TECHNICAL REPORT No. 30

THE INFLUENCE OF STRAIN RATE AND TEMPERATURE ON THE DUCTILITY OF AUSTENITIC STAINLESS STEEL

In Cooperation With
The Office of Naval Research, U. S. Navy
N6-ONR-273/I Project NR-031-049
September, 1954

An Investigation of

THE EFFECTS OF STRESS CONCENTRATION AND TRIAXIALITY ON THE PLASTIC FLOW OF METALS

Technical Report No. 30

THE INFLUENCE OF STRAIN RATE AND TEMPERATURE ON THE DUCTILITY OF AUSTENITIC STAINLESS STEEL

By

G. W. Form and W. M. Baldwin, Jr.

Conducted By

METALS RESEARCH LABORATORY
DEPARTMENT OF METALLURGICAL ENGINEERING
CASE INSTITUTE OF TECHNOLOGY

In Cooperation With

OFFICE OF NAVAL RESEARCH, U. S. Navy

Contract N6-ONR-273/I   Project NR-031-049

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THE INFLUENCE OF STRAIN RATE AND TEMPERATURE ON THE DUCTILITY OF AUSTENITIC STAINLESS STEEL[*]

By

G. W. Form[**] and W. M. Baldwin, Jr.[***]

ABSTRACT

The ductility of AISI 303 and 310 austenitic stainless steels was determined in tensile tests over a range of strain rates from 0.01 in./in./min. up to 19000 in./in./min., and over a range of temperatures from -321°F up to +750°F. Ductility drops as strain rate is increased, the drop being greatest at room temperature. The ductility shows a maximum at room temperature at low strain rate, but at high strain rates it increases slowly and steadily with the test temperature. Magnetic measurements on broken specimens showed that the γ- α transformation can not account for all these behaviors.

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[*] This paper is based upon a portion of a research program conducted in the Metals Research Laboratory, Case Institute of Technology in cooperation with the Office of Naval Research.

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INTRODUCTION

Stainless steels lose ductility at high strain rates at room temperature (1-4)*. The factors which cause this strain rate sensitivity have not been satisfactorily rationalized yet. It has been inferred at times that the strain rate sensitivity is due to the γ-α transformation. The ASTM Subcommittee V on Mechanical Tests (5), for example, reports "Since austenitic stainless steels transform when cold worked, the amount of transformation being dependent upon the amount of work and likely upon the rate of working, it is to be expected that rate of strain would affect the tensile properties". Yet an attempt to link the γ - α transformation with the ductility drop leads to a paradox. Binder (6) maintains the γ - α transformation lowers the ductility of 18-8 stainless steels. Cohen (7) states likewise, that if austenite could withstand decomposition it would display higher ductility. If the α-phase formed during a tensile test lowers the ductility of 18-8 stainless steel, it would then be natural to conclude that, at low strain rates, where ductility is high, less α-phase is present than at high strain rates, where ductility is low. This, however, contradicts Mathieu's results (8) which clearly show that the amount of α-phase drops markedly when the testing speed is increased.

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* The figures appearing in parentheses pertain to the references appended to this report.

Confusing the issue even further is the fact that ductility drops at low temperatures where increased α - phase formation is known to exist (8).

In the present investigation - designed to shed light on this discrepancy - tensile tests were conducted over a wide range of temperatures and strain rates in order to evaluate the influence of these factors on the ductility behavior of austenitic stainless steels. In addition, magnetic measurements supplemented by microhardness tests were made on broken test specimens to determine to what extent, if any, the γ - α transformation is involved in the strain rate sensitivity of this material.

MATERIAL AND PROCEDURE

Material

The two steels selected for this investigation were AISI 303 (an 18 percent Cr, 8 percent Ni steel) and AISI 310 (a 25 percent Cr, 20 percent Ni steel)*. The tensile specimens, 1 1/2 in. long with a minimum diameter of 0.212 in., were machined from fully annealed rod.

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* The analyses ran: 303 - Si, 0.54 percent; S, 0.300 percent; P, 0.016 percent; Mn, 1.37 percent; C, 0.045 percent; Cr, 17.49 percent; Ni, 10.30 percent; 310 - Si, 0.35 percent; S, 0.006 percent; P, 0.023 percent; Mn, 1.82 percent; C, 0.044 percent; Cr, 22.72 percent; Ni, 19.72 percent.

Tensile Test Procedure

Tensile tests were made at various temperatures and strain rates. The low strain rate tests (0.01 to 10 in./in./min.) were carried out on a Riehle and a Baldwin - Southwark tensile-testing machine, with the speed of the cross-head held constant. This, of course, yielded a variable strain rate as the specimen lengthened, but the true strain rate did not vary by more than a factor of 4 since the greatest reduction in area recorded was 75 percent. Since the strain rate was intentionally changed by a factor of almost two million in the various tests, the variability in strain rate during a given test can be reasonably overlooked. The strain rate of 100 in./in/min. was obtained on a hydraulic type draw bench, and the 8000 and 19000 in./in./min. on a drop-hammer. For the subzero temperature tests the specimens were immersed in a bath of liquid nitrogen (-321°F), a mixture of liquid nitrogen and isopentane (-200°F), or a mixture of isopentane and dry ice (-50°F). The room temperature tests (+70°F) were carried out in air, while all higher temperatures (+200°, +300°, +500° and +750°F) were obtained with an electrically heated furnace. In the tests carried out at low strain rates (0.01 to 10 in./in./min.) the specimens were held in a low-temperature box containing the cooling liquid or in a furnace so that the test temperature could be kept constant during the test period. At high strain rates, however, the specimens were transferred from the cold liquid or from the furnace after having reached the desired temperature and tested while surrounded by air at room temperature. The elapsed transfer and testing time was about four seconds.

The ductility $\varepsilon = 2 \ln \frac{d_o}{d_f}$ was obtained as an average of six measurements of the initial and final diameter, d_o and d_f, respectively on an optical comparator.

Magnetic Measurements

Magnetic measurements were made on the broken tensile test specimens in order to detect how much α - phase (martensite) had been formed during the tensile test. A relatively simple setup based on the induction principle was used, Fig. 1. The energizing magnetic field was produced in a coil of about 2700 turns, which was connected to an AC-source.

One half of a broken specimen was placed into a search-coil, whose shape was conical in order to minimize the air gap.* The specimen and search-coil were inserted into the center of the energizing coil and connected to the grid of an oscilloscope. The amount of α - phase formed in a specimen determined the potential

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* The air gap varied from specimen-to-specimen. However, the error thus involved was found to be negligibly small and therefore not taken into consideration when plotting the oscilloscope readings.

difference between grid and ground of the oscilloscope as indicated by the height of the sine wave amplitude on the screen. This amplitude was measured and expressed in terms of screen units (length of a square of the screen net). Both halves of a broken specimen were measured and the readings added. The amplitude produced by a non-magnetic specimen was then subtracted and the difference taken as a qualitative measure of the α - phase formed.*

In order to reveal the distribution of martensite formed during the tensile test, a few broken specimens were inspected by a magnetic powder method. A colloidal magnetite was prepared according to Elmore (9) and the sol stabilized with soap. A broken specimen-half was sectioned lengthwise, one half mounted in lucite and polished. The mount was inserted into a core of Swedish iron, and the assembly placed into the same energizing coil as used previously. The magnetic sol was applied so that it covered the entire top surface of the mounting. The coil was connected to a DC-source, thereby attracting the magnetic particles in the sol to those areas of the polished specimen surface which had undergone a $\gamma - \alpha$ transformation. The resulting patterns

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* This difference could be converted directly into the amount of α - phase formed, e.g. by a lineal analysis. Since the variation of α - phase under different test conditions is more important than absolute values for the present problems, it was not necessary to convert the oscilloscope readings into the equivalent of permeability or amount of martensite.

were photographed while the magnetic field was still in effect. The electrical circuit used in the magnetic powder method is shown in Fig. 2.

Microhardness Tests

The samples that were inspected magnetically for martensite distribution were subjected to microhardness tests. Readings were taken with a Knoop indenter and a load of 1000 grams on a Tukon tester and converted to Rockwell A Units.

RESULTS

AISI 303 Stainless Steel

The ductility, δ, is plotted as a function of strain rate, $\dot{\varepsilon}$, for various temperatures in Fig. 3. The three-dimensional graph of Fig. 4 represents the ductile behavior of AISI 303 steel over the entire range of temperatures and strain rates. These plots reveal three major characteristics of the ductility behavior:

(a) The strain rate sensitivity is most pronounced at room temperature, while it is relatively small at low temperatures and disappears at +500°F.

(b) At low strain rates the ductility increases sharply with temperature, reaches a maximum at room temperature and decreases at higher test temperatures.

(c) At high strain rates (19000 in./in./min.) the ductility increases slowly if irregularly as the test test temperature increases.

In Figs. 5 and 6 the oscilloscope readings which were obtained as a measure of the martensite present are plotted as a function of strain rate for four different tensile test temperatures. All measurements on the test specimens were made at room temperature. It is seen that at a given temperature the amount of α-phase is less at high strain rates; also at a given strain rate the amount of α-phase is less the higher the temperature*. No α-phase could be detected in the specimens pulled at 1200°F or higher. The temperature above which no transformation can be induced by

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* Scheil's theory of martensite formation (12) predicts the increase in martensite formed at low temperatures under constant strain rate found in Fig. 6. According to this theory a critical shear stress resolved in the slip plane has to be exceeded in order to overcome the resistance towards martensite formation. Once this critical value is surpassed, the amount of martensite formed increases with increasing plastic strain. It is further postulated that the shear resistance to martensite formation decreases with decreasing temperature, while the shear resistance towards slip increases with decreasing temperature.

The decrease in martensite with increasing strain rate at a given test temperature could be anticipated from either a) the increased heat retained in samples deformed at high speeds (which would by Scheil's theory give less martensite), or b) an increase in the stress required for martensite formation with increasing strain rate (which could be expected on dynamical grounds).

(If the stress reached during deformation drops with strain rate a decrease in martensite formation would also be expected, since this would mean that the resistance towards martensite formation might not be as readily overcome. At room temperature, for example, the fracture stress varied from 257000 psi. at 0.05 in./in./min. to 237,000 psi at 10 in./in./min.)

deformation before fracture (M_d temperature) must therefore lie between room temperature and +200°F. This agrees with results reported in the literature for stainless steels of similar analyses (8) (10). In contrast with the ductility curves the strain rate sensitivity of the γ-α transformation is more pronounced at -321°F than at room temperature, i.e., the drop in oscilloscope reading over the total range of strain rates is larger at -321°F than at room temperature. The specimens broken at -321°F were magnetically tested at both -321°F and room temperature. The results indicated that no α-phase present at low temperature had reverted to austenite when brought up to room temperature.

The distribution of the α-phase in four fractured specimens - two specimens pulled at room temperature (0.05 and 19000 in./in./min., respectively), and two at -321°F (0.05 and 19000 in./in./min., respectively) - is shown by the magnetic powder patterns in Fig. 7. The amount of magnetic particles attached to the samples agrees qualitatively with the result obtained by the induction method in that they indicate that the amount of α-phase decreases with both increasing strain rate and temperature. The specimen tested at room temperature at a strain rate of 19000 in./in./min. did not undergo any detectable transformation, which is in agreement with results given by Krivobok and Talbot (11).

The microhardness tests made along the longitudinal centerline of the above four specimens are given in Fig. 8. The three samples which had undergone transformation show an excess in hardness over that of the sample pulled at 19000 in./in./min. at room temperature which had undergone no transformation. At the same time the length of that portion of the specimen that evidences transformation in the magnetic sol test is greater than that over which the hardness shows a constant high value.

AISI 310 Stainless Steel

The ductility of the 310 stainless steel as a function of strain rate at various temperatures is given in Figs. 9 and 10. The temperature effect [illegible] ductility of the AISI 310 steel is similar to that of the AISI 303 steel. At low strain rates the ductility first rises with temperature, reaches a maximum at room temperature, and then decreases at higher test temperatures. At high strain rates the ductility increases slowly with increasing test temperature.

Magnetic measurements did not reveal any α-phase in any of the 310 specimens, even those deformed at -321°F.*

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* X-ray diffraction patterns of 310 steel deformed at -321°F showed no α -phase lines although patterns from the 303 steel deformed at -321°F did.

DISCUSSION

It appears that most if not all of the peculiarities in the ductility behavior of austenitic steels must be explained on some other basis than the γ-α transformation. The principal evidence for this conclusion is:

i) Both the 303 (18-8) and 310 (25-20) stainless steel possess similarly shaped ductility vs. temperature and strain rate surfaces, yet the 310 steel shows no γ-α transformation at any temperature or strain rate.

ii) Even in the 303 (18-8) steel no γ-α transformation is found above room temperature where ductility drops with increasing strain rate.

iii) Where the γ-α transformation is found in 303 (18-8) steel (room temperature and below) it is found in amounts that bear no direct relationship with ductility behavior; at constant strain rates a drop in temperature increases the amount of α-phase formed but decreases ductility; at constant test temperature an increase in strain rate drops both ductility and the amount of α-phase formed.

iv) Sundry experiments appear to show that the amount of α-phase can be without influence on ductility; A 303 stainless steel test specimen, for example, was prestrained at -321°F and

0.05 in./in./min. to the "upper yield point", which becomes very pronounced at this low temperature. The purpose of this operation was to render the specimen magnetic at the smallest prestrain possible. (The diameter after prestraining was 0.002 in. smaller than before.) The specimen was easily attracted by a hand magnet, indicating that transformation had taken place during prestraining at -321°F. The specimen was then pulled at room temperature and a strain rate of 0.05 in./in./min. The total ductility thus obtained equaled the one of the specimen which was tested at room temperature and 0.05 in./in./min. without prestraining. The broken halves of the prestrained specimen were magnetically inspected by means of the induction method and revealed an oscilloscope reading of 18 screen units. Although the amount of α-phase formed was more than 3 times as high as in the non-prestrained specimen (which Fig. 5a shows ran about

5.5 units), the ductility in the two specimens was the same.*

To complete the record, it should be mentioned that the gradual drop in ductility with increasing strain rate observed here in austenitic stainless steels is not to be confused with the sudden drop in ductility with strain rate that von Kármán predicts for all metals because of the finite speed of propagation of plastic deformation (13). The velocity at which this sudden drop in ductility should occur has been variously calculated and determined experimentally to be between 3600 inches per minute and 144000 inches

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* The microhardness results of the low carbon AISI 303 steel ($C=0.045\%$) seem to indicate that the α-formation is of little, if any, influence on the hardness. By comparing the data of the two specimens pulled at room temperature at strain rates of 0.05 and 19000 in./in./min., Fig. 7a and b, it can be seen that the hardness near the fracture is practically the same for both specimens, although only the one pulled at 0.05 in./in./min. has undergone transformation. Furthermore the true stress - true strain curve of the AISI 303 steel obtained at room temperature is similar to that of the AISI 310 steel, and the increase in fracture stress is about 65% for both the stable and the metastable steel, if the test temperature is lowered from room temperature to -321°F. One could conclude from these results that the high work hardening in stainless steel is rather a property of the austenitic phase and not due to the γ-α transformation. On this basis it can also be understood why the hardness in Fig. 8 does not show a discontinuity at that point of the centerline where the transformation ceases to take place. The fact that the distance from the cross-section over which α-phase was formed exceeds the length over which the hardness is constant, indicates that the maximum resolved shear stress built up in the specimen is higher than the stress necessary to initiate the γ-α transformation. The above discussion, however, does not exclude the possibility that the influence of the α-phase on the work hardening becomes more pronounced, if the carbon content is considerably higher than in the AISI 303 stainless steel.

per minute (1) (4) (14), whereas the gradual drop in ductility described here occurs at strain rates as low as 0.01 in./in./min.

CONCLUSIONS

1. At low strain rates 303 and 310 austenitic stainless steels have a maximum ductility at room temperature as test temperature is varied.
2. At high strain rates ductility increases steadily as the test temperature is increased.
3. The loss in ductility at high strain rates is greatest at room temperature.
4. The γ-α transformation can not account for these unusual features in ductility.

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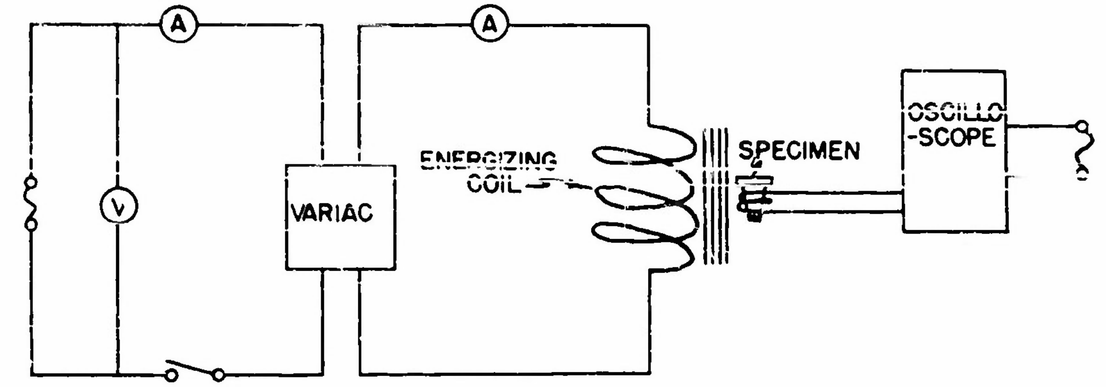

FIG. 1: ELECTRIC CIRCUIT USED IN THE MAGNETIC INDUCTION METHOD.

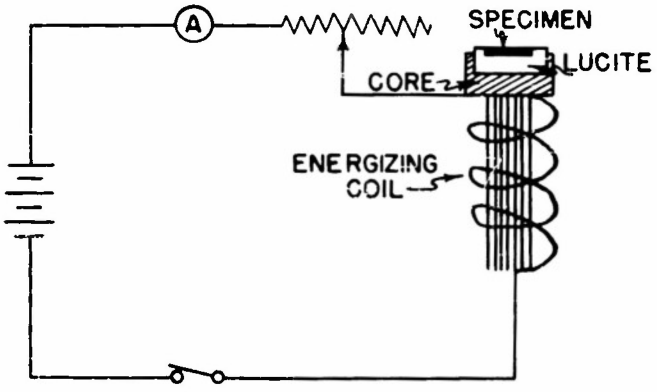

FIG. 2: ELECTRIC CIRCUIT USED IN THE MAGNETIC POWDER METHOD.

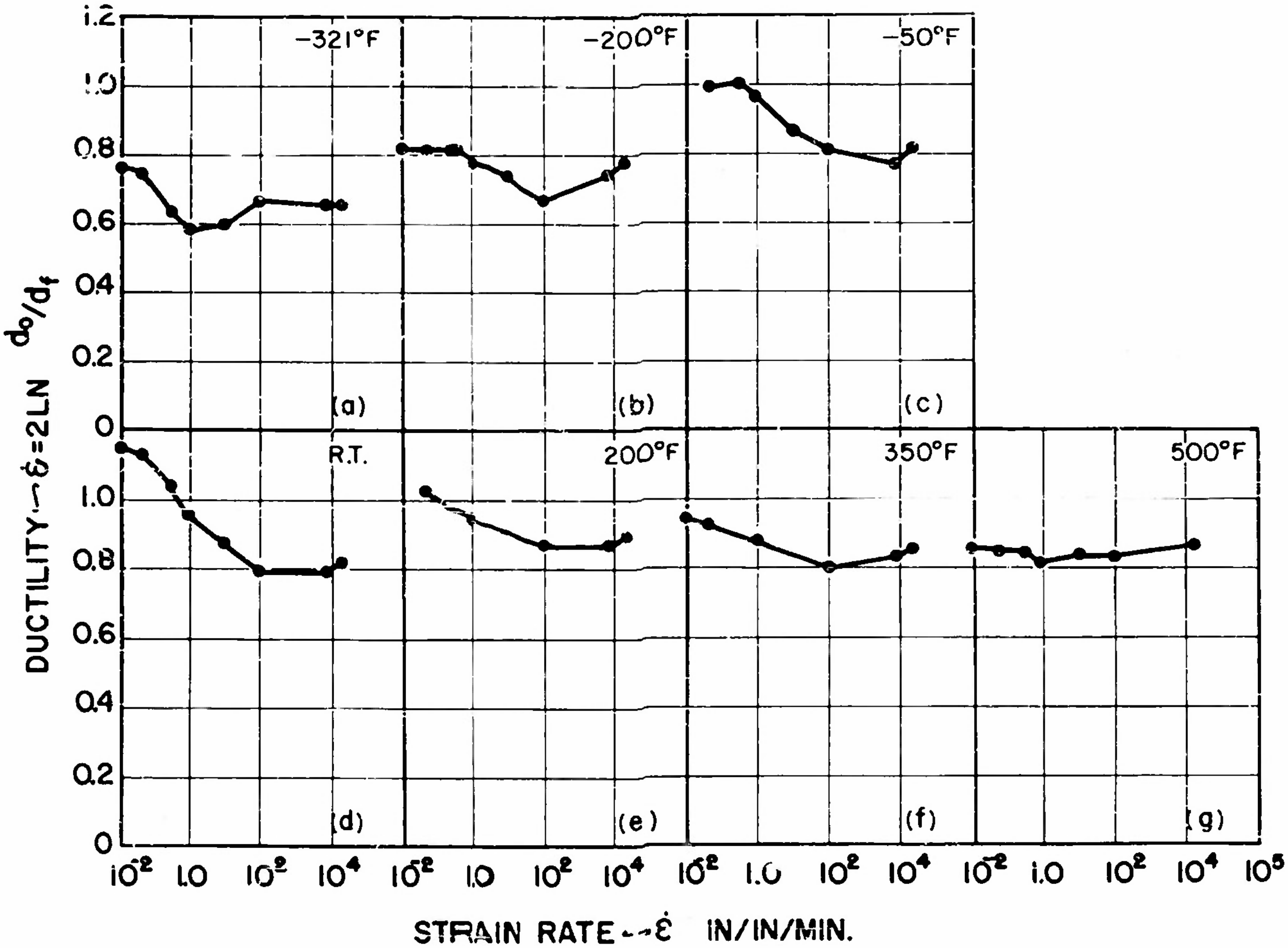

FIG.3(a–g): DUCTILITY OF AISI 303 STAINLESS STEEL AS A FUNCTION OF STRAIN RATE AT VARIOUS TEST TEMPERATURES.

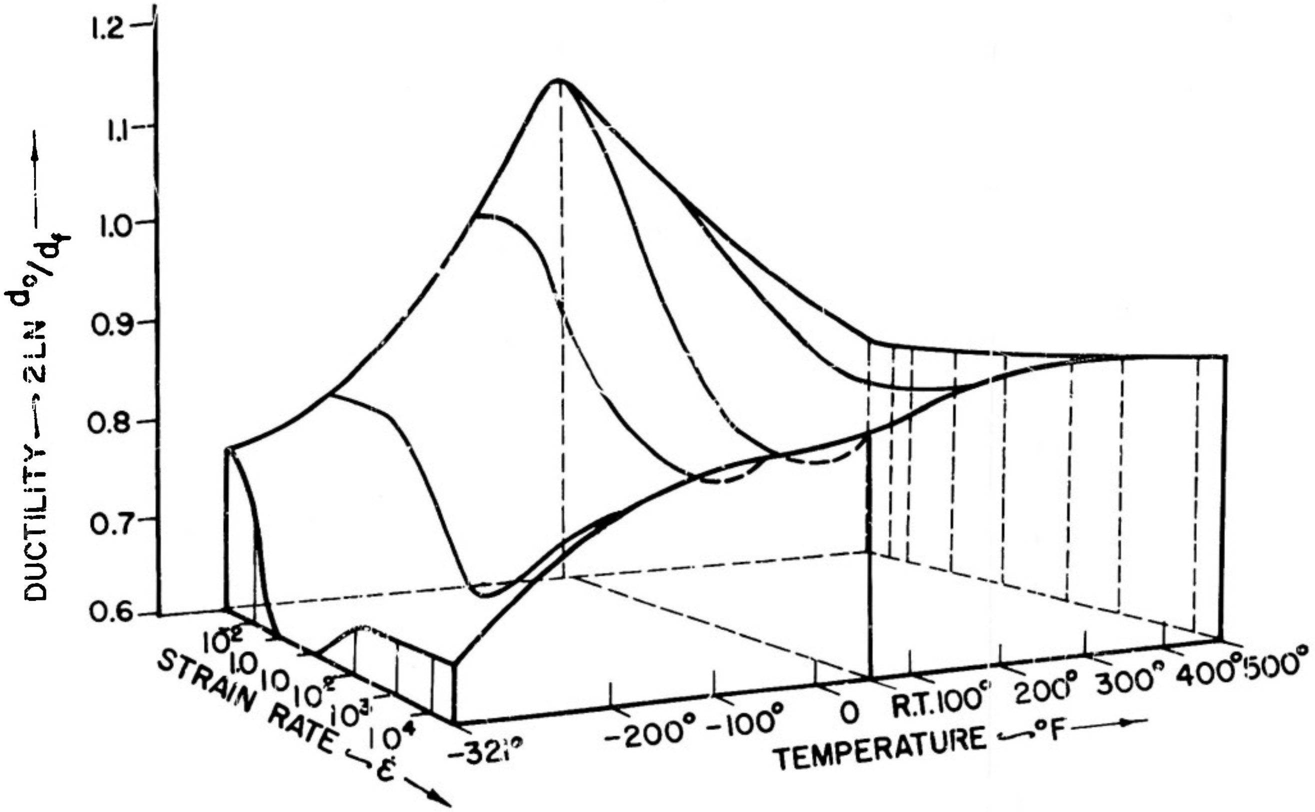

FIG. 4: DUCTILITY OF AISI 303 STAINLESS STEEL AS A FUNCTION OF STRAIN RATE AND TEST TEMPERATURE.

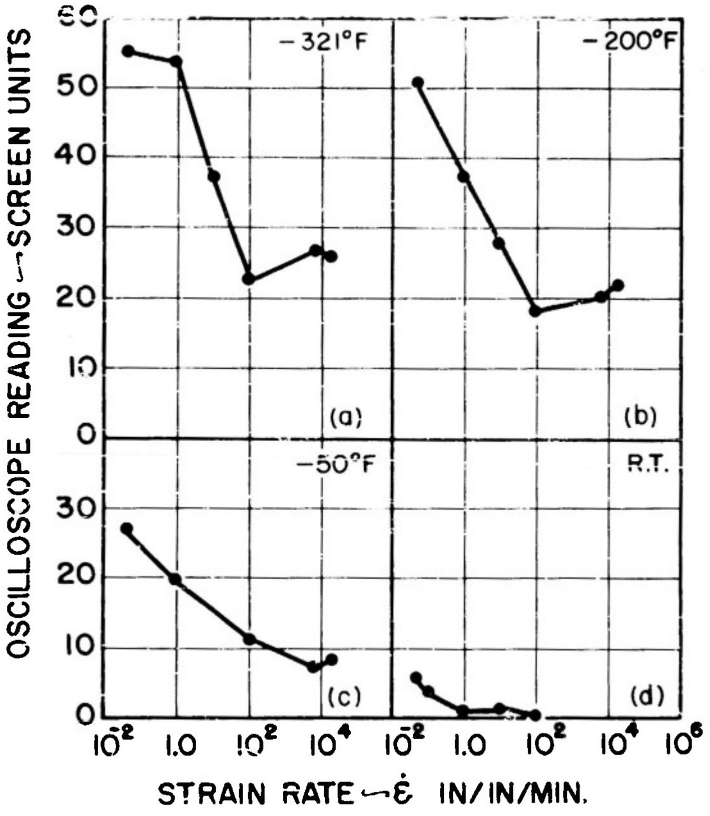

FIG.5 (a–d): EFFECT OF STRAIN RATE ON THE MAGNETIC BEHAVIOR OF AISI 303 STAINLESS STEEL AT VARIOUS TENSILE TEST TEMPERATURES.

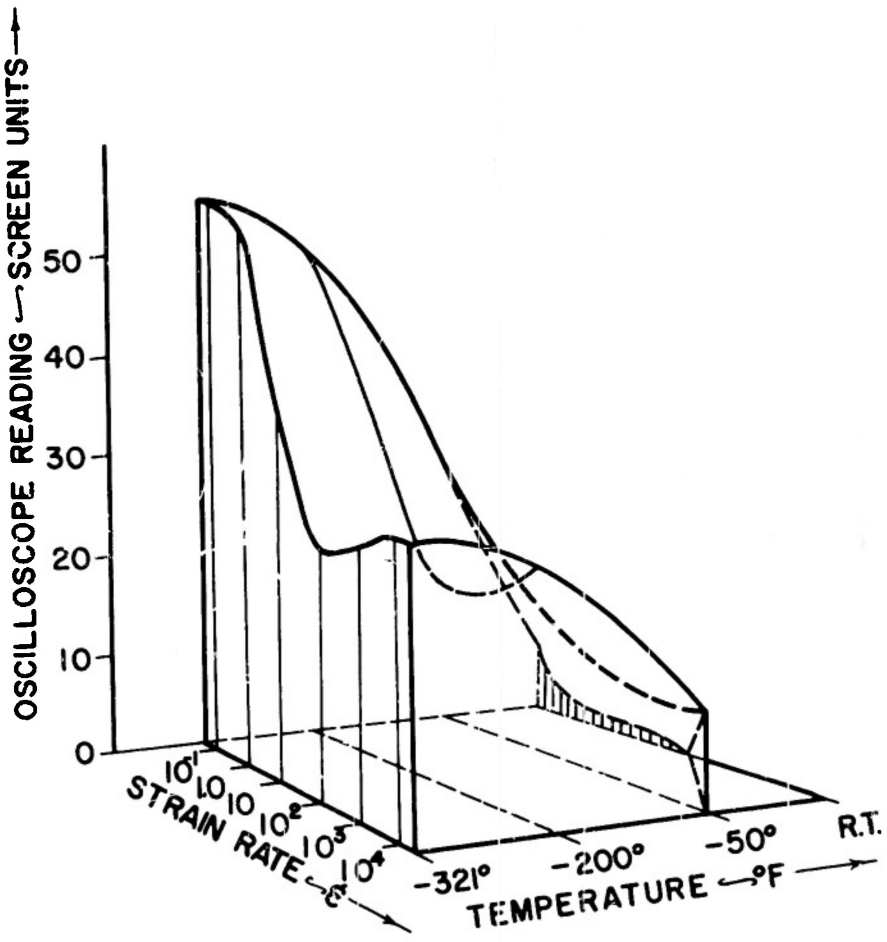

FIG.6: EFFECT OF TEST TEMPERATURE AND STRAIN RATE ON THE MAGNETIC BEHAVIOR OF AISI 303 STAINLESS STEEL.

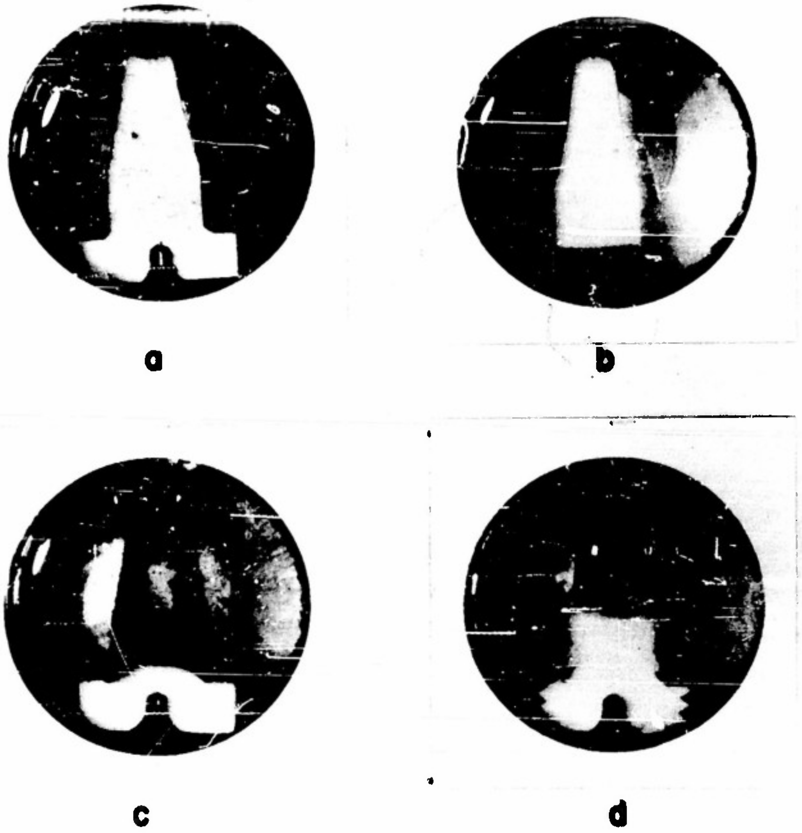

FIG. 7 (a–d): MAGNETIC POWDER PATTERNS ON BROKEN AISI 303 STAINLESS STEEL SPECIMENS. MAGN. 15X.

(a) SPECIMEN PULLED AT : R.T. ; 0.05 IN/IN/MIN.
(b) " " " : R.T. ; 19,000 " " "
(c) " " " : -321°; 0.05 " " "
(d) " " " : -321°; 19,000 " " "

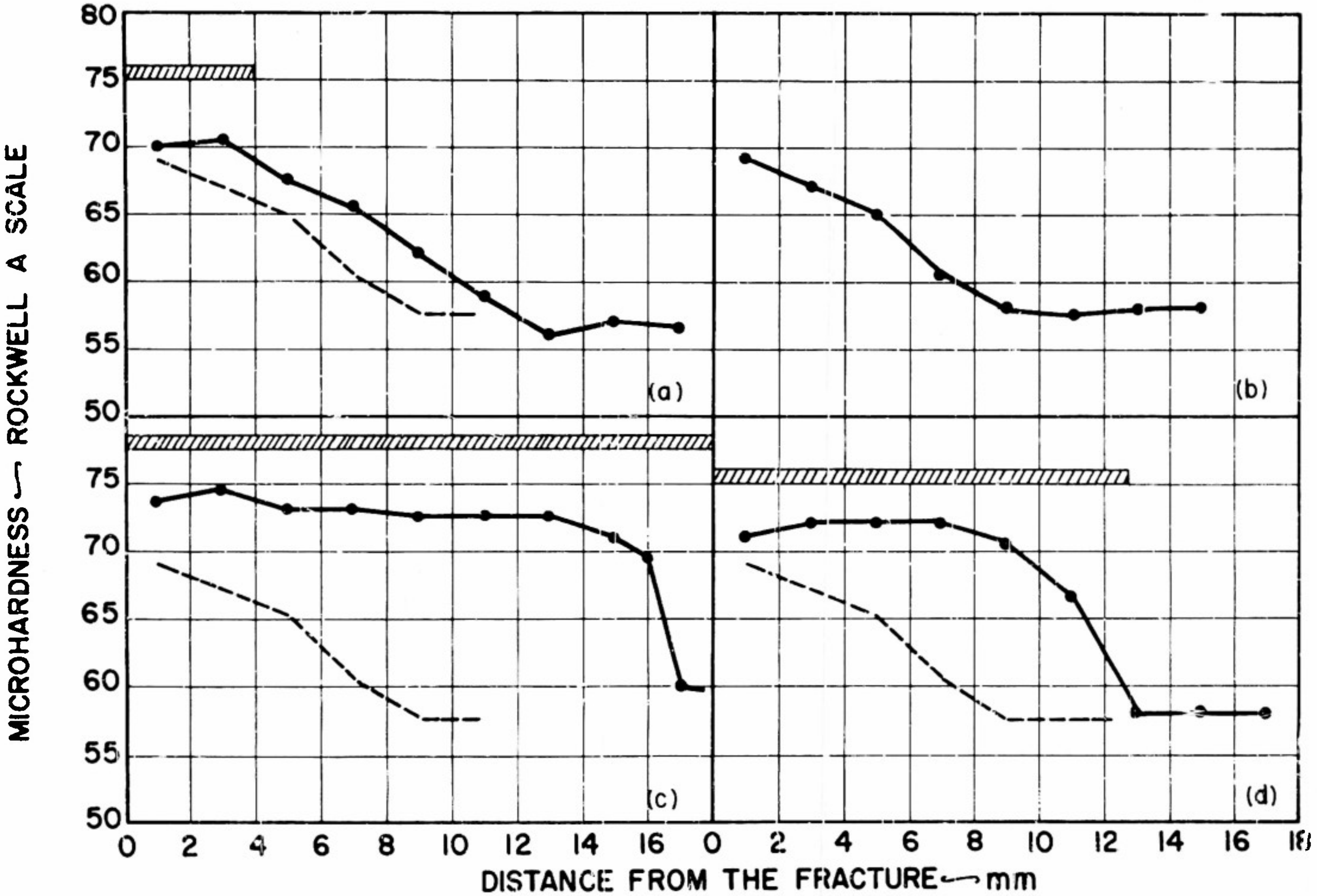

FIG. 8(a-d): MICROHARDNESS ALONG THE CENTERLINE OF BROKEN AISI 303 TENSILE SPECIMENS.

LEGEND:

—— MICROHARDNESS

- - - MICROHARDNESS ON SPECIMEN (b) WHICH HAS NOT UNDERGONE TRANSFORMATION.

▨ LENGTH OVER WHICH TRANSFORMATION TOOK PLACE.

(a) SPECIMEN PULLED AT: R.T.; 0.05 IN/IN/MIN.
(b) " " " : R.T.; 19,000" " "
(c) " " " : -321°; 0.05 " " "
(d) " " " : -321°; 19,000" " "

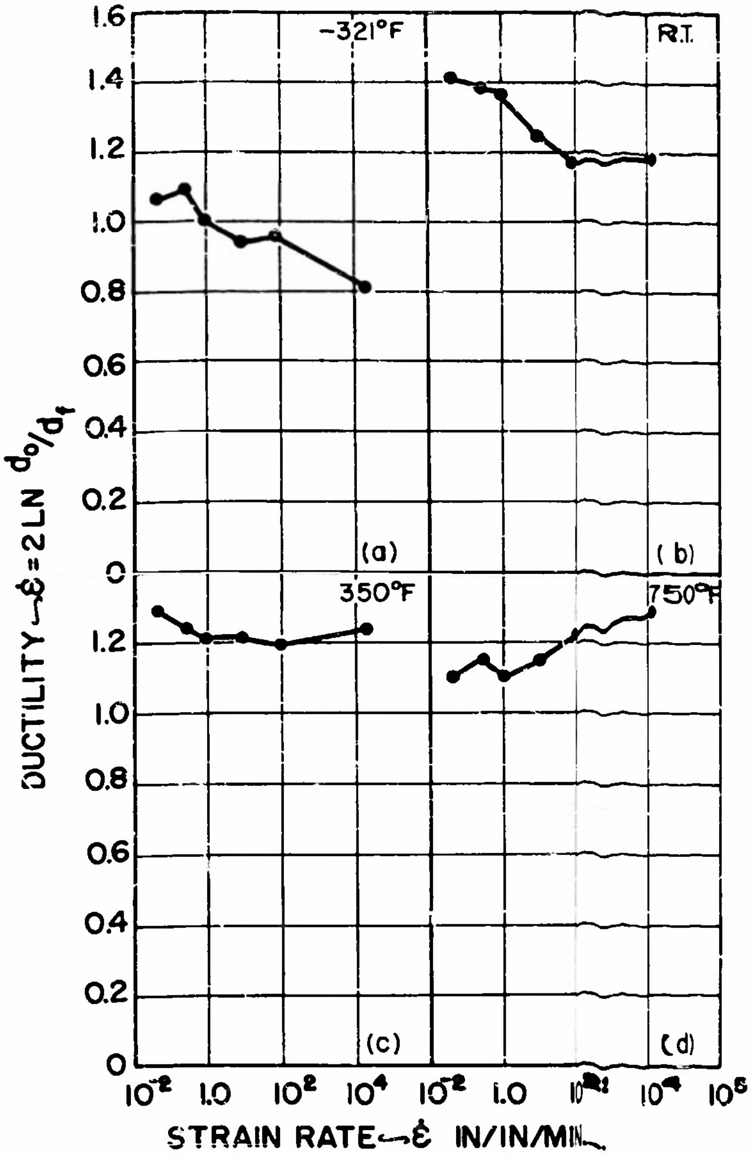

FIG. 9(a-d): DUCTILITY OF AISI 310 STAINLESS STEEL AS A FUNCTION OF STRAIN RATE AT VARIOUS TEST TEMPERATURES.

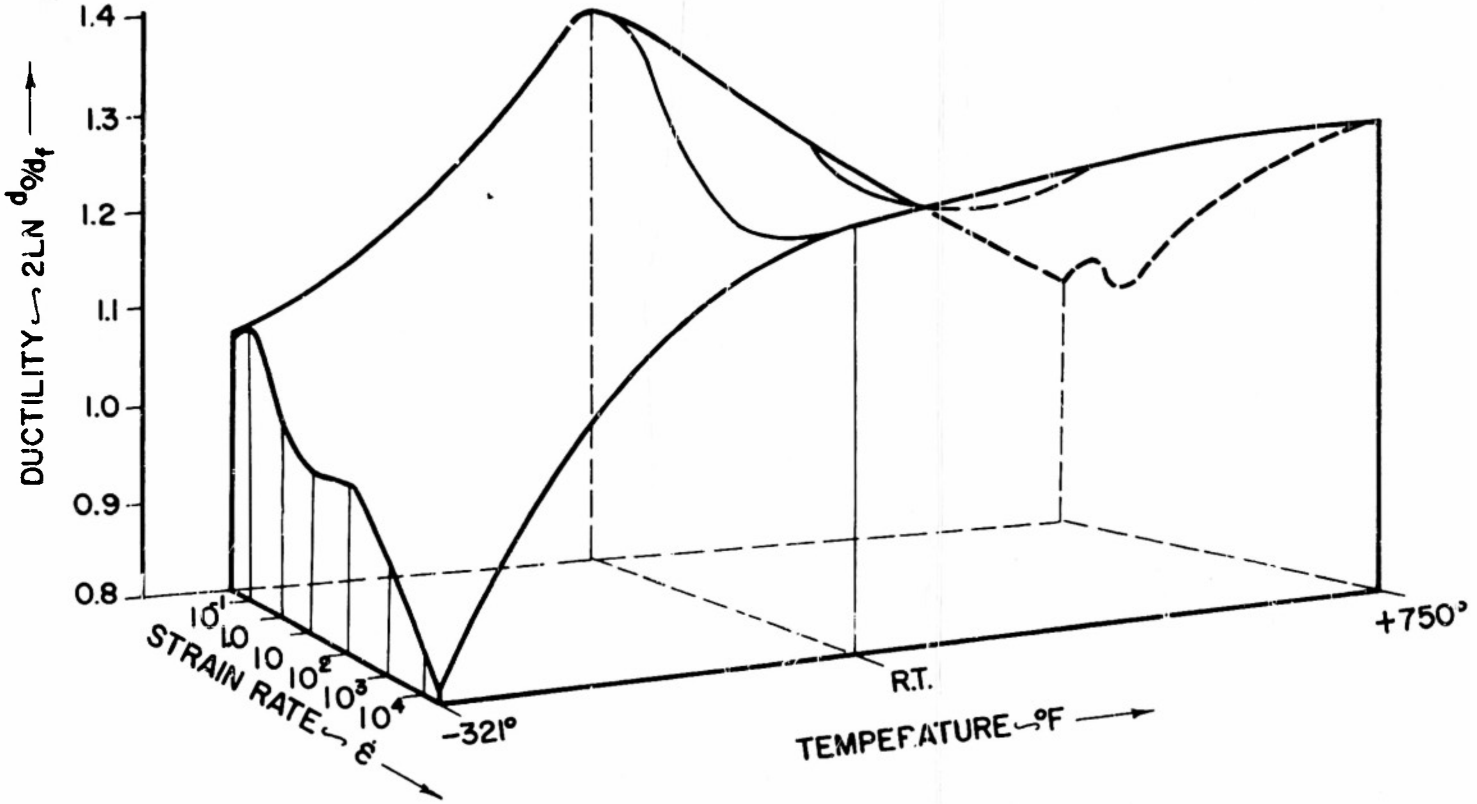

FIG. 10: DUCTILITY OF AISI 310 STAINLESS STEEL AS A FUNCTION OF STRAIN RATE AND TEST TEMPERATURE.

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