between structural variations and testing temperature.

Results

The structures obtained by the various cooling cycles are outlined in Table I together with the as-normalized and normalized and tempered hardnesses. These structures are illustrated in the as-normalized condition in Figures 4, 5, and 6. It should be noted that although, in most cases, the slower cooling cycles resulted in large percentages of bainite no attempt has been made in Table I to identify the bainites as "upper," "middle," or "lower" bainite as was previously done for the isothermally transformed structures. Inasmuch as the transformation occurred over a range of temperatures during cooling, the resulting structure is an intimate mixture of bainites which does not permit analysis. However, because of the slower cooling cycles and consequent longer time in the bainite transformation region, it might be expected that the structures of the 3- and 6-inch diameter bars would be composed of a larger percentage of the "upper" and "middle" bainites than the 1-inch bar. On the other hand, the cooling curves of Figures 1 and 2 indicate little change in temperature of transformation with rate of cooling. The temperature of major transformation as evidenced by the retardation of the cooling cycle appears to be essentially independent of the cooling cycle within the range investigated. In the case of the simulated 6-inch round of "17-22A"S the cooling cycle was sufficiently slow to permit some ferrite precipitation. However, the same cooling cycle for 4340 was fast enough to retain considerable martensite.

It was observed that the cooling cycles equivalent to 3- and 6-inch bars resulted in considerably larger grain sizes than the faster cooling rates for the "17-22A"S and H-40 steels. In particular, the H-40 steel showed a progressive increase in grain size with decreasing heating and cooling rates. The 3- and 6-inch bars of the "17-22A"S steel were quite similar but revealed a considerably coarser structure than the 1-inch bar. On the other hand, the 4340 steel showed little change in grain size although the bainitic structure appeared slightly coarser in slower cooled bars.

Although the "17-22A"S and 4340 steels exhibited approximately the same as-normalized hardnesses of about 315 to 330 Brinell as shown in Table I, it was possible to temper the former at 1200°F for 6 hours with little or no change in hardness whereas the latter could not be tempered without excessive loss in hardness. The tempering treatment of 1-hour at 1100°F previously employed for the normalized 1-inch rounds resulted in a Brinell hardness of about 250 for the 3- and 6-inch rounds. Consequently, the 4340 steel was not tempered.

Survey of Relationships between Section Size and Strength for 4340, "17-22A"S, and H-40 Steels

The test data obtained during the period covered by this report are summarized in Tables II, III, and IV for SAE 4340, "17-22A"S, and H-40 steels, respectively. For convenience of comparison, the data previously reported for 1-inch diameter normalized bars are included.

Although the data are not yet complete, the following trends may be noted:

1. Properties of 4340 Steel: The variation in properties resulting from the range in cooling cycles appears to be relatively small. The 1-inch and simulated 6-inch rounds appear to have remarkably similar properties at all testing temperatures. The simulated 3-inch diameter bars gave very slightly lower values which are hardly significant.

2. Properties of "17-22A"S Steel: In general, the simulated 3- and 6-inch rounds tended to exhibit slightly higher strength properties than the 1-inch normalized round. The exception to this statement occurred at 700°F when the simulated 3-inch diameter bar exhibited lower creep strength than the 1-inch bar. The test at 700°F for the 6-inch cooling cycle has not been completed.

3. Properties of H-40 Steel: The tests at 700° and 900°F are not yet complete but those at 1100° and 1200°F indicate only slight variation in response with testing temperature. At 1100°F, relatively short time tests indicate a slight superiority for the 3/4-inch bar and the simulated 3-inch diameter bar, both in rupture strength and minimum creep rate. However, the simulated 6-inch diameter bars resulted in considerably better ductility in the rupture test. At 1200°F the simulated 3- and 6-inch diameter bars gave similar rupture times that were somewhat longer than that of the 3/4-inch bar. In both cases, however, the differences are so small that more testing would be required to establish significant validity.

Discussion

The survey tests to evaluate the high temperature properties of structures formed during continuous cooling at various rates are nearing completion. While it is hazardous to draw conclusions from incomplete data, certain observations may be made.

1. In general, the trend of the data to date show that no

significant differences in creep-rupture properties exist for normalizing of stock ranging from 1-inch to 6-inch rounds for the three steels studied.

2. With the exception of the 4340 material, the slower heating and cooling cycles resulted in coarser microstructures than previously observed in the barstock material.

3. Detailed discussion of any differences in properties as a result of variations in cooling cycles and resulting structures is being withheld pending the completion of the testing program for this phase of the investigation.

Future Work

Future work shall consist of the continuation of the investigation to determine the effect of austenitizing temperature on the elevated temperature properties of 4340, "17-22A"S, and H-40 steels. In addition, the tests required to complete the investigation of properties of structures obtained by continuous cooling transformation will be conducted.

TABLE I

Microstructure and Hardness Values for 4340, "17-22A"S, and H-40 Steels Transformed during Continuous Cooling at Cooling Rates Equivalent to 1-, 3-, and 6-Inch Diameter Bars

Steel	Size of Round (in.)	Normalizing Temp (°F)	Microstructure Obtained	B H N	Tempering		B H N
					Temp(°F)	Time(hrs)	
4340	1	1750	35% martensite + 65% bainite	362/385	1100	1	290/311
	3	1750	25% martensite + 75% bainite	327/331	none	--	327/331
	6	1750	20% martensite + 80% bainite	315/329	none	--	315/329
"17-22A"S	1	1750	15% martensite + 85% coarse bainites	355	1200	10	291/317
	3	1750	100% bainite	320/330	1200	6	290/313
	6	1750	98% bainite + 2% ferrite	320/330	1200	6	291/322
H-40	3/4	1950	20% martensite + 80% bainites	435	1200	18	310/320
	3	1950	100% bainite	400	1200	4	304/313
	6	1950	100% bainite	390	1200	4	297/322

TABLE II

Rupture, Total Deformation, and Creep Data at 700°, 900°, 1000°, and 1100°F for SAE 4340 Steel Normalized to Obtain Cooling Cycles Equivalent to Those at the Center of 1-, 3-, and 6-Inch Diameter Bars

Temp (°F)	Size of Round (in.)	BHN	Stress (psi)	Rupture Time (hours)	Elong. (% in 2 in.)	Reduction of Area (%)	Deformation on Loading (%)	Time to Reach Specified Total Deformation (hrs) 0.1%	0.2%	0.5%	1.0%	Minimum Creep Rate (%/hr)
700	1	300	90,000	1294(d)	--	--	0.467	a	a	1	1000	0.00016
	3	327	90,000	1342(d)	--	--	0.463	a	a	~3	668	0.00021
	6	315	90,000	1342(d)	--	--	0.450	a	a	~5	1000	0.00021
900	1	300	55,000	842	12.0	22.3	0.26	a	a	8	64	0.00414
	1	300	40,000	1919(d)	--	--	0.164	a	5	1160	>3000(b)	0.00015
	3	331	40,000	1464(d)	--	--	0.185	a	~2	82	1800(b)	0.00024
	6	315	40,000	1483(d)	--	--	0.175	a	~4	430	>2000(b)	0.00015
1000	1	290	31,000	371	5.5	7.4	0.126	a	~5	50	145	0.00505
	1	300	20,000	1392	5.0	4.0	0.09	~1	20	228	650	0.00114
	1	301	12,000	1000(d)	--	--	0.05	12	114	802	2150(b)	0.00037
	3	331	31,000	259	12.5	15.7	0.148	a	~1	16	39	0.0114
	3	327	20,000	1310.5	8.5	6.6	0.101	a	5	110	387	0.0017
	6	315	31,000	362.1	11.0	11.1	0.157	a	~1	19	94	0.0065
	6	315	20,000	1488	6.0	6.6	0.092	~1	12	145	534	0.0012
1100	1	293	18,000	69.6	7.0	11.7	0.116	a	--	--	--	--
	1	311	4,000	1056(d)	--	--	0.017	18	96	484	1400(b)	0.00052
	3	328	18,000	78.6	17.5	22.5	0.107	a	<1	2.5	--	--
	6	321	18,000	77.2	18.0	21.8	0.112	a	<1	3	--	--

(a) Specimen reached this deformation on loading.
(b) Extrapolated value.
(c) 0.250-inch diameter specimen - elongation is percent in 1.0 inch.
(d) Test discontinued at given time.

TABLE III

Rupture, Total Deformation, and Creep Data at 700°, 900°, 1100°, and 1200°F for "17-22A"S Steel

Normalized to Obtain Cooling Cycles Equivalent to Those at the Center of 1-, 3-, and 6-Inch Diameter Bars

Temp (°F)	Size of Round (in.)	BHN	Stress (psi)	Rupture Time (hours)	Elong. (% in 2 in.)	Reduction of Area (%)	Deformation on Loading (%)	Time to Reach Specified Total Deformation (hrs) 0.1%	0.2%	0.5%	1.0%	Minimum Creep Rate (%/hr)
700	1	302	115,000	132	21.0(c)	61.9	0.66	a	a	a	1	0.0220
	1	307	102,000	1194(d)	--	--	0.465	a	a	~1	>2000(b)	0.00007
	3	291	102,000	1793(d)	--	--	0.62	a	a	a	150	0.00016
900	1	303	70,000	1482(d)	--	--	0.335	a	a	24	1400	0.00030
	3	302	70,000	1223(d)	--	--	0.288	a	a	235	>2000(b)	0.00013
	6	297	70,000	1152(d)	--	--	0.285	a	a	525	>2000(b)	0.00008
1100	1	309	41,000	111.5	2.5	3.1	0.212	a	a	26	--	0.00614
	1	311	20,000	773	2.0	--	0.090	~1	46	375	656	0.00086
	1	317	17,000	1035(d)	--	--	0.079	14	177	857	1500(b)	0.00045
	1	291	14,000	1150(d)	--	--	0.065	50	230	1200	--	0.00030
	1	302	10,000	1060(d)	--	--	0.040	32	140	1700(b)	--	0.00016
	3	291	41,000	109.4	2.1	(e)	0.206	a	a	34	--	0.00523
	3	295	19,000	1319.9	2.0	(e)	0.090	15	193	1045	--	0.00026
	6	293	41,000	114.9	2.0	3.5	0.221	a	a	29	--	0.00420
	6	291	19,000	1308.6	1.2	2.0	0.091	5	183	994	--	0.00028
1200	1	304	14,000	167.1	4.0	5.0	0.066	5	22	65	~140	0.0064
	1	313	7,500	918	10.0	14.9	0.046	6	46	176	333	0.0023
	3	290	14,000	158.2	2.0	2.8	0.072	5	22	91	~130	0.0040
	6	295	14,000	152.1	1.5	(e)	0.070	5	22	93	~127	0.0041

(a) Specimen reached indicated deformation on loading.
(b) Extrapolated value.
(c) 0.250-inch diameter specimen - elongation given in percent in 1.0 inch.
(d) Test discontinued at given time.
(e) Broken in shoulder radius.

TABLE IV

Rupture, Total Deformation, and Creep Data at 700°, 900°, 1100°, and 1200°F for H-40 Steel

Normalized to Obtain Cooling Cycles Equivalent to Those at the Center of 3/4, 3-, and 6-Inch Diameter Bars

Temp (°F)	Size of Round (in.)	BHN	Stress (psi)	Rupture Time (hours)	Elong. (% in 2 in.)	Reduction of Area (%)	Deformation on Loading (%)	Time to Reach Specified Total Deformation (hrs) 0.1%	0.2%	0.5%	1.0%	Minimum Creep Rate (%/hr)
700	3/4	310	90,000	1292(d)	--	--	0.416	a	a	13	1700(b)	0.00017
900	3/4	320	65,000	1052	18.0(c)	36.0	0.301	a	a	10	85	0.00328
1100	3/4	315	43,000	48.4	(f)	--	0.226	a	a	27	--	0.0058
	3/4	310	40,000	193	5.0	13.6	0.231	a	a	20	89	0.0074
	3/4	312	34,000	272	(e)	--	0.165	a	6	162	--	0.00148
	3/4	320	31,000	720	(e)	--	0.120	a	7	274	677	0.00105
	3/4	316	27,500	1130(d)	--	--	0.146	a	36	430	1054	0.00064
	3	304	40,000	213.1	4.0	9.5	0.230	a	a	15	107	0.0047
	6	297	40,000	149.1	10.5	31.0	0.230	a	a	9	44	0.0134
1200	3/4	315	25,000	100	17.0	45.0	0.142	a	~1	9	38	--
	3	304	25,000	188	10.4	11.7	0.170	a	~1	24	71	0.0118
	6	297	25,000	204.9	11.1	7.1	0.172	a	~1	29	82	0.0085

(a) Specimen reached specified deformation on loading.
(b) Extrapolated value.
(c) 0.250-inch diameter specimen - elongation given is percent in 1.0 inch.
(d) Test discontinued at given time.
(e) Specimen fractured in shoulder radius.
(f) Specimen fractured in threaded end.

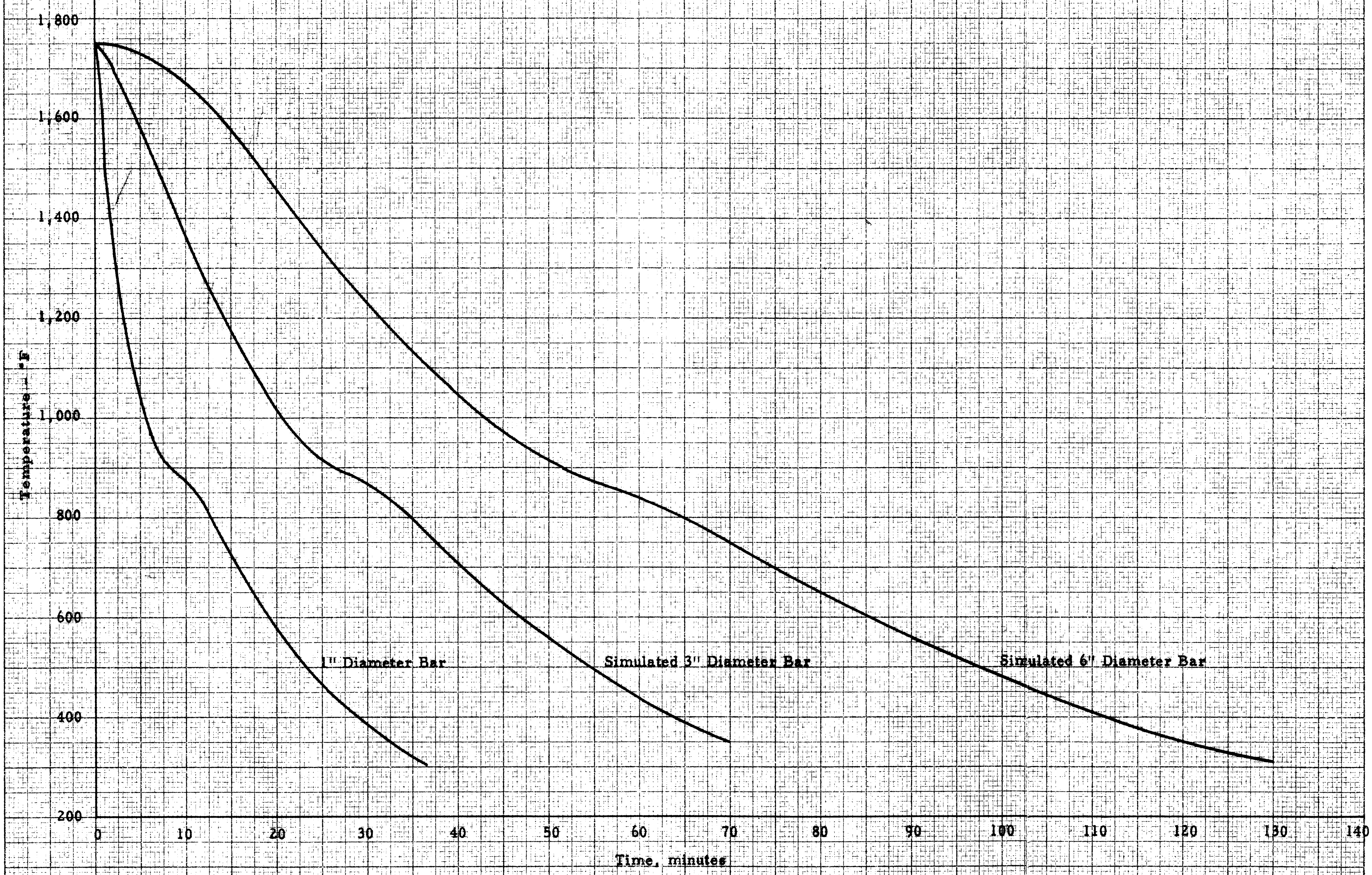


Figure 1. Cooling curves of 1 inch round, simulated 3 inch round, and simulated 6 inch round "17-22A"S Steel cooled from 1750°F in air.

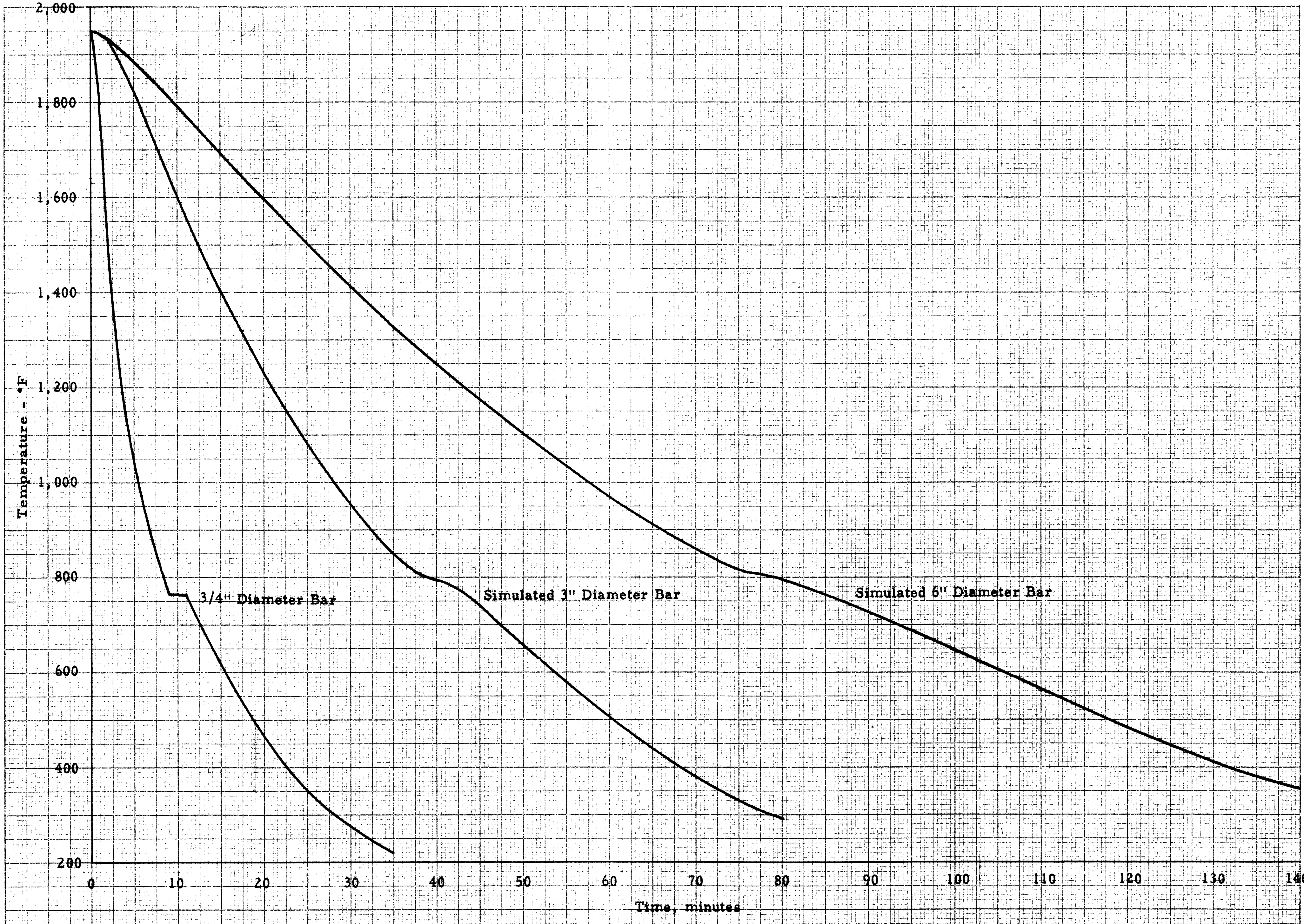


Figure 2. Cooling curves of 3/4 inch round, simulated 3 inch round, and simulated 6 inch round H-40 Steel cooled from 1950°F in air.

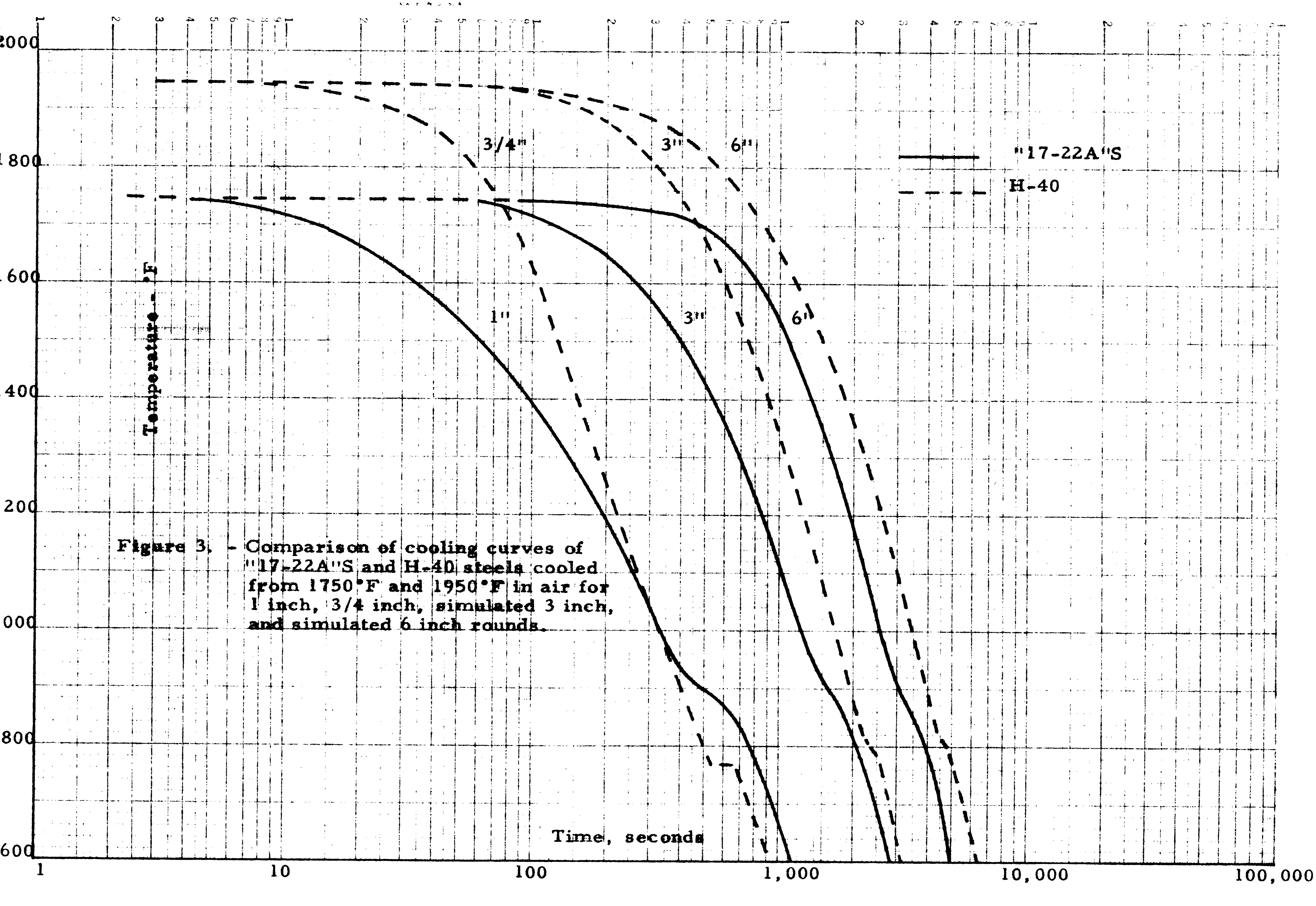
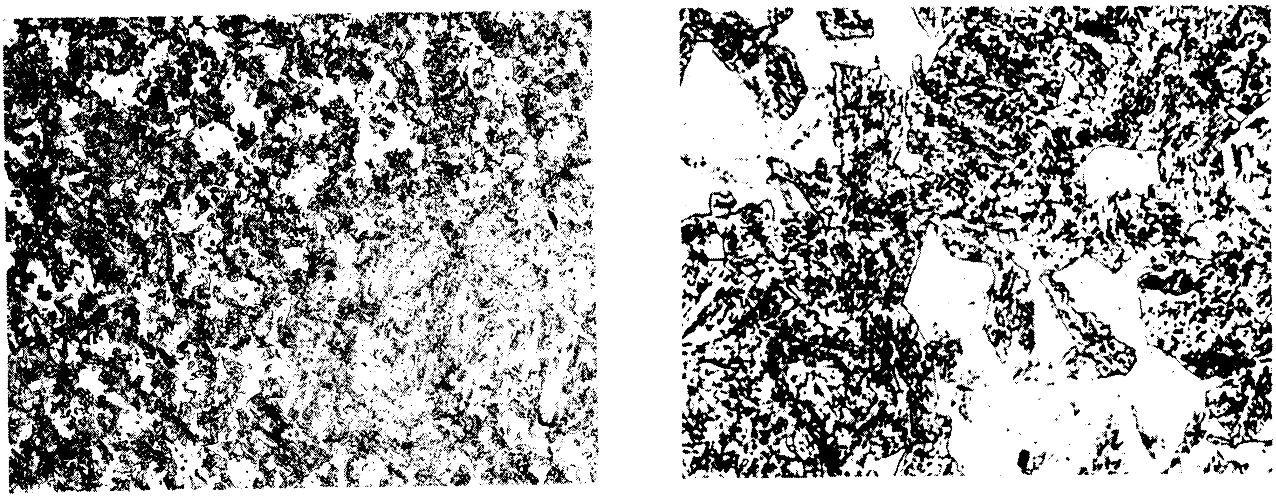
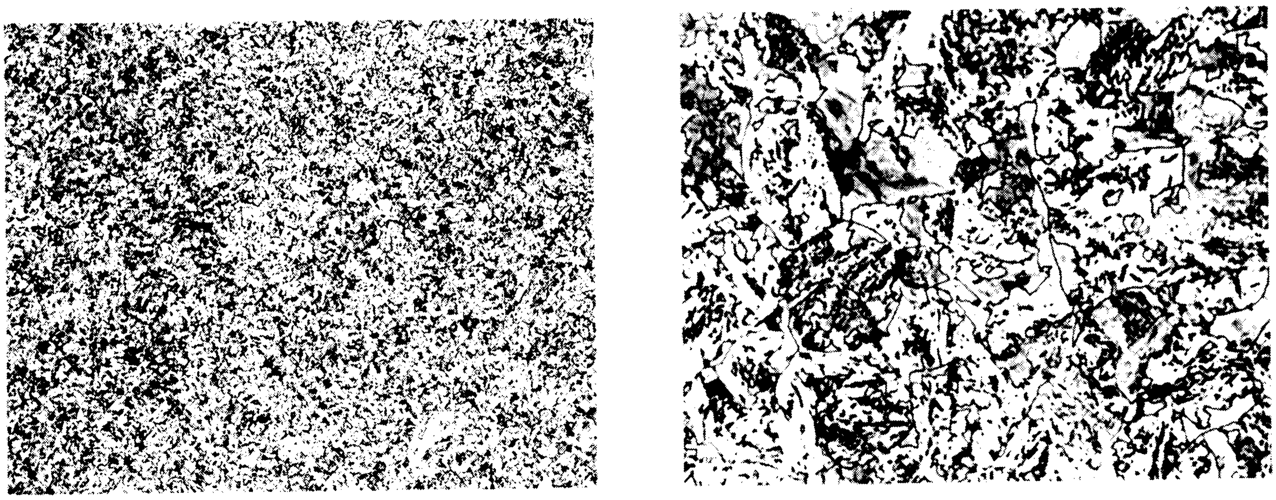


Figure 3. - Comparison of cooling curves of "17-22A"S and H-40 steels cooled from 1750°F and 1950°F in air for 1 inch, 3/4 inch, simulated 3 inch, and simulated 6 inch rounds.

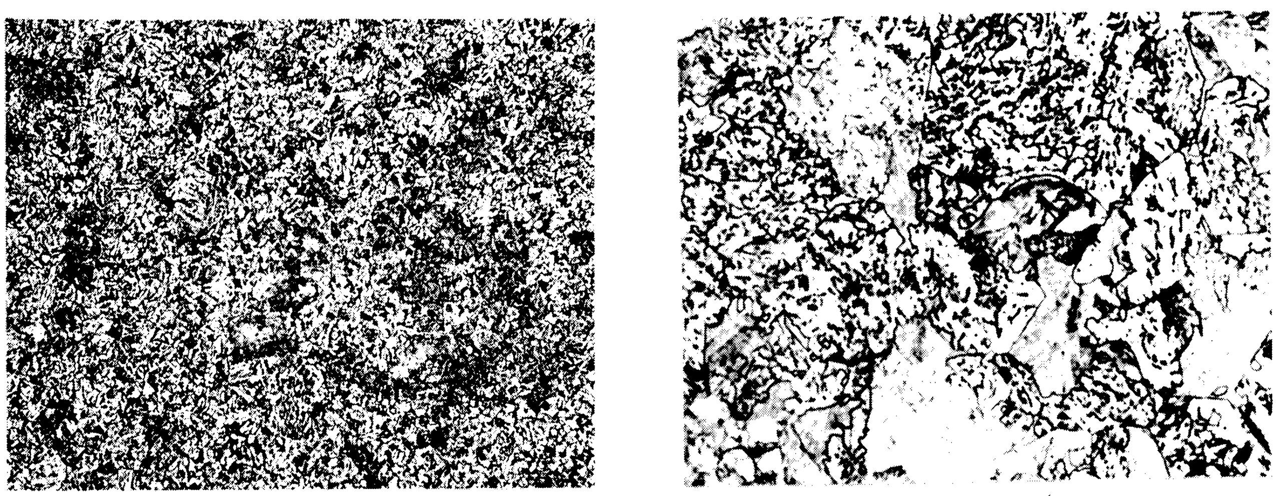
X100D X1000D



(a) Normalized as 1-inch diameter bar.



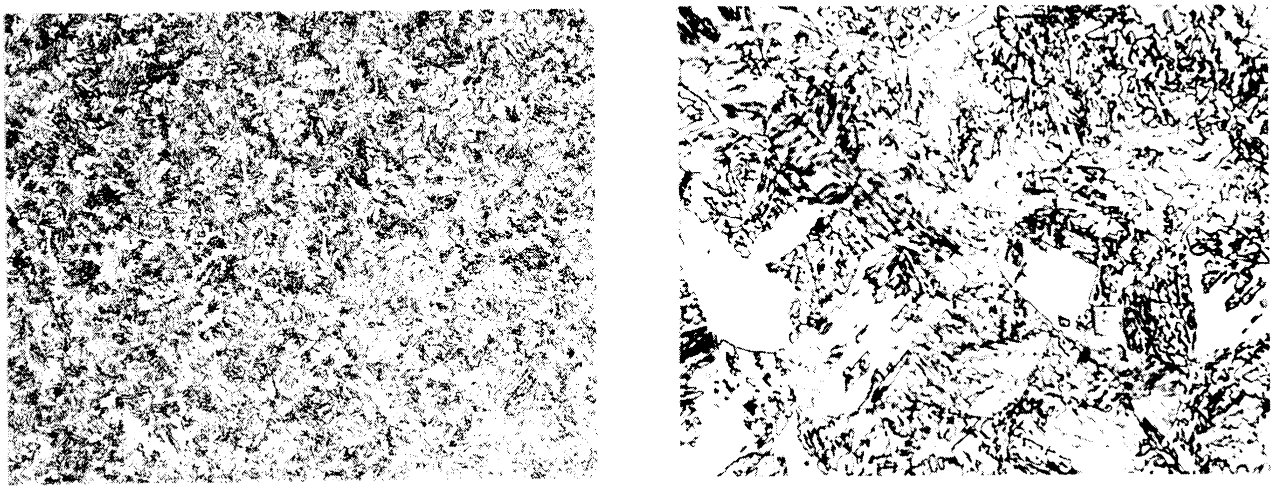
(b) Normalized with cooling cycle similar to that at center of 3-inch diameter bar.



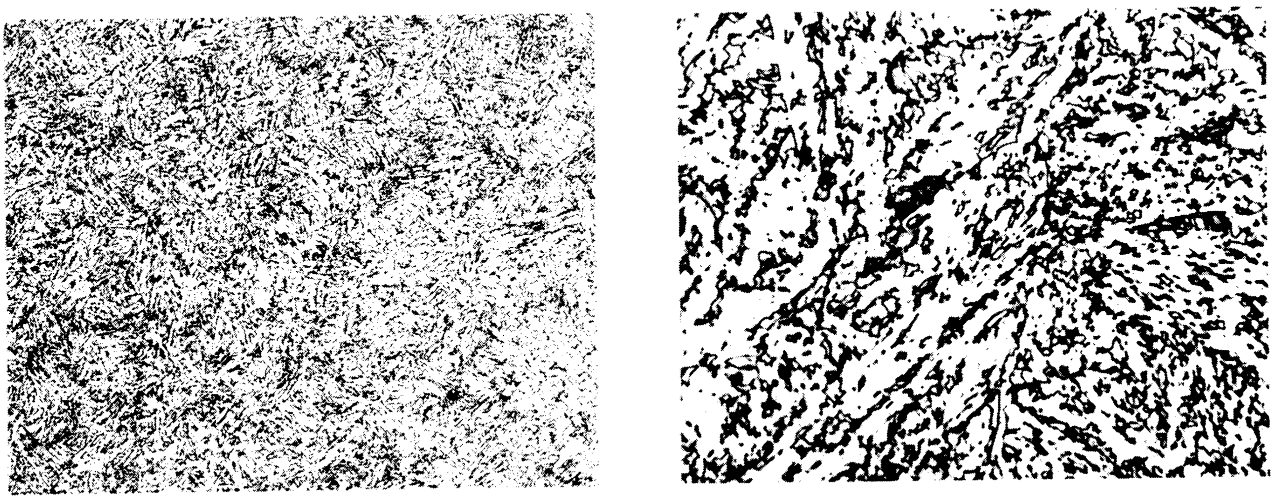
(c) Normalized with cooling cycle similar to that at center of 6-inch diameter bar.

Figure 4. - Microstructure of 4340 Steel Normalized at 1750°F with Various Cooling Cycles.

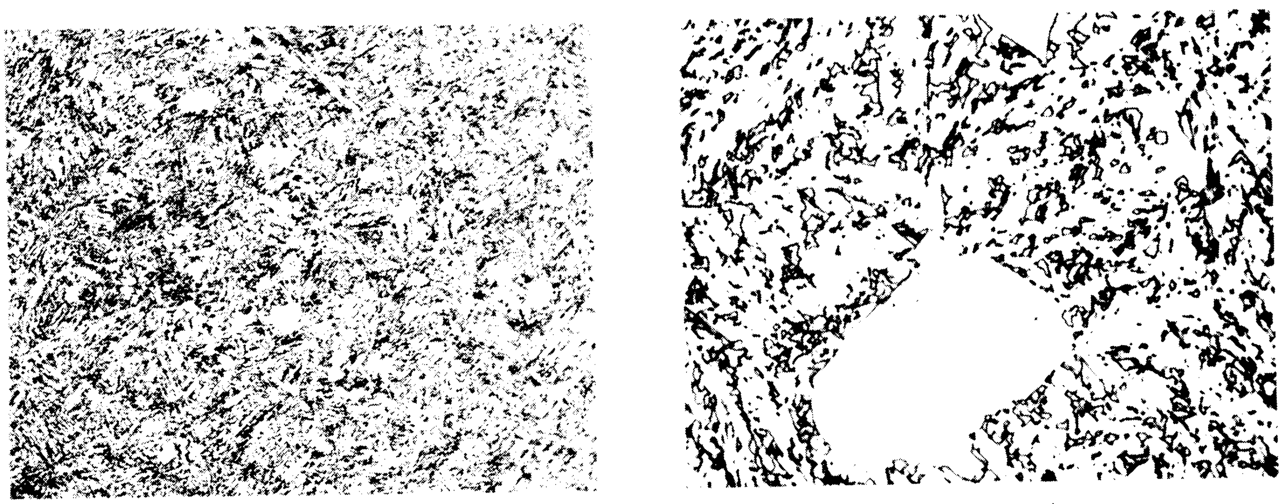
X100D X1000D



(a) Normalized as 1-inch diameter bar.



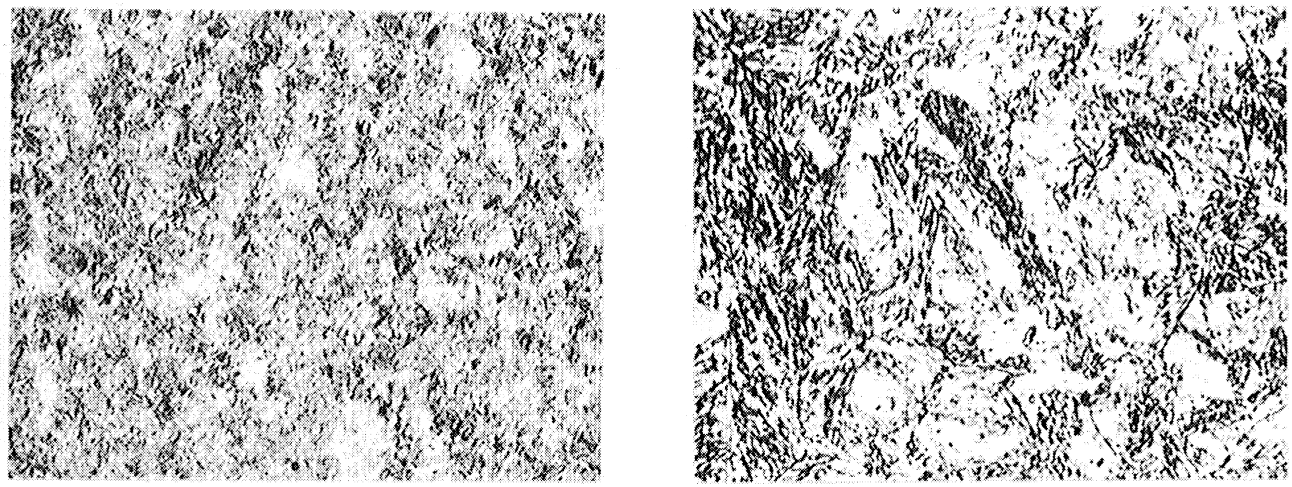
(b) Normalized with cooling cycle similar to that at center of 3-inch diameter bar.



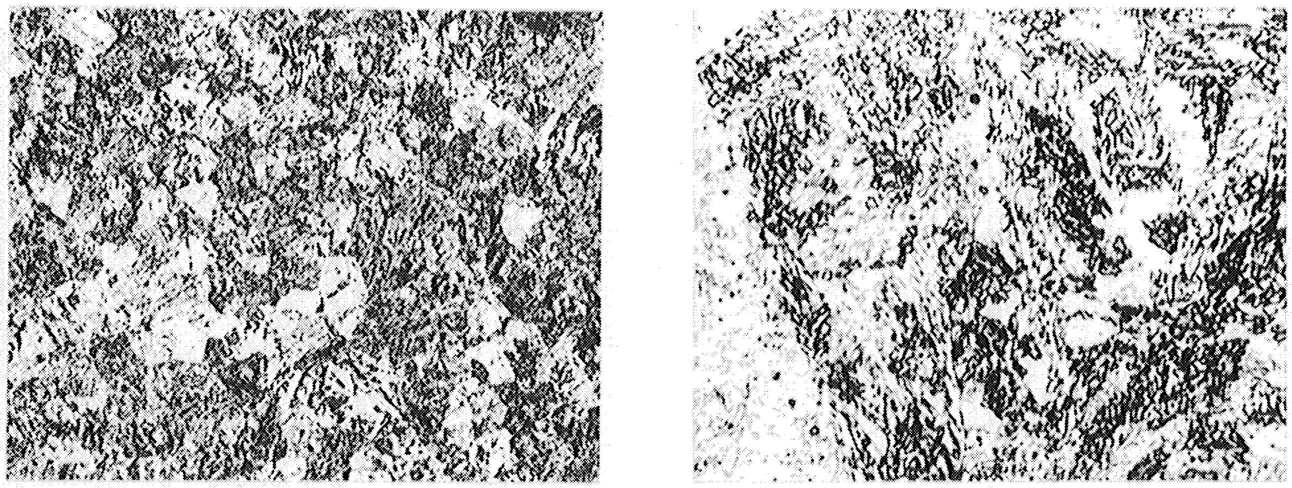
(c) Normalized with cooling cycle similar to that at center of 6-inch diameter bar.

Figure 5. - Microstructure of "17-22A"S Steel Normalized at 1750°F with Various Cooling Cycles.

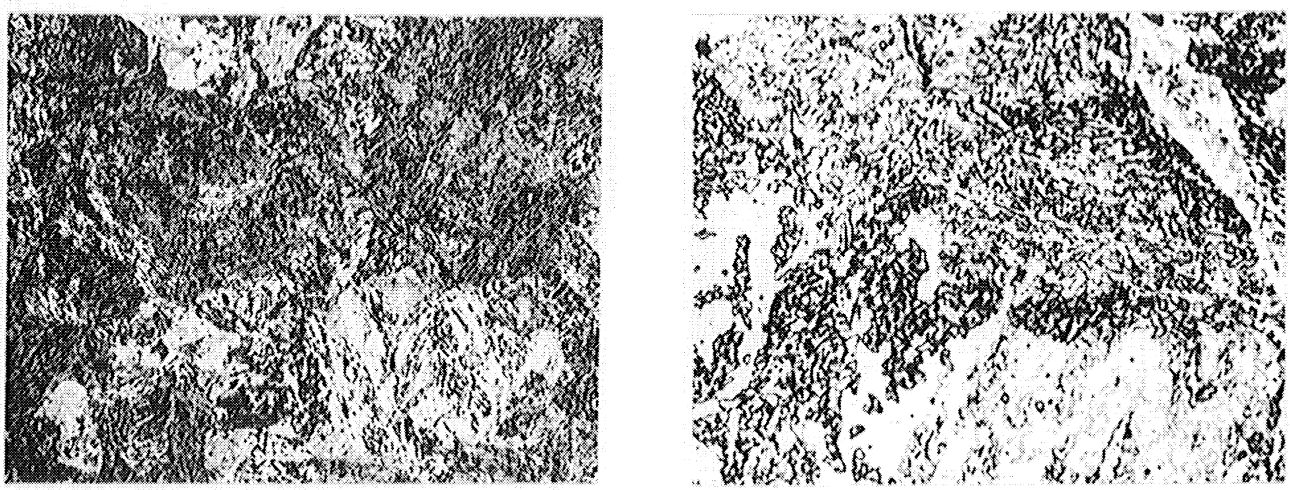
X100D X1000D



(a) Normalized as 3/4-inch diameter bar.



(b) Normalized with cooling cycle similar to that at center of 3-inch diameter round.



(c) Normalized with cooling cycle similar to that at center of 6-inch diameter round.

Figure 6. - Microstructure of H-40 Steel Normalized at 1950°F with Various Cooling Cycles.