AD

TECHNICAL REPORT ARCCB-TR-96005

COMPARISON OF ISOTHERMAL SALT QUENCH AND OIL QUENCH PLUS TEMPER OF 4XXX LOW ALLOY STEELS

RICHARD FARRARA

FEBRUARY 1996

US ARMY ARMAMENT RESEARCH,
DEVELOPMENT AND ENGINEERING CENTER
CLOSE COMBAT ARMAMENTS CENTER
BENÉT LABORATORIES
WATERVLIET, N.Y. 12189-4050

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

DISCLAIMER

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

The use of trade name(s) and/or manufacturer(s) does not constitute an official indorsement or approval.

DESTRUCTION NOTICE

For classified documents, follow the procedures in DoD 5200.22-M, Industrial Security Manual, Section II-19 or DoD 5200.1-R, Information Security Program Regulation, Chapter IX.

For unclassified, limited documents, destroy by any method that will prevent disclosure of contents or reconstruction of the document.

For unclassified, unlimited documents, destroy when the report is no longer needed. Do not return it to the originator.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
February 1996

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
COMPARISON OF ISOTHERMAL SALT QUENCH AND OIL QUENCH PLUS TEMPER OF 4XXX LOW ALLOY STEELS

5. FUNDING NUMBERS
AMCMS No. 6226.24.H180.0
PRON No. W16H1F586

6. AUTHOR(S)
Richard Farrara

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC
Benet Laboratories, AMSTA-AR-CCB-O
Watervliet, NY 12189-4050

8. PERFORMING ORGANIZATION REPORT NUMBER
ARCCB-TR-96005

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army ARDEC
Close Combat Armaments Center
Picatinny Arsenal, NJ 07806-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A comparison is provided of the mechanical properties resulting from heat treating two low alloy steels (AISI 4140 and AISI 4340) by the conventional procedure (austenitize, oil quench, temper) and by an isothermal salt quench (austenitize, hot salt quench), but with no temper procedure. Also, a comparison is provided of the dimensional changes and distortion for both steels heat treated by both procedures.

The hardness ranges evaluated are Rc 40/45 and Rc 45/50. The conventional rapid oil quench causes distortion and dimensional change of components, hence components heat treated to those high hardness levels have to be finish machined, typically with grinding tools after heat treatment. The isothermal salt quench is a relatively gentle quench cycle that produces a microstructure (mixture of martensite and lower bainite) known to result in excellent mechanical properties. The small distortion and dimensional changes from this procedure would allow finish machining to be completed prior to the heat treatment. The material would be readily machineable (annealed condition) and the associated reduced amount of fixturing/set-ups would provide economic benefits.

The primary purpose of this effort was to compare the mechanical properties that result from the conventional and isothermal salt quench heat-treating procedures. If the properties from the isothermal salt quench are equal to or better than the results from the conventional procedure, the engineering community could allow this cost-saving procedure. The results of this effort indicate that the properties obtained from the isothermal salt quench of AISI 4140 are not equivalent to those obtained from the conventional oil quench-temper, whereas the properties for AISI 4340 from the isothermal salt quench are equivalent or higher than from the conventional oil quench-temper procedure.

14. SUBJECT TERMS
Low Alloy Steel, High Hardness Levels, Oil Quench, Temper, Dimensional Change, Distortion, Yield Strength, Tensile Strength, Charpy V-Notch Impact Strength, Martensite, Upper Bainite

15. NUMBER OF PAGES
24

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

TABLE OF CONTENTS

TABLES

LIST OF ILLUSTRATIONS

INTRODUCTION

Recent experimental work by Barranco et al. (ref 1) and Cote et al. (ref 2) demonstrated that an interrupted isothermal, hot liquid salt quench and temper of a 4335 low alloy steel (ASTM A723) with high nickel (≈3%) and medium carbon (≈0.35%) will result in mechanical properties (ductility-low temperature toughness) at equivalent strength levels that are better than obtained from a continuous water quench to room temperature and temper. The basic conclusion is that the excellent properties result from a mixed microstructure of lower bainite (formed at a temperature below the start of martensitic formation, M_s, temperature) and martensite. This microstructure will be created by cooling rapidly enough to miss the austenite-to-bainite transformation on the continuous cooling diagram (named bainite knee) to somewhat below the M_s temperature, holding at this temperature long enough for the transformation of austenite to a mixture of lower bainite and martensite. If the bainite knee is not missed, austenite will transform to upper bainite, which is a microstructure that results in low or poor toughness especially at cold temperature, i.e., the transition temperature is usually between -40°F and room temperature.

The mechanical properties are not only excellent, but the quench cycle is quite slow ("gentle") as compared to a rapid ("violent") water or oil quench. The water or oil quench creates the conventionally desired microstructure of martensite, however, the large thermal gradient created between the surface and the interior can result in distortion, cracking at stress concentrations either created by geometrical configuration or material defects, and undesirable residual stress. Also, the residual stress is typically tension on the surface that results in distortion and dimensional change during machining, plus the potential for premature crack initiation from fatigue loading. Furthermore, dimensional growth occurs from the volumetric increase that accompanies the formation of martensite.

There are many components manufactured from low alloy steels such as AISI 4140 or 4340 that are conventionally heat treated (austenitize, oil quench to oil temperature, temper) to high hardness levels (Rc 40/45 or Rc 45/50). Because the post-heat treatment hardness level is too high for machining with conventional tools (high speed steel or carbide) and dimensional-distortion change will occur during the conventional heat treatment, the usual manufacturing procedure is to acquire the material in the annealed or normalized condition, rough machine to create configuration features with a minimum yet adequate amount of material remaining, heat treat, and then finish machine with grinding tools. This procedure is accepted but expensive because of the extra setups (setup and/or fixturing for both rough and finish machining), the cost of grinding tools, and the additional time for small amounts of material removal during finish-machining operations. The isothermal salt quench procedure has the potential for eliminating machining after the heat treatment, since the distortion and dimensional change would be minimal. The manufacturing procedure would be to purchase annealed material, rough and finish machine to the final dimensions, then heat treat via the isothermal salt quench procedure. The desired hardnesses can be created without tempering after the isothermal salt quench; however, this direct, step-saving procedure will only be applicable to heat treating components if the other properties (percent reduction in area, Charpy v-notch impact strength, yield strength) are acceptable.

APPROACH

The substitution of the isothermal salt quench for the conventional liquid quench-temper heat treatment would be based on mechanical property equivalence, and improvement in dimensional control/distortion. The approach to determine properties from both procedures was to heat treat rectangular bars of AISI 4140 and 4340 by both procedures and compare properties via testing tensile and Charpy v-notch specimens. The rectangular bars were removed from 1-1/2 inch thick plates with the longitudinal axis of the tensile specimen parallel to the rolling direction and the fracture plane of the Charpy specimen perpendicular to the rolling direction. See Figure 1. Orientation was selected to avoid erroneous results associated with the influence of stringers (oxides and/or sulphides) that are parallel to the rolling direction.

Since the hardness levels being evaluated are high (Rc 40/45 and Rc 45/50), the approach for the salt quench procedure was to control the salt temperature such that the hardness would be obtained in the "as-quenched" condition, i.e., tempering after quench was not employed. The quench temperature to obtain the Rc 40/45 hardness would be higher than required for the Rc 45/50 level because the higher hardness is obtained by more martensite, which is created by having the salt temperature closer to the M_f temperature. Avoiding the bainite knee, which would result in undesirable upper bainite, is controlled by both composition and salt temperature, hence the AISI 4140 material at the Rc 40/45 level would be the most likely combination for developing the unwanted upper bainite composition.

The specific temperature and times at temperature used for both heat-treating procedures for the two common alloys to develop the two hardness levels are shown in Table 1.

The approach to determine the potential improvement in dimensional change/distortion from both heat-treating procedures was to manufacture specimens from the 1-1/2 inch thick plates with configurations and features that could easily distort and/or crack. The configurations used for the AISI 4140 and 4340 alloys are shown in Figures 2A and 2B, respectively. Since a hot salt quench medium is less severe than a room temperature oil quench medium, the amount of distortion and potential for creating cracks is expected to be reduced. Also, since the transformation of austenite-to-bainite (lower and upper) results in less volumetric increase than transformation to martensite, the salt quench method should result in less dimensional change than the oil quench. However, since tempering of martensite results in contraction, the oil quench plus temper procedure may not produce more dimensional change than the salt quench with no temper procedure.

RESULTS

Mechanical Properties

The mechanical property results of 0.1 percent and 0.2 percent yield strength (YS), tensile strength (TS), YS/TS ratios, reduction in area, elongation, and Charpy v-notch impact strength (room temperature and -40°F) are listed in Table 2. Plots of yield strength (0.2 percent offset) and Charpy v-notch impact strength at -40°F versus hardness levels are shown in Figures 3 and 4 for both heat-treating procedures for AISI 4140 and 4340, respectively. Plots of the Charpy v-notch impact strength at -40°F and room temperature for both hardness levels/heat-treatment procedures of 4140 and 4340 are shown in Figures 5 and 6, respectively.

Analysis of the strength and yield/tensile strength ratios reveals that the oil quench procedure produces high YS/TS ratios, whereas the salt quench procedure produces low-to-medium YS/TS ratios with the exception of the 4340 Rc 40/45 hardness level. It has been established (ref 1) that the 0.1 percent YS/TS ratio decreases as the tensile strength increases and as the amount of bainite increases. Table 3 summarizes results of the 0.1 percent YS/TS analysis, which involved heat treating ASTM A723 steel (approximately 4335V mod steel).

The oil quench procedure resulted in the martensitic microstructure for both alloys, as shown in Figures 7 through 10, hence the high YS/TS ratios. The salt quench procedure resulted in the mixed microstructure of bainite and martensite for both alloys, as shown in Figures 11 through 14, hence the low-to-medium YS/TS ratios. The reason why the salt quench of the 4340 at the Rc 40/45 hardness level resulted in high YS/TS ratios is that the tensile strength was not high (≈180 Ksi). It is noted that the salt quench of 4140 and 4340 at the Rc 45/50 hardness level (salt temperature of 450°F), which has the smallest amount of bainite, resulted in a significant amount of strain hardening (large difference between 0.1 percent and 0.2 percent yield strength values). The reason for this condition is unknown.

Analysis of the Charpy v-notch impact strength value reveals that the oil quench procedure produced expected levels of toughness for the associated strength levels for both alloys. The toughness values and the difference between upper (room temperature) and lower shelf (-40°F) values decreased as the strength increased. The salt quench procedure for the 4140 alloy produced lower toughness values for both hardness levels than the oil quench procedure (see Table 2 and Figure 3). The oil quenched 4140, Rc 45/50 level, had approximately the same toughness as the salt quenched 4140, Rc 45/50; however, the strength levels of the oil quenched material were significantly higher than the salt quenched material, which of course, reduces the associated toughness. The reason for the inferior toughness of the salt quenched 4140 is that the microstructure, as seen in Figures 11 and 12, contains upper bainite. The salt quench was not rapid enough to miss the bainite knee due to the relative low hardenability of this alloy. The salt quench procedure for the 4340 alloy, however, produced essentially the same toughness values at both hardness levels as the oil quench procedure (see Table 2 and Figure 4). Although the salt quenched 4340 at the Rc 45/50 level had higher toughness than the oil quenched 4340, the yield strength level of the oil quenched material was higher than the salt quenched material. Hence if the strength were at the same level, it is postulated that the toughness would have been at the same level. The reason for the excellent toughness of the salt quenched 4340 is that the microstructure, as seen in Figures 13 and 14, is a mixture of martensite and low temperature bainite with very minor amounts of upper bainite. The toughness of the salt quenched 4340 material was expected to be higher than the oil quenched 4340 as shown in Reference 1, yet it is speculated that since there was a minor amount of upper bainite, the measured toughness levels were only equal to those obtained by the conventional oil quench procedure.

Dimensional-Distortion Change

Analyses of the dimensional changes and distortion are based on heat treating via the oil quench-temper and isothermal salt quench procedures with results shown in Table 4. The specimen used for the AISI 4140 material (Figure 2A) had a relatively complicated configuration with a v-notch, a hole, and a keyway. The purpose was to create stress concentrations to generate cracking, especially with the faster oil quench cooling rate. Since cracking after heat treatment was not evident via magnetic particle and visual inspection, the specimen design used for the AISI 4340 material (Figure 2B) was simplified. The starting materials (0.75-inch thick) for both specimens were annealed (1600°F, furnace cooled) prior to machining for the purpose of starting with material without any residual stress. Residual stress could create movement during the heat treating that would "mask" the movement attributed solely to the heat-treating procedures. The dimensions and flatness before and after the heat treatments are listed in Table 4, as well as the net change for each feature or characteristic. The results reveal that the dimensional changes for both alloys and for both heat-treating procedures are small and are essentially identical. The change in flatness (distortional change), however, was large with the oil quench-temper for both specimens, whereas it was very small for the isothermal salt quench for both specimens. Since the dimensional change and distortion from the isothermal salt quench are very small but not insignificant, the potential certainly exists for eliminating machining after heat treatment. Each component design would be evaluated by analyzing the tolerances specified. If tolerancing were small (estimated to be less than ± 0.002 for a ten-inch or less dimension), a small trial and error pilot run prior to production, would be prudent. Since the distortion from the oil quench (approximately 0.004 and 0.010), the manufacturing of a component heat treated by the conventional procedure typically requires finish machining after heat treatment.

CONCLUSIONS

1. The YS/TS ratio was higher (0.87 and higher) as expected, for the oil quench-temper than for the isothermal salt quench of both alloys, except for the AISI 4340, Rc 40/45 condition. The reason for this exception is presumed to be because the tensile strength level was not high.

2. Heat treating to a specific hardness range via both procedures results in lower yield strength but higher tensile strength values for the isothermal salt quench procedure than for the oil quench-temper procedure.

3. The toughness from an isothermal salt quench of AISI 4140 will be less than what is obtained from a conventional oil quench-temper, assuming equivalent yield strength levels. The reason is presumed to be that the relatively low hardenability resulted in a microstructure containing upper bainite which lowers toughness.

4. The toughness from an isothermal salt quench of AISI 4340 will be equivalent or higher than what is obtained from an oil quench-temper procedure. The reason is presumed to be that this alloy has sufficient hardenability to allow the cooling rate of a salt quench to miss the bainite knee thereby resulting in the desired microstructure of lower bainite-martensite.

5. The dimensional change from both heat treating procedures is small but not insignificant.

6. The distortion from the isothermal salt quench procedure is very small, however, it is relatively large for the oil quench-temper procedure applied to both alloys.

7. The isothermal salt quench procedure of AISI 4340 can be substituted for the oil quench-temper procedure and should eliminate finish machining and the associated costs after the heat treatment.

REFERENCES

1. J. Barranco, P.J. Cote, and J.A. Kapp, "Tempering Effects for Lower Bainite, Martensite, and Mixed Microstructure on Impact, Fracture, and Related Mechanical Properties of ASTM A723 Steel," ARDEC Technical Report ARCCB-TR-92024, Benet Laboratories, Watervliet, NY, June 1992.

2. P.J. Cote, R. Farrara, T. Hickey, and S.K. Pan, "Isothermal Bainite Processing of 723 Components," ARDEC Technical Report ARCCB-TR-93035, Benet Laboratories, Watervliet, NY, September 1993.

Table 1

Heat Treatment Procedure

Conventional Versus Isothermal Salt Quench Procedures

Material	4140		4140		4340		4340	
Hardness (Rc) Range	40/45		45/50		40/45		45/50	
Austenitize °F/hr	1550/1		1550/1		1550/1		1550/1	
Quench Media	Salt	Oil	Salt	Oil	Salt	Oil	Salt	Oil
Temperature (°F)	560	80	450	80	560	80	450	80
Time (°F/hr)	2	0.25	2	0.25	2	0.25	2	0.25
Temper °F/hr	--	875/1	--	725/1	--	875/1	--	725/1
M_s Temperature (°F):								
Calculated	561/637				517/594			
Measured	572				565			

Table 2. Mechanical Properties for AISI 4140 and 4340 Oil Quench and Temper Versus Isothermal Salt Quench
(Average value from two specimens)

MATERIAL	4140		4140		4340		4340	
QUENCH MEDIA	OIL		SALT		OIL		SALT	
Quench Temperature (°F)	80/90		560	450	80/90		560	450
Tempering Temperatures (°F)	875	725	–	–	875	725	–	–
Hardness Range (Rc)	40 45	45 50	40 45	45 50	40 45	45 50	40 45	45 50
Yield Strength 0.1% offset	196.9	221.8	189.3	175.6	179	197.75	178.7	165.6
0.2% offset	197.5	223.7	196.2	204.4	179	199.4	181.25	184.4
Tensile Strength (Ksi)	210.0	241.8	231.7	253.75	194.7	225.5	190.5	241.25
Reduction In Area (%)	42.1	38.8	50.8	28.4	47.5	42.1	46.2	40.8
Yield/Tensile Ratio 0.1% YS/TS	.94	.92	.82	.69	.92	.87	.94	.68
0.2% YS/TS	.94	.925	.85	.805	.92	.88	.95	.76
Elongation (% in 4D)	13.9	12.7	11.6	11.6	–	11.5	–	11.5
Charpy V-Notch Impact Strength (ft-lbs) Room Temp	17	8.5	10	8	23	9	23.5	15
-40°F	12.5	5	8	5	14.5	10	11.5	14.5
Actual Hardness (Rc) (average of four measurements)	41	46	43	52	40	44	38	44
Microstructure	TM	TM	UB LB TM	UB LB TM	TM	TM	TM LB	TM LB

TM – tempered martensite
LB – low temperature bainite
UB – upper bainite

Table 3. 0.1 Percent YS/TS Ratio Versus Tensile Strength
(ASTM A723 Steel (ref 1))

Tensile Strength (Ksi)	0.1 Percent YS/TS Ratio			
	100 Percent Martensite	25 Percent Bainite	66 Percent Bainite	100 Percent Bainite
180	0.96	0.95	0.93	0.78
200	0.95	0.91	0.76	0.58
220	0.92	0.82	0.54	--
240	0.78	--	--	--

Table 4. Dimension-Distortion Change

A. Dimensions-Distortion of AISI 4140 Before and After Final Heat Treatment

	Before		After		Change	
Specimen	#1	#2	#1	#2	#1	#2
Length	6.0015	6.0038	6.0000	6.0025	-0.0015	-0.0013
	3.0020	3.0030	2.9990	3.0020	-0.0030	-0.0010
Width	0.4904	0.4903	0.4915	0.4915	-0.0011	-0.0012
Height	0.5010	0.5000	0.5015	0.5010	-0.0005	-0.0010
	1.0005	1.0004	1.0010	1.0010	+0.0005	+0.0006
	0.8485	0.8490	0.8485	0.8505	0.0000	+0.0015
Keyway	0.1278	0.1277	0.1285	0.1290	+0.0007	+0.0013
Flatness	0.0002	0.0010	0.0100	0.0000	0.0098	0.0010

Table 4. Dimension-Distortion Change (Cont'd)

B. Dimensions-Distortion of AISI 4340 Before and After Final Heat Treatment

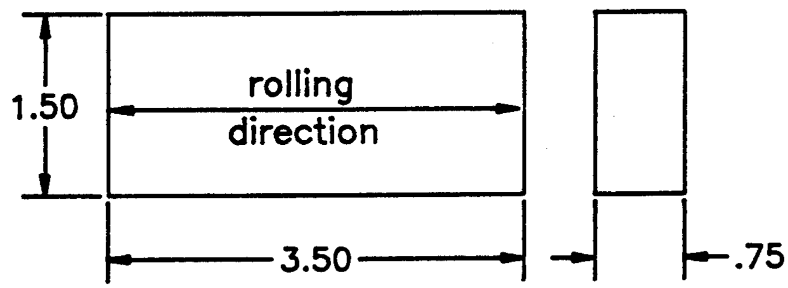
	Before		After		Change	
Specimen	#1	#2	#1	#2	#1	#2
Length	3.2062	3.2060	3.2040	3.2060	-0.0022	0
Width	1.3028	1.3015	1.3020	1.3045	-0.0008	+0.003
Thickness	0.2008	0.2007	0.2012	0.2006	+0.0004	-0.0001
Flatness	0.0001	0.0001	0.0040	0.0010	0.0039	0.0009

FIG. 1

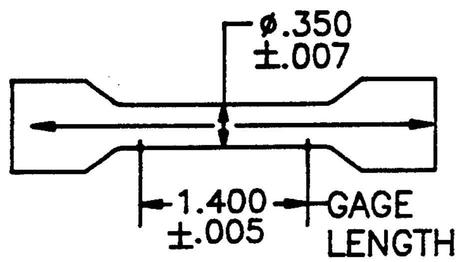
SPECIMENS— FOR HEAT TREATMENT & MECHANICAL PROPERTY TESTS.

TENSILE SPECIMEN

A.) HEAT TREATMENT SPECIMEN

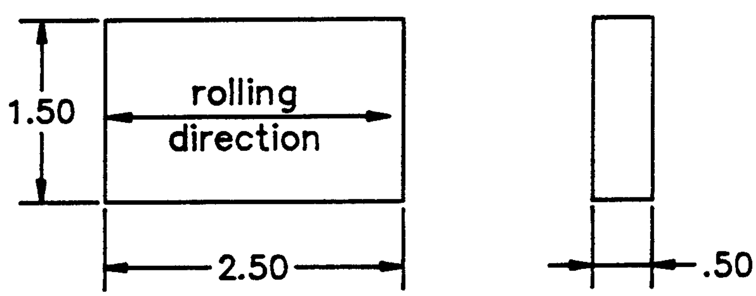


B.) TENSILE SPECIMEN

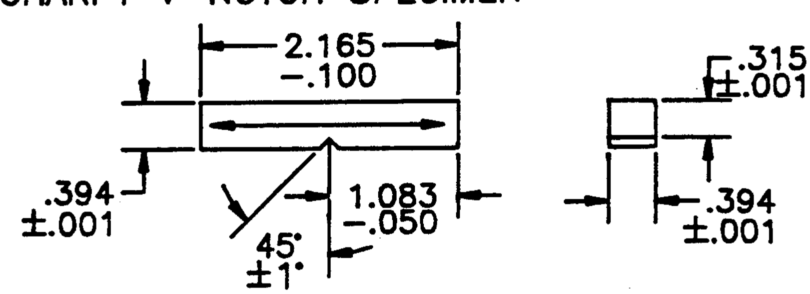


CHARPY SPECIMEN

A.) HEAT TREATMENT SPECIMEN



B.) CHARPY V–NOTCH SPECIMEN



Rolling Direction of 1.50 inch thick plates (AISI 4140 & 4340).

FIG. 2A

DIMENSION-DISTORTION SPECIMEN

1) Material-AISI 4140

2) Heat Treatments-Initial: Anneal at 1600° F, 1.5 hr, furnace cool.
Final: Specimen #1- 1550° F, .5 hr, oil quench, temper at 875° F, .5 hr, air cool.
Specimen #2- 1550° F, in salt, .5 hr, salt quench at 560° F, 2 hrs, air cool.

3) Specimen Design-

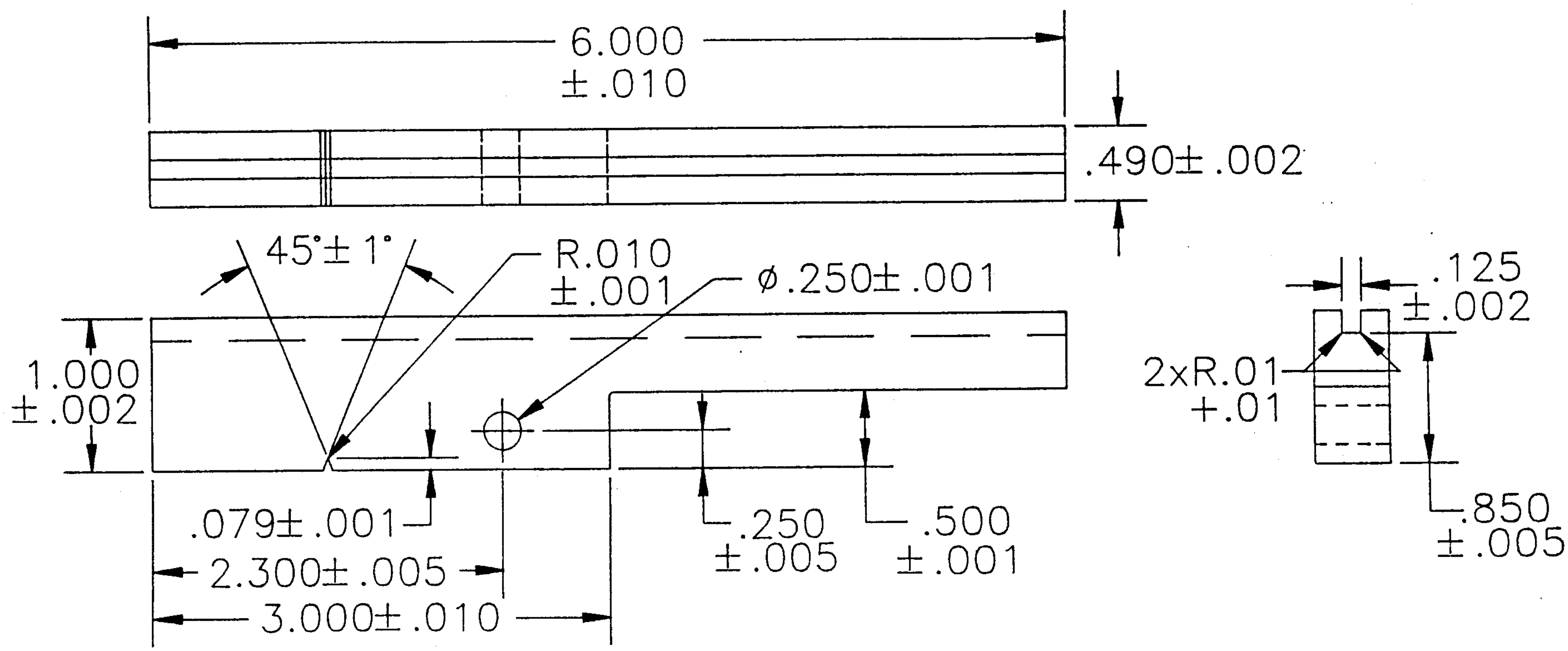


FIG. 2B

DIMENSION-DISTORTION SPECIMEN

1) Material-AISI 4340

2) Heat Treatments-Initial: Anneal at 1600° F, 1.5 hr, furnace cool.
Final: Specimen #1- 1550° F, .5 hr, oil quench, temper at 875° F, .5 hr, air cool.
Specimen #2- 1550° F, in salt, .5 hr, salt quench at 560° F, 2 hrs, air cool.

3) Specimen Design-

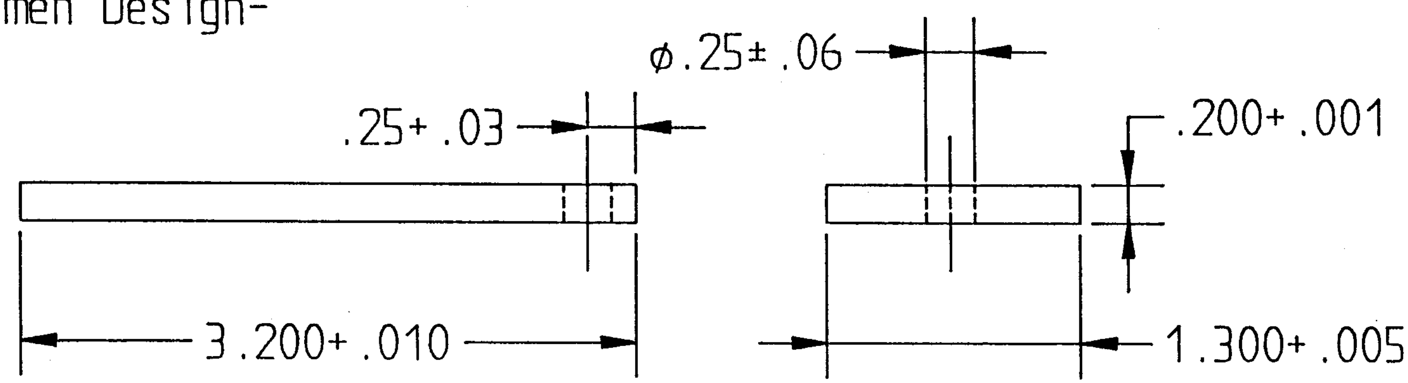
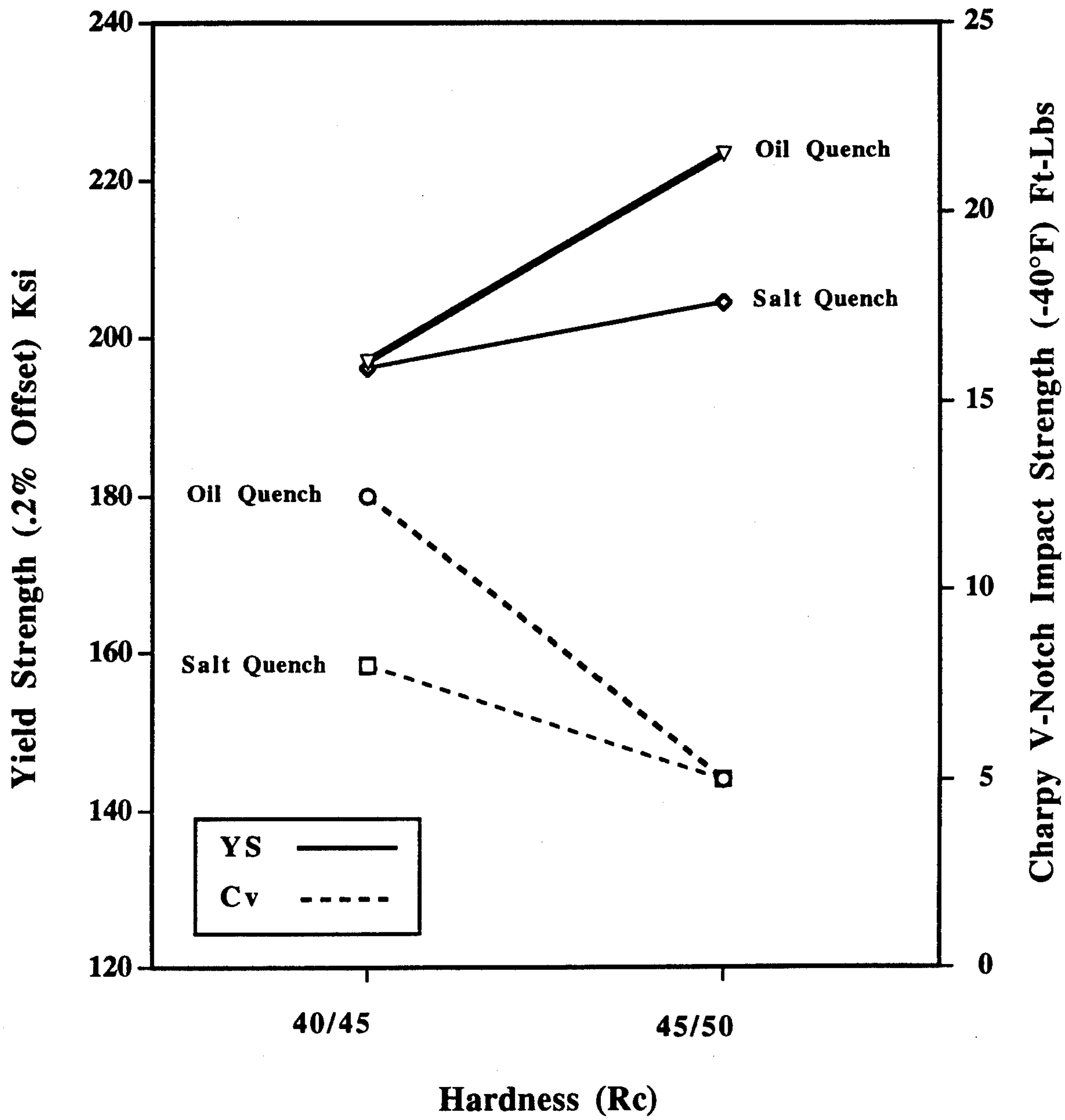


FIG 3

YS & Cv(-40°F) vs Rc
AISI 4140
Oil vs Isothermal Salt Quench



<u>FIG 4</u>

YS & CV(-40°F) vs Rc
AISI 4340
Oil vs Isothermal Salt Quench

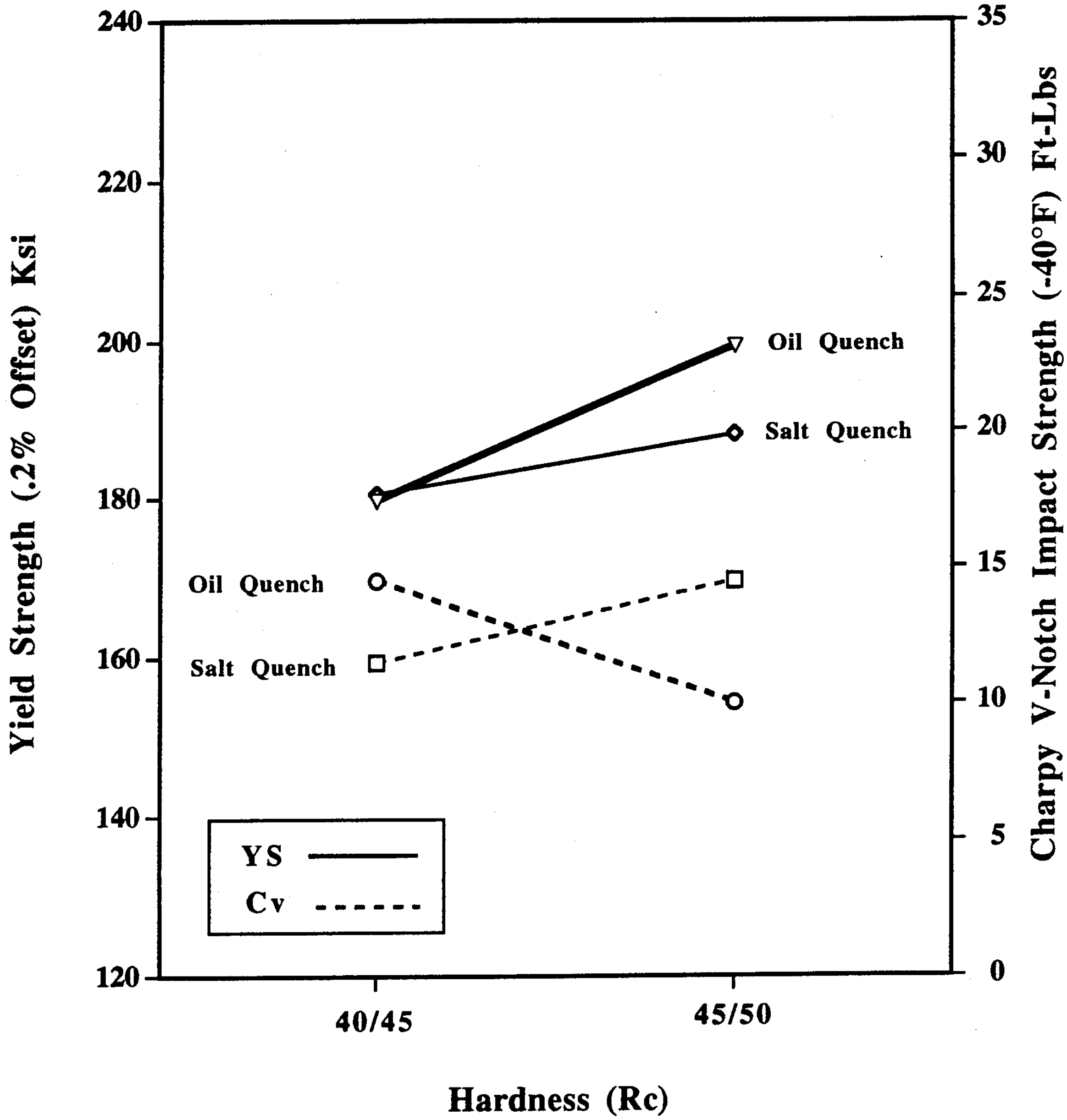
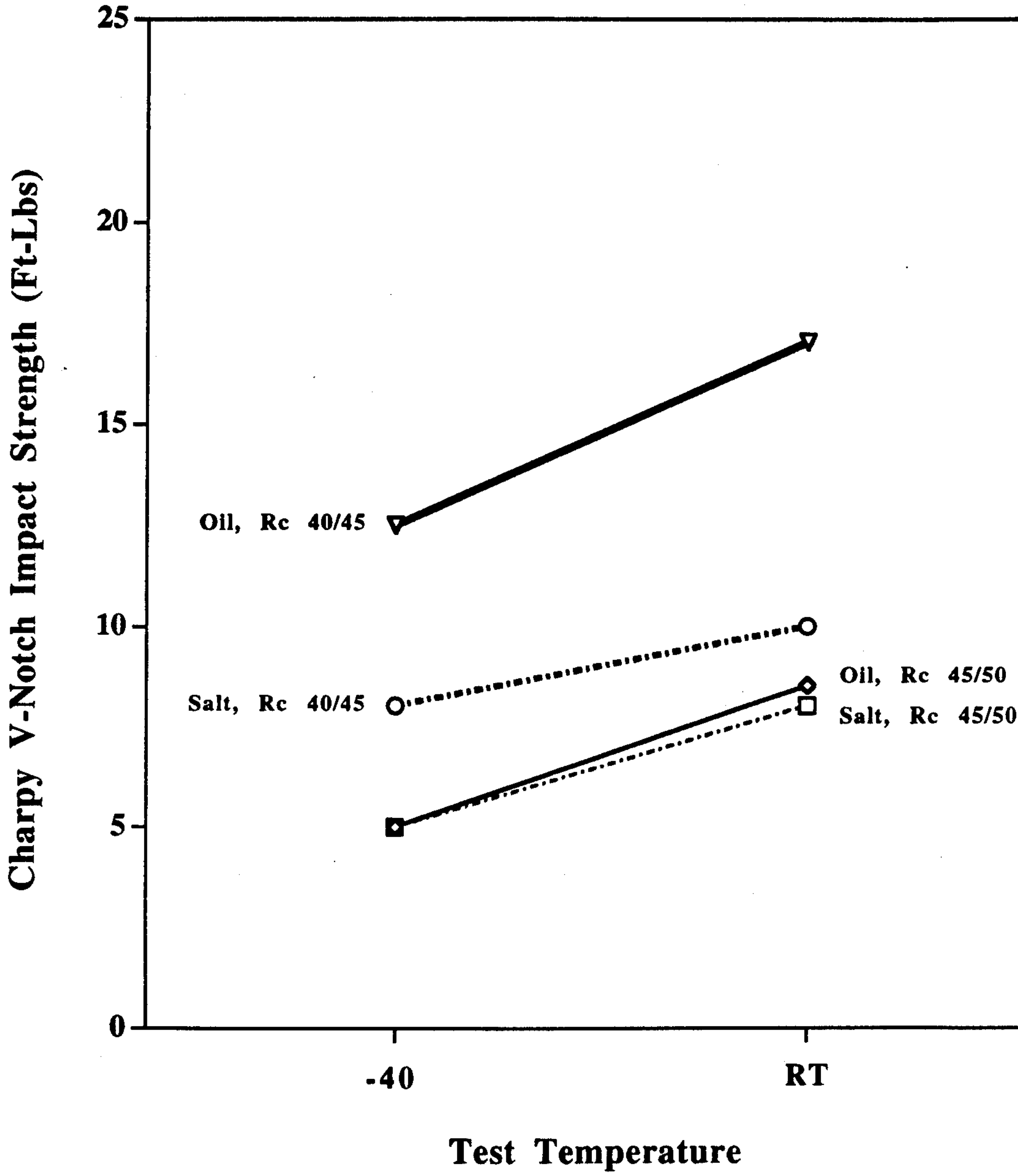


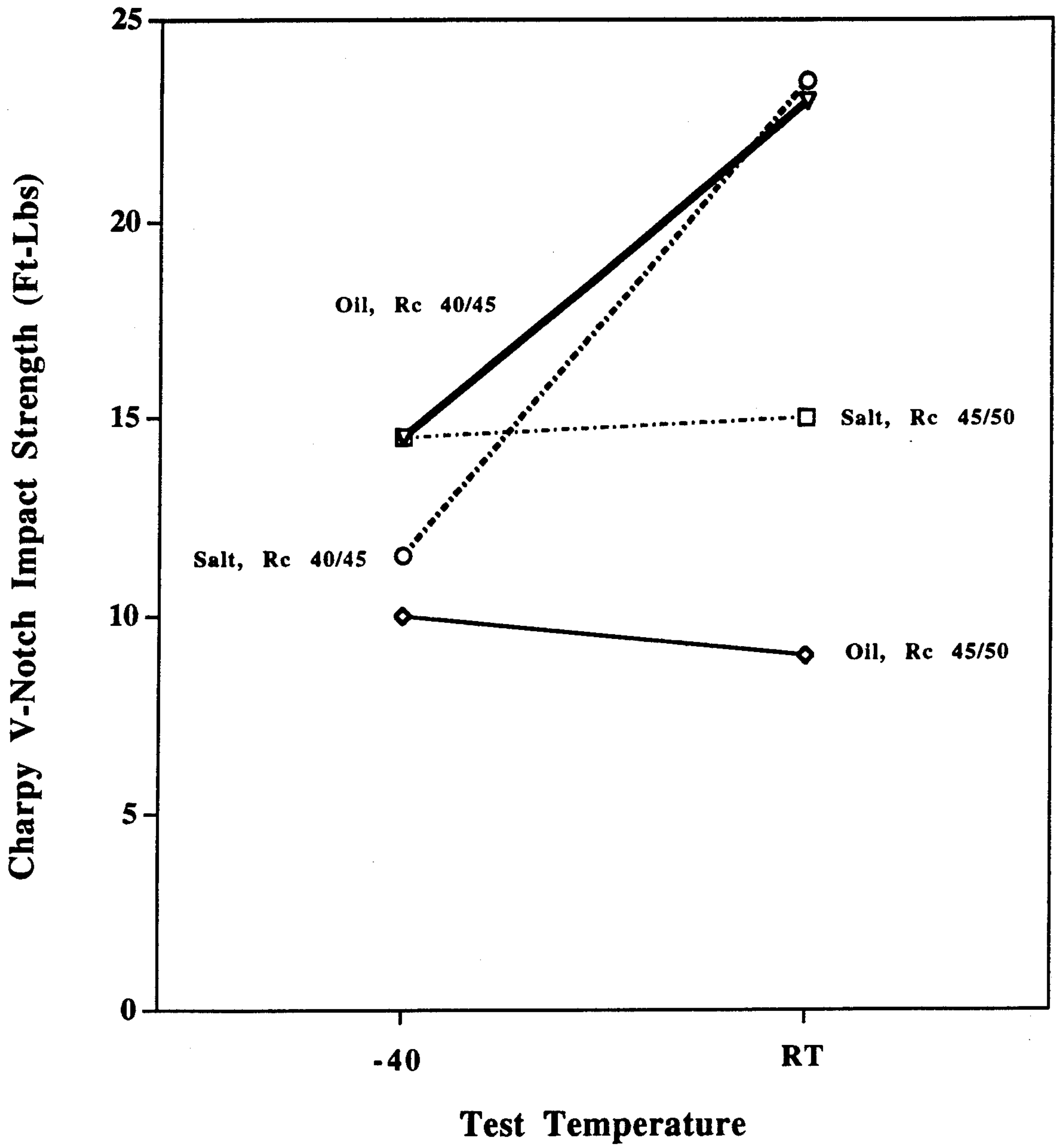
FIG 5

Cv vs Test Temperature
AISI 4140
Oil vs Isothermal Salt Quench



<u>FIG 6</u>

Cv vs Test Temperature
AISI 4340
Oil vs Isothermal Salt Quench



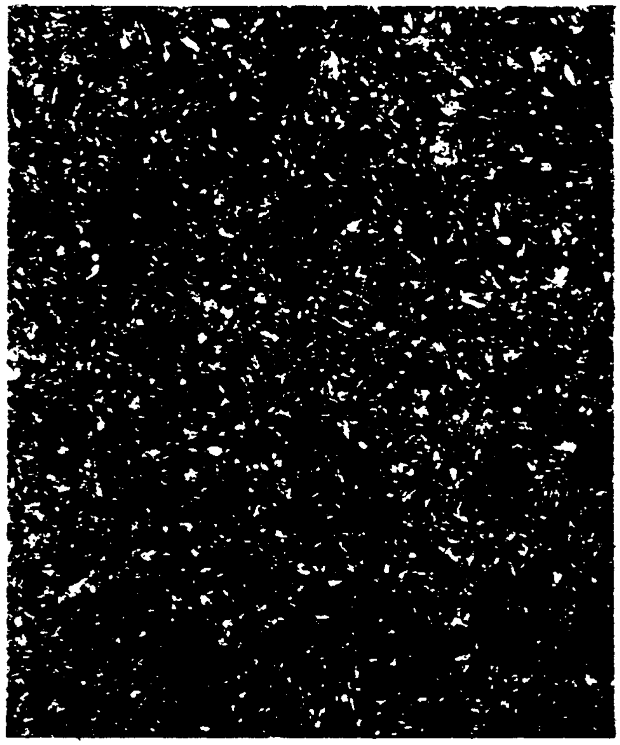


Figure 7. Martensitic microstructure for AISI 4140, oil quenched, Rc 40/45, at 500X

Figure 8. Martensitic microstructure for AISI 4140, oil quenched, Rc 45/50, at 500X

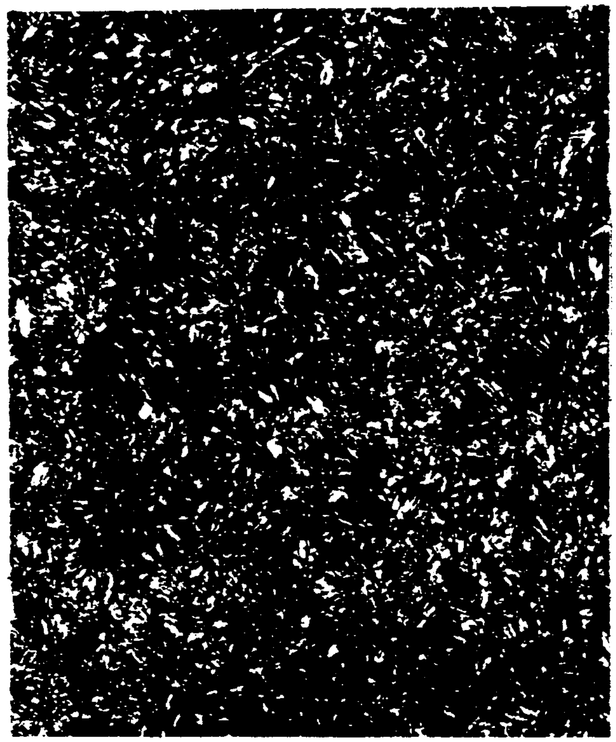


Figure 9. Martensitic microstructure for AISI 4340, oil quenched, Rc 40/45, at 500X

Figure 10. Martensitic microstructure for AISI 4340, oil quenched, Rc 45/50, at 500X

Figure 11. Upper-lower bainite and martensitic microstructure for AISI 4140, salt quenched, Rc 40/45, at 500X

Figure 12. Upper-lower bainite and martensitic microstructure for AISI 4140, salt quenched, Rc 45/50, at 500X

Figure 13. Lower bainite and martensitic microstructure for AISI 4340, salt quenched, Rc 40/45, at 500X

Figure 14. Lower bainite and martensitic microstructure for AISI 4340, salt quenched, Rc 45/50, at 500X

TECHNICAL REPORT INTERNAL DISTRIBUTION LIST

	NO. OF COPIES
CHIEF, DEVELOPMENT ENGINEERING DIVISION	
ATTN: AMSTA-AR-CCB-DA	1
-DB	1
-DC	1
-DD	1
-DE	1
CHIEF, ENGINEERING DIVISION	
ATTN: AMSTA-AR-CCB-E	1
-EA	1
-EB	1
-EC	1
CHIEF, TECHNOLOGY DIVISION	
ATTN: AMSTA-AR-CCB-T	2
-TA	1
-TB	1
-TC	1
TECHNICAL LIBRARY	
ATTN: AMSTA-AR-CCB-O	5
TECHNICAL PUBLICATIONS & EDITING SECTION	
ATTN: AMSTA-AR-CCB-O	3
OPERATIONS DIRECTORATE	
ATTN: SIOWV-ODP-P	1
DIRECTOR, PROCUREMENT & CONTRACTING DIRECTORATE	
ATTN: SIOWV-PP	1
DIRECTOR, PRODUCT ASSURANCE & TEST DIRECTORATE	
ATTN: SIOWV-QA	1

NOTE: PLEASE NOTIFY DIRECTOR, BENÉT LABORATORIES, ATTN: AMSTA-AR-CCB-O OF ADDRESS CHANGES.

TECHNICAL REPORT EXTERNAL DISTRIBUTION LIST

	NO. OF COPIES
ASST SEC OF THE ARMY RESEARCH AND DEVELOPMENT ATTN: DEPT FOR SCI AND TECH THE PENTAGON WASHINGTON, D.C. 20310-0103	1
DEFENSE TECHNICAL INFO CENTER ATTN: DTIC-OCP (ACQUISITIONS) 8725 JOHN J. KINGMAN ROAD STE 0944 FT. BELVOIR, VA 22060-6218	2
COMMANDER U.S. ARMY ARDEC ATTN: AMSTA-AR-AEE, BLDG. 3022	1
AMSTA-AR-AES, BLDG. 321	1
AMSTA-AR-AET-O, BLDG. 183	1
AMSTA-AR-FSA, BLDG. 354	1
AMSTA-AR-FSM-E	1
AMSTA-AR-FSS-D, BLDG. 94	1
AMSTA-AR-IMC, BLDG. 59 PICATINNY ARSENAL, NJ 07806-5000	2
DIRECTOR U.S. ARMY RESEARCH LABORATORY ATTN: AMSRL-DD-T, BLDG. 305 ABERDEEN PROVING GROUND, MD 21005-5066	1
DIRECTOR U.S. ARMY RESEARCH LABORATORY ATTN: AMSRL-WT-PD (DR. B. BURNS) ABERDEEN PROVING GROUND, MD 21005-5066	1
DIRECTOR U.S. MATERIEL SYSTEMS ANALYSIS ACTV ATTN: AMXSY-MP ABERDEEN PROVING GROUND, MD 21005-5071	1
COMMANDER ROCK ISLAND ARSENAL ATTN: SMCRI-SEM ROCK ISLAND, IL 61299-5001	1
MIAC/CINDAS PURDUE UNIVERSITY 2595 YEAGER ROAD WEST LAFAYETTE, IN 47906-1398	1
COMMANDER U.S. ARMY TANK-AUTMV R&D COMMAND ATTN: AMSTA-DDL (TECH LIBRARY) WARREN, MI 48397-5000	1
COMMANDER U.S. MILITARY ACADEMY ATTN: DEPARTMENT OF MECHANICS WEST POINT, NY 10966-1792	1
U.S. ARMY MISSILE COMMAND REDSTONE SCIENTIFIC INFO CENTER ATTN: AMSMI-RD-CS-R/DOCUMENTS BLDG. 4484 REDSTONE ARSENAL, AL 35898-5241	2
COMMANDER U.S. ARMY FOREIGN SCI & TECH CENTER ATTN: DRXST-SD 220 7TH STREET, N.E. CHARLOTTESVILLE, VA 22901	1
COMMANDER U.S. ARMY LABCOM, ISA ATTN: SLCIS-IM-TL 2800 POWER MILL ROAD ADELPHI, MD 20783-1145	1

NOTE: PLEASE NOTIFY COMMANDER, ARMAMENT RESEARCH, DEVELOPMENT, AND ENGINEERING CENTER, BENÉT LABORATORIES, CCAC, U.S. ARMY TANK-AUTOMOTIVE AND ARMAMENTS COMMAND, AMSTA-AR-CCB-O, WATERVLIET, NY 12189-4050 OF ADDRESS CHANGES.

TECHNICAL REPORT EXTERNAL DISTRIBUTION LIST (CONT'D)

	NO. OF COPIES
COMMANDER U.S. ARMY RESEARCH OFFICE ATTN: CHIEF, IPO P.O. BOX 12211 RESEARCH TRIANGLE PARK, NC 27709-2211	1
DIRECTOR U.S. NAVAL RESEARCH LABORATORY ATTN: MATERIALS SCI & TECH DIV WASHINGTON, D.C. 20375	1
WRIGHT LABORATORY ARMAMENT DIRECTORATE ATTN: WL/MNM EGLIN AFB, FL 32542-6810	1
WRIGHT LABORATORY ARMAMENT DIRECTORATE ATTN: WL/MNMF EGLIN AFB, FL 32542-6810	1

NOTE: PLEASE NOTIFY COMMANDER, ARMAMENT RESEARCH, DEVELOPMENT, AND ENGINEERING CENTER, BENÉT LABORATORIES, CCAC, U.S. ARMY TANK-AUTOMOTIVE AND ARMAMENTS COMMAND, AMSTA-AR-CCB-O, WATERVLIET, NY 12189-4050 OF ADDRESS CHANGES.