NATIONAL BUREAU OF STANDARDS REPORT

10 015

EFFECT OF REFRIGERATION AND STRAIN ON THE CHARPY V-NOTCH IMPACT PROPERTIES OF TYPE 431 STAINLESS STEEL

Sponsor

Materials and Processing Branch
Naval Air Systems Command
Department of the Navy

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

NATIONAL BUREAU OF STANDARDS

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Effect of Refrigeration and Strain on the Charpy V-Notch Impact Properties of Type 431 Stainless Steel

By

I. J. Feinberg

The Naval Air Systems Command has requested an investigation of the effects of refrigeration after hardening and subsequent straining on the notch toughness of type 431 stainless steel.

It is known that an entirely martensitic structure cannot be obtained by heat treatment alone, even with refrigeration, and there will always be some retained austenite. It is also known that retained austenite may transform on straining to untempered martensite and this phase is generally considered to be embrittling. Little data are available from which to ascertain the effects of refrigeration treatments and straining on the properties of 431 stainless steel. Data are presented, obtained from tensile and Charpy V-notch tests, which show that either refrigeration after hardening or straining after hardening or both, exert a strong influence on notch toughness. The observed effects on properties are related to microstructural changes produced in the steel by the treatments applied.

Material:

Specimens for this investigation were machined from one inch diameter bar stock. The chemical composition of the material in percent by weight was as follows: carbon, 0.151; manganese, 0.59; phosphorus, 0.021; sulfur, 0.018; silicon, 0.30; chromium, 16.17; nickel, 211; molybdenum, 0.17; nitrogen, 0.085. The composition complies with that specified for type 431 in specification, Mil-S-18732C. The bar stock was furnished in the annealed condition with an austenitic grain size of 6-8, classified in accordance with ASTM designation E-19.

Specimens and Procedure:

Notch impact tests were conducted on four groups of specimens identified as follows:

NRUS	(Not refrigerated, unstrained)
NRS	(Not refrigerated, strained)
RUS	(Refrigerated, unstrained)
RS	(Refrigerated, strained)

Figure 1 is a flow diagram describing the specimen preparation sequence. Standard Charpy V-notch specimens were used in the impact tests. The loads at which Charpy specimens were strained were determined from data obtained in tensile tests on 0.252 inch diameter subsize control specimens. The heat treatment sequence in Figure 1 that included refrigeration is essentially the same as that specified for heat treating AISI 431 to the HT-200 condition, as given in paragraph 3.4.1, Mil-S-18732C.

In fabricating the NRUS and RUS impact specimens, blanks with a 0.50 in. by 0.50 in. square cross-section were first rough machined from the as-received stock. These blanks were first heat treated and then ground to finished dimensions and notched. The procedure for making NRS and RS specimens involved first producing tensile test bars with a 0.50 in. by 0.50 in. square reduced cross section. These bars were heat treated, then strained by stressing at approximately 138 percent of their yield strength at 0.20 percent offset as determined in the tensile control tests. The stress was the maximum attainable before the onset of the accelerated strain (necking) characteristic of the material prior to fracture. Impact specimens cut from the strained tensile bars were ground to finished dimensions and notched.

Retained austenite contents were determined by X-ray diffraction measurements using the Ogilvie-Bechtoldt technique[1]. This technique compares the integrated peak intensities of the (110), (200), (211) and (220) martensite lines and the (111), (200), (220) and (311) austenite lines and is claimed to give an accuracy of ± 1%.

Results and Discussion:

Table 1 indicates that longitudinal tensile properties that were obtained for RUS control material complied in all respects with that specified for the HT-200 condition in Mil-S-18732C. All of the longitudinal properties of NRUS control material complied with that specified for the HT-200 condition except yield strength which at 145.3 ksi was slightly low. Tempering the NRUS material at a temperature slightly lower than 550°F would probably raise the yield strength sufficiently to meet Mil-S-18732C requirements without adversely affecting the other tensile properties. However, the NRUS control material, as heat-treated with a 550°F temper, had a better combination of tensile strength and ductility than the RUS control material similarly tempered.

1 Technique described by Robt. E. Ogilvie, Massachusetts Inst. of Technology in Norelco Reporter, Vol. VI, page 60 and adapted to computer by C. J. Bechtoldt, National Bureau of Standards.

Table 2 gives the approximate retained austenite, untempered martensite and tempered martensite contents of the test material. Untempered and tempered martensite contents are differences obtained after retained austenite determinations were made.

Strains at 138 percent of the yield stress at 0.2 percent offset of the NRS material reduced the retained austenite content of this material from 23.1 percent to 10.6 percent. Strains at 138 percent of the yield stress of the RS material reduced its retained austenite content from 4.5 to 3.6 percent. These values imply that a high stress (greater than the yield stress) will readily convert austenite to martensite when the initial austenite proportion is either high or low. However, when the ratio of austenite to martensite is initially low, the proportion of austenite converted to martensite on high stress application is less.

From Table 3 which lists Charpy V-notch impact properties obtained and Figure 2 which presents percent losses in notch impact strength the following observations may be made:

1. The room temperature notch impact strength of the NRUS material is more than twice that of the RUS material.

2. Marked losses in the impact strength of both NRUS and RUS material occurred on testing at -40°F. However, the tests at this temperature indicated a far greater loss of notch toughness in the RUS material.

3. The notch toughness of both NRS and RS materials is reduced by strain as indicated in room temperature tests.

4. Refrigeration reduced notch toughness to a greater extent than strain.

5. The reduction in notch toughness is most severe in RS material as indicated in tests at -40°F.

<u>Macroscopic Features</u>:

The fracture surfaces of broken impact test specimens are shown in Figure 3. Ductile fracture is indicated by large shear lips and large fibrous areas in a fracture surface while in brittle fracture shear lips are either very small or absent and flat cleavage areas predominate in the fracture surface. From the standpoint of fracture surface appearance the specimens that were not refrigerated and not strained fractured in the most ductile manner while those that were refrigerated and strained fractured in the most brittle manner. These observations coincide with the impact test results.

Microscopic Features:

Figure 4 presents the microstructural features that influenced impact test results. Austenite bands are revealed in the NRUS material, Figure 4a, that are not evident in the RUS and RS material, Figures 4c and 4d, respectively. The absence of austenite banding in the refrigerated material is attributed to the martensite generation occurring within band areas of this material on refrigeration. Untempered martensite formed in the austenite bands of non-refrigerated material on straining is visible in Figure 4b. However, the structure of RUS material, Figure 4c, is quite similar to that of the RS material, Figure 4d, evidently due to the very small amount of untempered martensite formed on straining the latter material.

Both austenite and tempered martensite have relatively high notch toughness in this steel in comparison to any untempered martensite that may be present. It is apparent, particularly at lower temperatures, that the austenite is less notch sensitive than the tempered martensite. Obviously, the three phases will vie as factors affecting the notch toughness of 431 depending on their concentration in the material.

Austenite is the important factor in imparting superior notch toughness to unrefrigerated 431 at room temperature and at -40°F. As the unrefrigerated material was strained, retained austenite was converted to untempered martensite. The loss in notch toughness of NRS material on straining is attributed to the decrease in retained austenite occurring on straining and to the presence of strain-induced untempered martensite. Because of its high initial retained austenite content NRS material is capable of undergoing more plastic deformation before rupture than RS material with a lower retained austenite content. Both theory and experiment suggest that the volume fraction of untempered martensite formed during deformation is a continuous function of plastic strain. Thus under progressively higher strains the untempered martensite in an NRS material may increase to a point where the NRS material will have a very low notch toughness.

Conclusions:

431 stainless steel that has been heat treated to the HT-200 condition using refrigeration in the heat treating sequence is considerably more notch sensitive than 431 heat treated to the HT-200 condition without refrigeration. The superior notch toughness of the unrefrigerated material is due to the large retained austenite content resulting from the omission of refrigeration.

Plastic strain reduces the notch toughness of both refrigerated and non-refrigerated 431. The loss in notch toughness from plastic strain is due to a decrease in the retained austenite content and an accompanying increase in the untempered martensite content in the material. After being subjected to severe strains, strains approaching necking in specimens of both refrigerated and non-refrigerated material, the non-refrigerated 431 continued to exhibit better notch toughness.

Refrigeration severely reduces the notch toughness of 431 and subsequent plastic strain will greatly add to the notch sensitivity of the material. From these considerations it appears that any advantage refrigeration might impart would be nullified if part geometry included notches or other areas of stress concentration where plastic strain could occur, and/or if parts were subjected to inpact loading. Therefore, refrigeration is not recommended for 431 stainless steel used in such applications.

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Table 1. Average Longitudinal Tensile Properties of Heat Treated 431 Control Material Used in Notch Impact Tests

Specimen Group	Hardness	Yield Strength at 0.2% Offset	Ultimate Tensile Strength	Elongation in 1 inch	Reduction of Area
	Rc	ksi	ksi	%	%
RUS	47	158.4	224.4	17.16	58.67
NRUS	45	145.3	215.5	20.57	59.53
Specified HT-200 longitudinal properties, Mil-S-18732C	-	150.0 (min.)	200.0 (min.)	10.00 (min.)	40.00 (min.)

Table 2. Approximate Retained Austenite, Untempered Martensite and Tempered Martensite Contents of Heat Treated 431 Test Material Used in Notch Impact Tests. (Strained Material Stressed at 138% of Yield Strength at 0.2% Offset.)

Volume Percent	Material Condition NRUS (Not refrigerated unstrained)	NRS (Not refrigerated strained)	RUS (Refrigerated unstrained)	RS (Refrigerated strained)
Retained austenite	23.1	10.6	4.5	3.6
Untempered martensite	0	12.5	0	0.9
Tempered martensite	76.9	76.9	95.5	95.5

Table 3. Charpy V-notch Impact Properties of Type 431 Stainless Steel; Stress Relieved 1/2 Hour at 1200 F, Austenitized 1/2 Hour in Air at 1900 F, Quenched in Oil at 100-105 F and Refrigerated for 2 Hours at -140 F as Noted. Tempered Twice at 550 F for 2 Hours. Specimens Strained by Stressing at 138 percent of Yield Stress at 0.2% Offset, as Noted. Specimens Ground to Finished Dimensions After Heat Treatment or After Heat Treatment and Strain.

Conditioning	Specimen No.	Charpy V-notch, ft. lbs. R. T.	Charpy V-notch, ft. lbs. -40 F
Stress relieve	NRUS - 1	55.5	30.0
Austenitize	2	52.5	27.5
Quench	3	52.5	29.0
Temper	Avg	53.5	28.8
Stress relieve	NRS - 1	25.0	11.5
Austenitize	2	26.5	13.0
Quench	3	30.5	14.0
Temper	Avg	27.3	12.8
Strain			
Stress relieve	RUS - 1	22.5	7.0
Austenitize	2	21.0	5.5
Quench	3	28.5	8.5
Refrigerate	Avg	24.0	7.0
Temper			
Stress relieve	RS - 1	18.5	4.5
Austenitize	2	19.5	5.5
Quench	3	15.0	4.0
Refrigerate	Avg	17.7	4.7
Temper			
Strain			

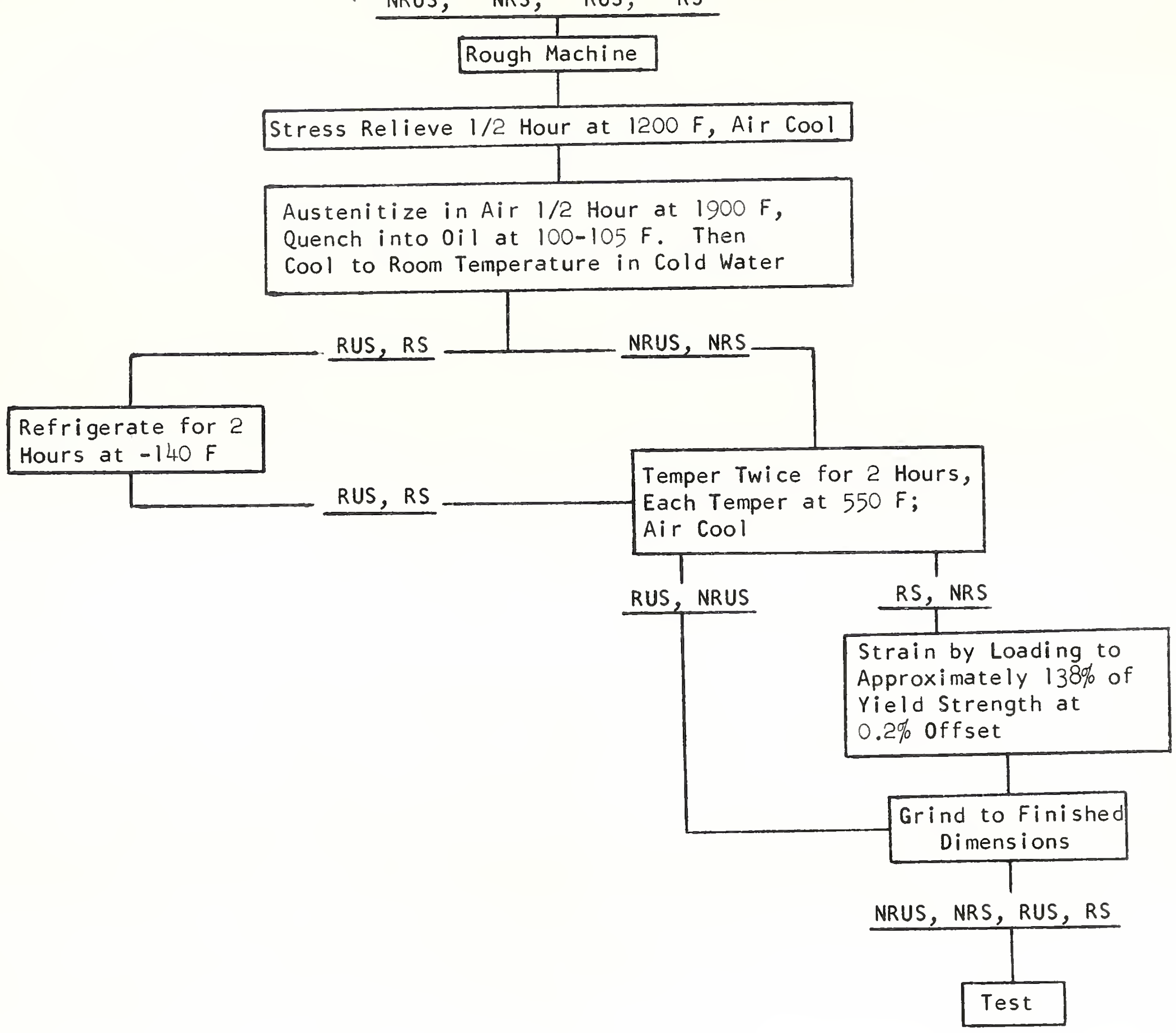


Figure 1. Procedure for Preparing Tensile Control and Notch Impact Specimens for Tests.

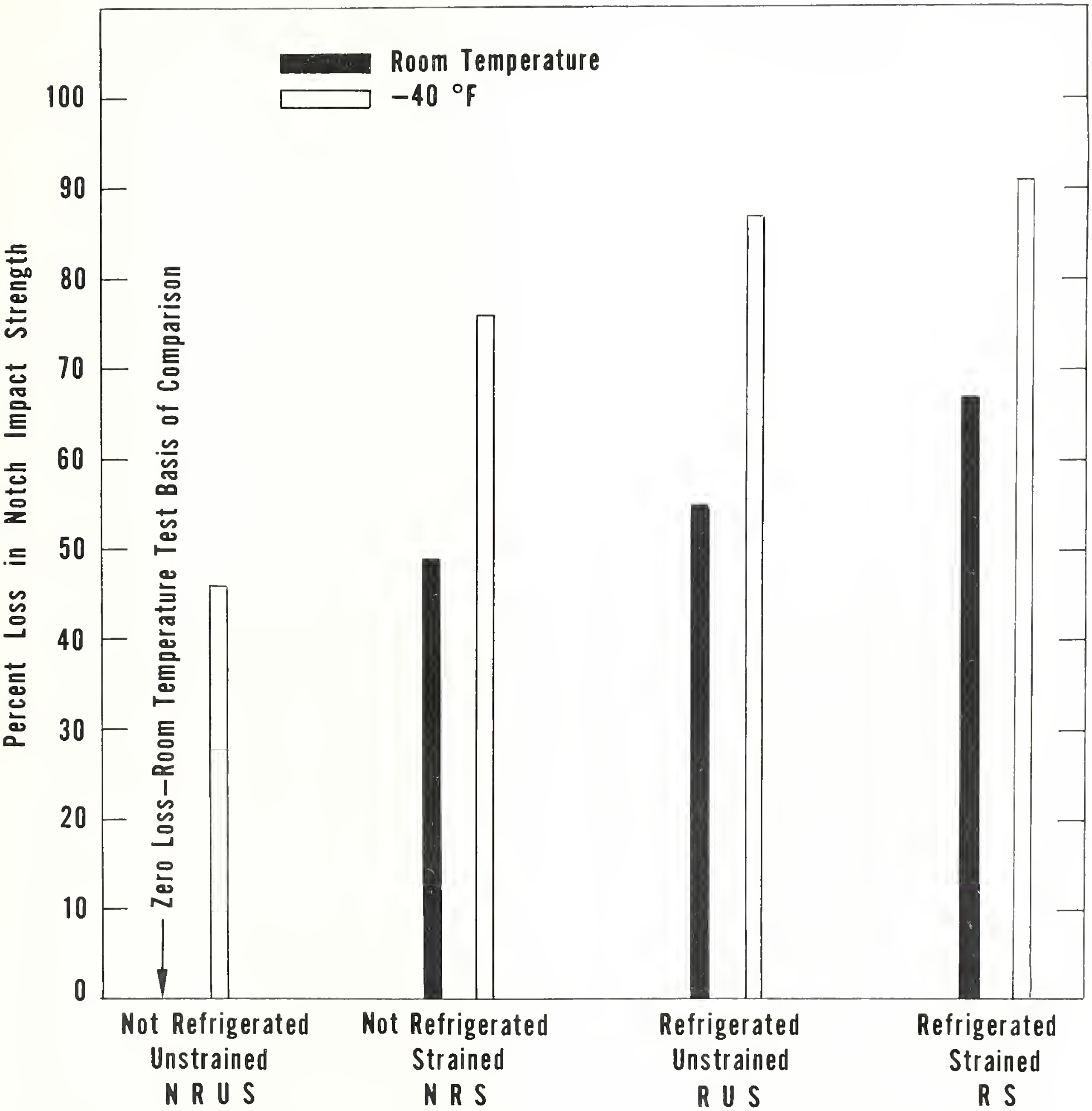
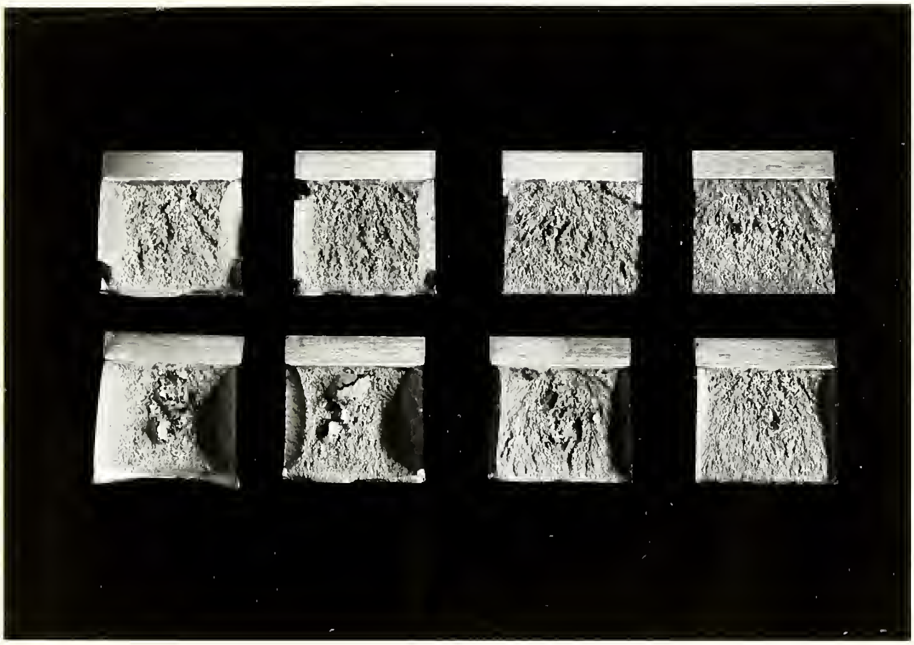


Fig 2 Relative Embrittlement of AISI 431 Test Material as Measured by Percent Loss in Notch Impact Strength in Tests at Room Temperature (72 °F) and at −40 °F. Effects of Various Combinations of Heat Treatment and Strain Compared.

Not Refrigerated | Refrigerated
RT -40 F | RT -40 F



Strained

Unstrained

Figure 3. Fracture surfaces of notched impact test specimens. Specimens broken at room temperature (RT) and at -40 F. Superior notch toughness of non-refrigerated specimens is indicated by larger shear lips and fibrous fracture areas. These two criteria also indicate a loss in notch toughness or embrittlement in both non-refrigerated and refrigerated specimens as a result of strain. X 2.

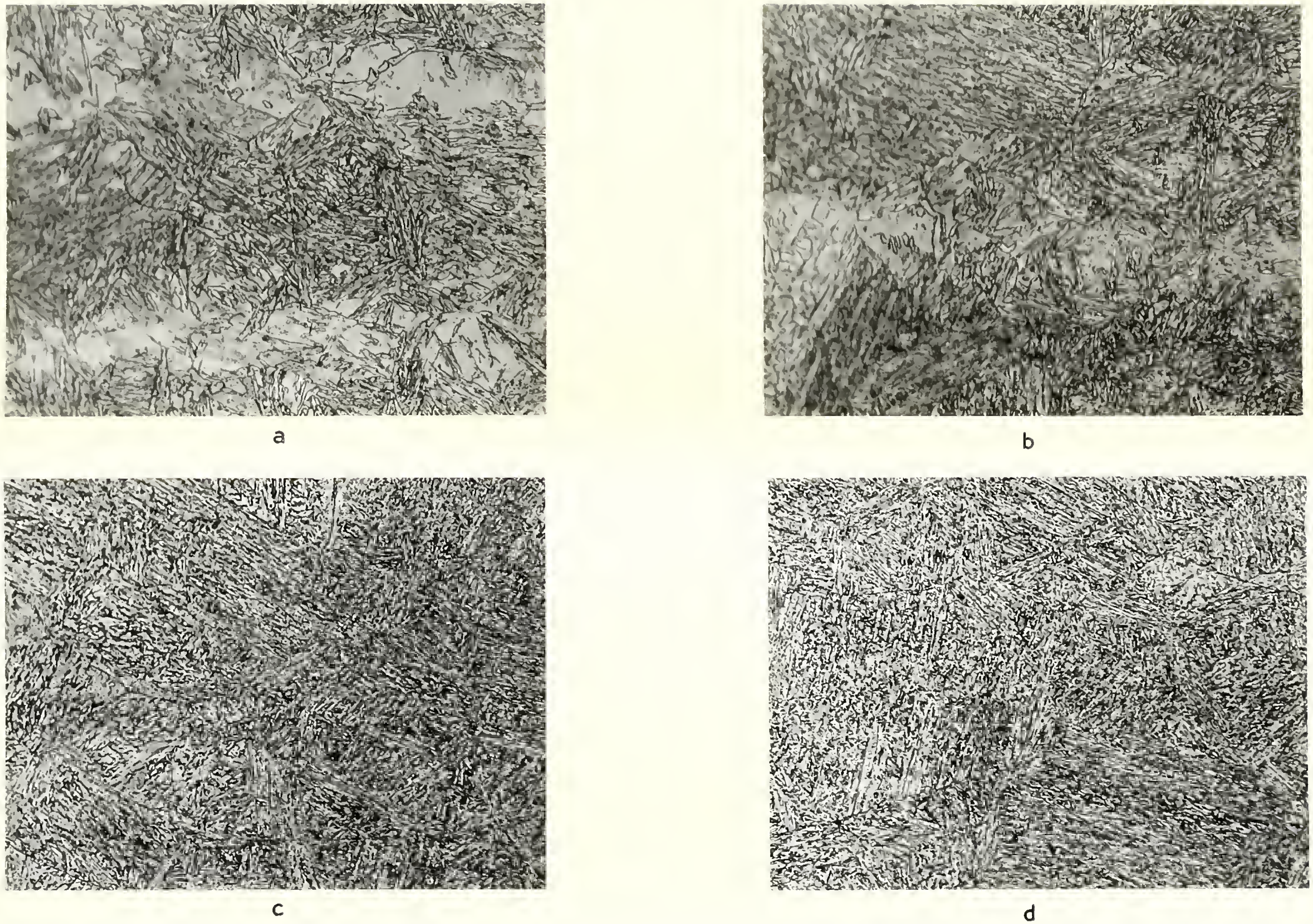


Figure 4. Longitudinal microstructures of the test steel diversely conditioned. Etched with Beraha's No. 1 reagent (10 ml, HCl, 50 ml H_2O, 0.5 g, $K_2S_2O_5$). X 500.

a. Hardened, tempered, unstrained (NRUS).
b. Hardened, tempered, strained (NRS).
c. Hardened, refrigerated, tempered, unstrained (RUS).
d. Hardened, refrigerated, tempered, strained (RS).