NASA-CR-159842
IITRI-M6001-82

THERMAL FATIGUE AND OXIDATION DATA OF OXIDE DISPERSION-STRENGTHENED ALLOYS

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Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

March 1980

CONTRACT NAS3-17787

NASA-Lewis Research Center
Cleveland, Ohio

Peter T. Bizon, Project Manager

1. Report No.
NASA CR-159842

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
THERMAL FATIGUE AND OXIDATION DATA OF OXIDE DISPERSION-STRENGTHENED ALLOYS

5. Report Date
March 1980

6. Performing Organization Code

7. Author(s)
K. E. Hofer, V. L. Hill, and V. E. Humphreys

8. Performing Organization Report No.
IITRI-M6001-82

10. Work Unit No.

9. Performing Organization Name and Address
IIT Research Institute
10 West 35th Street
Chicago, Illinois 60616

11. Contract or Grant No.
NAS3-17787

13. Type of Report and Period Covered
Contractor Report

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

14. Sponsoring Agency Code

15. Supplementary Notes
Project Manager, Peter T. Bizon, Structures and Mechanical Technologies Division, NASA-Lewis Research Center, Cleveland, Ohio 44135

16. Abstract
Thermal fatigue and oxidation data were obtained on 24 specimens, representing 9 discrete oxide dispersion-strengthened alloy compositions or fabricating techniques. Double-edge wedge specimens, both bare metal and coated for each system, were cycled between fluidized beds maintained at 1130°C and 357°C with a three minute immersion in each bed. The systems included alloys identified as 262 in hardness of HRC 38; 264 in hardness of HRC 38, 40 and 43; 265 HRC 39, 266 of HRC 37 and 40; 754; and 956. Specimens in the bare condition of 265 HRC 39 and 266 HRC 37 survived 6000 cycles without cracking on the small radius of the double-edge wedge specimen. A coated specimen of 262 HRC 38, 266 HRC 37, and 266 HRC40 also survived 6000 cycles without cracking. A duplicate coated specimen of 262 HRC 38 alloy survived 5250 cycles before cracks appeared. All the alloys showed little weight change compared to alloys tested in prior programs.

17. Key Words (Suggested by Author(s))
Oxide dispersion strengthening
Thermal fatigue
Nickel alloys
Coatings
Oxidation
Fluidized bed
Heat resistance alloys
Thermal resistance

18. Distribution Statement
Unclassified - unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	36	$3.00

* For sale by the National Technical Information Service, Springfield, Virginia 22161

N80-25415 #

FOREWORD

This report describes the results of thermal fatigue and oxidation testing of Series 6 test specimens on NASA Contract NAS3-17787. The report covers part of the work conducted on this contract during the period 1 March 1977 to 15 June 1979. Other IITRI work on fluidized bed thermal fatigue testing has been reported in NASA CR-72738, CR-121211, CR-121212, CR-134775, CR-135272, CR-135299, and CR-159798.

Peter T. Bizon was the NASA-Lewis Research Center Project Manager. IITRI personnel assigned to this program included V. L. Hill (Science Advisor, Materials Technology Division), K. E. Hofer (Project Manager), V. E. Humphreys (Project Engineer), M. Yerman and J. Anderson (Contract Specialists), M. Scroll, D. Brown, and V. Johnson.

The IITRI internal designation for this report is IITRI-M6001-82. Thermal fatigue and oxidation data contained in this report are recorded in Logbooks Nos. C23103 and C24427.

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SUMMARY

Thermal fatigue and oxidation testing described in this report are part of a general study of thermal fatigue being conducted by the NASA-Lewis Research Center. Earlier work in the study has been reported in NASA CR-72738, CR-121211, CR-121212, CR-134775, CR-135272, CR-135299, and CR-159798. All testing on this contract has been conducted employing fluidized bed heating and cooling. Testing in this program was over the temperature range 1130°/357°C employing double-edge wedge specimens.

Thermal fatigue and oxidation data were obtained on 24 specimens representing six different experimental oxide dispersion-strengthened (ODS) systems. One of the alloys contained three levels of hardness. All systems were investigated in both bare and coated conditions.

Specimens in the bare condition of 265 HRC 39 and 266 HRC 37 survived 6000 cycles without cracking on the small radius ofthe double-edge wedge specimen. A coated specimen of 262 HRC 38, 266 HRC 37, and 266 HRC 40 also survived 6000 cycles without cracking. Another coated specimen of the 262 HRC 38 alloy and a coated specimen of the 264 HRC 43 alloy survived 5250 cycles before the appearance of cracks. Alloy 956 developed transverse cracks prior to 50 thermal cycles in both the bare and coated conditions. Compared to alloys previously examined, these alloys exhibited little weight change. Substantial separation of the coating from the base metal on the 754 specimen occurred after 2500 thermal cycles. Similarly the 265 HRC 39 specimen exhibited coating separation after 3000 cycles. Some slight separation of the coating from the base metal on the 264 HRC 40 specimen appeared upon completion of 5000 thermal cycles. This slight separation was near the sample ends and hence the specimen was retained and completed 6000 thermal cycles.

1. INTRODUCTION

This report, NASA CR-159842, on Contract NAS3-17787 summarizes thermal fatigue and oxidation data for 24 specimens of oxide dispersion-strengthened (ODS) alloys. A coating on each of the nine investigated alloy compositions or fabricating techniques was also evaluated in this program. The specimens of double-edge wedge cross-section were cycled in a fluidized bed facility over the temperature range 1130°/357°C (2065°/675°F) for periods up to 6000 cycles. Heating and cooling times were 180 seconds each, for a total thermal cycle duration of 360 seconds. Weight changes, as well as cycles crack initiation and crack propagation, were obtained in the program.

Thermal fatigue data obtained previously have been reported on this contract.(1-2) Additional thermal fatigue data obtained in the IITRI fluidized bed have been reported on Contracts NAS3-14311(3-5), NAS3-18942,(6) and NAS3-19696.(7) This effort comprises part of the general study of thermal fatigue being conducted by the NASA-Lewis Research Center. Further details of the study have been reported by Spera et al.,(8,9) Bizon et al.,(10-12) and Howes.(13)

Any material exposed to repeated rapid thermal transients is subjected to tensile failure by thermal fatigue, also sometimes defined as thermal shock. The thermal fatigue degradation mechanism involves accumulation of damage during multiple thermal cycles. Thermal shock, on the other hand, generally involves failure in relatively few cycles. The difference generally lies in the tensile ductility of the material within the temperature range of the imposed thermal cycle. Ductile materials tend to fail by thermal fatigue, whereas brittle materials fracture by thermal shock.

Material properties, other than ductility, important in thermal fatigue are hot tensile strength, elastic modulus, thermal conductivity, and thermal expansion. Oxidation resistance apparently also plays a role in thermal fatigue. The interrelationship of material properties, the imposed thermal cycle, and component geometry defines the ability of a structure to resist thermal fatigue. However, the synergistic effects of these variables are quite complex and prediction of thermal fatigue behavior from basic properties is difficult. A major objective of the current NASA fatigue program is to develop and verify a usable model for thermal fatigue by comparing experimental data with computer-derived predictions of thermal fatigue life.

Thermal fatigue data in this report was generated using a multiple retort fluidized bed test facility consisting of one heating bed and two cooling beds. Glenny and coworkers reported the first use of fluidized beds to study thermal fatigue.(14)

Fluidized bed heating and cooling provides very rapid heat transfer for both portions of the thermal cycle. An additional advantage of fluidized bed testing is that it provides a ready means of exposing a number of samples under identical test conditions. In this program, 18 test specimens were exposed simultaneously.

The objective of the thermal fatigue test program was threefold:

1) Determine the number of imposed thermal cycles to initiation of the first transverse crack.

2) Obtain data on the rate of propagation of the three largest cracks.

3) Generate qualitative oxidation data for the various materials.

Cycling of test specimens was generally continued until the three largest cracks reached a length of about 10 mm (0.4 in.). This corresponds to the approximate width of the tapered section of the test specimen. In some cases, exposure of specimens was continued in order to obtain oxidation data for specific alloys.

2. EXPERIMENTAL PROCEDURE

2.1 Materials

Thermal fatigue testing in this program was performed on 24 specimens of bare and coated oxide-dispersion strengthened alloys consisting of six alloys, one of which had three different hardness levels. All test specimens were supplied by the NASA-Lewis Research Center.

A summary of the compositions of the experimental alloys is shown in Table 1. The compositional data was supplied by NASA-Lewis Research Center. The coating was a commercial NiCrAlY electron-beam vapor-deposited overlay coating.

Tensile properties at 760°C (1400°F) and stress-rupture properties at 982°C (1800°F) of the test alloys are summarized in Tables 2 and 3, respectively. These data were generated at the NASA-Lewis Research Center on the same heats of the alloys used to fabricate the thermal fatigue specimens.

2.2 Test Facility and Procedure

The fluidized bed thermal fatigue test facility is shown schematically in Figure 1. This equipment includes one hot bed mounted between two cold, or intermediate, temperature beds. Although the facility contains two cooling beds, only one cooling bed was employed in this program. The lower bed temperature is maintained by a water-cooled heat exchanger for testing near ambient temperatures. For testing at the 357°C (675°F) intermediate bed temperature in this program, the heat exchanger was removed and the desired intermediate bed temperature was maintained by the heating elements. Heat transfer media in both hot and cold beds was 28-48 mesh tabular alumina.

During testing in this program, 18 test specimens were cycled simultaneously in a single holding fixture. At any time during testing, the holding fixture was either in the hot bed or the intermediate bed. The transfer carriage, operated by air cylinders, can be programmed for any combination of heating and cooling time. Transfer time between beds was about 5 s, and the heating and cooling time 180 s each in the current test program.

Thermal fatigue data in this program was obtained using the nominal 102 mm long double-edge wedge simulated blade shape and the holding fixture, shown in Fig. 2. Test specimens were supported by 6.3 mm wide notches machined 7 mm deep in the ends of the specimen. The notched specimens provided ease of fabrication and specimen removal from the fixture for examination. In addition, the potential for superimposition of mechanical stresses due to the fixture was minimized.

The holding fixture, shown in Fig. 2, capable of retaining 18 test specimens, was fabricated from austenite stainless steel (310). End plates were 12.7 mm thick 310 stainless steel with a radius 0.25 mm less than the specimen notches. The side supports were fabricated from 304 stainless steel channel. During testing, the test fixture also generated thermal fatigue cracks and required frequent replacement.

Thermal fatigue testing was conducted by cycling a holder of up to 18 test specimens for a total of 6000 cycles. In addition, a dummy sample was mounted at each end of the holder to eliminate end effects. Of the original 18 specimens, only 12 completed the full 6000 thermal cycles. The remaining 6 samples were removed earlier because of excessive cracking or coating separation. In addition, six samples were added to the group at the 3000 thermal cycle milestone. Four (4) of these samples did not develop cracks, although they had accumulated 3000 thermal cycles at the termination of the testing. Thus these 24 test specimens comprised test Series 6 of Contract NAS3-17787.

During testing at 1130°/357°C (2065°/675°F), specimens were removed at selected intervals for gravimetric analysis and crack length measurements. The nominal removal times were 25, 50, 100, 200, 300, 500, 700, and 1000 cycles, followed by examination every 500 cycles for exposures greater than 1000 cycles. Lengths of the three longest cracks were determined visually using a microscope at 30X. The number of cycles to crack initiation was taken as the average of the number of cycles at the last inspection without cracks and the number of cycles at the first inspection with a crack. However, specimens were generally retained in the test program after crack initiation to obtain additional oxidation data.

Table 4 summarizes the dimensions and identification of the 24 test specimens evaluated in the program. Both the as-received and final dimensions are shown. Data on total thermal cycles imposed on each specimen are included for reference..

3. RESULTS

3.1 Oxidation Behavior

Weight change data for the 24 test specimens are contained in Table 5. Figures 3 to 8 are plots of the oxidation data for these same specimens.

Oxidation data in Table 5 and Figures 3 to 8 are expressed in percent of the original weight, since oxidation was not uniform over the test specimen. In general, the majority of the oxidation occurred on the wedge areas of the specimen. This is because these areas were exposed to the maximum temperature of the thermal cycle for longer periods than the thicker center section of the specimen. Thermocouple calibration tests reported in NASA CR-121211(4) indicated that for double-edge wedge specimens, the center section of the specimen is nominally 17°-30°C (31°-54°F) less than the maximum temperature of the wedge section at the end of a 180 s heating cycle. Thermocouple calibration data also indicate that the wedge sections of the specimen were within 25°C of the 1130°C maximum temperature for the average time of about 75 s, at the end of the 180 s. Qualitatively, therefore, the cumulative exposure was equivalent to about 20 hr at 1105° ± 25°C (2020° ± 45°F) for each 1000 cycles of testing. This corresponds to 120 hr for 6000 cycle exposure. Rapid thermal cycling, however, accelerates oxidation significantly in comparison to isothermal exposure.

Overall, the oxidation behavior of all of the oxide-dispersion hardened alloys was considerably less than most alloys previously studied(1-5) during the course of this program. In general, the coated samples lost weight steadily, while the bare samples initially gained weight and then lost weight. For example, Fig. 3 shows that after 6000 thermal cycles, the uncoated 262 HRC 38 samples were at the original weight. This occurred after they had first gained approximately 0.1% weight after 3000 cycles. On the other hand the coated 262 HRC 38 samples steadily lost weight to the 0.1% level at 6000 cycles. Similar behavior was noted for the 264 alloy (Fig. 4). The 754 alloy showed the reversed to be true (see Fig. 7).

Both the 265 and 266 alloys (Figs. 5 and 6, respectively) show a slow and very small weigh: loss for the coated specimens and sporadic, moderate weight losses for the uncoated specimens.

Since all weight losses (or gains) were small compared to that shown in previous thermal fatigue tests, the comparisons above should be made only with the overall thermal cycling data taken into consideration (i.e., thermal crack growth).

3.2 Thermal Fatigue Resistance

Accumulated thermal cycles to first crack initiation for the ODS specimens are summarized in Table 6. In this table, the cycles to first crack initiation on both the 0.64 mm small radius and on the 1.02 mm large radius are included for comparison. Generally, cracking of the large radius is of lesser importance, particularly if preceded by cracking of the small radius . The emergence of thermal cracks on the small radius influences the stress distribution in the specimen. This can increase the cycle time to initiation of cracks on the large radius.

Cycles to first crack in Table 6 is based on the mean between the last inspection period without a crack and the inspection period when a crack was first visible. For example, if no cracks were observed at 100 cycles but became visible at 200 cycles, origination of the first crack is considered to be 150 cycles. Accordingly, thermal fatigue data in Table 6 have an inherent potential error varying from ±12 cycles to ±150 cycles for exposure less than 1000 cycles. The error is ±250 cycles for exposures above 1000 cycles, based on the inspection periods described previously.

Table 7 contains optically measured crack lengths for the three longest cracks on each ODS specimen as a function of accumulated cycles. Crack lengths shown are measured on both top and bottom surfaces and averaged to obtain the mean crack length. Each of the cracks is located from the bottom (numbered end) of the test specimen. Also identified in these tables is the total number of observable cracks on both the small (0.64 mm) and large (1.02 mm) radii.

Figures 9 through 11 show the as-received appearance of typical experimental oxide-dispersion strengthened alloys. Figure 12 shows the appearance of typical materials after thermal cycling. In all photographs, the small radius is at the right.

Fatigue data in Tables 6 and 7 indicate that the lowest fatigue resistance was exhibited by the 956 bare and coated alloy, with cracking of the small radius occurring prior to the accumulation of 50 thermal cycles. The highest thermal fatigue cracking resistance appeared to be for the 265 HRC 39 and the 266 HRC 37 alloys, since none of these alloys exhibited cracking during the tests in either the bare or coated conditions. Following closely after these alloys was 266 HRC 40 with no cracking observed to 6000 cycles when coated, and to 4250 cycles in the bare condition.

Ranking the uncoated alloys in terms of small radius crack initiation results in the following order of increasing fatigue resistance: 956, 264 HRC 40, 262 HRC 38 (with one exception), 264 HRC 43, 754, 264 HRC 38, 266 HRC 40, 265 HRC 39, and 266 HRC 37.

4. SUMMARY OF RESULTS

Thermal fatigue crack propagation and oxidation data on the 24 ODS test specimens at 1130°/357°C indicate the following conclusions:

1) The oxidation resistance for all of the ODS alloys tested was very high. The poorest oxidation resistance was obtained for alloys 265 HRC 39 and 266 HRC 37; however, this oxidation was still relatively small compared to other alloys previously studied.

2) The highest resistance to thermal fatigue cracking for materials in the bare condition was exhibited by 265 HRC 39 and 266 HRC 37 which survived 6000 cycles without cracking.

3) The highest resistance to thermal fatigue cracking for coated materials was exhibited by alloys 262 HRC 38, 266 HRC 37, and 266 HRC 40 which survived 6000 cycles without cracking. Also coated alloys 265 HRC 39 and 754 had not cracked after a limit of 3000 cycles was imposed. One coated sample each of the 262 HRC 38 and 264 HRC 43 alloys survived 5250 cycles before crack initiation.

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Table 1

COMPOSITION AND HEAT TREATMENT

Alloy	Heat No.	Analyzed Composition, wt. % Al	C	Cr	Fe	Ni	Ta	Ti	S	N	Y_2O_3	Total O (ppm)	Heat Treatment
ODS NiCrAl	262*	4.61	.05	15.78	.28	Bal	< .01		< .002	.032	1.93	5345	slow heat treat[a]
ODS NiCrAl	264*	4.61	.05	15.65	.64	Bal	< .01		< .002	.032	1.93	5507	fast heat treat[b]
ODS NiCrAlTa	265*	4.69	.05	15.80	.24	Bal	1.76		< .002	.032	1.90	5165	slow heat treat[a]
ODS NiCrAlTa	266*	4.77	.05	15.90	.23	Bal	1.25		< .002	.031	1.93	5270	slow heat treat[a]
MA 754	DT0065B	.30	.07	20.24	1.34	Bal		.44			.59		vendor heat treat
MA 956	DH0001F3	9.09	.02	20.60	Bal			.32	.017		.76		vendor heat treat

[a] slow heat treat: into furnace set at 1204°C (2200°F); raise temp to 1260°C (2300°F) in 4 hrs; hold 1 hr, raise temp to 1316°C (2400°C) in 2 hrs; hold 1 hr; air cool.

[b] fast heat treat: into furnace set at 1204°C (2200°F); raise temp to 1343°C (2450°F) in 2 hrs; hold 1 hr; air cool.

*Heat of material produced by Stellite Division of Cabot Corporation under NASA Contract NAS3-17806. Additional informationmay be found in NASA CR-134901.

Table 2

TENSILE PROPERTIES OF TEST MATERIALS AT 760°C (1400°F)

	TENSILE PROPERTIES					
	Proportional Limit		Ultimate Tensile Strength			
Alloy/Heat	MN/m^2	ksi	MN/m^2	ksi	Reduction of Area, %	Ductility[a]
262 HRC 38	729.5	105.8	777.7	112.8	17.1	.188
264 HRC 38	734.3	106.5	775.7	112.5	16.8	.184
264 HRC 40	739.1	107.2	770.8	111.8	17.0	.186
264 HRC 43	718.4	104.2	768.8	111.5	18.8	.209
265 HRC 39	794.3	115.2	835.6	121.2	10.6	.112
266 HRC 37	817.0	118.5	854.9	124.0	11.3	.120
266 HRC 40	803.2	116.5	834.3	121.0	7.7	.080
MA 754	317.2	46.0	366.8	53.2	68.4	1.151
MA956	144.8	21.0	151.7	22.0	>98	--

All results are average of duplicate tests except for 266 HRC 40 which is a single test.

Crosshead speed = 2.5 mm (0.1 in.)/min.

[a] Ductility = $\ln\left(\frac{100}{100 - \text{Reduction of Area in Percent}}\right)$

TABLE 3
SUMMARY OF 982°C (1800°F) STRESS-RUPTURE PROPERTIES

	Stress-Rupture Properties				
	Stress				
Alloy/Heat	MN/m^2	ksi	Time to Rupture, hrs	Reduction of Area, %	Ductivity[a]
262 HRC 38	103	15.0	2.8	25.2	.290
	100	14.5	9.6,35.6	19.4	.218
	97	14.0	52.3	17.1	.188
	93	13.5	78.1,375.0	13.3	.143
264 HRC 38	100	14.5	179.7,250.3	16.4	.179
264 HRC 40	100	14.5	32.5	27.1	.316
	97	14.0	342.7	20.3	.227
264 HRC 43	103	15.0	38.1	16.7	.183
	100	14.5	123.8	22.4	.254
265 HRC 39	103	15.0	67.8,262.1	13.3	.143
266 HRC 37	103	15.0	59.5	8.4	.088
	100	14.5	136.6,200.6	10.5	.112
266 HRC 40	100	14.5	201.0	16.1	.175
MA 754	110	16.0	>5757, >5613		
	124	18.0	>4211		
MA 956	90	13.0	0.1	61.5	.955
	83	12.0	0.6	50.3	.700
	76	11.0	3.0	44.6	.590

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[a] Ductility = $\ln\left(\frac{100}{100 - \text{Reduction of Area in Percent}}\right)$

Table 4

DIMENSIONS AND IDENTIFICATION OF TEST SPECIMENS

Alloy	Specimen Identification	Measured Radius, mm		Initial Dimension, mm			Total Test Cycles	Final Dimension, mm		
		Small	Large	Length	Width	Thickness		Length	Width	Thickness
262 HRC 38	11	0.69	.89/.81	102.46	31.55	6.43	6000	102.57	31.93	6.50
262 HRC 38	8	0.66	.79/.89	102.43	31.55	6.69	4500	102.62	31.75	6.51
262 HRC 38	6	.38/.58	.74/.81	102.44	31.55	6.44	3000	102.49	31.60	6.48
262 HRC 38 coated	7	0.69	.97/.99	102.39	31.80	6.72	6000	102.49	31.88	6.75
262 HRC 38 coated	3	0.71	0.94	102.39	31.72	6.69	4500	102.39	31.88	6.72
264 HRC 38	3	.51/.48	.81/.89	102.39	31.50	6.47	6000	102.49	31.88	6.56
264 HRC 38 coated	4	.64/.69	.94/.89	102.41	31.78	6.71	6000	102.41	31.85	6.75
264 HRC 40	2	0.64	.74/.71	102.41	31.52	6.46	3000	102.59	31.83	6.55
264 HRC 40 coated	1	0.71	.84/.91	102.41	31.80	6.69	6000	102.38	31.93	6.72
264 HRC 43	2	0.66	.76/.79	102.36	31.55	5.51	3000	102.57	31.83	5.58
264 HRC 43 coated	4	0.66	.84/.66	102.49	31.81	5.76	6000	102.69	31.93	6.44
265 HRC 39	6	0.61	1.14	102.36	31.55	6.41	6000	102.57	31.65	6.39
265 HRC 39 coated	1	.66/.74	0.89	102.54	31.95	6.27	3000	102.41	31.93	6.40
265 HRC 39 coated	2	.64/.86	.94/.46	102.46	31.78	6.33	3000	102.44	31.83	6.36
266 HRC 37	1	0.71	.79/.94	102.39	31.52	6.51	6000	102.54	31.67	6.63
266 HRC 37 coated	3	0.66	1.09	102.74	31.80	6.72	6000	102.49	31.88	6.74
266 HRC 40	2	0.64	.74/.71	102.26	31.55	6.34	6000	102.41	31.80	6.42
266 HRC 40 coated	1	0.74	.97/.71	102.44	31.76	6.62	6000	102.23	31.93	6.64
754	8	0.69	.84/.79	102.41	31.24	6.48	6000	102.67	31.55	6.55
754	3	0.66	00[a]	102.41	31.32	6.49	3000	102.57	31.39	6.53
754 coated	1	.58/.69	.86/.89	102.51	31.60	6.59	2500	102.49	--[b]	--[b]
754 coated	2	0.74	.71/.86	102.64	31.62	6.49	3000	102.44	31.83	6.36
956	1	0.70	.91/.89	102.13	31.39	5.54	1500	102.13	31.39	5.54
956 coated	4	0.53	.86/.81	102.11	31.67	6.72	1500	102.08	31.65	6.74

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[a] The radius was comprised of two curved segments, separated by a flat segment (curved segment radii were 0.61 and 0.56 mm).

[b] Coating peeled off specimen (see Fig. 12(h)).

Table 5

WEIGHT CHANGE DATA FOR ODS SPECIMENS

Material	Sample Identification	Starting Weight, g	Weight Change at Given Cycles, %															
			100	200	300	500	700	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000
262 HRC 38	11	119.8454	.013	.014	.014	.017	.022	.031	.054	.092	.136	.138	.118	.032	0	.003	.007	.011
262 HRC 38 (coated)	7	124.4353	.001	.001	.002	.002	.005	.003	-.002	-.013	-.036	-.092	-.099	-.088	-.105	-.108	-.111	-.114
262 HRC 38	8	119.7063	-	-	-	.021	-	.036	.067	.067	.086	.078	.075	.074	.075			
262 HRC 38 (coated	3	125.9527	-	-	-	.001	-	0	-.016	-.019	-.022	-.032	-.040	-.046	-.049			
262 HRC 38	6	120.1453	-	-	-	.014	-	.017	.013	.009	-.010	-.011						
264 HRC 38	3	120.2908	.019	.017	.018	.026	.034	.046	.063	.088	.118	.140	.130	.106	.080	.076	.080	.064
264 HRC 38 (coated)	4	124.4566	.001	.002	.002	.002	.002	.001	-.002	-.004	-.003	-.026	-.032	-.027	-.039	-.040	-.042	-.042
264 HRC 40	2	120.3697	.016	.015	.016	.020	.028	.039	.063	.094	.130	.155	-	-	-	-	-	-
264 HRC 40 (coated)	1	125.3003	.004	.004	.004	.003	.005	.004	-.001	-.005	-.011	-.046	-.075	-.067	-.077	-.078	-.080	-.084
264 HRC 43	2	109.3924	.016	.016	.017	.021	.028	.039	.051	.088	.125	.164	-	-	-	-	-	-
264 HRC 43 (coated)	4	115.7103	.002	.001	.002	.001	.002	-.001	-.007	-.026	-.045	-.079	-.088	-.090	-.093	-.093	-.094	-.107
265 HRC 39	6	119.7075	.016	.012	.012	.015	.020	.031	.059	.100	.106	-.241	-.68	-.75	-.77	-.77	-.77	-.78
265 HRC 39 (coated)	1	122.8130	.002	.002	.003	.003	.004	.004	.002	-.006	-.003	-.006	-	-	-	-	-	-
265 HRC 39 (coated)	2	121.6602	-	-	-	.001	-	.005	.005	.001	-.001	-.011						
266 HRC 37	1	118.6671	.014	.012	.011	.003	-.003	.005	.012	-.057	-.129	-.52	-.56	-.63	-.65	-.65	-.65	-.65
266 HRC 37 (coated	3	123.8250	0	0	0	.001	.002	.002	-.001	-.003	-.003	-.014	-.024	-.037	-.046	-.048	-.049	-.087
266 HRC 40	2	119.6235	.013	.012	.012	.012	.014	.019	.036	.062	.093	-.010	-.035	-.089	-.111	-.110	-.106	-.108
266 HRC 40 (coated)	1	124.5271	0	0	0	.001	.002	.001	0	-.007	-.009	-.026	-.032	-.041	-.054	-.069	-.071	-.090
754	8	126.3525	.002	-.009	-.018	-.034	-.051	-.069	-.087	-.101	-.116	-.143	-.153	-.150	-.168	-.171	-.175	-.180
754 (coated)	1	129.9261	0	0	0	0	0	.006	.006	.016	.021	-	-	-	-	-	-	-
754 (coated)	2	130.2482	-	-	-	.002	-	.003	-.001	-.003	-.006	-.014						
754	3	126.0427	-	-	-	.005	-	-.020	-.054	-.063	-.074	-.087						
956	1	98.9587	.025	.027	.033	.036	.044	.050	.047[a]	-	-	-	-	-	-	-	-	-
956 (coated)	4	113.2309	.007	.013	.018	.024	.030	.032	.039[a]	-	-	-	-	-	-	-	-	-

---

[a] Spalling of material from base of thermal fatigue cracks.

Table 6

ACCUMULATED THERMAL CYCLES TO FIRST CRACK INITIATION FOR ODS SPECIMENS

Alloy	Condition	Specimen Identification	Cycles to First Crack	
			Small Radius 0.64 mm (0.025 in.)	Large Radius 1.02 mm (0.040 in.)
262 HRC 38	Bare	11	1750	--
	Bare	8	1250	--
	Bare	6	>3000[a]	>3000[a]
	Coated	7	>6000	>6000
	Coated	3	5250	--
264 HRC 38	Bare	3	3750	--
	Coated	4	1750	4750
264 HRC 40	Bare	2	850	--
	Coated	1	1750	5750
264 HRC 43	Bare	2	1750	--
	Coated	4	5250	--
265 HRC 39	Bare	6	>6000	>6000
	Coated	1	>3000[a]	>3000[a]
	Coated	2	>3000[a]	>3000[a]
266 HRC 37	Bare	1	>6000	>6000
	Coated	3	>6000	>6000
266 HRC 40	Bare	2	4250	--
	Coated	1	>6000	>6000
754	Bare	8	1750	--
	Bare	3	>3000[a]	>3000[a]
	Coated	1	>3000[a]	>3000[a]
	Coated	2	>3000[a]	>3000[a]
956	Bare	1	12	400
	Coated	4	37	75

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[a] Did not develop cracks during 3000 applied cycles (most of these samples were added after others had been removed).

Table 7

SUMMARY OF CRACK PROPAGATION FOR ODS SPECIMENS

Edge Radius, mm	Cycles	Crack Length, mm									Total Cracks Observed
		1st Crack			2nd Crack			3rd Crack			
		Front	Back	Avg	Front	Back	Avg	Front	Back	Avg	
		Specimen 262-11 HRC 38									
Distance from bottom, mm:				69.9			31.8			60.3	
.69	1500	No cracks									0
	2000	2.0	2.3	2.2							1
	2500	5.1	5.3	5.2							1
	3000	6.4	5.8	6.1	1.0	1.0	1.0				2
	3500	6.4	6.4	6.4	1.0	1.0	1.0				2
	4000	7.6	7.4	7.5	2.8	1.8	2.3	1.3	.76	1.0	6
	4500	7.6	7.9	7.8	2.8	3.3	3.1	1.3	1.3	1.3	6
	5000	7.6	8.1	7.9	4.3	4.1	4.2	1.3	1.8	1.6	13
	5500	7.6	8.1	7.9	5.6	5.6	5.6	1.8	1.8	1.8	13
	6000	8.1	8.1	8.1	6.1	6.9	6.5	3.1	2.8	3.0	14
		Specimen 262-8 HRC 38									
Distance from bottom, mm:				41.3			50.8			55.5	
.66	1000	No cracks									0
	1500	.76	.25	.51	.76	.51	.64	.25	.76	.51	3
	2000	.76	.25	.51	.76	.76	.76	.25	1.0	.63	4
	2500	1.5	.25	.88	1.3	.76	1.0	1.5	1.0	1.3	11
	3000	1.5	.51	1.0	1.3	.76	1.0	1.5	1.0	1.3	11
	3500	2.3	1.8	2.1	1.3	1.0	1.2	2.5	2.8	2.7	11
	4000	3.8	2.5	3.1	1.3	1.0	1.2	4.3	3.6	4.0	14
	4500	4.6	4.3	4.5	1.3	1.0	1.2	4.6	4.1	4.4	14

Table 7 (cont.)

Edge Radius, mm	Cycles	Crack Length, mm									Total Cracks Observed
		1st Crack			2nd Crack			3rd Crack			
		Front	Back	Avg	Front	Back	Avg	Front	Back	Avg	
		Specimen 264-3 HRC 38 (coated)									
Distance from bottom, mm:				60.3			41.3			27.0	
.48/.51	3500	No cracks									0
	4000	.76	.76	.76							1
	4500	1.5	1.0	1.3	1.5	1.5	1.5	2.0	1.5	1.8	4
	5000	1.8	1.5	1.7	2.3	2.0	2.2	2.5	2.3	2.4	7
	5500	2.0	1.5	1.8	2.5	3.1	2.8	3.8	2.8	3.3	7
	6000	2.0	1.5	1.8	3.6	3.6	3.6	4.6	5.1	4.9	12
		Specimen 264-4 HRC 38 (coated)									
Distance from bottom, mm:				47.6			38.1			68.2	
.64/.69	1500	No cracks									0
	2000	1.0	1.0	1.0							1
	2500	3.8	4.1	4.0	1.8	2.5	2.3	4.6	5.1	4.8	4
	3000	6.1	6.9	6.6	4.6	5.1	4.8	6.9	7.6	7.4	4
	3500	6.4	6.9	6.7	4.8	5.6	5.2	7.1	7.6	7.4	4
	4000	6.6	7.1	6.9	5.6	5.8	5.7	7.6	8.1	7.9	6
	4500	7.6	8.1	7.9	6.4	7.1	6.8	8.4	8.4	8.4	6
	5000	8.1	8.6	8.4	6.4	7.9	7.2	8.4	9.4	8.9	6
	5500	8.6	9.1	8.9	7.9	8.4	8.2	8.8	9.4	9.1	6
	6000	9.4	9.9	9.7	9.1	9.1	9.1	9.7	10.1	9.9	6
Distance from bottom, mm:				25.4			30.1			68.2	
.89/.94	4500	No cracks									0
	5000	.25	.25	.25	.25	-	.13	.76	.25	.51	3
	5500	.25	.25	.25	.25	-	.13	.76	.25	.51	9
	6000	.76	.25	.51	.25	.25	.25	.76	.25	.51	13

Table 7(cont.)

Edge Radius, mm	Cycles	Crack Length, mm									Total Cracks Observed
		1st Crack			2nd Crack			3rd Crack			
		Front	Back	Avg	Front	Back	Avg	Front	Back	Avg	
		Specimen 264-2 HRC 40									
Distance from bottom, mm:				74.6			25.4			50.8	
.64	700	No cracks									0
	1000	2.3	1.8	2.0							1
	1500	5.6	5.6	5.6	3.6	3.1	3.3	1.5	2.0	1.8	4
	2000	7.6	5.8	6.7	5.8	5.1	5.5	4.8	4.3	4.6	5
	2500	8.6	7.1	7.9	7.1	6.1	6.6	6.4	5.8	6.1	6
	3000	9.4	7.6	8.6	7.9	6.9	7.4	8.1	6.9	7.5	6
	Removed at 3000 cycles										
		Specimen 264-1 HRC 40 (coated)									
Distance from bottom, mm:				60.3			46.0			42.8	
.71	1500	No cracks									0
	2000	.25	1.5	1.0							1
	2500	.25	2.0	1.3	.25	1.5	1.0				2
	3000	.25	2.5	1.4	1.3	2.3	1.8	1.5	2.0	1.8	3
	3500	.25	2.8	1.6	2.0	2.3	2.2	2.0	2.0	2.0	4
	4000	.25	2.8	1.6	2.0	3.1	2.6	2.0	2.5	2.3	4
	4500	.25	2.8	1.6	2.0	3.1	2.6	2.3	5.1	3.7	4
	5000	.25	2.8	1.6	2.0	3.6	2.8	2.5	5.1	3.8	4
	5500	4.8	5.8	5.3	2.0	3.6	2.8	6.4	7.1	6.8	9
	6000	5.8	6.9	6.4	2.0	3.6	2.8	7.9	7.9	7.9	9
Distance from bottom, mm:				41.3			54.0			65.1	
.84/.91	5500	No cracks									0
	6000	.25	-	.13	.25	.51	.38	.25	.25	.25	5

Table 7 (cont.)

Edge Radius, mm	Cycles	Crack Length, mm									Total Cracks Observed
		1st Crack			2nd Crack			3rd Crack			
		Front	Back	Avg	Front	Back	Avg	Front	Back	Avg	
				Specimen 264-2 HRC 43							
Distance from bottom, mm:				28.6			50.8			71.4	
.66	1500	No cracks									0
	2000	4.6	3.8	4.2	5.6	4.8	5.2	5.6	4.8	5.3	4
	2500	6.9	6.1	6.5	6.9	6.4	6.6	7.6	6.6	7.1	7
	3000	8.1	7.9	8.0	7.9	7.9	7.9	8.4	7.9	8.1	7
	Removed at 3000 cycles										
				Specimen 754-8							
Distance from bottom, mm:				22.2			33.3			76.2	
.69	1500	No cracks									0
	2000	.25	.76	.51							1
	2500	1.0	1.0	1.0							1
	3000	3.6	3.6	3.6	2.3	2.0	2.2	1.3	1.3	1.3	4
	3500	3.6	3.8	3.7	2.3	2.0	2.2	2.0	2.0	2.0	5
	4000	4.3	3.8	4.1	3.1	3.1	3.1	3.6	2.8	3.2	5
	4500	4.6	3.8	4.2	3.8	3.8	3.8	4.3	3.8	4.1	7
	5000	4.6	3.8	4.2	3.8	3.8	3.8	4.8	3.8	4.3	7
	5500	5.8	4.6	5.2	3.8	4.6	4.2	5.6	5.1	5.4	8
	6000	5.8	4.6	5.2	4.1	4.6	4.4	6.1	5.3	5.7	9
				Specimen 956-1							
Distance from bottom, mm:				74.6			61.9			44.5	
.69	25	6.4	6.4	6.4							1
	50	6.4	6.4	6.4							1
	100	8.6	8.4	8.5	3.3	3.3	3.3	2.0	2.0	2.0	10
	200	8.9	8.4	8.6	6.6	6.1	6.4	5.1	5.3	5.2	12
	300	9.4	9.4	9.4	7.9	8.1	8.0	6.4	6.6	6.5	12
	500	9.7	9.4	9.6	8.4	8.4	8.4	6.4	7.1	6.9	13
	700	9.9	9.4	9.7	9.4	9.4	9.4	9.4	8.4	8.9	13
	1000	10.4	10.7	10.6	9.9	10.4	10.2	9.9	9.4	9.7	13
	1500	10.4	10.7	10.6	9.9	10.4	10.2	10.2	9.4	9.9	15
	Removed at 1500 cycles										

Table 7 (cont.)

Edge Radius, mm	Cycles	Crack Length, mm 1st Crack Front	 Back	 Avg	 2nd Crack Front	 Back	 Avg	 3rd Crack Front	 Back	 Avg	Total Cracks Observed
Distance from bottom, mm:				22.2			71.4			34.9	
.91/.89	300	No cracks									0
	500	2.5	2.8	2.6	.25	.25	.25				2
	700	3.8	6.9	5.3	3.1	6.9	5.1	3.8	6.6	5.2	5
	1000	4.6	7.6	6.1	4.3	7.6	6.0	4.3	7.6	6.0	6
	1500	4.6	7.9	6.4	4.3	9.4	6.9	4.3	8.9	6.6	7
	Removed at 1500 cycles										
Specimen 956-4 (coated)											
Distance from bottom, mm:				30.1			42.8			52.3	
.53	25	No cracks									0
	50	6.4	6.4	6.4	6.4	6.4	6.4	5.1	5.1	5.1	6
	100	7.9	6.9	7.4	7.6	6.9	7.3	6.6	5.6	6.1	7
	200	7.9	6.9	7.4	7.6	6.9	7.3	6.6	6.6	6.6	7
	300	8.9	8.9	8.9	8.4	8.4	8.4	7.4	6.9	7.1	7
	500	9.9	9.9	9.9	9.1	8.9	9.0	7.4	7.4	7.4	7
	700	9.9	10.2	10.1	9.4	8.9	9.1	8.4	7.6	8.1	7
	1000	10.4	10.4	10.4	9.7	9.7	9.7	8.4	8.1	8.3	7
	1500	10.7	10.7	10.7	9.9	10.2	10.1	8.9	8.4	8.6	7
	Removed at 1500 cycles										
Distance from bottom, mm:				69.9			60.3			52.3	
.86/.81	50	No cracks									0
	100	2.5	3.1	2.8							1
	200	5.6	5.3	5.4							1
	300	6.4	5.6	6.0	2.5	2.3	2.4	4.6	4.6	4.6	3
	500	6.6	5.8	6.2	3.1	3.1	3.1	5.8	5.6	5.7	6
	700	6.9	5.8	6.4	4.1	3.8	4.0	6.4	6.1	6.3	7
	1000	6.9	5.8	6.4	4.6	4.6	4.6	6.9	6.9	6.9	7
	1500	6.9	5.8	6.4	6.1	5.8	6.0	7.1	6.9	7.0	7
	Removed at 1500 cycles										

Table 7 (cont.)

Edge Radius, mm	Cycles	Crack Length, mm 1st Crack Front	 1st Crack Back	 1st Crack Avg	 2nd Crack Front	 2nd Crack Back	 2nd Crack Avg	 3rd Crack Front	 3rd Crack Back	 3rd Crack Avg	Total Cracks Observed
				Specimen 266-2 HRC 40							
Distance from bottom, mm:				27.0							
.71	4000	No cracks									0
	4500	1.3	1.3	1.3							1
	5000	1.3	1.3	1.3							1
	5500	1.5	1.5	1.5							1
	6000	3.3	3.1	3.2							1
				Specimen 262-3 HRC 38 (coated)							
Distance from bottom, mm:				73.0							
.71	5000	No cracks									0
	5500	1.5	1.3	1.4							1
	6000	1.5	1.3	1.4							1
				Specimen 264-4 HRC 43 (coated)							
Distance from bottom, mm:				38.1			50.8			57.2	
.66	5000	No cracks									0
	5500	-	.25	.13	-	.25	.13	.51	.25	.38	4
	6000	1.0	1.0	1.0	.51	.51	.51	1.0	.25	.63	7

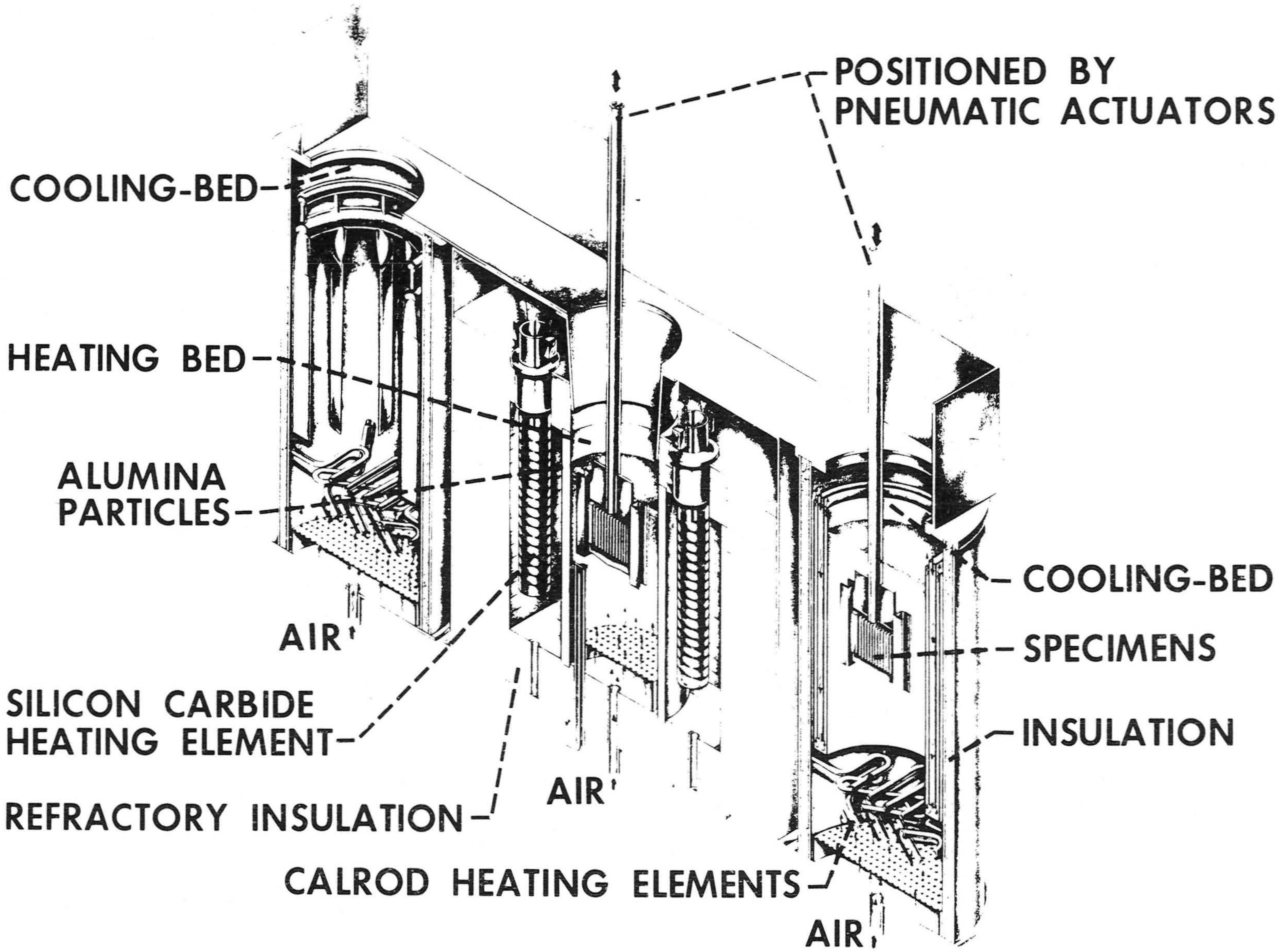
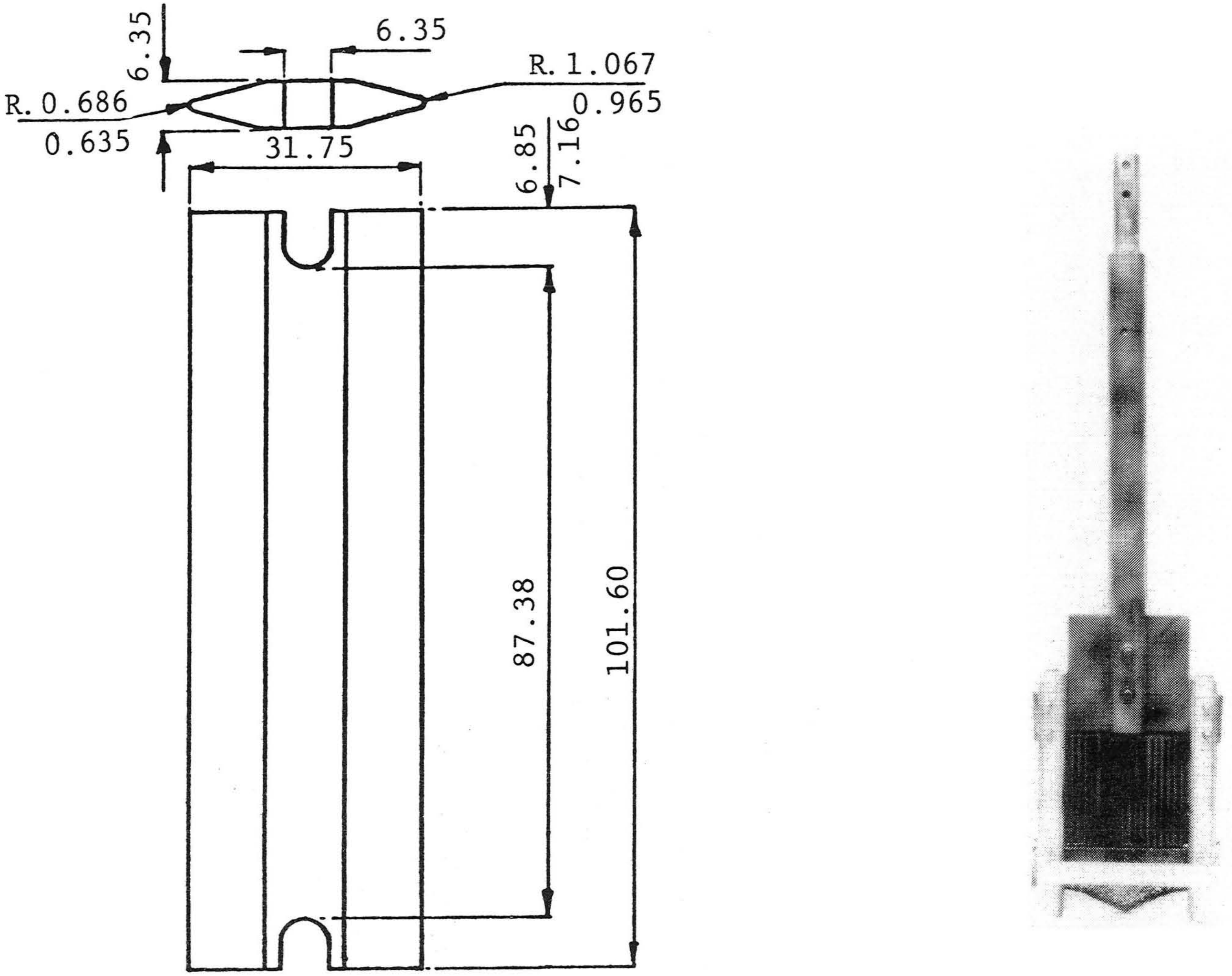


Figure 1
Fluidized Bed Thermal Fatigue Facility



Neg. No. 45935

X 1/12

(a) Double-edge wedge specimen
(dimensions in mm)

(b) Holding fixture

Figure 2

Double-Edge Wedge Test Specimen and Holding Fixture

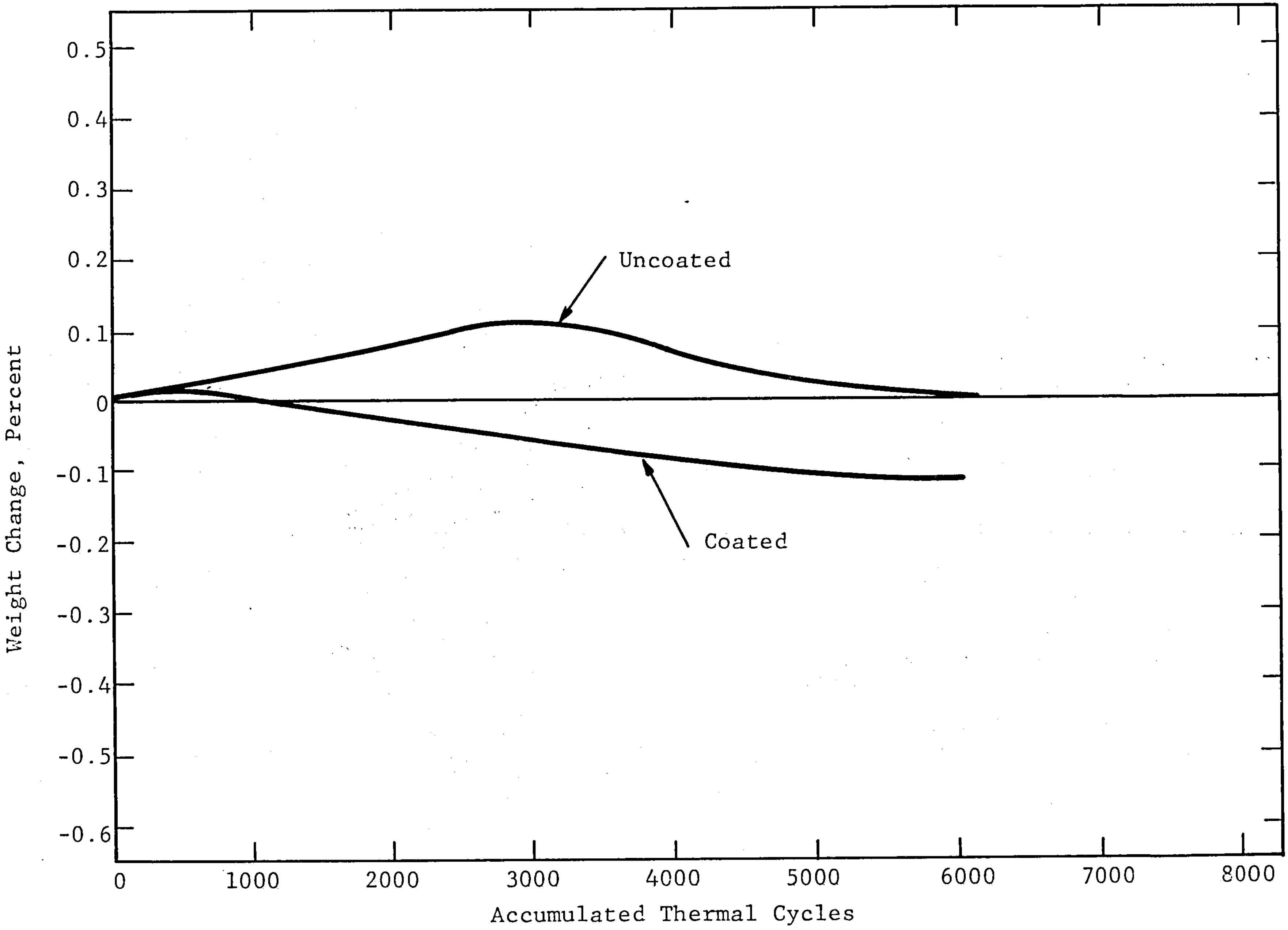


Figure 3

Percent Weight Change vs. Accumulated Cycles for Coated and Uncoated Alloy 262 (HRC 38)

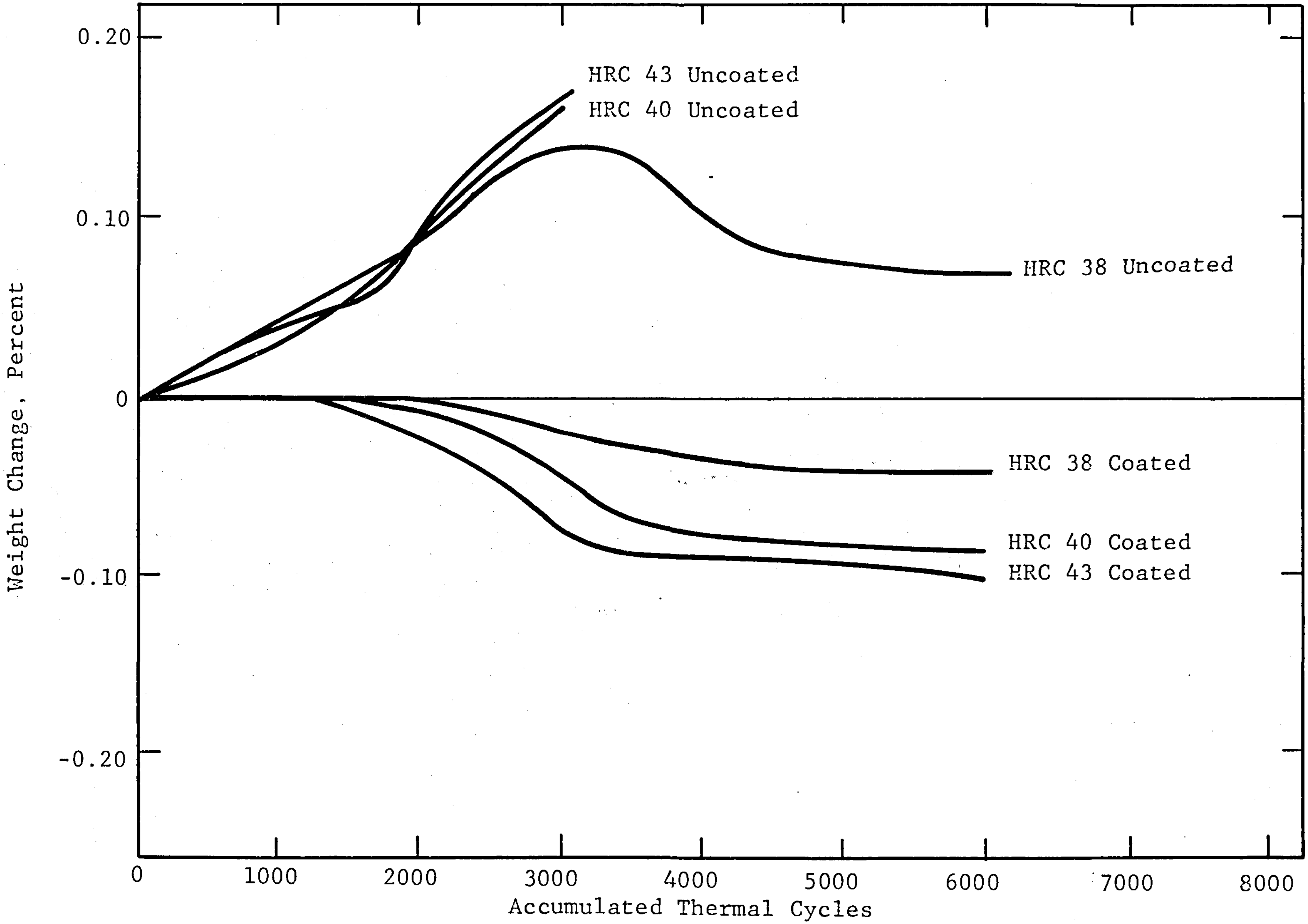


Figure 4

Percent Weight Change vs. Accumulated Cycles for Coated and Uncoated Alloy 264 at Various Hardnessess

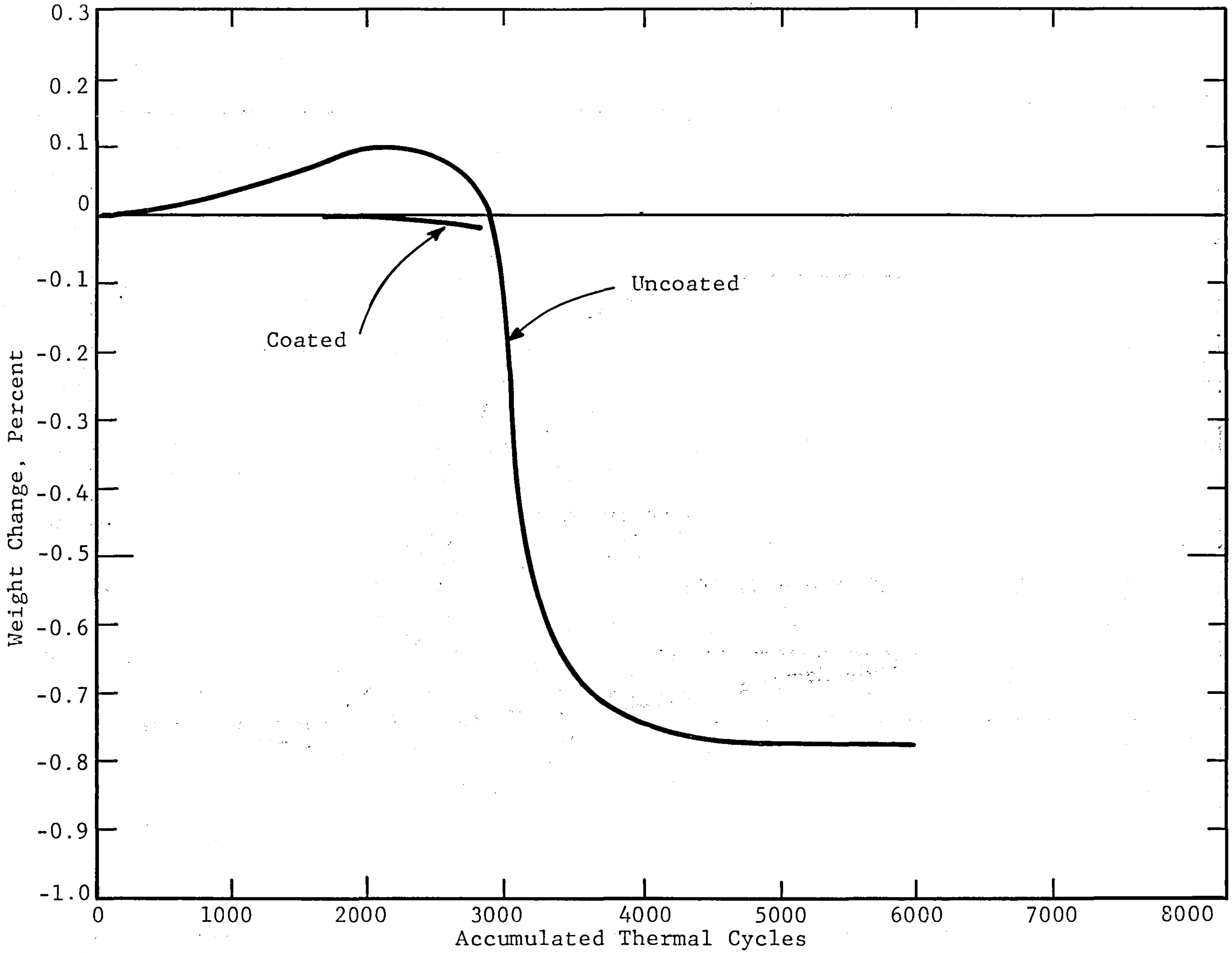


Figure 5

Percent Weight Change vs. Accumulated Cycles for Coated and Uncoated Alloy 265 (HRC 39)

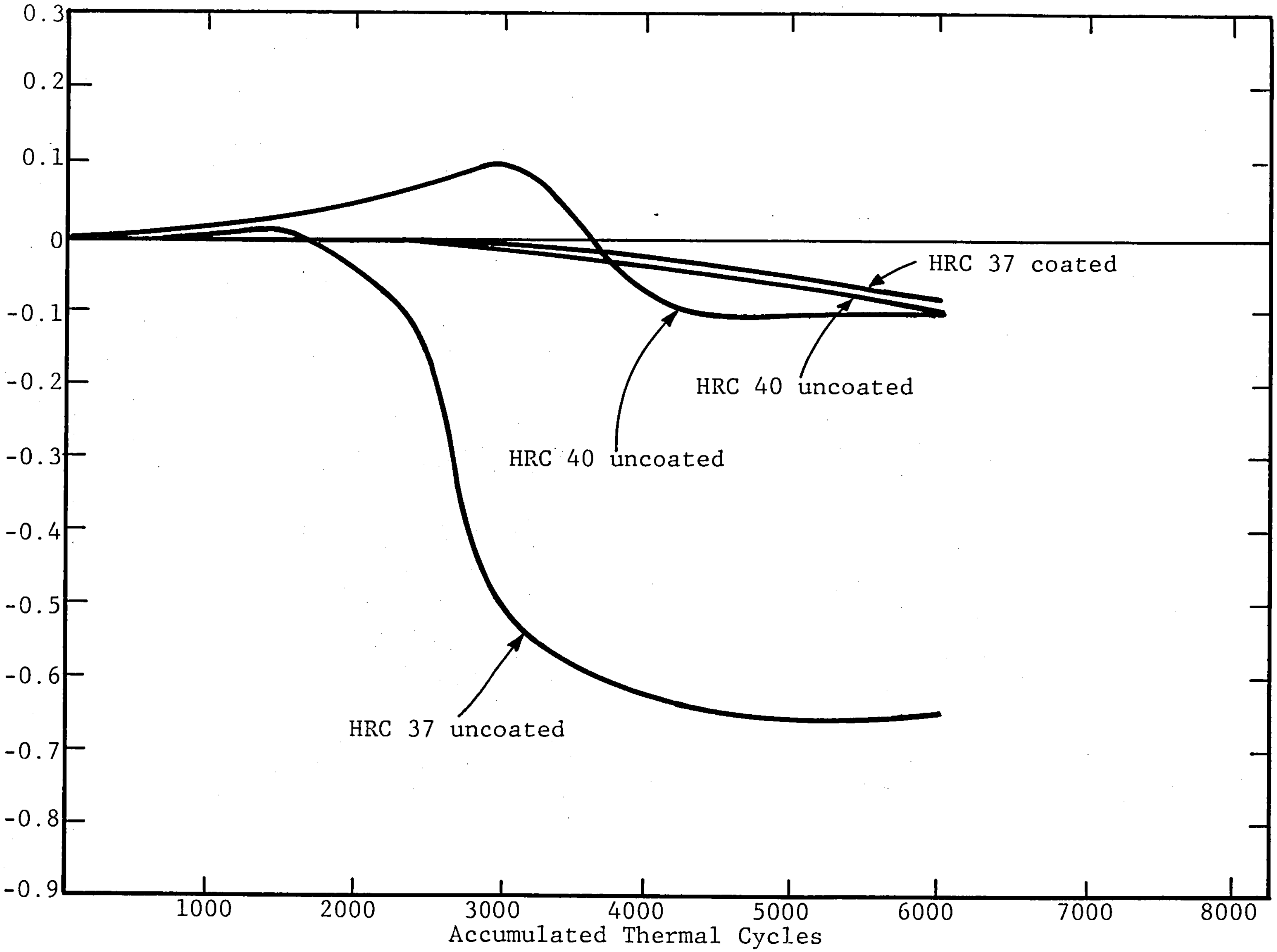


Figure 6

Percent Weight Change vs. Accumulated Cycles for Coated and Uncoated Alloy 266 at Various Hardnesses

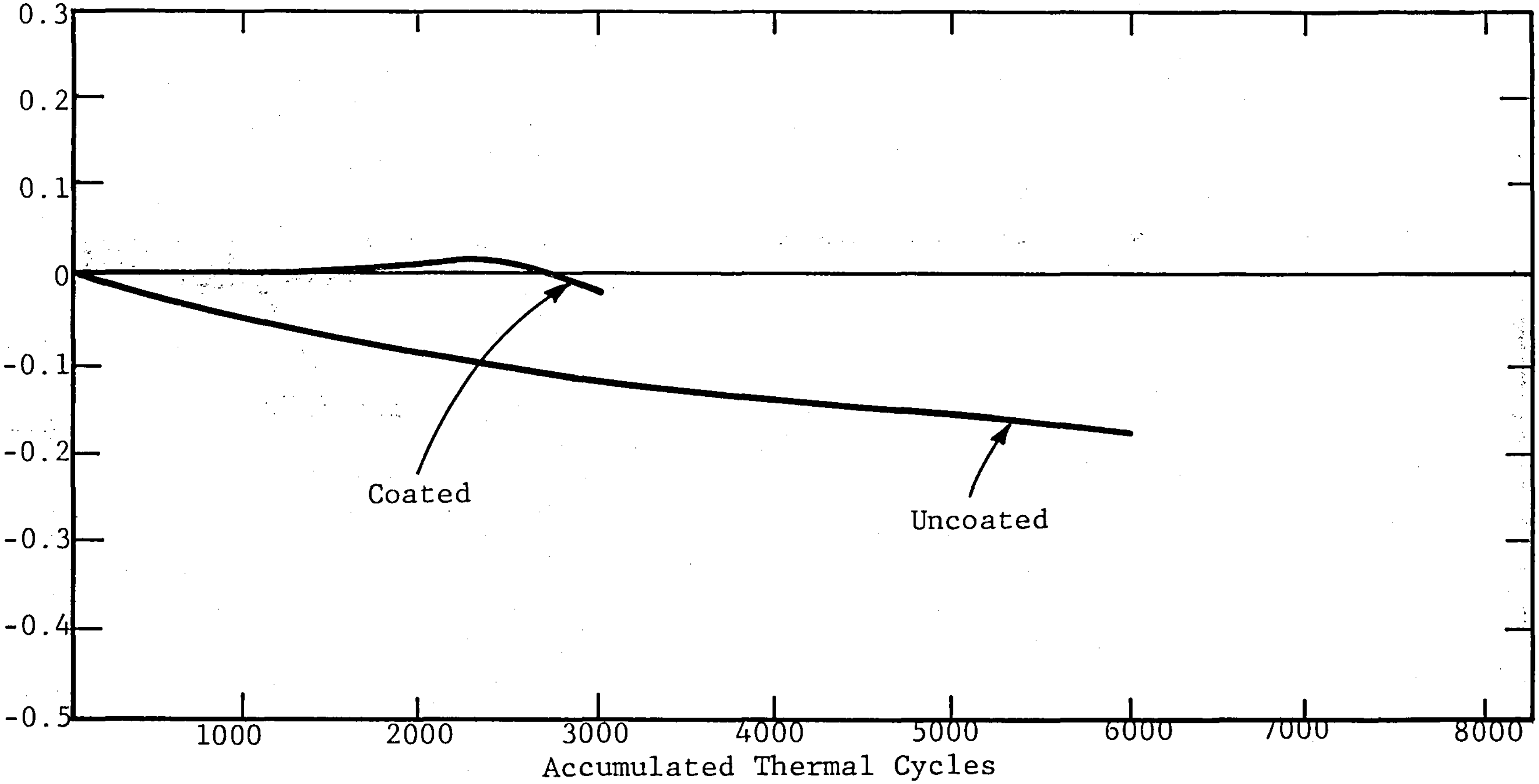


Figure 7

Percent Weight Change vs. Accumulated Cycles for Coated and Uncoated Alloy 754

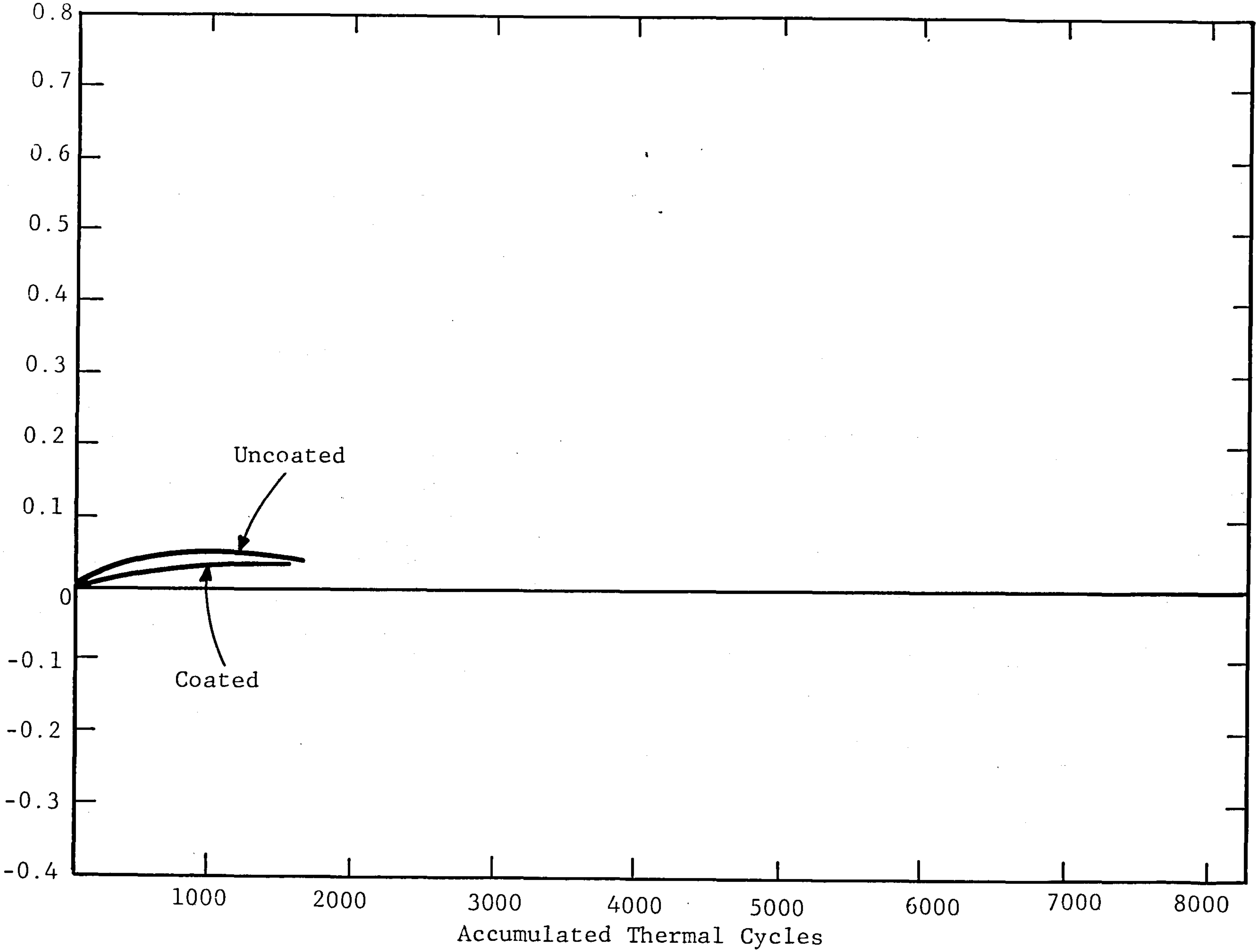
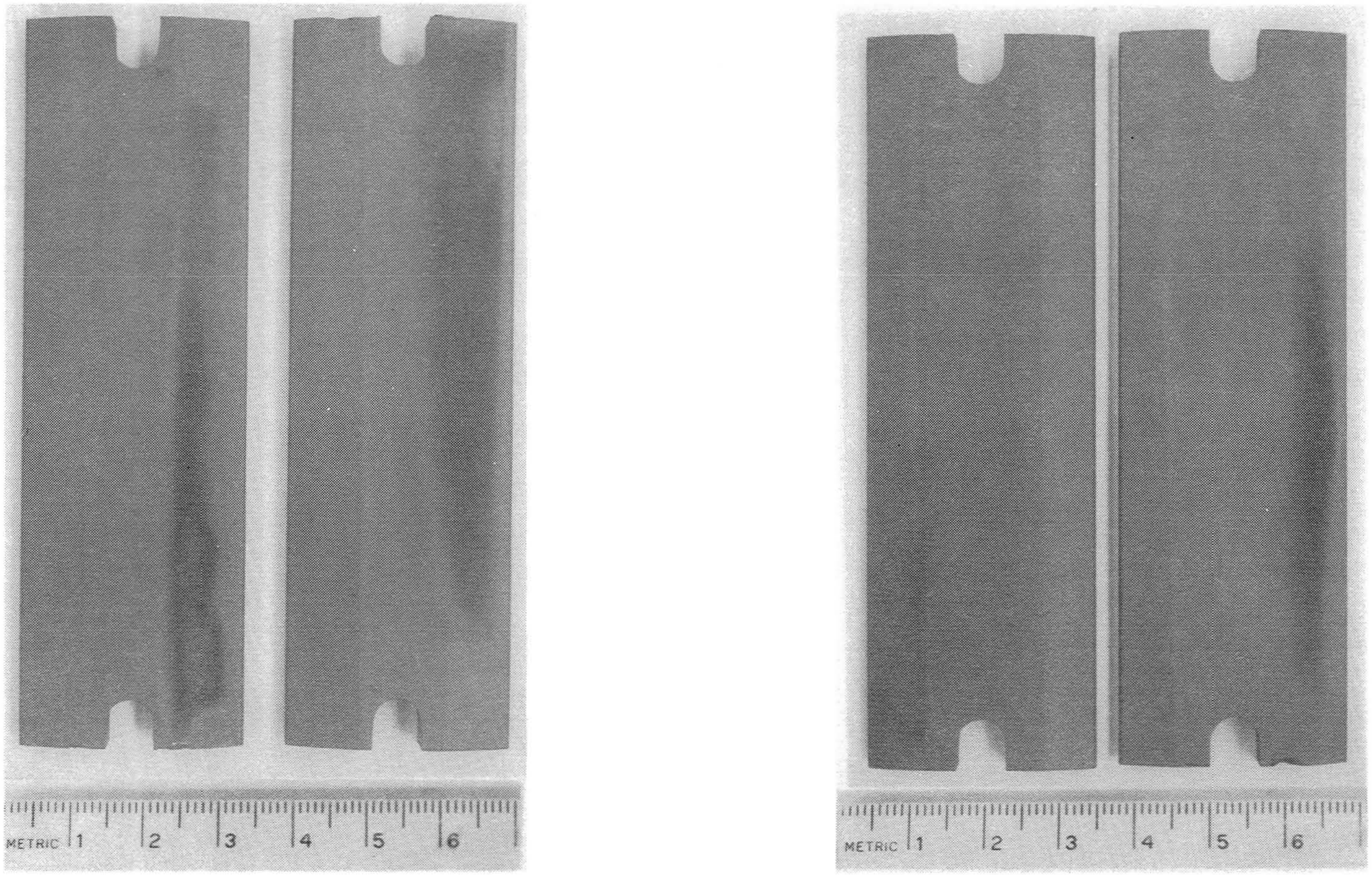


Figure 8

Percent Weight Change vs. Accumulated Cycles for Coated and Uncoated Alloys 956



Neg. No. 45556 1X

3 7

(a) Alloy 262

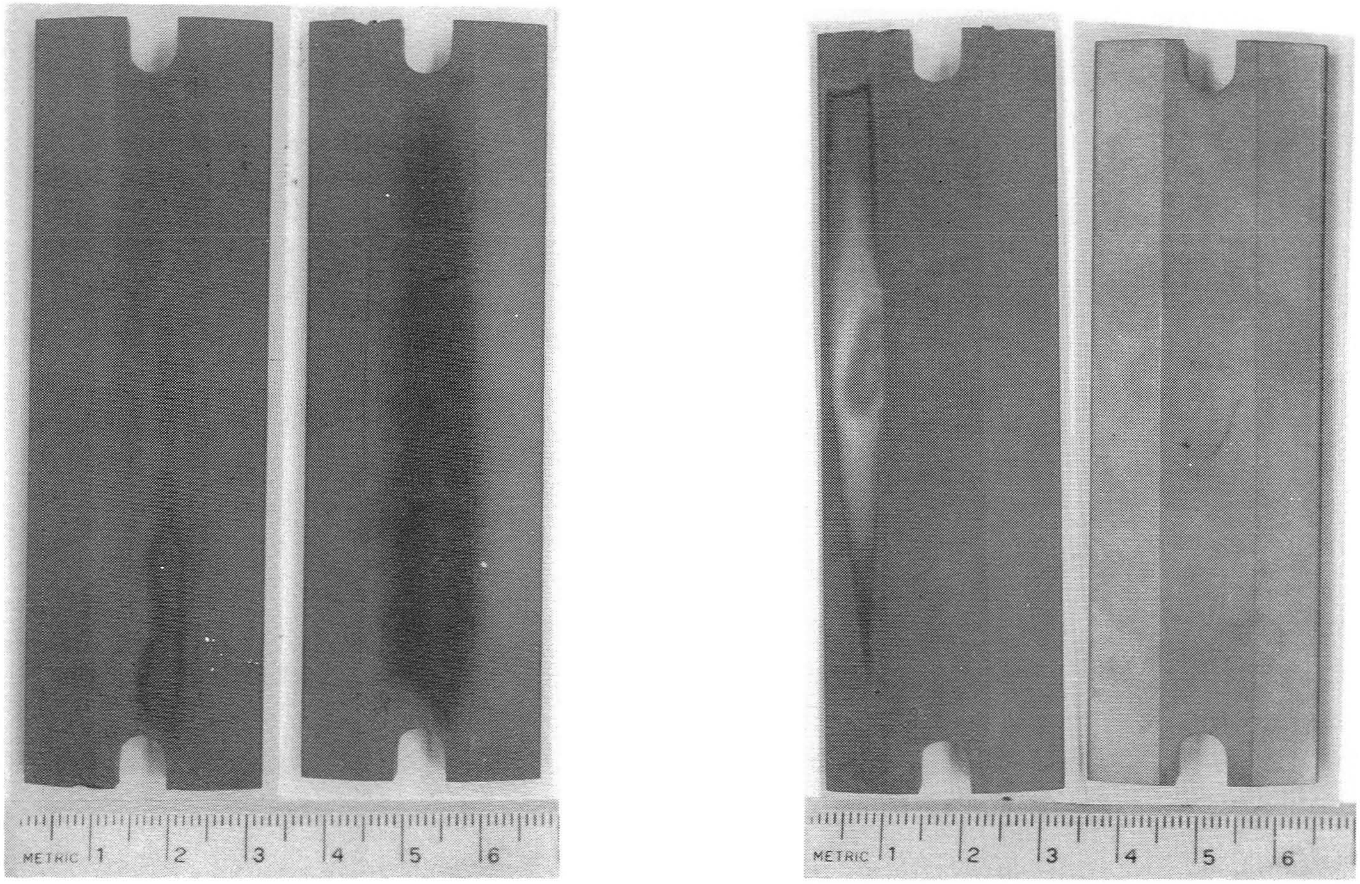
Neg. No. 45559 1X

1 4

(b) Alloy 264 HRC 43

Figure 9

Typical Appearance of Experimentally Fabricated 262 and 264 Alloy Double-Edge Wedge Specimens As-Received. (The small radius is at the right.)



Neg. Nos. 45560 & 49735 1X

1 2

(a) Alloy 265

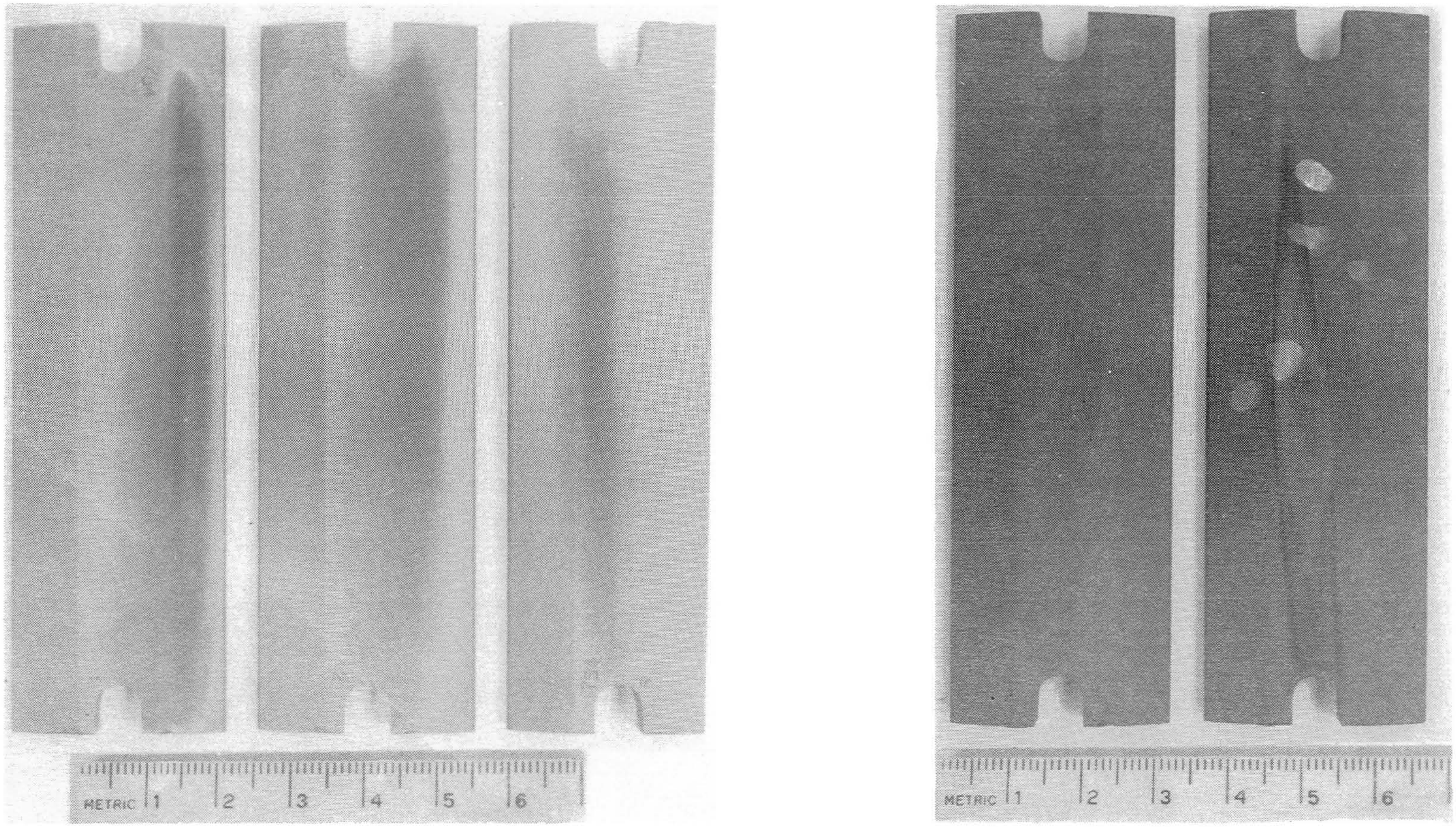
Neg. Nos. 45558 & 45583 1X

1 4

(b) Alloy 266 HRC 40 (left) and
Alloy 266 HRC 37 (right)

Figure 10

Typical Appearance of Experimentally Fabricated 265 and 266 Alloy Double-Edge Wedge Specimens As-Received



Neg. No. 45554 1X

1 2 6

(a) Alloy 754

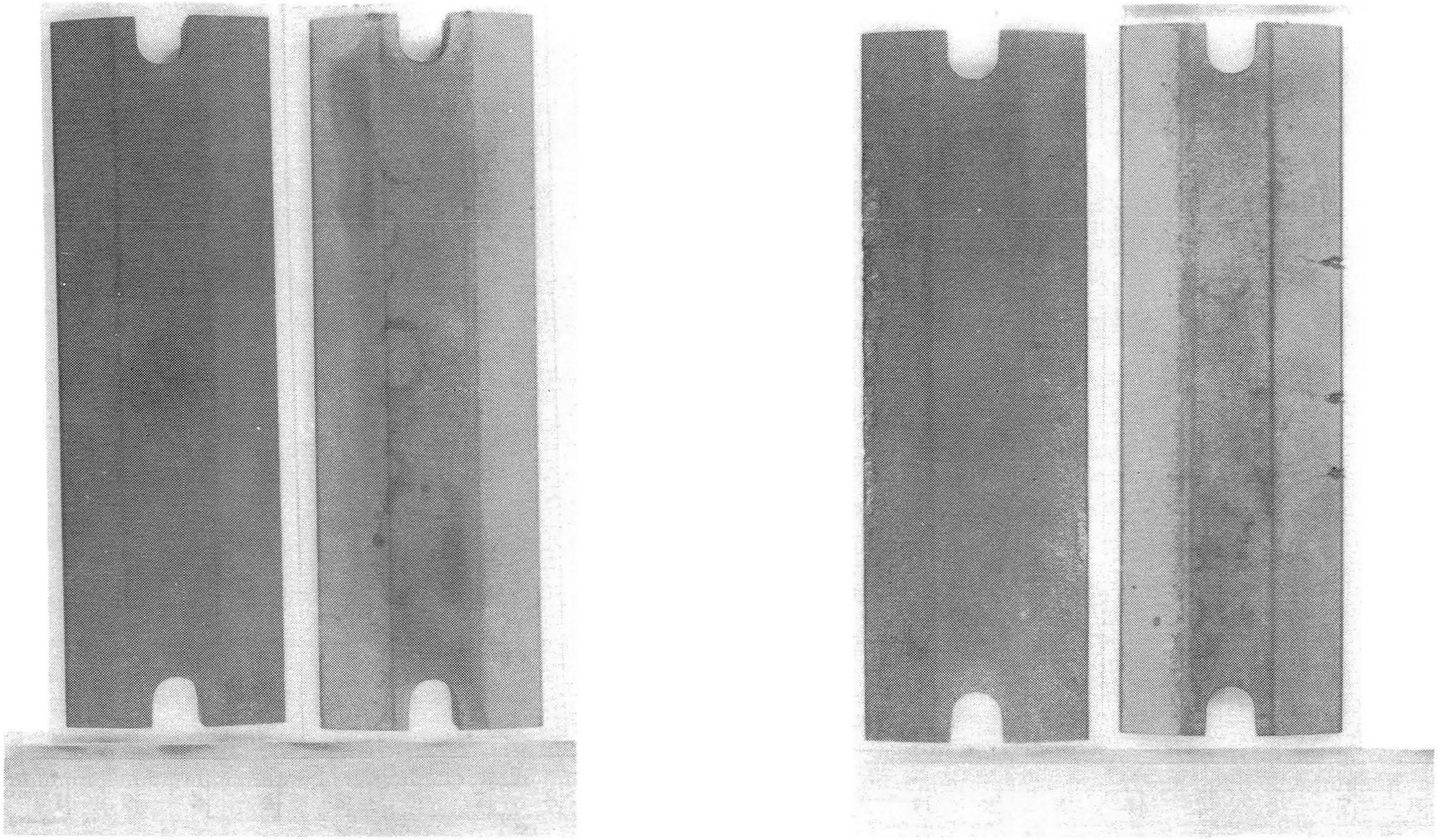
Neg. No. 45561 1X

4 6

(b) Alloy 956

Figure 11

Typical Appearance of Experimentally Fabricated 754 and 956 Alloy Double-Edge Wedge Specimens As-Received

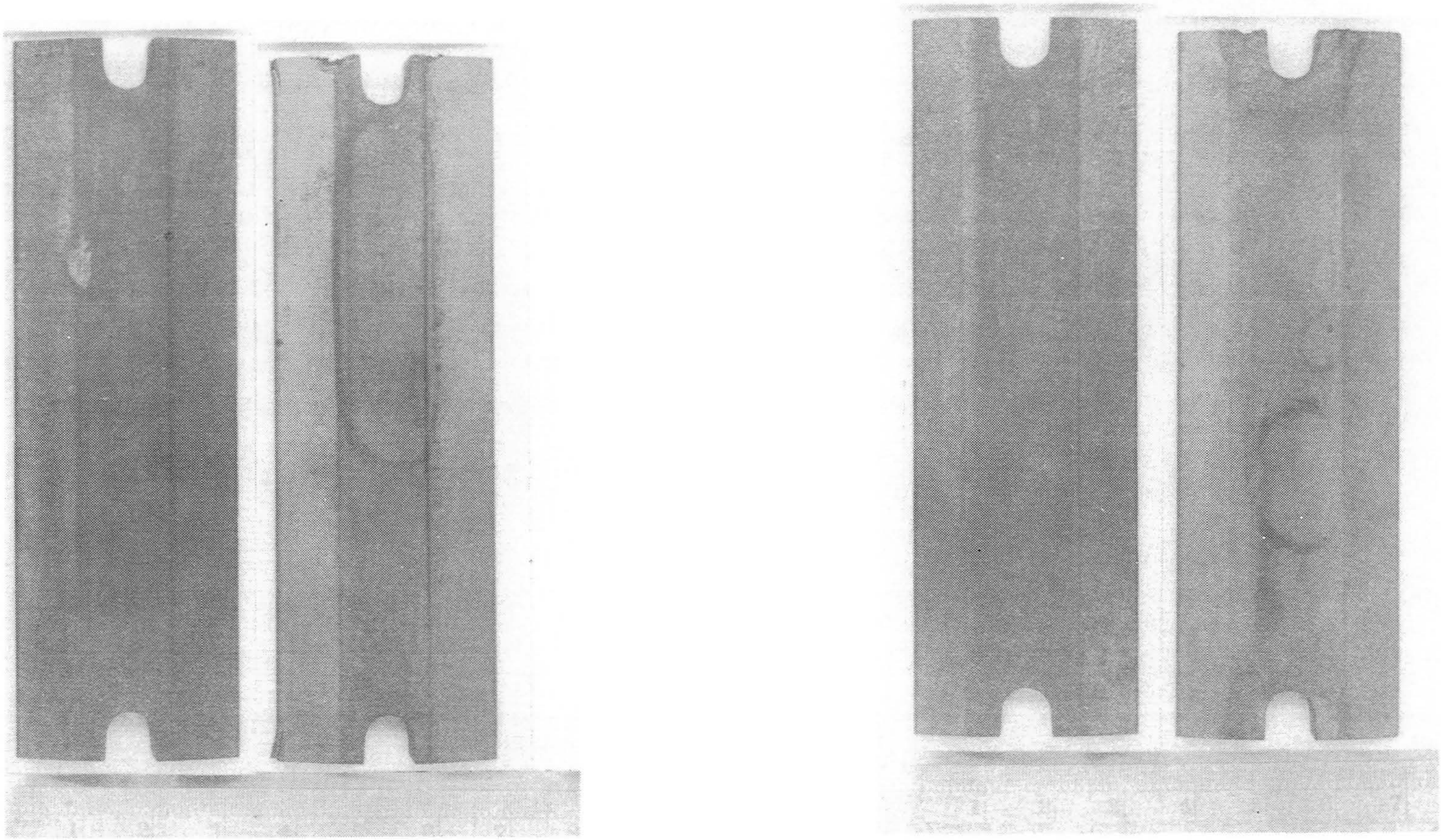


Neg. Nos. 51490 & 51492 1X
8 3
bare coated
(a) 262 HRC 38, 4,500 cycles

Neg. Nos. 51489 & 51491 1X
3 4
bare coated
(b) 264 HRC 38, 6,000 cycles

Figure 12

Appearance of Selected Specimens After Indicated Thermal Cycles
(The small radius is at the right)



Neg. Nos. 51495 & 51491 1X

bare,^{2} 3,000 cycles/coated,^{1} 6,000 cycles

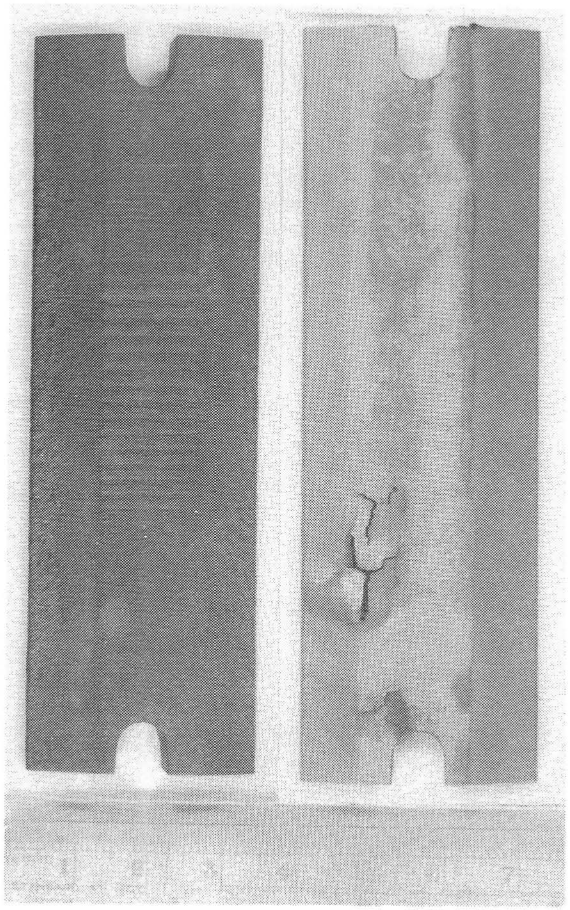
(c) 264 HRC 40

Neg. Nos. 51495 & 51492 1X

bare,^{2} 3,000 cycles/coated,^{4} 6,000 cycles

(d) 264 HRC 43

Figure 12 (Continued)

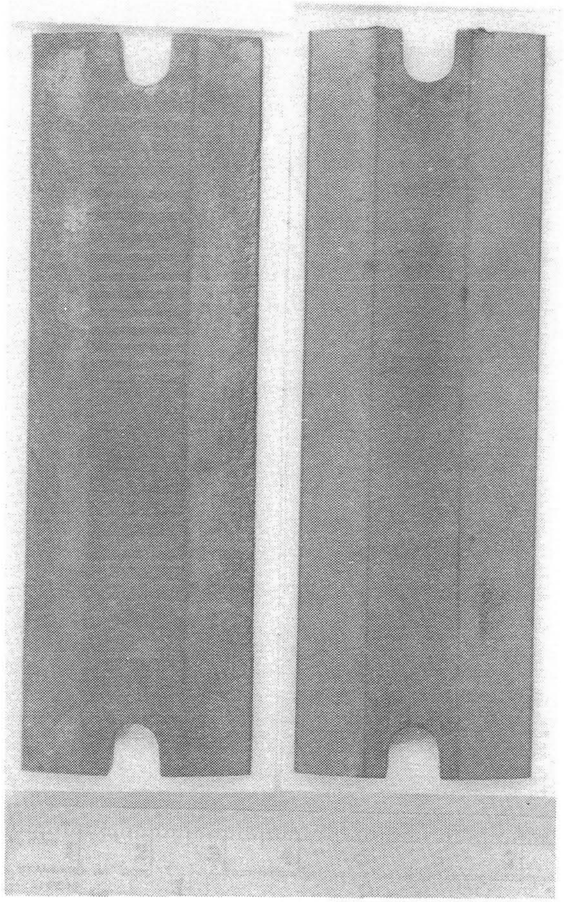


Neg. Nos. 51488 & 51494 1X

6 1

bare, 6,000 cycles/coated, 3,000 cycles

(e) 265 HRC 39



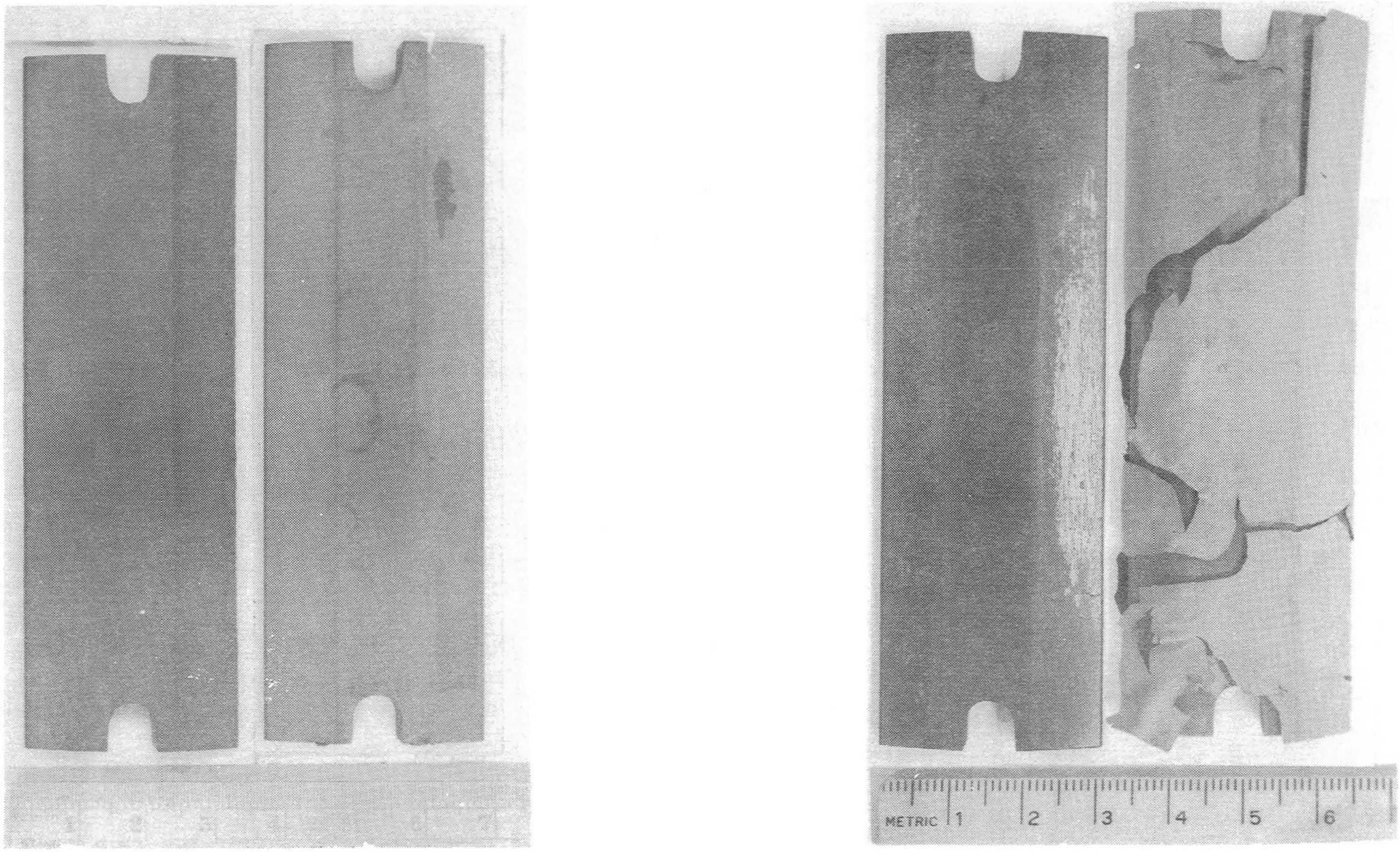
Neg. Nos. 51489 & 51493 1X

1 3

bare coated

(f) 266 HRC 37, 6,000 cycles

Figure 12 (Continued)



Neg. Nos. 51490 & 51498 1X

2 bare

1 coated

(g) 266 HRC 40, 6,000 cycles

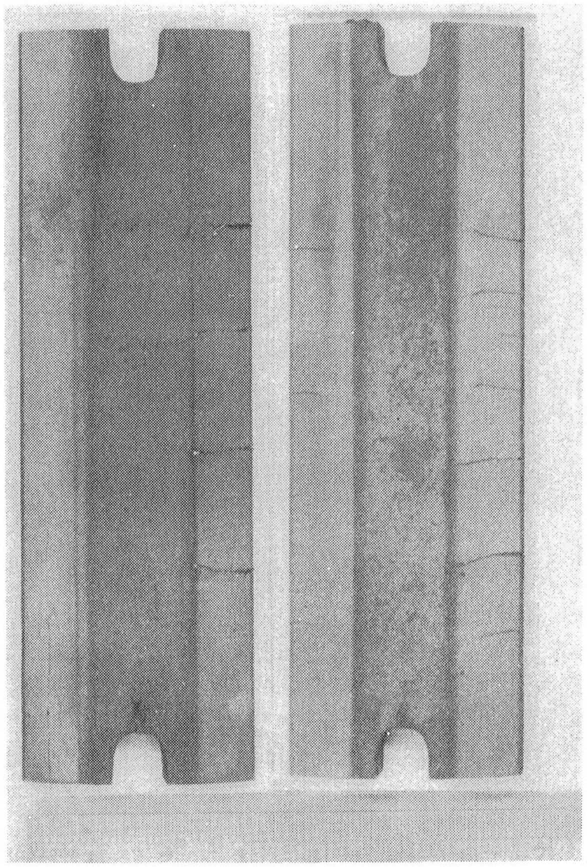
Neg. Nos. 45801 & 45698 1X

8 bare 3,000 cycles

1 coated 2,500 cycles

(h) Alloy 754

Figure 12 (Continued)



Neg. No. 5194 1X

1 bare 4 coated

(i) 956, 1,500 cycles

Figure 12 (Concluded)