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Technical Report

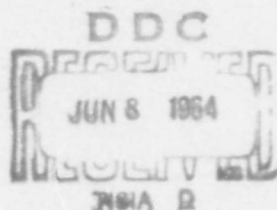
A Preliminary Evaluation of
Rapid Heat Treatment

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Applied Research Laboratory
United States Steel

Monroeville, Pennsylvania



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Project No. 40.018-002(15)

NObs-88540 SS050-000 Task 1567 S-21302

A PRELIMINARY EVALUATION OF RAPID HEAT TREATMENT
(40.018-002) (15) (a-AS-NP-48) (S-21302)

By R. P. Haak

Approved by J. H. Gross, Division Chief

Abstract

As part of the HY-180/210 feasibility study, various special processing techniques are being evaluated to establish their potential for improving the toughness of high-yield-strength steels. One processing technique that appears promising in this respect is rapid heat treatment. Therefore, the Applied Research Laboratory initiated a preliminary evaluation of the process by determining the mechanical properties of a 5 $\frac{1}{2}$ Ni-Cr-Mo-V steel that was heat treated by various combinations of rapid austenitizing, rapid tempering, conventional austenitizing, and conventional tempering.

The results showed that the yield strength of the rapidly austenitized specimens was 10 to 20 ksi higher than that of the conventionally austenitized specimens with no loss of notch toughness or ductility. ~~The improved properties of the rapidly austenitized specimens were associated with a refinement of the austenite grains. The best properties were obtained when the specimens were rapidly austenitized several times. The finest grain size (ASTM No. 14.5) was obtained when a specimen was austenitized five times at a heating rate of 200 F per second.~~

Rapid tempering (4 F per second) after rapid austenitizing produced a slightly better combination of strength and toughness at low tempering temperatures than conventional tempering, but conventional tempering produced a slightly better combination of strength and toughness at high tempering temperatures for rapidly austenitized specimens.

These preliminary results indicate that rapid heat treatment offers considerable promise for increasing the yield strength of alloy steels by as much as 30 ksi with no loss in ductility or toughness. Thus experimental steels that meet the strength and toughness requirements for an HY-150 steel may meet similar requirements for an HY-180 steel after rapid heat treatment.

On the basis of the favorable results of the preliminary evaluation, a statistical program to evaluate further the potential of rapid heat treatment has been initiated.

Introduction

As a part of the HY-180/210 feasibility study, various special processing techniques are being evaluated to establish their potential for improving the toughness of high-yield-strength steels. Among the promising approaches is the rapid heat-treating process. Earlier work at the Applied Research Laboratory has indicated that the strength-toughness relation for USS "T-1" constructional alloy steel and for HY-80 steel can be improved by rapid heat treatment. The Laboratory, therefore, initiated a preliminary study to determine the effect of rapid heat treatment on the tensile and impact properties of an experimental 5½Ni-Cr-Mo-V steel. The present report describes the results of that preliminary investigation.

Material and Experimental Work

Material

The material used for the present study was a 1/2-inch-thick hot-rolled plate (No. 229344C) from an experimental 5½Ni-Cr-Mo-V steel (heat No. X14332) which was previously evaluated¹⁾* in the HY-130/150 program. The check chemical analysis of the steel is presented in Table I. Forty plate samples (3 inches wide by 9 inches long, Figure 1) were cut from the plate.

Processing Procedures

The experimental procedure was organized as shown in Figure 2. The heating rate for the conventional austenitizing treatment varied with

*See References.

temperature because conventional heating utilizes a fixed-temperature heating source. Above the lower critical temperature (approximately 1190 F for the 5½Ni-Cr-Mo-V steel), the average heating rate was about 0.6 F per second, with a holding time at peak temperature of about 30 to 40 minutes. A Westinghouse 100 kw, 3000-cycle-per-second induction-heating scanner was used to obtain the rapid heating rates. The plate samples were induction-heated while passing through the center of a solenoid heating coil, as shown in Figure 3. Different heating rates were obtained by changing the scanning speed of the specimens and/or by changing the power input.

A series of tests was also made to study the effect of multiple-hardening treatments on grain size. The number of passes at austenitizing heating rates of 200 F per second was varied from one through five. Temperatures were measured and recorded by a Leeds and Northrup strip chart recorder and chromel-alumel thermocouples. At peak temperatures, the temperature varied only ± 10 F over the specimen-blank area within the plate sample.

Testing Procedures

Eight test-specimen blanks were cut from each plate sample described in Figure 2. Six Charpy V-notch impact-test specimens and duplicate 0.252-inch-diameter tension-test specimens were machined from each of the blanks. The tension specimens were tested at room temperature, and the impact specimens were tested at +80 F and -80 F.

In addition to the study of the mechanical properties of the rapidly heat-treated steels, a metallurgical evaluation of the effect of rapid austenitizing on the austenitic grain size was conducted. Special emphasis was given to specimens taken from each of the multiple-hardening-pass treatments (one through five passes). Because little further refinement of the austenite grains occurred after three hardening passes, mechanical properties were not determined on the specimens that were hardened with five treatments.

Results and Discussion

Mechanical Properties

The tension- and impact-test results are summarized in Tables II and III. Table II includes all the specimens that were conventionally tempered (1 hour at temperature, water-quenched) and Table III includes all the specimens that were induction tempered (4 F per second and water-quenched).

The relation between yield strength and notch toughness after various heat treatments is illustrated in Figures 4 through 7. Figures 4 and 5, respectively, show the relation between yield strength and energy absorption at +80 F for conventionally and rapidly tempered specimens. Figures 6 and 7, respectively, show the relation between yield strength and energy absorption at -80 F for conventionally and rapidly tempered specimens.

At a toughness level of 85 ft-lb at 80 F after conventional tempering, Figure 4, the yield strength of the conventionally austenitized material was approximately 152 ksi. The 4 F per second and 10 F per second austenitizing rates increased the yield strength 12 ksi to about 164 ksi. The three-pass hardening treatments further increased the yield strength to 172 ksi. The 200 F per second heating rate showed the smallest increase in yield strength (5 ksi) of any of the rapid austenitizing cycles employed. Similar increases in the yield strength of rapidly austenitized compared with conventionally austenitized specimens were also observed for the conditions illustrated in Figures 5, 6, and 7. Thus, rapid austenitizing, as compared with conventional austenitizing, increased the yield strength for all conditions examined.

Stress-Strain Curves

The specimens that were hardened by multiple-austenitizing treatments exhibited stress-strain curves in which the stress decreased continuously from that of the yield stress. A schematic example of this behavior is shown in Figure 8 (Curve A). This behavior did not appear to affect the ductility (elongation and reduction of area) adversely, in that the rapidly austenitized specimens had slightly better ductility than the conventionally treated specimens. For example, specimens machined from Plate Sample A (conventionally treated) having a tensile strength of 159 ksi had an average elongation and reduction of area of 17.0 percent and

66.3 percent, respectively, see Table II, whereas rapidly austenitized specimens having similar strengths (Specimens 3, 15, 12, and 26 in Table II and Specimens 9, 20, and 31 in Table III) had a minimum elongation of 18.0 percent and a minimum reduction of area of 67.5 percent.

Several of the specimens that were hardened in one pass exhibited stress-strain characteristics similar to those shown in Curve B, Figure 8. Specimens 20, 9, 27, 13, 16, and 5 in Tables II and III had stress-strain curves in which the maximum load did not exceed the yield strength. Although rapidly austenitized alloy steels normally exhibit very high yield-tensile ratios, they do not necessarily exhibit stress-strain curves of the type shown in Figure 8. Some early work on "T-1" steel showed tendencies toward this stress-strain behavior, but only when peak austenitizing temperatures lower than normal were used.

Rapid Versus Conventional Tempering

Higher tempering temperatures than those possible in conventional heat treatment are feasible when a rapid tempering treatment is used. The lower critical temperature of the 5 $\frac{1}{2}$ Ni-Cr-Mo-V steel used in the present study was not exceeded by a 1220 F peak temperature and a 4 F per second heating rate, whereas with conventional heat treatment, the lower critical temperature is approximately 1190 F. (See Specimens 6, 17, 28, and 39 in Table II.) The 1220 F rapid temper did, however, produce somewhat poorer combinations of mechanical properties than the 1170 F conventional tempering

treatment. The strengths were similar, but the ductility and toughness were superior for the 1170 F conventional temper, Tables II and III.

A comparison of the data plotted in Figures 4 and 5 shows that at the lower tempering temperatures (830 F), rapid tempering produced slightly better combinations of strength and toughness than conventional tempering. For example, after rapid austenitizing at 4 F per second or 10 F per second, the specimens that were rapidly tempered exhibited a yield strength 4 ksi higher at the 70 ft-lb toughness level (+80 F) than that of the conventionally tempered material.

Metallographic Examination

The results of the metallographic examination are presented in Figures 9 through 11.

Figure 9A shows the material in the as-rolled condition prior to heat treatment. A photomicrograph of a portion of Plate Sample C, which was conventionally hardened and tempered (see Figure 9B), shows a duplexed structure with an average ASTM grain size of 9.5.

A comparison of specimens austenitized at 4 F per second, 10 F per second, and 200 F per second (single pass) shows that the finest and most uniform prior austenitic grain size (ASTM No. 11.5) was obtained with the slowest rate of 4 F per second, Figures 10A, 10B, and 11A. These photomicrographs confirm the results of mechanical tests on the same plate samples.

Although the preceding discussion indicates that the 4 F per second single-pass hardening treatments were better than the 10 F per second or 200 F per second treatments, this observation is not conclusive because of the limited number of variables investigated. A study of other variables such as the peak austenitizing temperature and holding times may show another heating rate to be optimum. Other investigators²⁾ have, in fact, reported that fast heating rates elevate the transformation temperatures of the steel.

The favorable results obtained with the 4 F per second heating rate are important because of the practical considerations involved. Very high heating rates are not commercially feasible on thick sections. A computer study at the Applied Research Laboratory has indicated that on 2-inch-thick steel plate, the highest feasible induction-heating rate would be approximately 10 F per second.

The study of the effect of multiple hardening treatments on grain size showed a continuing grain refinement from one through five passes (see Figure 11). The one-pass, 200 F per second treatment (Figure 11A) resulted in a strongly duplexed grain structure. This type of structure might be responsible for the small strength increase shown in Figures 4 through 7 for the single 200 F per second treatment compared with that of the 4 F per second and 10 F per second treatments.

By the end of the third hardening pass (Figure 11 C) the duplexing appears to have been eliminated, and an ASTM grain size of 13.5 was obtained. Mechanical test results with this treatment are plotted in Figures 4 through 7 and show very good combinations of strength and toughness.

After four and five hardening passes, further grain refinement occurred. The smallest ASTM grain size that was observed was 14.5 after a five-hardening-pass treatment with a 200 F per second heating rate. Although the mechanical properties of the specimens that were austenitized four or five times were not determined, further improvements in the strength and toughness based on the grain sizes would probably have been obtained.

Summary

This preliminary investigation of the effect of rapid heat-treating cycles on the mechanical properties of an experimental $5\frac{1}{4}$ Ni-Cr-Mo-V steel may be summarized as follows:

1. Specimens that were rapidly austenitized exhibited significantly better combinations of strength and toughness than those that were conventionally austenitized. For example, at a toughness level of 85 ft-lb (+80 F) the yield strength of the conventionally austenitized specimens was approximately 152 ksi, whereas at the 4 F per second and 10 F per second heating rates, the yield strength was increased by 12 ksi to about 164 ksi. The three-pass hardening treatments at 200 F per second raised the yield strength still further to 172 ksi.

2. The specimens that were hardened by multiple austenitizing treatments exhibited stress-strain curves in which the stress decreased continuously from that of the yield stress. This behavior did not deleteriously affect the tensile ductility.

3. After rapid austenitizing, rapid tempering (4 F per second) produced a slightly better combination of strength and toughness at low tempering temperatures, whereas conventional tempering produced a slightly better combination at high tempering temperatures.

4. Improvements in the strength and toughness produced by rapid austenitizing were associated with a refinement of the austenite grains. A five-pass austenitizing treatment produced an austenite grain size of 14.5.

These preliminary results indicate that rapid heat treatment offers considerable promise for increasing the yield strength of alloy steels by as much as 30 ksi with no loss in ductility or toughness. Thus experimental steels that meet the strength and toughness requirements for an HY-150 steel may meet similar requirements for an HY-180 steel after rapid heat treatment.

Future Work

Because of the favorable outcome of this preliminary work, a more detailed study is under way with the new experimental 5Ni-Cr-Mo-V HY-130/150 steel. A statistical program has been planned to more comprehensively evaluate the rapid heat-treating process. The following variables are being studied:

1. Prior microstructure.
2. Heating rate.
3. Peak austenitizing temperature.
4. Holding time between the end of heating and start of quenching.
5. Number of hardening passes.

References

1. S. J. Manganello and L. F. Porter, "Mechanical Properties of Mill-Treated Plates of Promising HY-130/150 Submarine-Hull Steel," Applied Research Laboratory Report, Project No. 40.18-001(7), (S-11104-1), September 16, 1963.
2. W. J. Feuerstein and W. K. Smith, "Elevation of Critical Temperatures in Steel by High Heating Rates," Transactions, American Society for Metals, Vol 46, 1953, pp 1270-1284.

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Table I

Composition of the 5 $\frac{1}{2}$ Ni-Cr-Mo-V Steel Investigated, Percent
(Check Analysis)

<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>	<u>Ni</u>	<u>Cr</u>	<u>Mo</u>	<u>V</u>	<u>Al*</u>	<u>N**</u>
0.15	0.26	0.006	0.003	0.22	5.02	0.46	0.40	0.06	0.048	0.011

*Acid soluble.

**Kjeldahl determination.

Table II

Effect of Rapid Heat Treatment on the Mechanical Properties* of a 5%Ni-Cr-Mo-V Steel (Heat No. X14332) —
Conventionally Tempered (1 hour at Temperature Water-quenched)

Plate Austenitizing Cycle** (Peak Temp, 1480 F)	Tensile Properties										Charpy V-Notch Impact Properties					
	Upper Yield					0.2% Offset Yield					Energy Absorbed, ft-lb	Fracture, %	Shear Fracture, %	Lateral Expansion, mils	Hardness RC	
	Temp, F	Strength, ksi	Yield Strength, ksi	Ratio	Yield-Tensile Ratio	Elongation in 1 Inch, %	Reduction of Area, %	+80 F	-80 F	+80 F						-80 F
36 3-200-20	830	186.5	182.6	186.5***	—	12.5	66.2	68	56	100	100	37	29	38.0		
25 1-200-20	—	—	166.0	168.8	0.98	15.0	66.4	69	53	100	100	40	28	36.5		
11 1-10-10	—	—	170.1	172.5	0.99	15.0	67.0	63	55	100	100	40	28	36.8		
14 1-10-30	—	—	169.1	171.1	0.99	16.0	67.1	71	65	100	100	42	37	37.0		
2 1-4-30	—	—	170.4	173.6	0.98	14.5	65.9	69	61	100	100	40	35	36.8		
A Conventional	—	—	152.5	159.3	0.96	17.0	66.3	85	69	100	85	51	40	34.0		
37 3-200-20	1000	172.9	170.3	172.9***	—	19.0	69.8	88	83	100	100	50	45	37.0		
26 1-200-20	—	—	161.6	165.4	0.98	18.5	67.6	76	65	100	83	46	36	36.0		
12 1-10-10	—	—	164.1	165.6	0.99	19.0	68.3	85	77	100	100	51	43	36.2		
15 1-10-30	—	—	162.8	165.0	0.99	19.0	67.5	85	74	100	95	49	39	36.2		
3 1-4-30	—	—	162.4	164.3	0.99	18.5	68.0	87	85	100	98	51	45	35.5		
B Conventional	—	—	150.1	156.7	0.96	19.5	68.9	93	84	100	85	58	47	36.8		
38 3-200-20	1170	161.7	157.9	161.7***	—	18.5	68.8	106	102	100	100	62	56	34.0		
27 1-200-20	—	—	155.5	155.0†	—	20.5	71.4	93	91	100	90	57	48	34.5		
13 1-10-10	—	—	153.8	153.0†	—	21.0	71.6	109	100	100	100	68	56	33.2		
16 1-10-30	—	—	155.7	154.6†	—	19.5	71.6	98	100	100	100	60	53	34.0		
5 1-4-30	—	—	155.2	153.8†	—	20.5	70.4	106	105	100	100	64	62	34.0		
C Conventional	—	—	143.4	146.8	0.98	20.0	70.6	112	102	100	98	69	59	31.5		
39 3-200-20	1220	—	113.6	150.0	0.76	20.0	62.3	87	87	100	100	57	52	31.5		
28 1-200-20	—	—	118.1	144.2	0.82	20.0	66.0	104	99	100	99	67	58	30.2		
17 1-10-30	—	—	121.0	144.2	0.84	20.5	66.0	101	96	100	100	64	57	30.2		
6 1-4-30	—	—	115.2	141.2	0.82	20.0	66.5	112	109	100	100	71	63	30.0		

*Results shown are averages from duplicate 0.252-inch-diameter tensile specimens and three Charpy V-notch impact specimens.

**Code - The first number refers to the number of hardening cycles, the second number is the average heating rate (F per second) from room temperature to peak temperature (1480 F) and the third number is the approximate dwell time (sec) between the end of heating and start of quenching.

***The upper yield and maximum load points coincided. (See stress-strain curve A in Figure 8).

†The conventional maximum load point did not reach the upper yield level in these tests. (See stress-strain curve B in Figure 8).

‡All the specimens had fissures. (40.018-002)(15)

Table III

Effect of Rapid Heat-Treatment on the Mechanical Properties* of a 5Ni-Cr-Mo-V Steel--
Rapid Temper (4 F per Second Water-quenched)

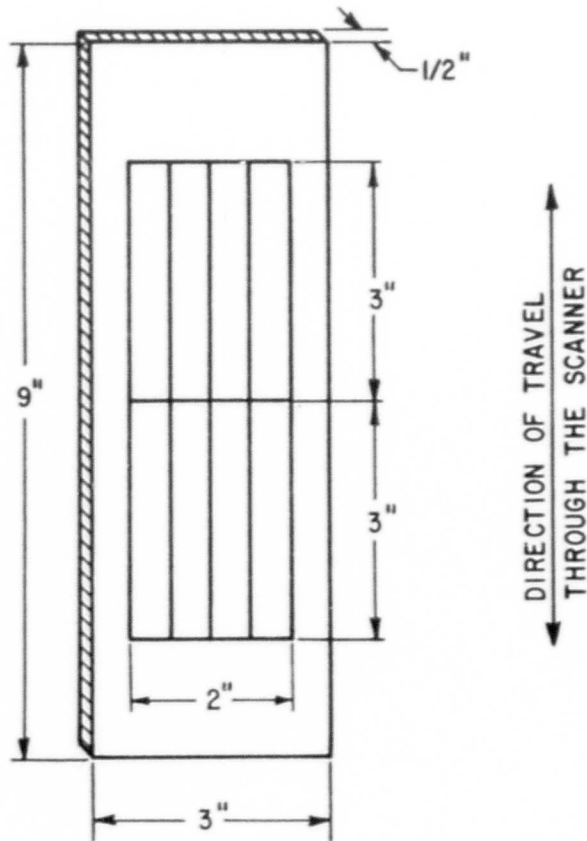
Plate Austenitizing Sample No.	Tempering Cycle** (Peak Temp., F)	Tensile Properties					Charpy V-Notch Impact Properties					Hardness K _C		
		Upper Yield Strength, ksi	Yield Strength, ksi	Tensile Strength, ksi	Yield-Tensile Ratio	Elongation in 1 Inch, %	Reduction of Area, %	Energy Absorbed, ft-lb		Fracture, %			Lateral Expansion, mils	
								+80 F	-80 F	+80 F	-80 F			
														+80 F
40	3-200-20	190.4	188.0	190.4***	—	14.0	66.2	56	58	100	100	26	29	39.8
29	1-200-20	—	172.6	179.1	0.96	15.0	67.7	58	46	100	100	32	22	38.0
18	1-10-30	—	175.1	180.7	0.97	15.5	68.6	66	60	100	100	36	31	37.0
7	1-4-30	—	174.4	179.4	0.97	15.0	68.2	67	59	100	99	36	30	37.5
41	3-200-20	183.2	175.0	183.2***	—	14.2	67.8	79	75	100	100	44	40	37.0
30	1-200-20	—	161.9	163.4	0.99	16.0	69.8	80	68	100	100	50	35	35.5
19	1-10-30	—	162.4	163.3	0.99	16.0	70.2	89	79	100	100	51	43	35.0
8	1-4-30	—	161.1	162.8	0.99	16.0	70.1	89	77	100	99	51	43	35.0
42	3-200-20	176.7	170.0	176.7***	—	15.2	68.4	86	77	100	100	49	41	35.5
31	1-200-20	—	157.4	160.4	0.98	18.5	70.5	84	79	100	95	48	40	35.0
20	1-10-30	160.3	157.3	159.3†	—	18.5	70.5	89	80	100	98	56	44	35.0
9	1-4-30	158.8	157.2	158.2†	—	18.0	70.3	95	83	100	100	55	45	34.5
43	3-200-20	174.0	166.0	174.0***	—	16.5	69.0	89	89	100	100	52	48	35.5
32	1-200-20	157.7	157.6	159.6	0.99	18.5	70.6	87	82	100	95	50	44	34.7
21	1-10-30	158.7	156.6	158.6†	—	18.5	69.3	99	92	100	100	57	51	34.0
10	1-4-30	157.1	155.7	157.1†	—	19.0	71.7	101	90	100	100	57	50	34.5

*Results shown are averages from duplicate 0.252-inch-diameter tensile specimens and three Charpy V-notch impact specimens.
**Code - The first number refers to the number of hardening cycles, the second number is the average heating rate (F per second) from room temperature to peak temperature (1480 F) and the third number is the approximate dwell time (sec) between the end of heating and start of quenching.

***The upper yield and maximum load points coincided. (See stress-strain curve A in Figure 8).
†The conventional maximum load point did not surpass the upper yield level in these tests. (See stress-strain curve B in Figure 8).

††All the broken specimens had fissures.

(40.018-002)(15)



EIGHT SPECIMEN BLANKS ARE REMOVED FROM EACH HEAT-TREATED PLATE SAMPLE AS SHOWN

DETAILS OF TEST-SPECIMEN BLANKS FOR INDUCTION HEAT TREATMENT

DRAWN BY E.J.S.	CHK'D BY R.P.H.	APPROVED BY J.H.G.	UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA.	FIGURE NO. 1
DRAWING No. ARL 18-328		PROJECT No. 40.018-002 (15)		
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As-Rolled Prior Microstructure

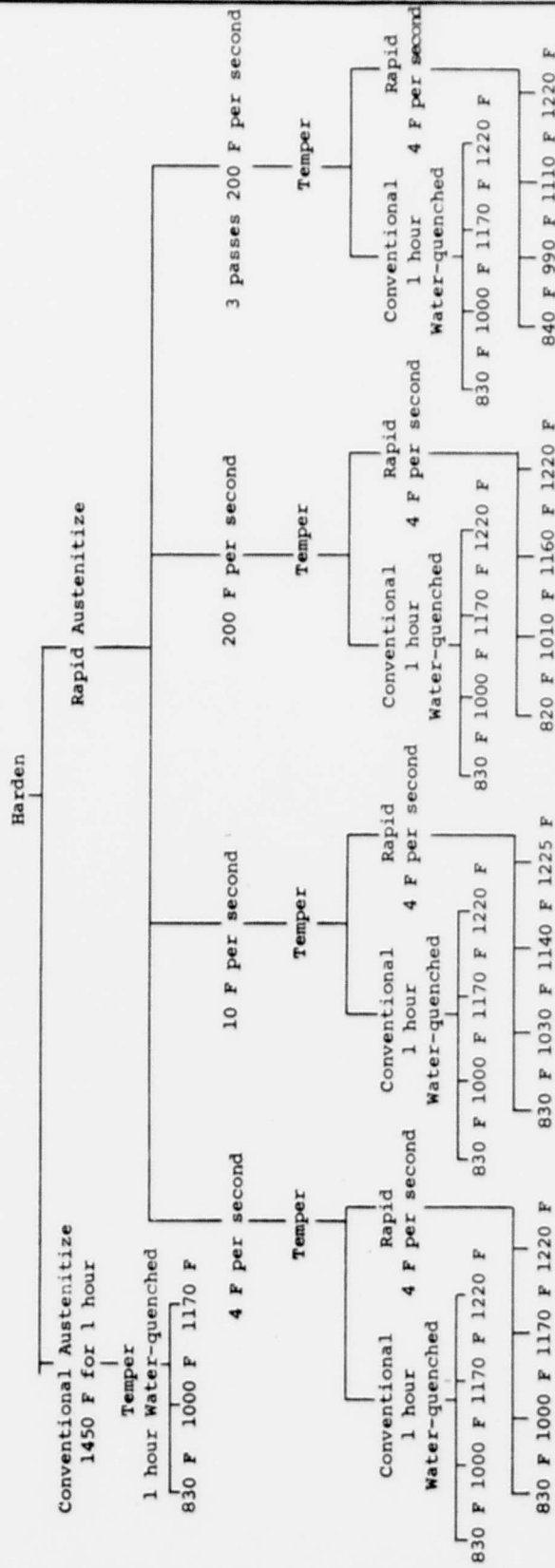
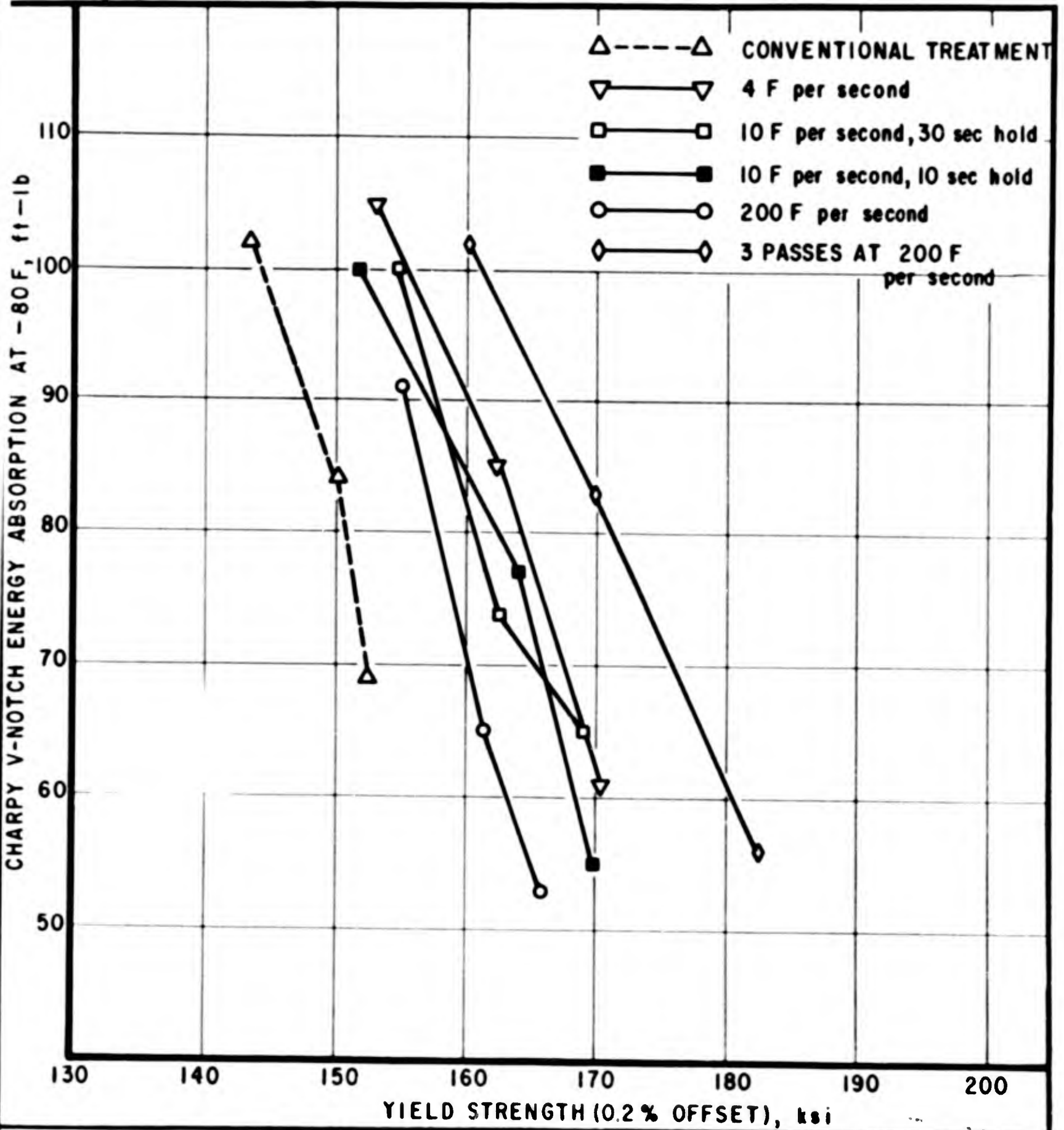


Figure 2. Flow Diagram Showing the Organization of the Heat-Treating Tests

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STRENGTH-TOUGHNESS RELATIONS RESULTING FROM VARIOUS AUSTENITIZING RATES - CONVENTIONAL TEMPERING

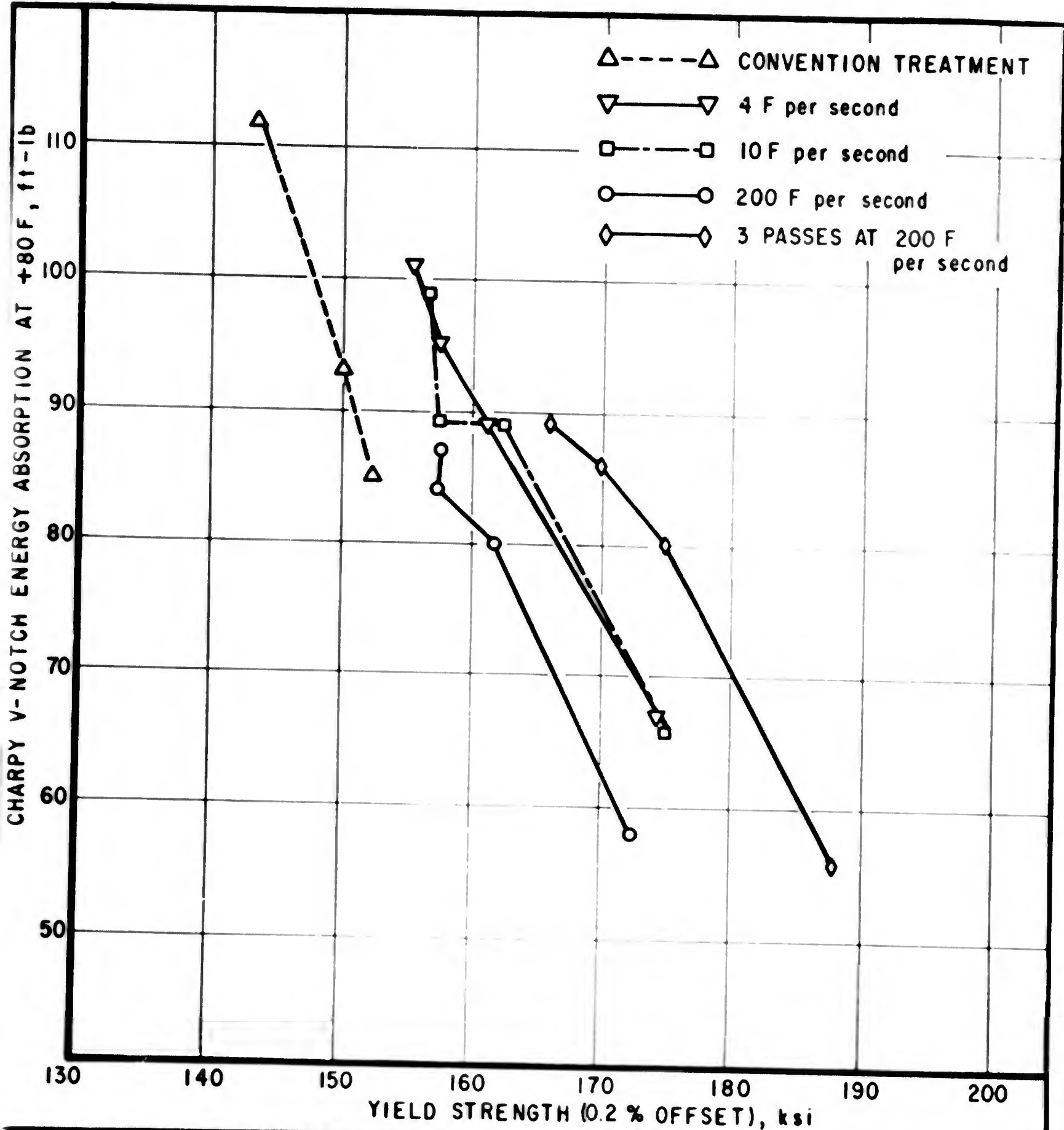
DRAWN BY E. J. S.	CHK'D BY R. P. H.	APPROVED BY J. H. G.
DRAWING NO ARL 18-331		PROJECT NO 40.018-002(15)
		DATE 3-20-64

UNITED STATES STEEL CORPORATION
APPLIED RESEARCH
PITTSBURGH, PA.

FIGURE NO. 6

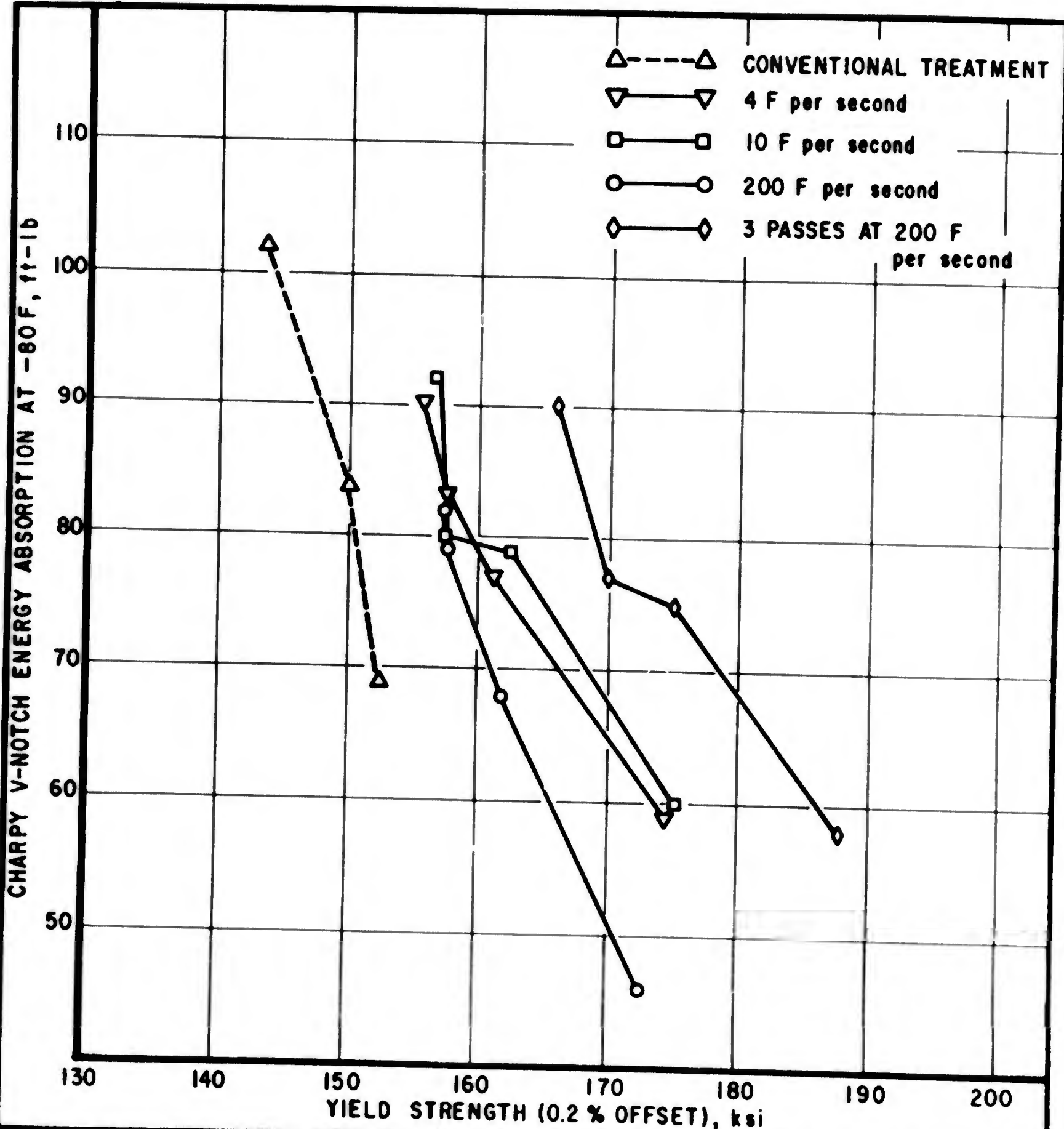


Figure 3. The induction scanner in operation.



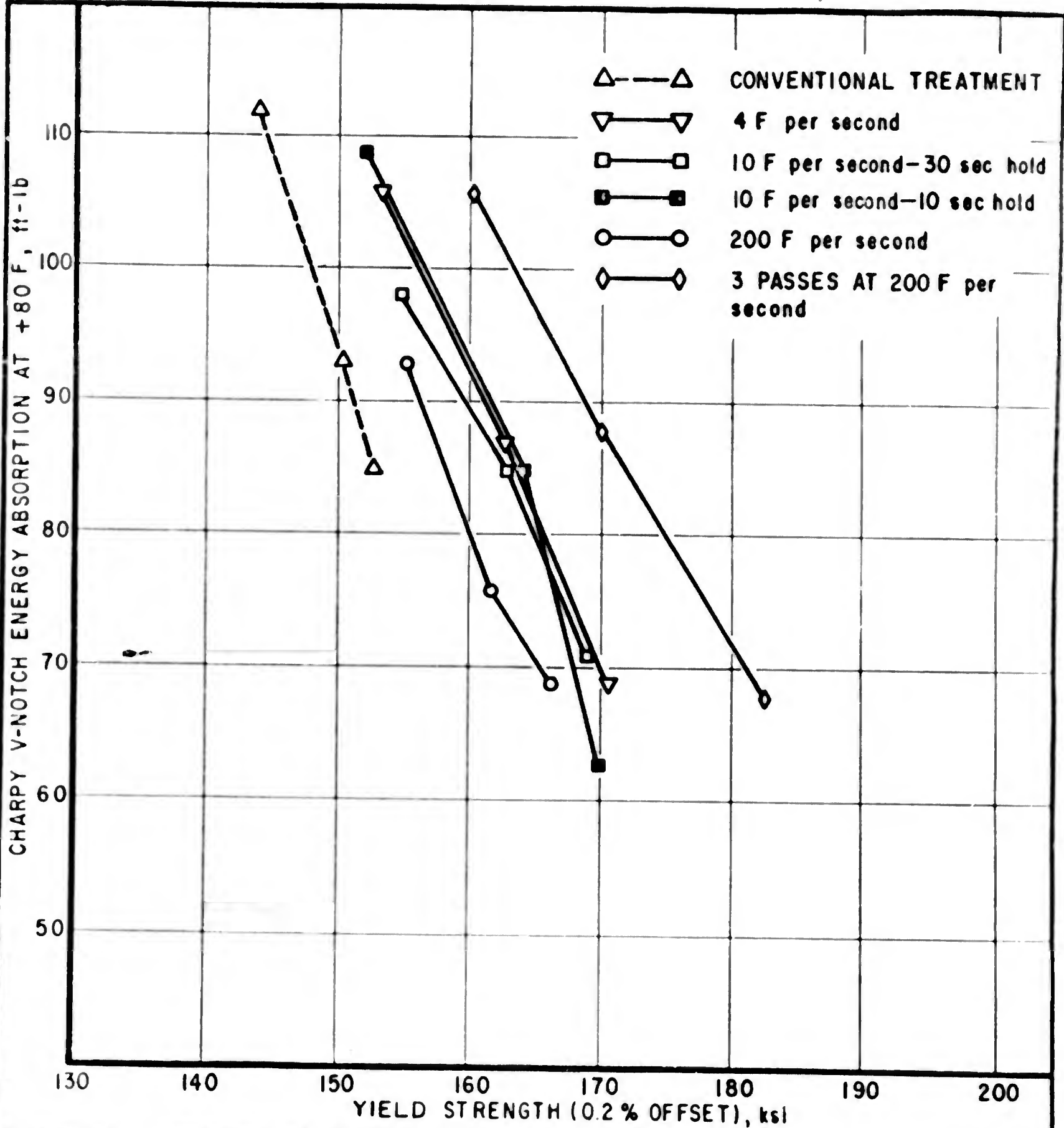
STRENGTH-TOUGHNESS RELATIONS RESULTING FROM VARIOUS AUSTENITIZING RATES - RAPID TEMPERING AT 4 F PER SECOND

DRAWN BY E.J.S.	CHK'D BY R.P.H.	APPROVED BY J.H.G.	UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA.	FIGURE NO. 5
DRAWING NO ARL 18-330		PROJECT NO 40,018-002 (15)		
		DATE 3-20-64		



STRENGTH-TOUGHNESS RELATIONS RESULTING FROM VARIOUS AUSTENITIZING RATES—RAPID TEMPERING AT 4 F PER SECOND

DRAWN BY E. J. S.	CHK'D BY R. P. H.	APPROVED BY J. H. G.	UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA.	FIGURE NO. 7
DRAWING NO ARL 18-332		PROJECT NO 40-018-002(15)		
		DATE 3-20-64		



STRENGTH-TOUGHNESS RELATIONS RESULTING FROM VARIOUS AUSTENITIZING RATES - CONVENTIONAL TEMPERING

DRAWN BY EJS	CHECKED BY R.P.H.	APPROVED BY J.H.G.	UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA.	FIGURE NO. 4
DRAWING NO ARL 18-329		PROJECT NO 40,018-002 (15)		
		DATE 3-19-64		

STRESS

CURVE A

TYPICAL CURVE FOR SPECIMENS
HARDENED BY THREE RAPID
AUSTENITIZING TREATMENTS
(200 F per second)



CURVE B

TYPICAL CURVE FOR CERTAIN
SPECIMENS HARDENED BY SINGLE
RAPID AUSTENITIZING TREATMENT



STRAIN



**SCHEMATIC STRESS-STRAIN CURVES FOR CERTAIN
RAPIDLY AUSTENITIZED SPECIMENS**

DRAWN BY
E. J. S. R.P.H.

DRAWING NO.

ARL 18-333

APPROVED BY

J. H. G.

PROJECT NO.

40,018-002(15)

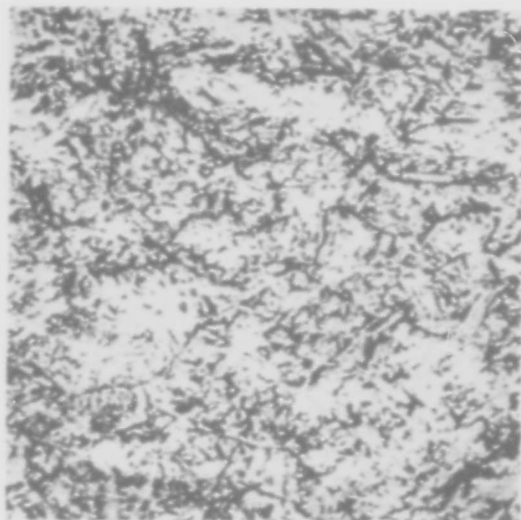
DATE

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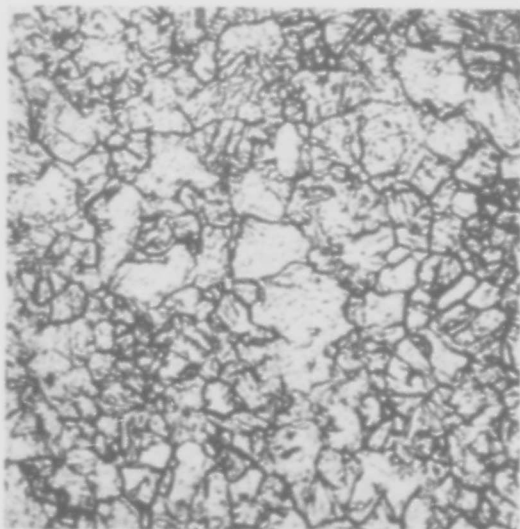
UNITED STATES STEEL CORPORATION
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FIGURE
NO.

8



A. Hot-rolled condition.



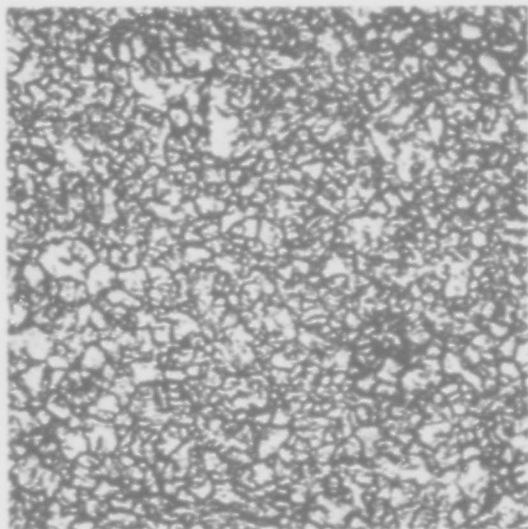
B. Conventionally heat-treated.
Plate sample C. ASTM Grain
Size 9.5.

Figure 9. Photomicrographs of $5\frac{1}{4}$ Ni-Cr-Mo-V steel. Etched
in aqueous picric acid at 200 F. X500.

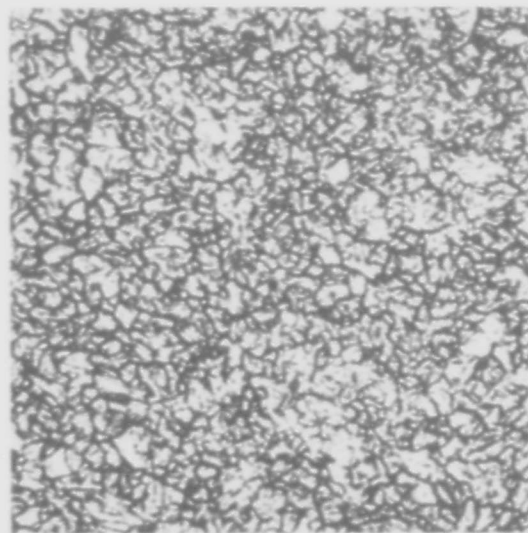
2-9330B-2
2-9331B-2

(40.018-002) (15)

Figure 9A, B



A. Austenitized at 4 F per second. Rapid temper 1170 F. Plate Sample 9. ASTM Grain Size 11.5.



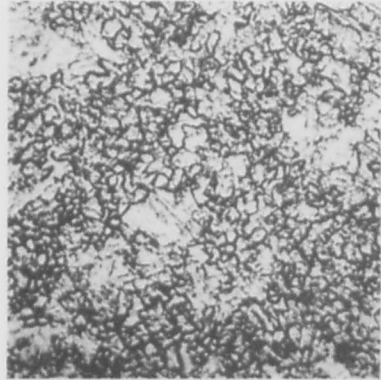
B. Austenitized at 10 F per second. Rapid temper 1170 F. Plate Sample 20. ASTM Grain Size 11.

Figure 10. Photomicrographs of rapidly heat-treated $5\frac{1}{2}$ Ni-Cr-Mo-V steel specimens. Etched in aqueous picric acid at 200 F. X500.

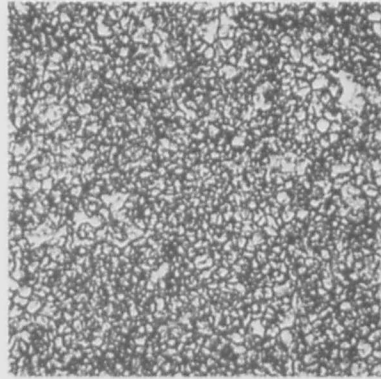
2-9337B-2
2-9338B-2

(40.018-002) (15)

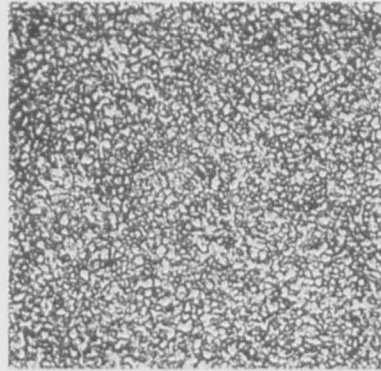
Figure 10A, B



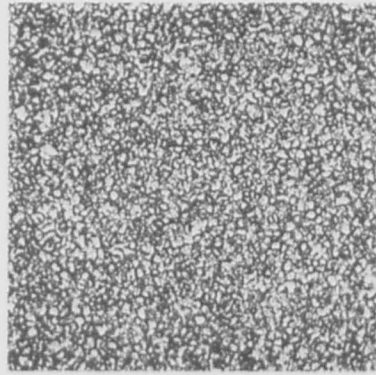
A. 1 Pass. $R_C = 45.0$. ASTM
Grain Size (duplexed) 30%
No. 6, 30% No. 9, 40%
No. 12.5



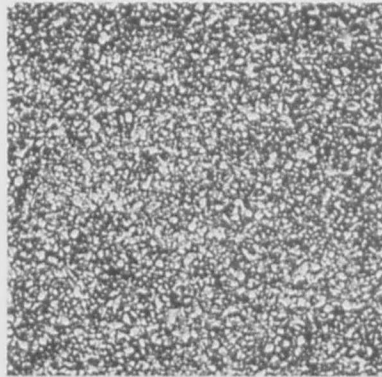
B. 2 Pass. $R_C = 45.2$. ASTM
Grain Size (duplexed) 30%
No. 10, 70% No. 12.5.



C. 3 Pass. $R_C = 46.3$. ASTM
Grain Size 13.5.



D. 4 Pass. $R_C = 45.6$. ASTM
Grain Size 13.75.



E. 5 Pass. $R_C = 46.9$. ASTM
Grain Size 14.5.

Figure 11. Photomicrographs showing the austenite grain refinement produced by multiple hardening passes at a 200 F per second heating rate. Etched in aqueous picric acid at 200 F. X500.

2-9332B-2
2-9333B-2
2-9334B-2
2-9335B-2
2-9336B-2

(40.018-002) (15)

Figure 11A, B, C, D, E.