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A STUDY OF IRRADIATION EFFECTS IN TYPE "A" NICKEL AND TYPE 347 STAINLESS STEEL TENSILE SPECIMENS

by

S. H. Paine, W. F. Murphy and D. W. Hackett

Final Report of Program 6.10.2

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1. Plott, R. F., "Tensile Elastic Properties of Type 347 Stainless Steel," ANL-4316, pp. 39-40, January-March, 1949.
2. Plott, R. F., "Irradiated Specimen Measurements," ibid, p. 40.
3. Murphy, W. F., and Paine, S. H., Jr., "Effect of Irradiation Upon Certain Properties of "A" Nickel and Type 347 Stainless Steel," ANL-4507, pp. 47-56, January-March, 1950.
4. Hackett, D. W., and Paine, S. H., Jr., "Comparative Measurements on the Magne-Gage," ANL-4508, pp. 33-36, April-June, 1950.
5. Paine, S. H., Jr., and Murphy, W. F., "Effect of Irradiation Upon Nickel "A" and Type 347 Stainless Steel Tensile Specimens," ANL-4860, pp. 120-122, April-June, 1952.

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ABSTRACT

In a comparison of nickel and stainless steel subsize tensile specimens, it was found that property changes induced by irradiation to an estimated fast flux of 4 x 10^{20} nvt were qualitatively similar to those produced by cold working No basis for direct correlation was found, however. Tensile properties, elongation, hardness, density, electrical resistivity, corrosion and annealing results are presented. It was determined that irradiation left the nickel and stainless steel specimens more ductile than did cold working to a comparable ultimate strength. Radiation hardening was found to be completely removed by a one-hour anneal at 500°C, whereas temperatures of 600 to 800°C were required to anneal cold-work hardening.

A. INTRODUCTION

Early radiation damage work at ORNL indicated that the mechanical properties of structural metals could be changed appreciably by exposure in reactors. Hardnesses of certain materials were known to increase, and there were hints at such effects as stress relaxation and alteration of strength properties. At the time that austenitic stainless steels and commercially pure nickel were first considered as structural metals for Experimental Breeder Reactor I (CP-4), under design at Argonne National Laboratory, more definite information concerning irradiation effects was desired by the Reactor Engineering Division. The Metallurgy Division had similar interests, so a cooperative study was started, based on the two specific materials, Type A nickel and Type 347 stainless steel. The major work was done on small subsize tensile specimens. Results were circulated as internal memoranda and in progress reports, and some of them have appeared in project literature. Inasmuch as the study is pertinent to reactor technology, the various data obtained have been collected and critically evaluated for presentation in this final report.

B. DESCRIPTION OF SPECIMENS AND THEIR IRRADIATION

The specimens were subsize tensiles made of flat stock. This design is shown in Figure 1. As two thicknesses of material were used (0.75 and 0.020 in.), two widths of gauge were selected (0.075 and 0.250 in.) so that the total cross-sectional area would be approximately the same for all specimens.

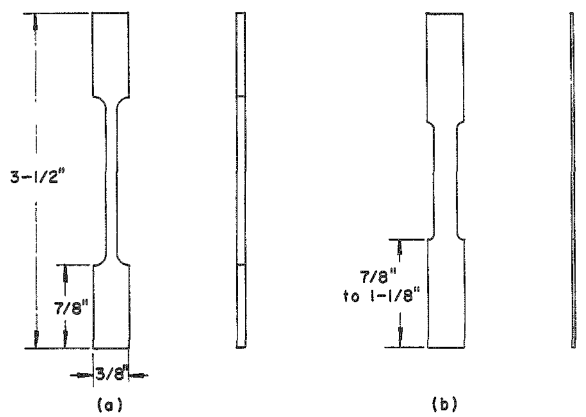


Figure 1. Design of Tensile Specimens
(a) Cross Section of gauge, 0.075" x 0.075"
(b) Cross Section of gauge, 0.020" x 0.250"

Twenty-four nickel and twenty-four stainless steel specimens were fabricated and identified, twelve each in the two thicknesses of material mentioned above. All were annealed in evacuated quartz capsules after finish machining: the nickel at 760°C for 10 minutes, followed by slow cooling, and the stainless steel at 1120°C for 10 minutes, followed by water quenching. Four hardness impressions were then taken on the grip sections of each specimen, after which half of the specimens were packed tightly with aluminum foil in the irradiation capsules and half were retained as unirradiated controls. The capsules were enclosed in hollow uranium slugs designed for enhancement of fast flux.

After a period of irradiation, all the specimens were discharged from the reactor and were returned to ANL for examination. Only half of them were subjected to tensile testing at that time, however, and the remainder were recanned and returned to the reactor for further exposure. It was intended to double the integrated flux in the latter group. However, unforeseen delays limited the second exposure to about two-thirds of that anticipated. The irradiation data are summarized in Table I.

TABLE I

IRRADIATION DATA[a]

Exposure	Capsule No.	Estimated Integrated Flux, nvt x 10^{-20}	
		Fast (>0.5 Mev)	Thermal (<0.5 Mev)
First	ANL-119 to-122	2.4	1.56
Second	ANL-163 to-165	1.6	1.04
Totals		4.0	2.6

[a]Irradiated in hollow uranium slugs.

C. POSTIRRADIATION TESTS AND MEASUREMENTS

Three each of the two gauge sizes in both nickel and stainless steel were tested after each of the reactor exposures. All control specimens were tested at the time the initial irradiated group was studied.

Indentation hardnesses were taken on Rockwell machines, using the B and 15T scales, respectively, for the two thicknesses of specimen. Electrical resistivity measurements were made on the gauge sections of the specimens by means of a Kelvin double bridge. Densities were measured by the displacement of carbon tetrachloride method. The tensile tests were made on a 1000-lb Tinius Olsen machine, with the aid of a Microformer extensometer to obtain elongation data. Broken fragments of the specimens were submitted to aqueous and liquid NaK tests at elevated temperatures, and some were also used in a rough study which was undertaken to determine the temperature range in which radiation-induced hardening could be healed. The data obtained from these tests are presented in Appendix A.

As the initial results were analyzed, it became apparent that the tensile and hardness properties had changed in a direction similar to that which is produced by cold work. It seemed, therefore, very desirable to use the same specimen design for an auxiliary study which would compare the effects of cold work with radiation-induced changes. The identical materials from which the specimens for irradiation had been made were not available. However, they were known to be of commercial grade, so comparable materials were selected from stock and given varying degrees of cold work before being fabricated into specimens. The chemical compositions of these materials varied from the original ones somewhat, as seen in Table II. Details of the fabrication procedure are given in Appendix B. All specimens made for this part of the study were 0.075 in. thick and were made to the dimensions shown in Figure 1(a).

TABLE II

Quantitative Chemical Analysis of Specimen Materials (w/o)

Element	Type A Nickel			Type 347 Stainless Steel		
	Pile Test		Cold-worked Series	Pile Test		Cold-worked Series
	s Series	r Series		s Series	r Series	
Cr				17.44	17.91	18.38
Mn	0.29	0.27	0.33	~1[a]	~1[a]	~1[a]
Fe	0.18	0.12	0.19	68.3[b]	68.6[b]	68.3[b]
Ni	99.4[b]	99.3[b]	99.3[b]	11.58	10.99	10.88
Cu	0.03	0.23	0.13			
Cb				0.96	0.79	0.72
C				0.08	0.08	0.07
Si	0.05	0.07	0.08	0.5[a]	0.5[a]	0.5[a]
P				<0.1[a]	<0.1[a]	<0.1[a]
S				0.019	0.023	0.026

[a] Spectroanalysis

[b] By difference

Testing program for the cold-worked specimens included those measurements which were made on the irradiated pieces: tensile properties (including elongation), hardness, density, electrical resistivity and change in hardness due to pulse annealing. In addition, a way was found to make a comparison of the magnetic attraction of the various specimens, and such a study was added to the pulse-annealing program. Measurements of the various properties are recorded in the tables of Appendix C. Pertinent results of these tests will be discussed in the following section.

D. DISCUSSION OF RESULTS

Property Changes in Irradiated Specimens

In Table III are summarized most of the measurements recorded in Appendix A. These averages show that irradiation to integrated fast flux levels in the order of 10^{20} nvt produced sharp changes in some of the properties and relatively minor shifts in others. Yield strength was most radically affected, with increases ranging from 250 to 500% for stainless steel and nickel, respectively, and hardness rising as much as 250% in nickel. Ultimate tensile strength was increased 50 to 70%, and there was a strong decrease in the ductility of both materials, as measured by per cent elongation. The rate of change in all these properties fell off with increased irradiation. Shifts in density and electrical resistivity were relatively minor, and there was practically no change in the corrosion resistances of either material to 600°C eutectic sodium-potassium or 260°C aerated distilled water.

The property changes of nickel proved to be appreciably greater, in the main, than those of stainless steel. Initially softer and with less strength, the nickel specimens gave property numbers after irradiation which were about equivalent to those obtained from the stainless steel. In both nickel and stainless steel the two thicknesses of material reacted alike to irradiation, except for a tendency of the thin material to show more erratic tensile changes than the heavier gauge.

Comparison of Radiation Damage with Cold Work

As has been mentioned, the auxiliary study was undertaken because radiation changes in some properties suggested the behavior which cold work was known to induce. It was recognized, of course, that a close correlation probably did not exist, inasmuch as cold work alters the macrostructure of a metal and radiation damage proceeds on a submicroscopic level. However, there is a body of information available concerning the effect of cold work upon the properties of metals, whereas radiation damage is a relatively new phenomenon, needing to be related to other known phenomena in order the better to be understood. Moreover, it is

TABLE III

Summary of Measurements of Properties of Controls and Irradiated Specimens[(a)]

Properties Measured	Type A Nickel Specimens			Type 347 Stainless Steel Specimens		
	Unirradiated	Irradiated		Unirradiated	Irradiated	
		2.4×10^{20} nvt Fast Flux	4.0×10^{20} nvt Fast Flux		2.4×10^{20} nvt Fast Flux	4.0×10^{20} nvt Fast Flux
Specimens with 0.075-in. square section						
Yield Strength YS (1000 psi)[(b)]	17.1 ± 1.0	77.7 (1)	91.2 ± 11.4(2)	33.2 ± 1.8	72.8 ± 3.2(2)	86.9 ± 1.4
Ultimate Strength UTS(1000 psi)	62.5 ± 1.7	95.3 ± 0.5(2)	106.0 ± 0.2	85.0 ± 1.5	102.9 ± 0.9	106.9 ± 0.5
Ratio YS/UTS	0.274	0.815 (1)	0.860 (2)	0.391	0.707 (2)	0.813
Percent Elongation[(c)]	33 ± 4	17 ± 1	17 ± 2	55 ± 2	34 ± 3	29 ± 2
Hardness (Rockwell B)	39.8 ± 2.6(24)	93.5 ± 0.1(12)	99.3 ± 0.3(9)	73.7 ± 0.8(24)	95.7 ± 0.2(12)	99.0 ± 0.4(9)
Density (g/cc)	8.875 ± 0.008	8.898 ± 0.003	8.866 ± 0.000	7.937 ± 0.005	7.953 ± 0.007	7.931 ± 0.003
Resistivity (μ ohm-cm)	10.45 ± 0.22(4)	10.45(1)	10.20 ± 0.15	75.28 ± 0.20(3)	76.98(1)	74.27 ± 0.15
Specimens with 0.020 x 0.250-in. Section						
Yield Strength YS(1000 psi)[(b)]	16.6 ± 2.3	82.8(1)	>61.2(1)	33.0 ± 1.1(5)	82.5 ± 1.2	83.8 ± 13.1
Ultimate Strength UTS(1000 psi)	56.0 ± 1.2	85.7 ± 0.8	89.0 ± 1.1	86.4 ± 1.6	105.8 ± 2.1	104.0 ± 1.6
Ratio YS/UTS	0.296	0.966(1)	> 0.688(1)	0.382	0.780	0.806
Percent Elongation[(c)]	45 ± 1	23 ± 4	13 ± 1	64 ± 6	37 ± 1	36 ± 2
Hardness (Rockwell 15T)	71.2 ± 2.6(24)	87.8 ± 0.5(12)	85.6 ± 1.4(9)	68.4 ± 7.0(24)	88.4 ± 0.2(12)	84.0 ± 2.6(9)
Density (g/cc)	8.885 ± 0.003	8.902 ± 0.003	8.875 ± 0.005	7.915 ± 0.012	7.965 ± 0.006	7.940 ± 0.001
Resistivity (μ ohm-cm)	9.08 ± 0.14(4)	9.31(1)	9.44 ± 0.14	74.97 ± 0.63(3)	74.88 (1)	75.59 ± 0.28

(a)Unless otherwise indicated in parentheses, averages are based on six measurements of control specimens and three measurements of irradiated specimens.

(b)Based on 0.2% offset.

(c)One-inch gauge length.

easier to fabricate and test cold-worked specimens than to deal with those which have to be placed in a reactor and then handled by remote control methods. The interest in such a collateral study is understandable in the light of these considerations.

Comparison of tables in Appendix C with the data in Table III shows that the magnitude of effect in the irradiated stainless steel specimens corresponds roughly to the changes brought about by 10 to 20% cold reduction in thickness. In nickel the effect corresponds, in different properties, to cold work all the way from 10 to 60%. Hardness and tensile properties yield the higher values, whereas elongation gives the lower. It is at once evident that a good correlation for nickel does not exist; but for stainless steel the similarities between the radiation effect and cold work are more consistent, though no direct relationship can be proved.

There is further reason for not pursuing the idea of a direct correlation between neutron dose and degree of cold work in this study. With reference to flux, the difficulties in stating accurately the magnitude of the fast component are known to be very great. On the other hand, one is faced with the knowledge that property changes produced by cold work are exceedingly arbitrary and dependent on a complex of variables which defy standardization. It seems best, therefore, after observing that there are general similarities between the changes created by these two variables, not to labor a direct correlation.

Relative Effects

A relative comparison which is not based on the flux and cold work parameters can be made, and in the case of this study, permits more fruitful conclusions than would otherwise be possible. The method used was to plot one sensitive property as a function of another and to compare the behavior of irradiated and cold-worked specimens in the same graph.

Any property, such as tensile strength or elongation, may be used as the base. In the present study, we have chosen the former, and have constructed Figures 2 and 3 to illustrate the method. The envelope curves are taken from Figures 8 and 9 of Appendix C, and represent the behavior of specimens from the cold work study. Against these have been plotted the data from all the irradiated specimens. The ratio of yield to ultimate strength is shown as solid squares and triangles, and per cent elongation appears as open polygons of similar shape. These are significant measures of changes in strength and ductility which have been produced by radiation and cold work, but it is evident that the damage parameters enter the comparison only indirectly.

Examination of Figure 2 reveals the fact that radiation changes in the elastic and ductile properties of nickel are not as radical as those produced by cold work, if the ultimate tensile strength is taken as the basis

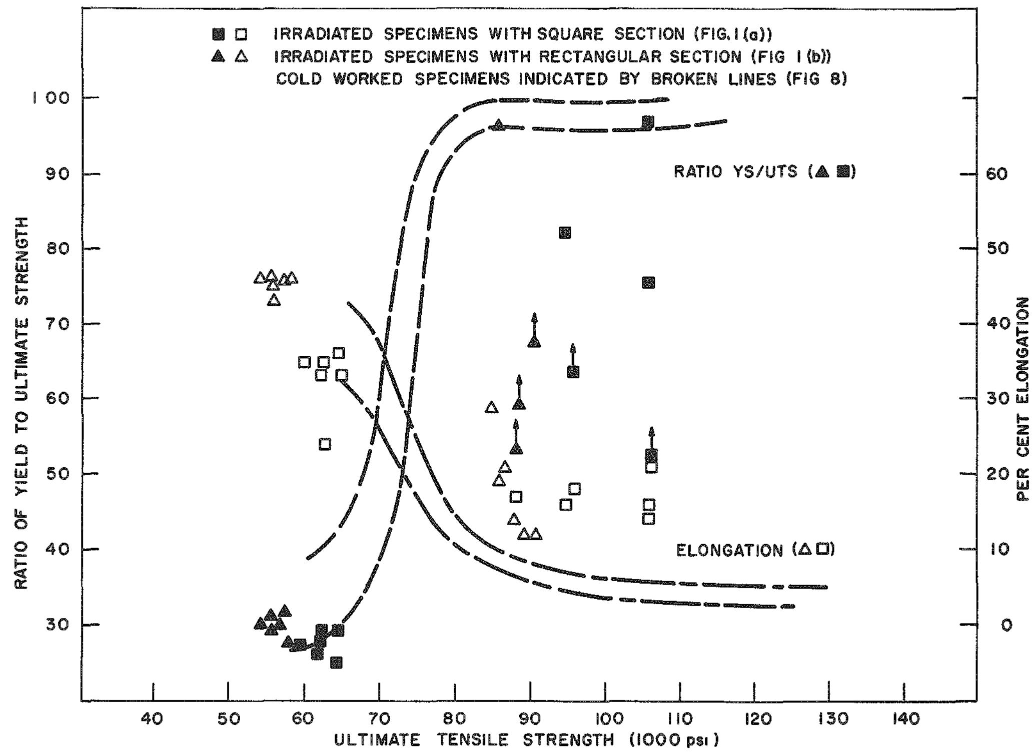


Figure 2. Comparison of Tensile Properties: Irradiated vs Cold Worked Type A Nickel.

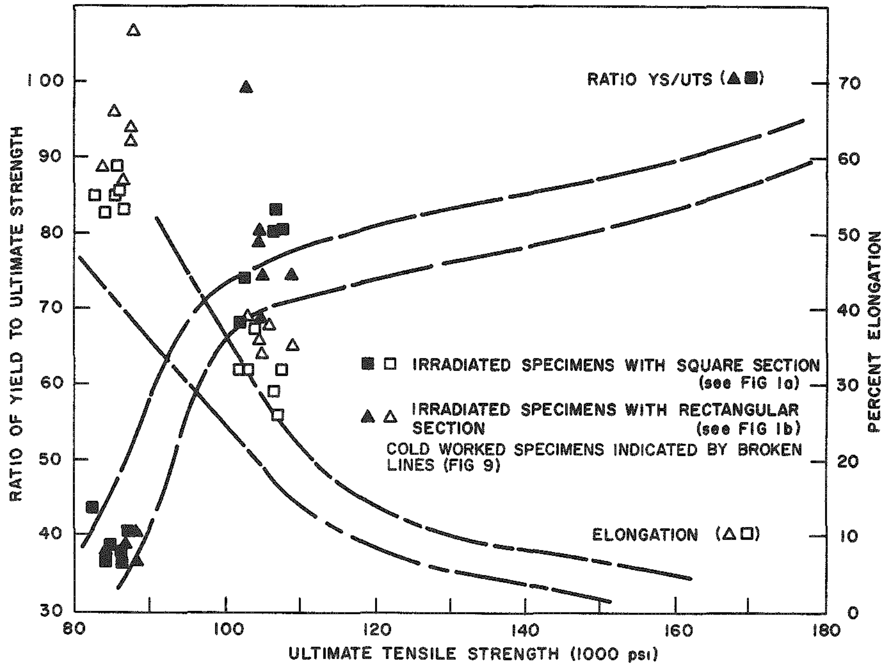


Figure 3. Comparison of Tensile Properties: Irradiated vs Cold Worked Type 347 Stainless Steel.

for comparison. Greater statistical strength in the YS/UTS data could be desired, as half of the points shown are questionable because of deficiencies in the stress-strain curves which were obtained. However, the true scatter of values probably has the cold-work envelope as its upper boundary. The elongation data are much more consistent and definitive, and show that irradiated nickel has appreciably better ductility than material cold-worked to the same ultimate strength, at least at the level reached in the present study.

The same sort of analysis of Figure 3 indicates that the ratio of yield to ultimate strength in stainless steel is increased more by radiation damage than by cold-working to a comparable strength. In this respect its behavior differs from nickel. As in nickel, however, the ductility (measured by elongation) does not suffer as much from irradiation as from cold-working to a comparable strength.

From this analysis it may be generalized that irradiation leaves both nickel and stainless steel in a more ductile condition than does cold-working to a comparable strength, and that irradiation produces an elastic range smaller in nickel and greater in stainless steel than the range resulting from cold-working to a comparable strength. It is not known whether this statement will hold for longer reactor exposures. Both the nickel and stainless steel studies could doubtless have profited by the examination of test specimens irradiated to appreciably higher flux levels.

Effect of Pulse Annealing on Hardness of Materials

A characteristic difference between radiation hardening and that produced by cold-working was demonstrated by the pulse-annealing program. Unfortunately, the annealing program for the irradiated specimens was quite skeletal (See Appendix A, Table IX). It did show, however, that radiation hardening was not removed, either in nickel or stainless steel, by one day at 400°C. It was almost entirely removed in both metals by one hour at 500°C. By contrast, 8 days at 800°C were barely sufficient to remove cold-work hardening from stainless steel, and cold-worked nickel was only slightly more tractable (See Tables XVII and XVIII, Appendix C). The implication is that the healing of radiation hardening proceeds by a narrower band and lower level of activation energy than is required for that produced by cold work. For a further discussion of the complexities seen in the annealing data from the study of cold-worked stainless steel, the reader is referred to Appendix C.

E. CONCLUSIONS

The findings of this study may be summarized as follows:

1. Irradiation to an estimated fast flux dose of 4×10^{20} nvt produced in Type A Nickel and Type 347 stainless steel tensile specimens

sharp increases in yield strength, ultimate tensile strength, ratio of yield to ultimate strength, and hardness. Elongation declined sharply. Changes in density and electrical resistivity were small, and there were no appreciable changes in corrosion resistance to 600°C NaK or to 260°C distilled water. Property changes tended to saturate as the rate of change decreased with reactor exposure.

2. The irradiation changes proved to be qualitatively similar to those induced in comparable materials by cold-working. However, no direct correlation of the effects of flux dose and degree of cold work upon the properties of the two metals was found.

3. A method of comparison based on equivalent ultimate strength has been presented, which shows that, in the specimens studied, irradiation left both nickel and stainless steel in a more ductile condition than did cold-working, and that irradiation produced an elastic range (YS/UTS ratio) smaller in nickel and greater in stainless steel than the range resulting from cold working.

4 Radiation hardening was completely removed from both nickel and stainless steel by one hour at 500°C, whereas 8 days at 800°C were barely sufficient to remove cold-work hardening from stainless steel, and cold-worked nickel was only slightly more tractable.

ACKNOWLEDGMENTS

The original tensile specimens were fabricated under the direction of D E. Walker, Metallurgy. The irradiations and aqueous corrosion work were scheduled by members of the Reactor Engineering Division of ANL. Examinations of irradiated specimens were performed by A. C. Klank, of the Metallurgy Division.

APPENDIX A

Measurements of Properties of Irradiated Specimens and of Their Controls

Tensile Properties

Tables IV and V record the data from which yield and ultimate tensile strengths have been computed. Columns have been included for remarks on the tensile behavior and for the ratio of yield to ultimate strength. Unfortunately, a nonaveraging extensometer was used, and the stress-strain curves obtained from the tests were often distorted in the lower proportional range. In these cases, however, it was usually possible to recover the yield data by assuming a constant Poisson ratio. Photographs of fractured tensile specimens are shown in Figures 4 and 5.

Computation of Per Cent Elongation

A number of the tensile specimens tested during the course of this investigation failed outside the 1-in. extensometer gauge length. It is very important to know the effect of irradiation on the ductility of structural materials; therefore, a method was sought whereby these lost data might be retrieved. The approximate equivalent elongation of these specimens has been reconstructed according to the following analysis.

In Figure 6, let x = extensometer gauge length, g = length of specimen machined to gauge dimensions, and L = overall length of specimen. Use subscript "0" to indicate original measurement. Then, let

$$g = g_0 + (L - L_0) \quad . \tag{1}$$

Also,

$$g = g_0 \, (x/x_0) + k \quad , \tag{2}$$

where k = additional increment due to necking down at point of fracture. Upon equating (1) and (2), there is obtained

$$k = (L - L_0) - g_0 \left(\frac{x}{x_0} - 1 \right) \quad . \tag{3}$$

Now, if break had occurred inside of the extensometer gauge length, x, the total elongation of this element would have been $k + (x - x_0)$.

TABLE IV

TENSILE PROPERTIES OF TYPE A NICKEL BEFORE AND AFTER IRRADIATION

Specimen No.	Integrated Fast Flux (10^{20} nvt)	Dimensions of Gauge[a] Cross Section		Load at 0.2% Offset (lb)	Breaking Load (lb)	Yield Strength, 0.2% Offset (1000 psi)	Ultimate Tensile Strength (1000 psi)	% Ratio $\frac{YS}{UTS}$	Remarks on Tensile Behavior (Stress-Strain Curves)
		Thickness(in.)	Width (in.)						
1s	2.4	0.0779 ± 0.0002	0.0731 ± 0.0002		>500		>87.8		Bent specimen. Accidentally loaded too rapidly.
2s	2.4	0.0789 ± 0.0001	0.0781 ± 0.0004	>375	590	>60.9	95.8	>63.6	Bent specimen. Proportional limit estimated.
3s	2.4	0.0764 ± 0.0002	0.0729 ± 0.0008	433	528	77.7	94.8	82.0	Bent specimen.
4s	4.0	0.0785 ± 0.0003(3)	0.0723 ± 0.0001(3)	>317	603	>55.8	106.2	>52.6	Proportional limit estimated.
5s	4.0	0.0783 ± 0.0001(3)	0.0770 ± 0.0001(3)	481	638	79.8	105.8	75.4	Bent specimen
6s	4.0	0.0789 ± 0.0001(3)	0.0721 ± 0.0001(3)	584	602	102.7	105.8	97.0	Bent specimen. Proportional limit estimated.
7s	0	0.0781 ± 0.0003	0.0787 ± 0.0007	100	380	16.3	61.9	26.3	Normal.
8s	0	0.0781 ± 0.0001	0.0776 ± 0.0004	110	378	18.2	62.4	29.1	Slightly irregular.
9s	0	0.0780 ± 0.0001	0.0781 ± 0.0005	104	378	17.1	62.1	27.5	Bent specimen.
10s	0	0.0782 ± 0.0003	0.0792 ± 0.0004	100	369	16.2	59.6	27.1	Bent specimen.
11s	0	0.0794 ± 0.0004(3)	0.0752 ± 0.0007(3)	112	386	18.8	64.6	29.0	Very irregular.
12s	0	0.0782 ± 0.0003	0.0782 ± 0.0006	98	393	16.0	64.3	24.9	Bent specimen.
1r	2.4	0.0217 ± 0.0001(3)	0.2462 ± 0.0002(3)		463		86.7		Bent specimen. Proportional limit masked.
2r	4.0	0.0220 ± 0.0001	0.2449 ± 0.0001	>282	477	>52.3	88.5	>59.1	Bent specimen. Proportional limit estimated.
3r	2.4	0.0217 ± 0.0001(3)	0.2458 ± 0.0002(3)		454		84.8		Bent specimen. Proportional limit masked.
4r	4.0	0.0214 ± 0.0001	0.2457 ± 0.0001	>322	476	>61.2	90.5	>67.7	Bent specimen. Proportional limit estimated.
5r	2.4	0.0217 ± 0.0002(3)	0.2467 ± 0.0005(3)	443	458	82.8	85.6	96.7	Bent specimen. Curve extrapolated to offset.
6r	4.0	0.0219 ± 0.0001	0.2473 ± 0.0003	>253	476	>46.7	87.9	>53.2	Bent specimen.
7r	0	0.0219 ± 0.0001	0.2467 ± 0.0005	88	302	16.3	55.9	29.1	Slightly irregular.
8r	0	0.0227 ± 0.0002	0.2479 ± 0.0003	91	304	16.2	54.0	29.9	Bent specimen. Proportional limit estimated.
9r	0	0.0219 ± 0.0000	0.2471 ± 0.0006	87	302	16.1	55.8	28.9	Normal
10r	0	0.0220 ± 0.0001	0.2470 ± 0.0006	93	302	17.1	55.6	30.8	Irregular
11r	0	0.0219 ± 0.0001	0.2462 ± 0.0002	85	311	15.8	57.7	27.3	Normal. Breaking load estimated.
12r	0	0.0222 ± 0.0002(2)	0.2462 ± 0.0003(2)	98	312	17.9	57.0	31.5	Irregular

(a) Four measurements per dimension, except as indicated in parentheses.

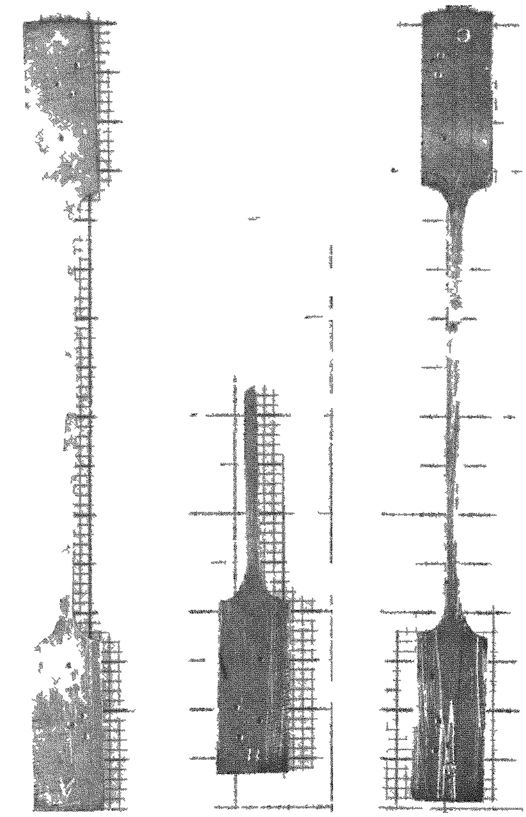
TABLE V

TENSILE PROPERTIES OF TYPE 347 STAINLESS STEEL. IRRADIATION SPECIMENS

Specimen No.	Integrated Fast Flux (10^{20} nvt)	Dimensions of Gauge[(a)] Cross Section: Thickness (in.)	Dimensions of Gauge[(a)] Cross Section: Width (in.)	Load at 0.2% Offset (lb)	Breaking Load (lb)	Yield Strength, 0.2% Offset (1000 psi)	Ultimate Tensile Strength (1000 psi)	% Ratio YS/UTS	Remarks on Tensile Behavior (Stress-Strain Curves)
As	2.4	0.0809 ± 0.0001	0.0757 ± 0.0002		638		104.2		Bent specimen. Proportional limit masked.
Bs	2.4	0.0803 ± 0.0005	0.0773 ± 0.0009	432	633	69.6	102.0	68.3	Curve extrapolated to offset.
Cs	2.4	0.0806 ± 0.0003	0.0799 ± 0.0001	490	661	76.1	102.6	74.1	Curve extrapolated to offset.
Ds	4.0	0.0801 ± 0.0001(3)	0.0750 ± 0.0000(3)	512	639	85.3	106.4	80.2	Bent specimen. Curve extrapolated to offset.
Es	4.0	0.0794 ± 0.0003(3)	0.0777 ± 0.0001(3)	535	664	86.7	107.6	80.6	Bent specimen. Curve extrapolated to offset.
Fs	4.0	0.0797 ± 0.0004(3)	0.0724 ± 0.0002(3)	512	616	88.8	106.8	83.2	Bent specimen. Proportional limit estimated.
Gs	0	0.0801 ± 0.0005	0.0737 ± 0.0005	183	496	31.0	84.0	36.9	Bent specimen. Proportional limit estimated.
Hs	0	0.0802 ± 0.0002	0.0779 ± 0.0002	205	532	32.8	85.2	38.5	Bent specimen. Proportional limit estimated.
Is	0	0.0798 ± 0.0002	0.0722 ± 0.0002	188	494	32.6	85.8	38.0	Bent specimen. Proportional limit estimated.
Js	0	0.0810 ± 0.0006	0.0736 ± 0.0004	188	512	31.5	85.9	36.7	Bent specimen. Proportional limit estimated.
Ks	0	0.0779 ± 0.0003	0.0752 ± 0.0005	211	482	36.0	82.2	43.8	Bent specimen. Breaking load estimated.
Ls	0	0.0782 ± 0.0003	0.0763 ± 0.0003	210	517	35.2	86.6	40.6	Bent specimen. Breaking load estimated.
Ar	4.0	0.0212 ± 0.0001(3)	0.2469 ± 0.0005(3)	375	547	71.6	104.5	68.6	Bent specimen. Curve extrapolated to offset.
Br	2.4	0.0211 ± 0.0003	0.2453 ± 0.0005	435	540	84.0	104.4	80.5	Bent specimen. Curve extrapolated to offset.
Cr	2.4	0.0210 ± 0.0001	0.2463 ± 0.0004	420	562	81.2	108.7	74.7	Curve extrapolated to offset.
Dr	2.4	0.0211 ± 0.0002	0.2467 ± 0.0007	428	543	82.2	104.3	78.8	Slightly irregular.
Er	4.0	0.0211 ± 0.0000(3)	0.2471 ± 0.0009(3)	406	546	77.9	104.7	74.4	Bent specimen. Curve extrapolated to offset.
Fr	4.0	0.0212 ± 0.0001(3)	0.2470 ± 0.0007(3)	534	538	102.0	102.7	99.3	Bent specimen. Accidentally loaded too rapidly
Gr	0	0.0212 ± 0.0001	0.2460 ± 0.0007	174	450	33.4	86.3	38.7	Bent specimen.
Hr	0	0.0208 ± 0.0001	0.2456 ± 0.0010		447		87.5		Bent specimen. Proportional limit masked.
Ir	0	0.0215 ± 0.0001	0.2477 ± 0.0006	172	453	32.3	85.1	38.0	Bent specimen.
Jr	0	0.0211 ± 0.0002	0.2476 ± 0.0012	168	460	32.2	88.0	36.5	Bent specimen
Kr	0	0.0219 ± 0.0005	0.2472 ± 0.0005	175	453	32.3	83.7	38.6	Bent specimen. Breaking load estimated.
Ir	0	0.0208 ± 0.0001	0.2466 ± 0.0010	180	449	35.1	87.6	40.1	Bent specimen. Breaking load estimated.

(a) Four measurements per dimension, except as indicated in parentheses.

(a)



(b)

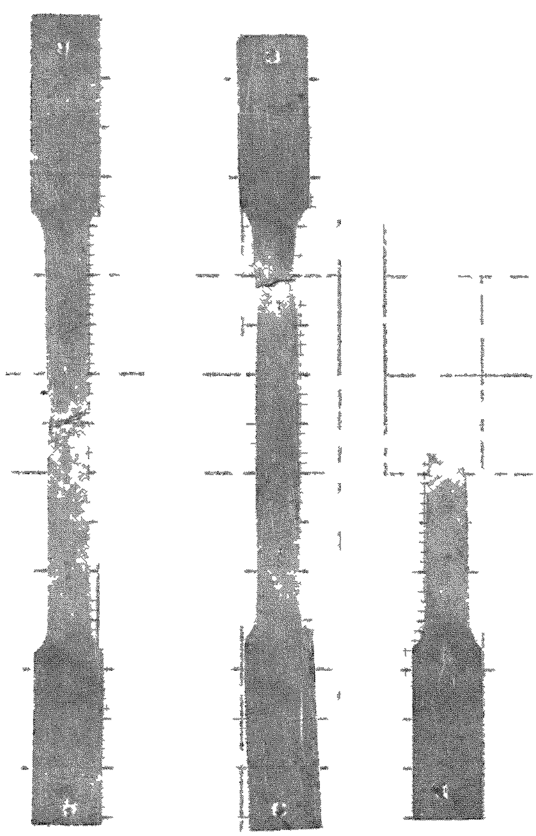


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Figure 4. Photographs of Nickel Specimens after Fracture.

a) Gauge Cross Section, 0.075 x 0.075 in.

b) Gauge Cross Section, 0.020 x 0.250 in.

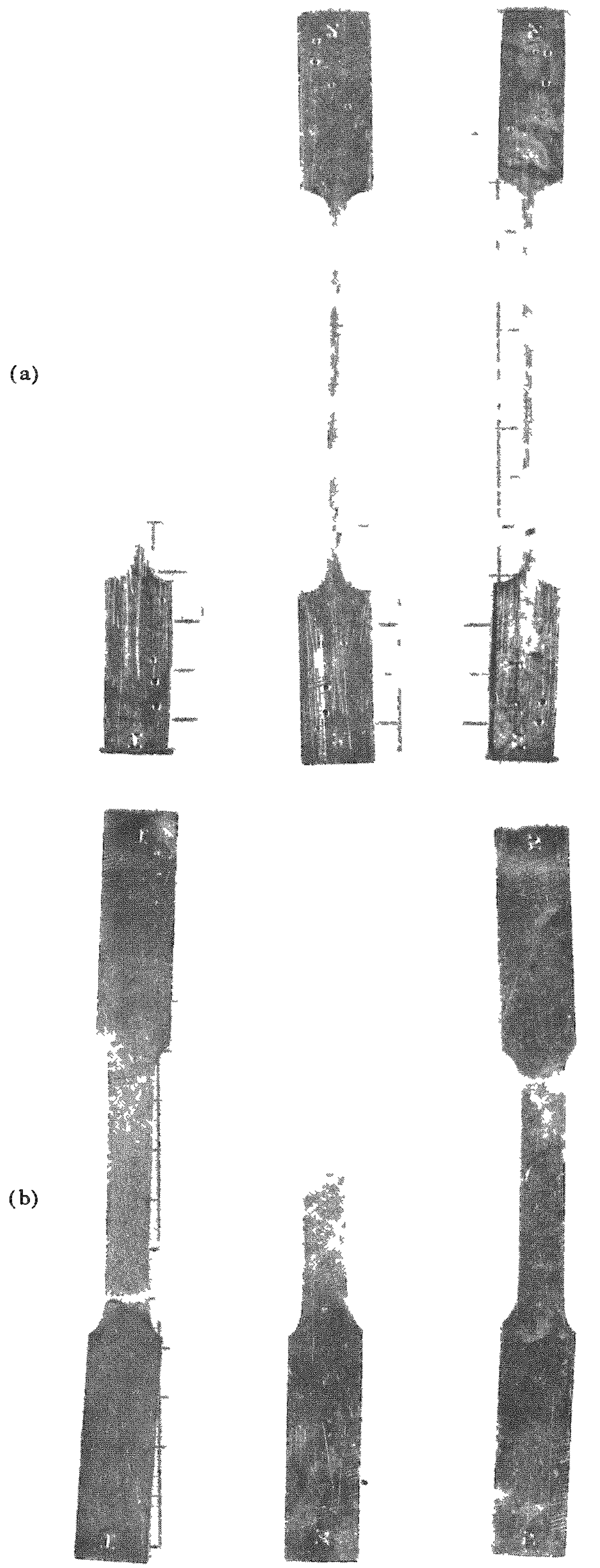

Figure 5. Photographs of Stainless Steel Specimens after Fracture.
(a) Gauge Cross Section, 0.075 x 0.075 in.
(b) Gauge Cross Section, 0.020 x 0.250 in.

M-4774, 4773 1X

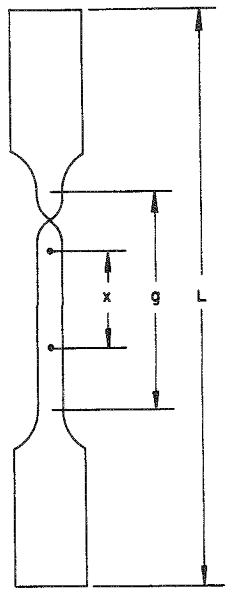

Figure 6. Diagram of Specimen Broken Outside Extensometer Gauge.

Therefore,

$$\%\,\text{Elongation} = 100\left[\frac{k + (x - x_0)}{x_0}\right] = 100\left[\frac{(L - L_0) - g_0\left(\frac{x}{x_0} - 1\right) + (x - x_0)}{x_0}\right]. \quad (4)$$

If the original extensometer gauge is $x_0 = 1$ in., this reduces to

$$\%\,\text{Elongation} = 100[(L - L_0) - (g_0 - 1)(x - 1)] \quad (4a)$$

Four specimens broke on the gauge mark. This circumstance calls for a slight modification of the above development, and the resulting corrections are somewhat smaller than those obtained by use of equation (4a). All data are listed in Tables VI and VII.

Hardness

Table VIII gives the averaged hardness data, together with their standard deviations. The effect of various annealing times upon the hardnesses of irradiated specimens is shown in Table IX.

Density and Electrical Resistivity.

Density data are given in Table X. Table XI records the values of specific electrical resistivity computed from the resistance and geometry of each specimen. Some of the thin specimens had gauge lengths somewhat shorter than the distance between potential contacts for the Kelvin Bridge. In these cases a correction has been applied to take account of the non-standard geometry.

TABLE VI

Measurements and Computation of Elongation
in the Type A Nickel Specimens

Specimen No.	Irradiation No.	Length Measurements Before and After Irradiation (in.)						Computed Per Cent Elongation
		L_0	L	g_0	g	x_0	x	
		0.075 x 0.075-in. Cross Section						
1s[a]	1	3.53	3.74	1.50		1.00	1.08	17
2s[a]	1	3.53	3.78	1.50		1.00	1.13	18
3s[a]	1	3.53	3.77	1.50		1.00	1.16	16
4s[a]	2	3.53	3.83	1.50	1.82	1.00	1.18	21
5s[a]	2	3.53	3.74	1.51	1.71	1.00	1.09	16
6s[a]	2	3.53	3.72	1.53	1.69	1.00	1.11	14
7s[a]	c	3.53	4.00	1.50		1.00	1.27	33
8s[a]	c	3.53	3.90	1.50		1.00	1.26	24
9s[a]	c	3.53	4.02	1.50		1.00	1.27	35
10s[a]	c	3.53	4.02	1.50		1.00	1.28	35
11s[a]	c	3.53	4.00	1.50		1.00	1.29	33
12s[a]	c	3.53	4.02	1.50		1.00	1.25	36
		0.020 x 0.250-in. Cross Section						
1r[b]	1	3.53	3.75	1.05		1.00	1.22	21
2r	2	3.53	3.68	1.07	1.11	1.00	1.12	12
3r	1	3.53	3.78			1.00	1.29	29
4r[b]	2	3.53	3.65	1.04	1.07	1.00	1.05	12
5r[b]	1	3.53	3.73	1.05		1.00	1.15	19
6r	2	3.54	3.68	1.04	1.08	1.00	1.14	14
7r	c	3.53	4.11			1.00	1.43	43
8r	c	3.53	4.16			1.00	1.46	46
9r	c	3.53	4.15			1.00	1.45	45
10r	c	3.53	4.16			1.00	1.46	46
11r	c	3.53				1.00	1.46	46
12r	c	3.53				1.00	1.46	46

[a] Broke outside the 1-in. gauge marks of extensometer.

[b] Broke at one of the gauge marks.

TABLE VII

Measurements and Computation of Elongation in the Type 347 Stainless Steel Specimens

Specimen No.	Irradiation No.	Length Measurements Before and After Irradiation (in.)						Computed Per Cent Elongation
		L_0	L	g_0	g	x_0	x	
		0.075 x 0.075-in. Cross Section						
As	1	3.53				1.00	1.38	38
Bs	1	3.53				1.00	1.32	32
Cs	1	3.53				1.00	1.32	32
Ds[a]	2	3.53	3.90	1.47	1.80	1.00	1.18	29
Es[a]	2	3.53	3.97	1.50	1.87	1.00	1.23	32
Fs[a]	2	3.53	3.87	1.40	1.79	1.00	1.20	26
Gs	c	3.53				1.00	1.53	53
Hs[a]	c	3.53	4.27	1.46		1.00	1.42	55
Is	c	3.53	4.27			1.00	1.59	59
Js	c	3.53	4.30			1.00	1.56	56
Ks	c	3.53				1.00	1.55	55
Ls	c	3.53				1.00	1.53	53
		0.020 x 0.250-in. Cross Section						
Ar	2	3.53	4.08	1.48	1.96	1.00	1.36	36
Br	1	3.53	4.06			1.00	1.38	38
Cr[a]	1	3.53	4.00	1.48		1.00	1.26	35
Dr	1	3.53				1.00	1.38	38
Er	2	3.54	4.08	1.48	1.97	1.00	1.34	34
Fr[b]	2	3.53	4.07	1.49	1.98	1.00	1.30	39
Gr	c	3.53				1.00	1.57	57
Hr	c	3.53	4.54			1.00	1.62	62
Ir	c	3.53	4.63			1.00	1.66	66
Jr[a]	c	3.53	4.58	1.48		1.00	1.56	77
Kr	c	3.53				1.00	1.59	59
Lr	c	3.53				1.00	1.64	64

(a) Broke outside the 1-in. gauge marks of extensometer.

(b) Broke at one of the gauge marks.

TABLE VIII

Hardness of Specimens Before and After Irradiation[(a)]

Type A Nickel					
Specimen No.	Irradiation No.[(b)]	Hardness R-B	Specimen No.	Irradiation No.[(b)]	Hardness R-15T
1s	1	93.6 ± 0.3	1r	1	87.7 ± 0.8
2s	1	93.5 ± 0.3	2r	2	83.7 ± 2.7(3)
3s	1	93.4 ± 0.4	3r	1	87.2 ± 1.1
4s	2	99.7 ± 0.4(3)	4r	2	86.1 ± 1.7(3)
5s	2	99.2 ± 0.4(3)	5r	1	88.4 ± 0.8
6s	2	99.1 ± 0.1(3)	6r	2	87.1 ± 2.1(3)
7s	c	36.4 ± 1.9	7r	c	69.5 ± 1.0
8s	c	41.3 ± 2.0	8r	c	70.0 ± 0.8
9s	c	39.0 ± 2.6	9r	c	69.3 ± 2.1
10s	c	37.1 ± 0.9	10r	c	71.1 ± 0.2
11s	c	43.9 ± 3.5	11r	c	70.3 ± 1.4
12s	c	41.4 ± 2.0	12r	c	76.9 ± 1.6
Type 347 Stainless Steel					
As	1	95.8 ± 0.1	Ar	2	80.6 ± 2.2(3)
Bs	1	95.8 ± 0.5	Br	1	88.7 ± 0.6
Cs	1	95.4 ± 0.2	Cr	1	88.3 ± 0.6
Ds	2	99.1 ± 0.5(3)	Dr	1	88.2 ± 0.9
Es	2	99.3 ± 0.4(3)	Er	2	84.6 ± 1.2(3)
Fs	2	98.5 ± 0.5(3)	Fr	2	86.9 ± 0.8(3)
Gs	c	74.4 ± 1.1	Gr	c	60.9 ± 10.1
Hs	c	72.2 ± 1.8	Hr	c	60.0 ± 6.1
Is	c	74.9 ± 0.9	Ir	c	74.5 ± 3.6
Js	c	73.8 ± 2.0	Jr	c	65.7 ± 1.8
Ks	c	73.7 ± 0.4	Kr	c	79.6 ± 1.2
Ls	c	73.0 ± 2.6	Lr	c	69.7 ± 7.0

(a) Averages obtained from four measurements, except as indicated otherwise in parentheses.

(b) Irradiation No. 1 refers to flux of integrated 2.4×10^{20} nvt; Irradiation No. 2 refers to integrated flux of 4.0×10^{20} nvt (fast); c refers to unirradiated controls.

TABLE IX

Effect of Annealing on Hardness of Irradiated Specimens

Rockwell Hardness Scale	Specimen No.	Time Annealed at 200°C[a]		Specimen No.	Time Annealed at 400°C	
		1 day	8 days		1 day[a]	8 days[b]
		Type A Nickel				
B	1s	94.4 ± 0.7	96.8 ± 0.7	2s	93.0 ± 0.4	78.4 ± 0.7
15T	1r	87.7 ± 0.5	88.8 ± 0.7	3r	88.8 ± 0.5	85.8 ± 1.3(4)[c]
		Type 347 Stainless Steel				
B	As	95.8 ± 0	97.2 ± 0.8	Cs	93.0 ± 0.2	88.0 ± 0.7
15T	Br	89.8 ± 0.2	89.9 ± 0.1	Cr	90.0 ± 0	87.3 ± 1.2(4)
Rockwell Hardness Scale	**Specimen No.**	**Time Annealed at 500°C**		**Specimen No.**	**Time Annealed at 600°C**	
		1 hr			1 day[a]	8 days[d]
		Type A Nickel				
B	1s	46.3 ± 0.6		3s	46.0 ± 2.7	45.3 ± 0.5
15T	1r	71.6 ± 0.1		5r	70.1 ± 2.1	67.2 ± 1.4
		Type 347 Stainless Steel				
B	As	77.0 ± 1.7		Bs	79.2 ± 1.2	80.8 ± 0.9
15T	Ar	81.8 ± 0.1		Dr	81.4 ± 0.8	81.4 ± 0.5

(a) ± 12°C

(b) 379 ± 33°C, with short periods as high as 440°C.

(c) All numbers are the average of 3 readings, except as indicated otherwise in parentheses.

(d) 594 ± 3°C.

TABLE X

Density Measurements[a]

0.075 x 0.075-in. Cross Section			0.020 x 0.250-in. Cross Section		
Specimen No.	Irradiation No.	Density (g/cc)	Specimen No.	Irradiation No.	Density (g/cc)
Type A Nickel Specimens					
1s	1	8.901	1r	1	8.898
2s	1	8.894	2r	2	8.872
3s	1	8.898	3r	1	8.906
4s	2	8.866	4r	2	8.870
5s	2	8.866	5r	1	8.903
6s	2	8.866	6r	2	8.882
7s	c	8.879	7r	c	8.889
8s	c	8.860	8r	c	8.884
9s	c	8.878	9r	c	8.882
10s	c	8.878	10r	c	8.883
11s	c	8.873	11r	c	8.883
12s	c	8.884	12r	c	8.888
Type 347 Stainless Steel Specimens					
As	1	7.962	Ar	2	7.939
Bs	1	7.948	Br	1	7.971
Cs	1	7.948	Cr	1	7.957
Ds	2	7.928	Dr	1	7.968
Es	2	7.932	Er	2	7.941
Fs	2	7.934	Fr	2	7.939
Gs	c	7.933	Gr	c	7.907
Hs	c	7.942	Hr	c	7.925
Is	c	7.943	Ir	c	7.926
Js	c	7.940	Jr	c	7.928
Ks	c	7.930	Kr	c	7.898
Ls	c	7.932	Lr	c	7.907

[a] One measurement per specimen.

TABLE XI

Electrical Resistivity Measurements

Type A Nickel Specimens			Type 347 Stainless Steel Specimens		
Specimen No.	Irradiation No.	Specific Resistance (μ ohm-cm)	Specimen No.	Irradiation No. (a)	Specific Resistance (μ ohm-cm)
		0.075 x 0.075-in. Cross Section			
2s	1	10.45	As	1	76.98
4s	2	10.01	Ds	2	74.45
5s	2	10.38	Es	2	74.08
6s	2	10.20	Fs	2	74.25
7s	c	10.33	Hs	c	75.41
8s	c	10.27	Is	c	73.44
9s	c	10.39	Js	c	77.00
10s	c	10.82			
		0.020 x 0.250-in. Cross Section			
1r	1	9.31	Ar	2	75.32
2r	2	9.60	Cr	1	74.88
4r	2	9.27	Er	2	75.49
6r	2	9.46	Fr	2	75.97
7r	c	9.00	Hr	c	74.53
8r	c	9.32	Ir	c	75.87
9r	c	9.01	Jr	c	74.53
10r	c	9.00			

(a) Tests on controls (c) were made at 26-27°C; tests on Irradiation No. 2 at 24-25°C.

Corrosion Test in Sodium-Potassium Alloy.

Broken halves of nickel and stainless steel specimens were tested for corrosion resistance in 600°C eutectic sodium-potassium alloy. The test lasted 6 days, and included irradiated and unirradiated specimens in both gauge cross sections as well as in both materials. Measurements consisted of careful weighing before and after the test. Results are given in Table XII.

TABLE XII

Weights of Corrosion Specimens Before and After Heating in NaK

Code	Cross Section (Gauge Section) (in.)	Condition	Weight (gm)		
			Before	After	Change
		Type 347 Stainless Steel			
Is	0.075 x 0.075	Unirradiated	4.0631	4.0635	+0.0004
As	0.075 x 0.075	Irradiated	4.0425	4.0428	+0.0003
Hr	0.020 x 0.250	Unirradiated	1.7414	1.7421	+0.0007
Cr	0.020 x 0.250	Irradiated	1.0567	1.0567	0.0000
		Type "A" Nickel			
#8s	0.075 x 0 075	Unirradiated	5.1769	5.1767	-0.0002
#3s	0.075 x 0.075	Irradiated	3.9307	3.9303	-0.0004
#7r	0.020 x 0.250	Unirradiated	1.5920	1.5928	+0.0008
#5r	0.020 x 0.250	Irradiated	1.4831	1.4831	0.0000

A dark film was found on the stainless steel specimens after the test. The film was rubbed off before weighing; the slight increases registered on the balance may be due to residual film on the metal, although all specimens appeared as clean as before the test. Three of the nickel specimens lost weight. whereas the fourth, a control specimen, seemed to gain slightly None of the changes equaled a milligram, and it was concluded that all are insignificant.

Aqueous Corrosion Test.

A similar group of broken tensile specimens was tested for aqueous corrosion resistance in the X-10 Reactor at Oak Ridge for a period of two weeks. The loop contained distilled water at 260°C (500°F), having 8 cc of O_2 per liter, a pH of 6.7, and a specific resistivity of 1.43 x 10^5 ohm-cm.

From Table XIII it can be seen that the corrosion rates for all the samples were small Only the stainless steel data showed any difference between control and irradiated specimens, and this was registered as a decrease of rate during irradiation. It appears, therefore, that irradiation does not induce in annealed austenitic steel any marked susceptibility toward precipitation of ferrite

TABLE XIII

Weights of Specimens Before and After Aqueous Corrosion Test

Code	Cross Section (Gauge Section) (in.)	Condition	Weight (gm)			Corrosion Rate ($mg/cm^2/m$)
			Before	After	Change	
		Type 347 Stainless Steel				
Gs	0.075 x 0.075	Unirradiated	5.1594	5.1585	-0.0009	-0.09
Bs	0.075 x 0.075	Irradiated	5.1403	5.1390	-0.0013	-0.14
Gr	0.020 x 0.250	Unirradiated	1.6426	1.6421	-0.0005	-0.05
Dr	0.020 x 0.250	Irradiated	1.6233	1.6215	-0.0018	-0.17
		Type "A" Nickel				
#12s	0.075 x 0.075	Unirradiated	5.1594	5.1575	-0.0019	-0.20
#1s	0.075 x 0.075	Irradiated	5.0133	5.0123	-0.0010	-0.10
#12r	0.020 x 0.250	Unirradiated	1.9620	1.9605	-0.0015	-0.14
#2r	0.020 x 0.250	Irradiated	1.8374	1.8353	-0.0021	-0.20

APPENDIX B

Fabrication of Cold-worked Material and Specimens

Type A Nickel

The following fabrication schedule was used on $1\frac{1}{4}$-in. round bar stock, flat rolling only:

1. Heat at 600°C for 30 min. Roll to 0.750 in. in several passes.
2. Reheat at 600°C for 30 min. Roll to 0.400 in. in several passes.
3. Cold roll to 0.375 in. Anneal at 625°C for 1 hr.
4. Machine stock to the following thicknesses: 0.075, 0.079, 0.083, 0.094, 0.125, 0.188, 0.375 in. Pieces were 1.54 in. wide and 8 in. long.
5. Because of spotty hardness (R_B 58-93), reanneal at 650-700°C for 30-45 min, depending on thickness (R_B 56-62).
6. Cold roll all pieces to 0.075 in. without intermediate annealing. This produced nominal reductions in thicknesses of 0, 5, 10, 20, 40, 60 and 80%.

As-rolled hardnesses and measured reductions in thickness are given in Appendix C. The various strips of stock were sheared into pieces slightly greater in dimensions than the flat tensile finished size. These were stacked and ends of each group were tack welded together so that they could be machined as a single unit. After widths and gauge sections were sized, ends were machined, and the separated specimens were carefully identified by steel die marks on each end grip.

Type 347 Stainless Steel

Flat bar, $\frac{3}{8}$ x 2 in., was available in the annealed condition (R_B 85-90). It was fabricated as follows:

1. Cut to 8-in. lengths. Machine to the following thicknesses: 0.075, 0.079, 0.083, 0.094, 0.125, 0.188 and 0.375 in.
2. Cold roll all pieces to 0.075 in. without intermediate annealing. This produced nominal reductions in thicknesses of 0, 5, 10, 20, 40, 60 and 80%.

Tensile specimens were fabricated by the same procedure as used with the nickel pieces. It was determined by careful testing that welding of the blanks into groups for machining created only local change of hardness. Enough extra stock was left, so that the affected material was entirely removed when the end welds were machined off.

APPENDIX C

Measurements of Properties of Cold-worked Specimens

Tensile Properties

In Tables XIV and XV are listed the yield and ultimate strength values of the nickel and stainless steel cold-worked specimens, together with test data from which they have been computed. Plotting the ultimate strength data against degree of cold work gives the characteristic curves shown in Figure 7. It will be observed by examining the tables and figure that there is considerable scatter in the percent reduction of thickness data associated with those specimens having lower amounts of cold work. A lack in uniformity of fabrication caused this. Dimensions of the pieces of stock prepared for rolling were such that four were required to provide sufficient material for specimens with 5 and 10% reductions. Apparently the rolling draft was not exactly duplicated for these reductions.

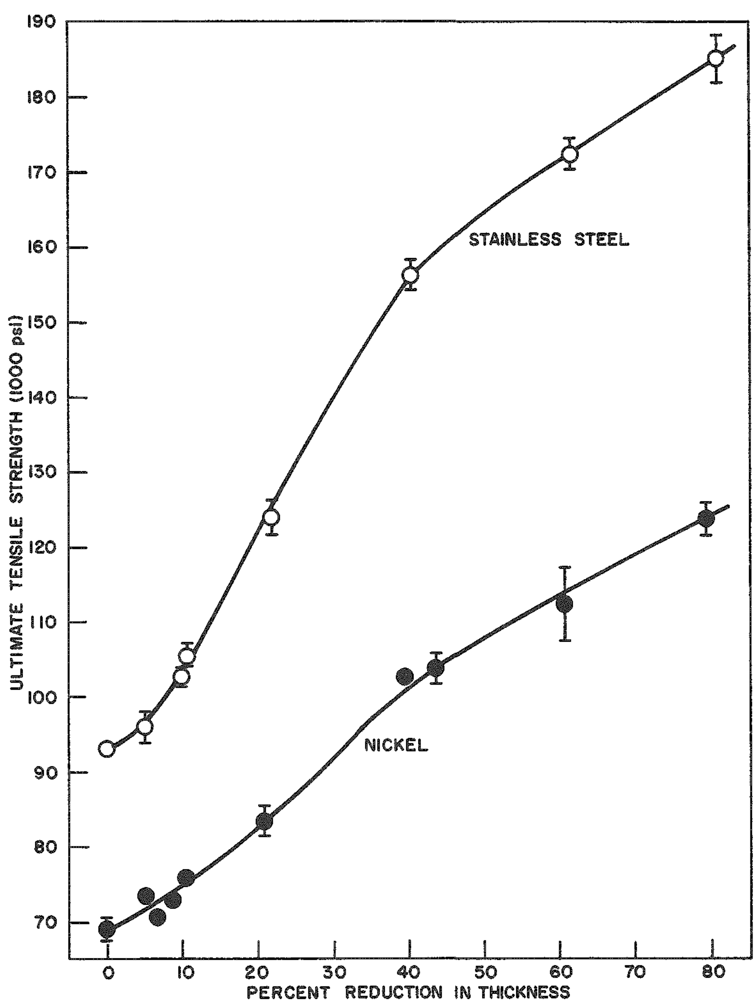

Figure 7
Effect of Cold Work on Ultimate Tensile Strength of Type A Nickel and Type 347 Stainless Steel.

TABLE XIV

Tensile Properties of Cold-worked Type A Nickel Specimens

Reduction in Thickness[a] (%)	Dimensions of Gauge Cross Section Thickness (in.)	Width (in.)	Load at 0.2% Offset (lb)	Breaking Load (lb)	Yield Strength 0.2% Offset (1000 psi)	Ultimate Tensile Strength psi	% Ratio YS/UTS	Elongation (%)[c]
0.0 (0.0)	0.0672	0.0730	156	344	30.5	67.3	45.4	31
	0.0658	0.0738	154	340	30.8	68.1	45.3	29
	0.0679	0.0749	146	364	27.9	69.5	40.2	32
	0.0680	0.0752	139	372	26.5	70.8	37.4	35
	0.0674	0.0764	147	367	27.7	69.2	40.1	37
	0.0693	0.0745	140	363	26.7	69.3	38.6	38
	0.0696	0.0707	140	362	26.9	69.7	38.7	36
	0.0672	0.0758	157	349	29.8	66.2	45.0	31
5.1 (5.0)	0.0692	0.0750	245	385	45.8	72.0	63.6	28
	0.0700	0.0752	247	400	45.8	74.2	61.8	31
5.3 (5.2)	0.0715	0.0755	264	400	48.4	73.3	66.1	23
	0.0694	0.0754	248	398	46.2	74.0	62.4	27
6.1 (5.9)	0.0700	0.0748	215	382	40.5	71.8	56.4	27
	0.0684	0.0751	255	378	48.0	71.0	67.6	27
7.4 (7.3)	0.0688	0.0762	217	382	40.3	70.8	56.9	27
	0.0673	0.0750	188	360	36.1	69.0	52.3	29
8.2 (7.9)	0.0676	0.0760	291	380	54.9	71.8	76.5	24
	0.0693	0.0752	309	388	58.2	73.1	79.6	25
9.3 (9.0)	0.0642	0.0751	284	364	57.5	73.8	77.9	23
	0.0649	0.0753	284	359	57.3	72.5	79.1	22
10.5 (10.2)	0.0682	0.0751	330	402	62.3	76.0	82.1	19
	0.0698	0.0766	357	410	66.0	75.7	87.2	18
10.6 (10.4)	0.0674	0.0752	335	392	64.0	74.9	85.5	21
	0.0694	0.0748	342	404	64.2	75.8	84.6	22
20.6 (20.0)	0.0723	0.0742	425	437	78.0	80.2	97.2	6
	0.0680	0.0759	440	446	83.0	84.2	98.6	8
	0.0667	0.0741	420	424	83.3	84.1	99.1	
20.8 (20.1)	0.0674	0.0751	426	434	82.2	83.8	98.0	8
	0.0640	0.0748	390	402	80.2	82.6	97.0	9
	0.0655	0.0750	400	411	79.6	81.7	97.3	9
21.1 (20.1)	0.0714	0.0748	461	466	85.9	86.9	98.9	7
	0.0701	0.0741	421	436	79.6	82.5	96.4	11
39.3 (38.2)	0.0698	0.0749	532	550	100.2	103.6	96.7	5
	0.0676	0.0760	534	542	100.3	101.8	98.5	4
	0.0674	0.0748	503	531	96.9	102.3	94.7	5
	0.0721	0.0752	563	571	101.2	102.6	98.6	5
43.5 (42.3)	0.0620	0.0740	473	480	99.2	100.7	98.5	4
	0.0690	0.0717	520	536	102.9	106.1	97.0	5
	0.0650	0.0729	501	510	102.3	104.0	98.3	5
	0.0620	0.0719	473	479	102.8	104.1	98.8	4
60.2 (60.0)	0.0743	0.0741	648	650	115.8	116.3	99.6	n
	0.0825	0.0750	655	678	102.1	105.6	99.7	n
	0.0740	0.0740	(b)	634		113.6		n
	0.0765	0.0750	(b)	699		119.8		5
60.8 (59.6)	0.0632	0.0751	554	572	110.8	114.4	96.9	5
	0.0670	0.0752	593	600	113.4	114.8	98.8	5
	0.0620	0.0740	538	542	110.2	111.0	99.3	n
	0.0600	0.0740		508		105.5		5
79.3 (78.1)	0.0710	0.0736	(b)	676		125.8		5
	0.0681	0.0737	(b)	641		123.0		3
	0.0675	0.0739	(b)	640		123.9		4
	0.0712	0.0740	(b)	684		126.8		4
	0.0699	0.0749	(b)	668		123.2		4
	0.0680	0.0748	(b)	657		123.4		3
	0.0653	0.0748	(b)	623		120.0		4
	0.0676	0.0738	(b)	636		122.4		3

(a) Corresponding reductions in area are given in parentheses.
(b) Data not obtained due to use of nonaveraging extensometer.
(c) One-inch gauge length; n - negligible.

TABLE XV

Tensile Properties of Cold-worked Type 347 Stainless Steel Specimens

Reduction in Thickness[a] (%)	Dimensions of Gauge Cross Section		Load at 0.2% Offset (lb)[b]	Breaking Load (lb)	Yield Strength 0.2% Offset (1000 psi)	Ultimate Tensile Strength (1000 psi)	% Ratio YS/UTS	Elongation (%)[c]
	Thickness (in.)	Width (in.)						
0.0 (0.0)	0.0731	0.0752		524		92.2		32
	0.0741	0.0748	319	520	56.6	92.2	61.3	46
	0.0729	0.0752		521		93.6		47
	0.0720	0.0738	296	507	54.1	92.7	58.4	46
	0.0748	0.0765	300	542	51.8	93.6	55.4	45
	0.0724	0.0760	317	525	56.4	93.5	60.4	46
	0.0761	0.0773		552		93.0		45
	0.0731	0.0770	270	530	47.3	92.9	50.9	43
4.8 (4.8)	0.0692	0.0755		527		99.9		36
	0.0684	0.0760		518		97.5		38
	0.0682	0.0759		511		97.0		38
	0.0669	0.0762	320	487	61.5	93.7	65.7	22
5.4 (5.4)	0.0650	0.0755	314	472	62.2	93.6	66.4	34
	0.0690	0.0755	329	506	62.5	96.2	65.0	36
	0.0712	0.0762	339	534	61.1	96.4	63.4	34
	0.0689	0.0756		502		94.8		34
9.9 (9.1)	0.0710	0.0758		563		101.4		26
	0.0716	0.0760		568		101.5		26
	0.0728	0.0756	425	589	75.4	104.4	72.2	30
	0.0730	0.0756	438	582	77.7	103.3	75.2	28
10.8 (10.2)				566		106.8		26
	0.0715	0.0756	418	590	75.5	106.5	70.9	24
	0.0705	0.0754	423	562	77.3	102.7	75.2	24
	0.0728	0.0762	424	600	74.8	105.8	70.7	26
21.9 (20.2)	0.0715	0.0761	516	676	92.0	120.5	76.4	10
	0.0708	0.0748	533	674	97.9	123.7	79.1	10
	0.0733	0.0752	601	710	106.6	126.0	84.6	10
	0.0700	0.0760	540	664	98.1	120.8	81.3	10
22.0 (20.2)	0.0740	0.0754	531	700	93.8	123.5	75.9	12
	0.0723	0.0745		700		125.2		8
	0.0725	0.0756	508	700	91.4	123.5	74.0	12
	0.0760	0.0741		725		127.7		4
40.5 (37.2)	0.0712	0.0746		844		157.0		4
	0.0726	0.0768		866		153.2		4
	0.0716	0.0743	740	858	136.1	157.9	86.2	4
	0.0735	0.0749	756	874	136.0	157.2	86.5	
	0.0721	0.0762	748	880	134.7	158.3	85.0	4
	0.0715	0.0742		854		158.3		4
	0.0711	0.0766	758	854	136.5	153.9	88.7	6
	0.0681	0.0769	690	817	130.6	154.6	84.4	6
61.4 (58.6)	0.0740	0.0762		968		171.9		n
	0.0700	0.0734	790	905	149.9	171.7	87.3	n
	0.0729	0.0756		964		173.7		n
	0.0682	0.0754	780	900	148.4	171.3	86.6	n
	0.0708	0.0750	860	944	157.8	173.1	91.1	n
	0.0680	0.0728	820	890	160.9	174.6	92.2	n
	0.0688	0.0732	823	900	158.4	173.2	91.4	n
	0.0682	0.0717	782	848	154.9	168.0	92.2	n
80.9 (77.7)	0.0715	0.0756	(d)	970		177.3		n
	0.0700	0.0750		1004		188.2		n
	0.0716	0.0717		966		185.6		n
	0.0706	0.0749		1010		187.7		n
	0.0706	0.0742		987		183.5		n
	0.0708	0.0719		964		187.3		n
	0.0706	0.0720		962		186.3		n
	0.0712	0.0715		950		184.0		n

(a) Corresponding reductions in area given in parentheses.
(b) Data frequently lost due to use of a nonaveraging extensometer.
(c) One-inch gauge; n - negligible.
(d) Data not obtained due to brittle fracture.

These tables also include columns for the ratio of yield to ultimate strength, and for percent elongation. Figures 8 and 9 show how these values are related when plotted as functions of ultimate tensile strength. A sharp transition from low to high YS/UTS ratio is seen to be virtually complete for nickel at 80,000 psi. The similar transition in stainless steel is not nearly as abrupt, and occurs at UTS about 25,000 psi higher. Decrease of percent elongation in both materials correlates with behavior of YS/UTS ratios, but in the case of stainless steel the knee of the elongation curve shows a lag of approximately 20,000 psi. Inasmuch as this type of a tensile property plot makes the degree of cold work implicit rather than explicit, it has been used in the text of the main report to provide a means of comparing radiation damage with cold work.

Hardness, Density and Electrical Resistivity

These data are presented together in Table XVI, with notations concerning the statistical strength of the averages. Figures 10 and 11 show the properties plotted as functions of cold work. The hardness property is seen to be much more sensitive to change induced by cold work than are the density and electrical resistivity.

Effect of Pulse Annealing upon Hardness

Fragments of the tensile specimens were pulse annealed at temperatures ranging from 400 to 800°C, and for times up to 8 days. Lead and salt pot furnaces were used.

Hardness data for the nickel specimens are presented in Table XVII, rounded off to whole numbers because the scatter was quite large. It is probable that surface reactions during the annealing cycles were responsible for this, although care was exercised to avoid areas which had reacted with the molten lead.

Data for the stainless steel specimens appear in Table XVIII. In general, they were more uniformly in agreement than the nickel data, and the standard deviations around the averages have been computed. Isothermal plots of the data from this table are shown in Figures 12 to 16. The data taken after the 6-hour anneal at 600°C have not been included because all specimens suddenly became uniformly soft, indicating that temperature control had failed. Materials were not available to start a duplicate set, as had been possible in the case of the 700 and 800°C studies.

The pulse-annealing results in nickel (Table XVII) may be understood in terms of stress relaxation and recrystallization. Nominal recrystallization temperature for nickel is 600°C, and it would be expected at this temperature and above that material most drastically cold worked would anneal with greatest speed.

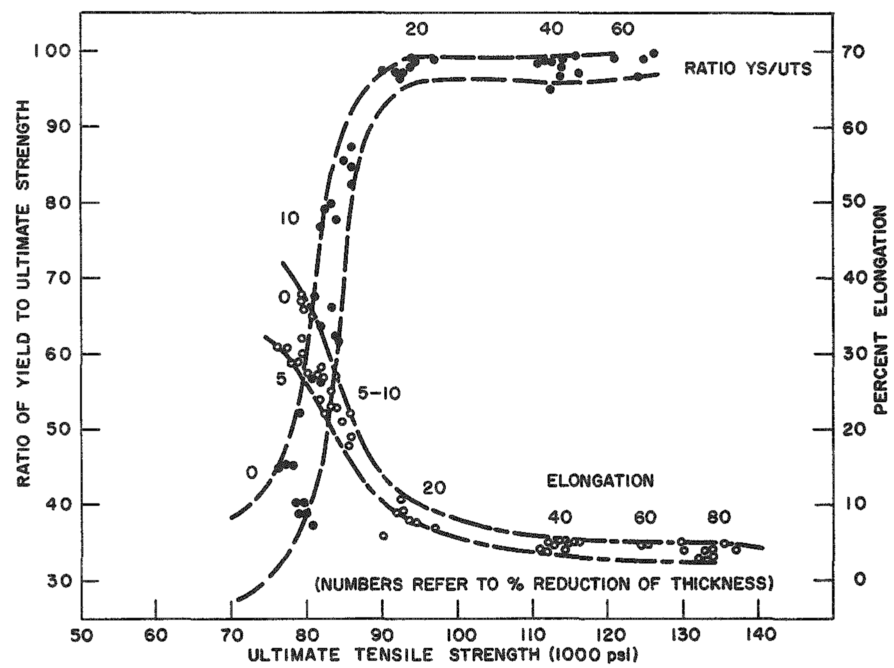

Figure 8. Effect of Cold Work on the Tensile Behavior of Type A Nickel.

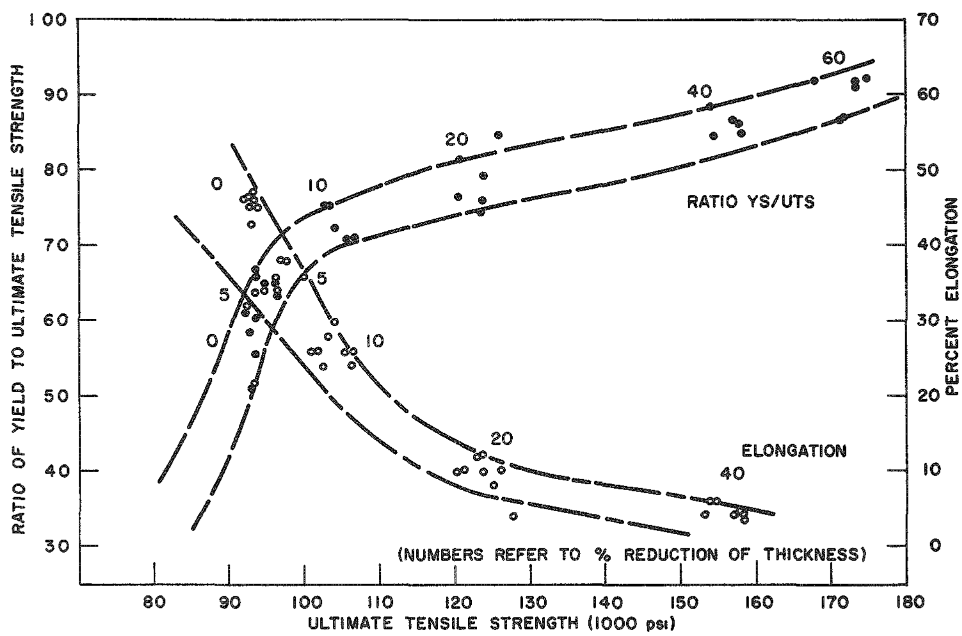

Figure 9. Effect of Cold Work on the Tensile Behavior of Type 347 Stainless Steel.

TABLE XVI

Effect of Cold Work on The Hardness, Density and Electrical Resistivity of Type A Nickel and Type 347 Stainless Steel

Reduction in Thickness (%)	Hardness		Density (g/cm^3)[c]		Electrical Resistivity[d] (μ Ω-cm)
	Rockwell A[a]	Rockwell B[b]	Two Series	Average	
			Type A Nickel		
0	38.8 ± 2.2	52.2 ± 1.7	8.8590 8.8664	8.8627 ± 0.0037	10.49 ± 1.93
5.8	46.9 ± 2.1	76.6 ± 4.5	8.8605 8.8697	8.8651 ± 0.0046	10.55 ± 0.68
9.6	52.3 ± 1.8	86.0 ± 1.8	8.8599 8.8687	8.8643 ± 0.0044	10.61 ± 0.68
20.8	57.0 ± 0.8	93.1 ± 1.3	8.8629 8.8682	8.8655 ± 0.0027	10.64 ± 0.84
41.4	60.8 ± 0.6	95.1 ± 4.7	8.8616 8.8672	8.8644 ± 0.0028	10.68 ± 0.97
60.5	60.4 ± 0.7		8.8564 8.8657	8.8611 ± 0.0047	10.76 ± 1.19
79.3	62.6 ± 0.7		8.8578 8.8682	8.8630 ± 0.0052	10.81 ± 1.14
			Type 347 Stainless Steel		
0	51.3 ± 0.9	87.6 ± 1.9	7.9099 7.9141	7.9120 ± 0.0021	76.53 ± 0.46
5.1	56.8 ± 0.7	91.9 ± 1.0	7.9095 7.9134	7.9115 ± 0.0020	76.86 ± 0.86
10.4	60.8 ± 0.7	98.4 ± 1.0	7.9081 7.9123	7.9102 ± 0.0021	76.93 ± 0.61
22.0	65.1 ± 0.4	104.3 ± 0.4	7.9055 7.9087	7.9071 ± 0.0016	77.93 ± 0.56
40.5	68.0 ± 0.9	108.3 ± 0.3	7.9007 7.9052	7.9029 ± 0.0023	77.53 ± 0.51
61.4	70.1 ± 0.9	110.3 ± 0.3	7.8950 7.9013	7.8982 ± 0.0032	77.07 ± 0.41
80.9	71.3 ± 0.2	111.8 ± 0.3	7.9066 7.9143	7.9104 ± 0.0039	79.78 ± 0.48

(a) Average of 32 measurements.
(b) Average of 16 measurements.
(c) Relative precision of the two sets is 0.01%, although deviation is ~0.05%.
(d) Average of 8 measurements.

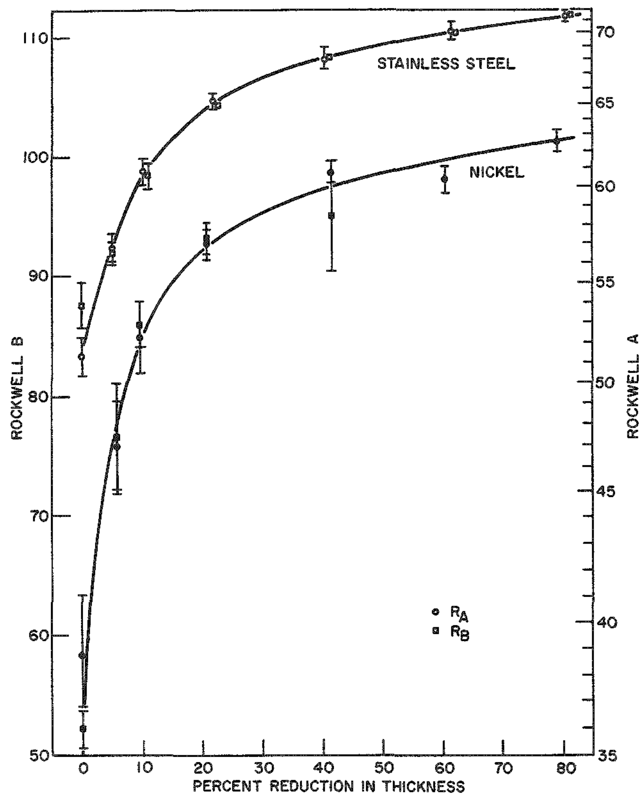

Figure 10
Effect of Cold Work on Hardness of Type A Nickel and Type 347 Stainless Steel.

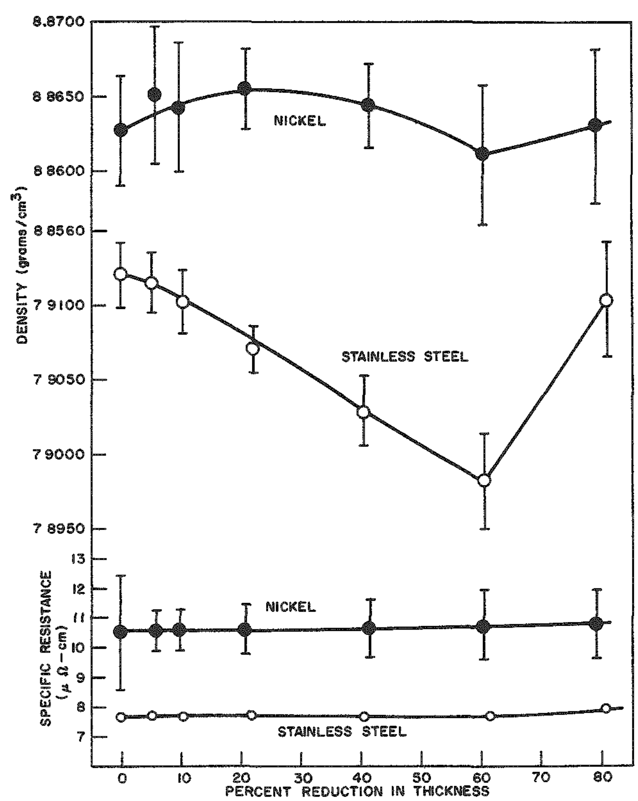

Figure 11
Effect of Cold Work on the Density and Electrical Resistivity of Type A nickel and Type 347 Stainless Steel.

TABLE XVII

Effect of Annealing on Hardness of Cold-worked Type A Nickel

Cold Work (%RT)	Rockwell A Hardness after Indicated Temperature and Time												
	as rolled	2.8 min	5.6 min	11.3 min	22.5 min	45 min	1.5 hr	3 hr	6 hr	12 hr	1 day	3 days	11 days
Annealed at 400°C													
0	38						41	40	38	40	37	36	37
5	47						47	47	45	46	45	44	44
10	55						54	54	53	52	52	50	48
20	58						58	58	56	54	54	54	51
40	62						61	61	60	59	59	58	57
60	61						62	63	62	61	61	59	58
80	62						62	63	62	61	61	59	60
Annealed at 500°C													
0	41					42	41	41	40	38	39	36	34
5	46					45	46	46	45	42	42	41	40
10	54					52	52	51	50	47	46	46	45
20	58					55	55	55	55	49	48	48	49
40	62					59	58	58	58	38	37	36	34
60	62					61	61	60	59	36	36	34	32
80	64					61	62	61	61	38	37	35	35
Annealed at 600°C													
0	39			41	41	40	36	36	39	38	32	32	
5	48			45	44	43	42	40	42	41	39	38	38
10	54			49	49	48	45	46	47	46	43	42	41
20	58			54	53	52	51	50	51	50	42	43	42
40	62			58	56	56	54	39	36	34	32	26	27
60	61			59	58	54	44	35	36	32	32	30	32
80	63			60	57	46	39	36	39	36	33	32	33
Annealed at 700°C													
0	42		40	38	38								
5	51		45	44	42								
10	53		48	47	44								
20	59		53	51	45								
40	61		35	34	31								
60	62		38	37	34								
80	64		39	38	35								
Annealed at 800°C													
0	42	40	37	36	34								
5	49	45	43	38	28								
10	53	46	36	29	26								
20	58	29	30	30	30								
40	61	32	36	34	32								
60	62	38	37	35	32								
80	64	38	37	35	33								

TABLE XVIII

Effect of Annealing on Hardness of Cold-worked Type 347 Stainless Steel

Cold Work (%RT)	Rockwell A Hardness after Indicated Temperature and Time[a]									
	as rolled	11.3 min	22.5 min	45 min	1.5 hr	3 hr	6 hr	12 hr	1 day	2 days	8 days
						Annealed at 400°C					
0	51.3 ± 1.0						53.0 ± 1.2	51.7 ± 1.2	51.8 ± 0.7	52.7 ± 0.9	52.9 ± 0.6
5	56.7 ± 0.3						57.3 ± 0.3	56.8 ± 0.4	56.2 ± 0.2	56.6 ± 0.5	56.7 ± 0.5
10	60.7 ± 0.6						61.1 ± 0.5	60.4 ± 0.6	60.2 ± 0.6	60.8 ± 0.5	61.3 ± 0.5
20	65.2 ± 0.2						66.2 ± 0.4	65.8 ± 0.9	65.3 ± 0.5	65.9 ± 0.5	66.4 ± 0.4
40	68.1 ± 0.2						69.5 ± 0.2	68.5 ± 0.6	68.7 ± 0.4	69.3 ± 0.4	69.9 ± 0.2
60	69.8 ± 0.3						71.7 ± 0.4	71.6 ± 0.2	70.9 ± 0.3	71.2 ± 0.3	71.9 ± 0.3
80	70.9 ± 0.2						72.9 ± 0.1	72.2 ± 0.3	71.9 ± 0.2	72.4 ± 0.4	73.0 ± 0.3
						Annealed at 500°C					
0	51.3 ± 1.0				51.7 ± 0.9	52.2 ± 0.6	50.8 ± 0.9	51.6 ± 0.6	Not Measured	51.5 ± 0.6	51.6 ± 0.4
5	56.7 ± 0.5				57.2 ± 0.4	56.5 ± 0.5	56.4 ± 0.5	56.0 ± 0.7		56.6 ± 0.4	57.1 ± 0.4
10	61.0 ± 0.6				61.2 ± 0.8	60.8 ± 0.8	58.4 ± 1.4	59.9 ± 0.5		60.5 ± 0.6	61.1 ± 0.5
20	64.8 ± 0.3				66.3 ± 0.2	65.8 ± 0.1	64.8 ± 1.1	65.3 ± 0.4		65.1 ± 0.2	65.9 ± 0.2
40	68.1 ± 0.3				69.8 ± 0.2	69.4 ± 0.2	68.1 ± 0.9	68.9 ± 0.5		69.0 ± 0.3	69.2 ± 0.5
60	69.8 ± 0.2				71.8 ± 0.2	71.5 ± 0.4	71.3 ± 0.6	70.2 ± 0.4		71.0 ± 0.3	71.2 ± 0.3
80	71.0 ± 0.2				73.0 ± 0.1	72.1 ± 0.2	71.7 ± 0.5	71.2 ± 0.6		71.6 ± 0.4	71.9 ± 0.2
						Annealed at 600°C					
0	51.3 ± 1.0			51.2 ± 0.5	50.9 ± 0.5	49.7 ± 0.6	50.1 ± 0.2	Specimens Uniformly Soft, Probable Furnace Excursion	Specimens Uniformly Soft	Specimens Uniformly Soft	Specimens Uniformly Soft
5	56.6 ± 0.5			56.1 ± 0.6	55.7 ± 0.4	55.6 ± 0.5	55.4 ± 0.4				
10	61.0 ± 0.5			61.0 ± 0.5	60.5 ± 0.5	59.9 ± 0.9	59.8 ± 0.7				
20	64.9 ± 0.4			65.8 ± 0.4	65.0 ± 0.4	65.1 ± 0.3	64.5 ± 0.8				
40	68.0 ± 0.3			69.0 ± 0.2	68.6 ± 0.1	68.7 ± 0.5	68.1 ± 0.3				
60	69.8 ± 0.2			71.1 ± 0.2	70.5 ± 0.3	69.9 ± 0.7	69.9 ± 0.5				
80	71.0 ± 0.3			72.1 ± 0.1	71.5 ± 0.2	71.3 ± 0.4	70.0 ± 0.5				
						Annealed at 700°C					
0	51.3 ± 1.0		51.1 ± 0.4	50.8 ± 0.6	50.9 ± 0.6	52.3 ± 0.3	Specimens Spoiled by Furnace Excursion				
5	57.5 ± 0.5		56.5 ± 0.7	56.2 ± 0.9	56.0 ± 0.5	56.3 ± 0.5					
10	60.7 ± 0.7		60.1 ± 0.6	59.0 ± 0.5	60.0 ± 0.7	60.4 ± 0.7					
20	64.8 ± 0.4		64.9 ± 0.5	63.3 ± 1.6	64.1 ± 0.6	64.4 ± 0.5					
40	67.8 ± 0.3		68.3 ± 0.3	67.0 ± 0.6	67.3 ± 0.2	66.7 ± 0.5					
60	69.7 ± 0.3		69.2 ± 0.5	67.0 ± 0.5	65.6 ± 0.5	64.1 ± 0.8					
80	70.8 ± 0.2		68.9 ± 0.1	65.9 ± 0.5	64.1 ± 0.4	63.6 ± 0.7					
	(2)						(2)	(2)	(4)	(2)	(2)
0	51.9 ± 0.4						51.2 ± 0.2	50.2 ± 0.4	51.7 ± 0.3	51.2 ± 0.1	51.8 ± 0.1
5	56.6 ± 0.2						56.1 ± 0.2	55.5 ± 0.2	56.2 ± 0.2	55.3 ± 0.2	55.7 ± 0.2
10	61.3 ± 0.5						61.1 ± 0.4	60.2 ± 0.2	60.8 ± 0.3	60.3 ± 0.1	59.6 ± 0.1
20	66.0 ± 0.3						65.2 ± 0.4	65.0 ± 0.3	64.6 ± 0.2	63.5 ± 0.1	63.1 ± 0.1
40	68.2 ± 0.2						66.6 ± 0.2	60.4 ± 0.2	63.2 ± 0.4	61.3 ± 0.1	58.2 ± 0.1
60	69.7 ± 0.2						64.5 ± 0.2	60.0 ± 0.2	61.8 ± 0.2	60.4 ± 0.1	60.1 ± 0.1
80	71.1 ± 0.2						62.9 ± 0.4	61.7 ± 0.6	62.2 ± 0.2	61.4 ± 0.4	61.0 ± 0.4
						Annealed at 800°C					
0	51.3 ± 1.0	50.2 ± 0.2	49.6 ± 1.2	50.1 ± 0.2	48.0 ± 1.1	48.8 ± 0.1	50.6 ± 0.4	Specimens Spoiled by Surface Contamination.			
5	57.5 ± 0.5	55.0 ± 0.7	55.0 ± 0.6	54.3 ± 0.6	54.2 ± 0.6	53.5 ± 0.6	54.6 ± 0.5				
10	60.7 ± 0.7	58.0 ± 0.8	57.9 ± 1.3	57.6 ± 1.2	57.4 ± 0.7	56.5 ± 0.4	57.9 ± 0.7				
20	64.8 ± 0.4	62.6 ± 0.4	63.2 ± 0.3	62.5 ± 0.4	59.4 ± 1.0	57.5 ± 0.5	56.9 ± 0.6				
40	67.8 ± 0.3	62.7 ± 0.6	62.2 ± 1.1	59.0 ± 0.6	55.4 ± 1.0	55.5 ± 0.5	57.0 ± 0.7				
60	69.7 ± 0.3	60.3 ± 0.6	60.2 ± 0.3	57.8 ± 0.6	56.9 ± 0.5	56.5 ± 0.5	58.5 ± 0.5				
80	70.8 ± 0.2	60.3 ± 0.1	60.2 ± 0.5	59.5 ± 0.1	57.2 ± 0.3	57.4 ± 0.8	58.7 ± 0.5				
	(4)					(4)	(4)	(4)	(4)	(4)	(4)
0	53.8 ± 0.5					51.5 ± 0.6	51.7 ± 0.4	51.2 ± 0.4	50.5 ± 0.4	49.8 ± 0.2	50.6 ± 0.2
5	57.0 ± 0.3					53.6 ± 0.5	54.7 ± 0.6	54.0 ± 0.4	53.9 ± 0.4	52.6 ± 0.2	53.2 ± 0.6
10	60.6 ± 0.6					57.9 ± 0.8	58.2 ± 0.7	57.7 ± 0.8	58.2 ± 0.7	55.9 ± 0.3	52.4 ± 1.2
20	65.1 ± 0.3					60.0 ± 0.6	57.7 ± 0.5	54.1 ± 0.6	52.2 ± 0.7	50.1 ± 0.7	49.9 ± 0.6
40	67.8 ± 0.4					56.0 ± 0.3	56.3 ± 0.2	55.1 ± 0.3	54.8 ± 0.4	52.1 ± 0.4	51.7 ± 0.1
60	70.4 ± 0.2					57.3 ± 0.6	58.0 ± 0.2	57.0 ± 0.4	56.0 ± 0.4	53.1 ± 0.3	52.9 ± 0.3
80	71.4 ± 0.3					58.5 ± 0.3	58.7 ± 0.3	57.6 ± 0.2	56.4 ± 0.2	53.2 ± 0.5	51.8 ± 0.5

(a) Each value is the average of 6 measurements except for the replacement sets at 700°C (2) and 800°C (4).

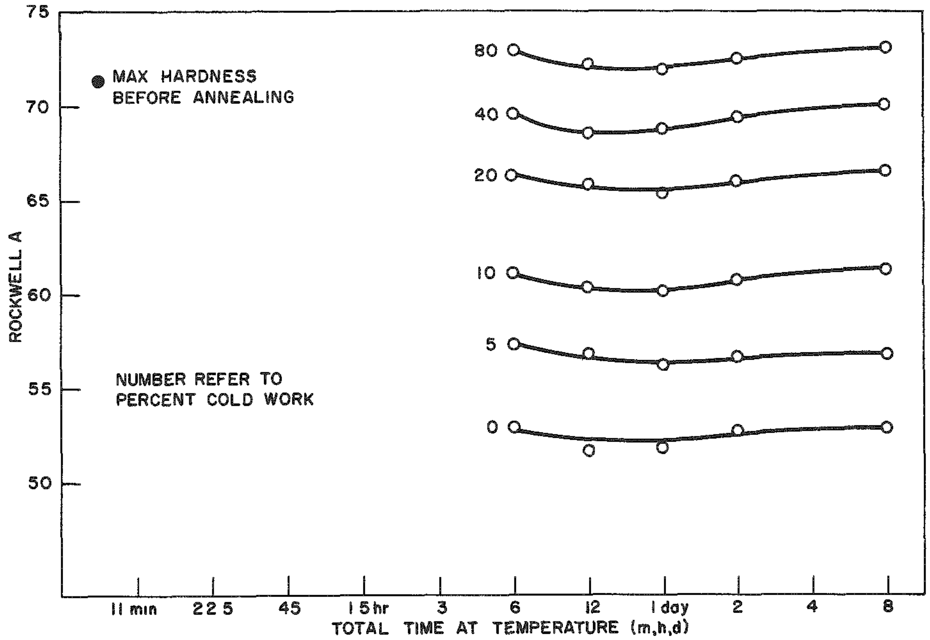

Figure 12. Effect of Pulse Annealing at 400°C on Hardness of Cold-worked Stainless Steel.

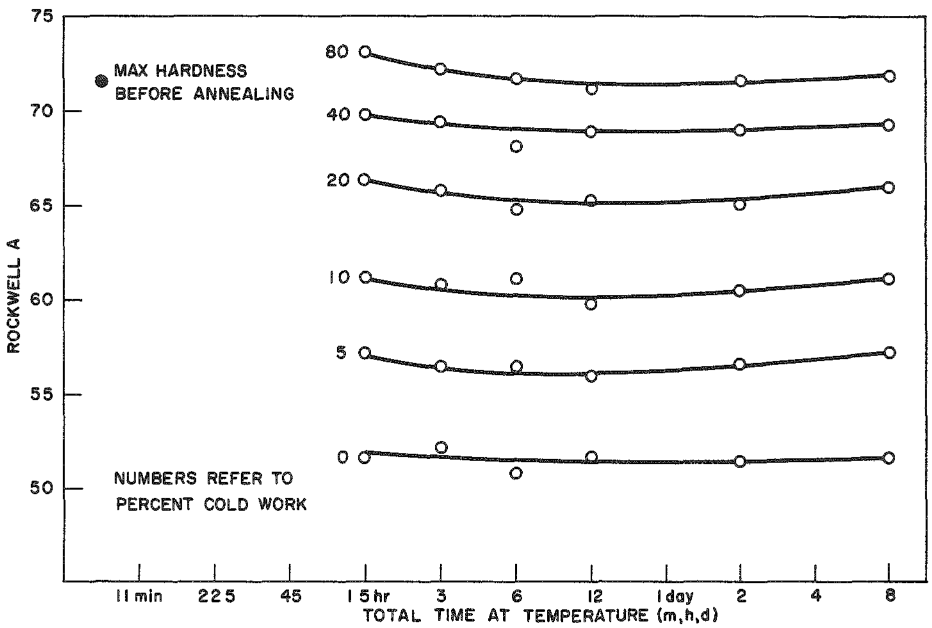

Figure 13. Effect of Pulse Annealing at 500°C on Hardness of Cold-worked Stainless Steel.

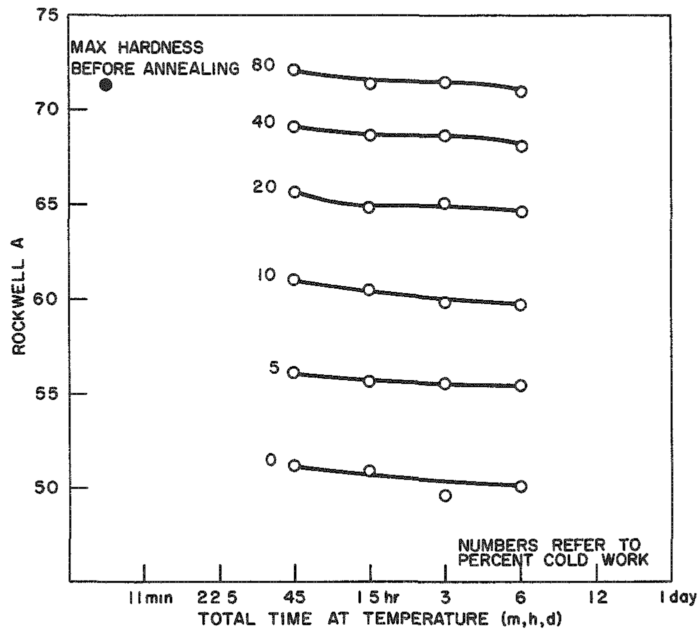

Figure 14. Effect of Pulse Annealing at 600°C on Hardness of Cold-worked Stainless Steel.

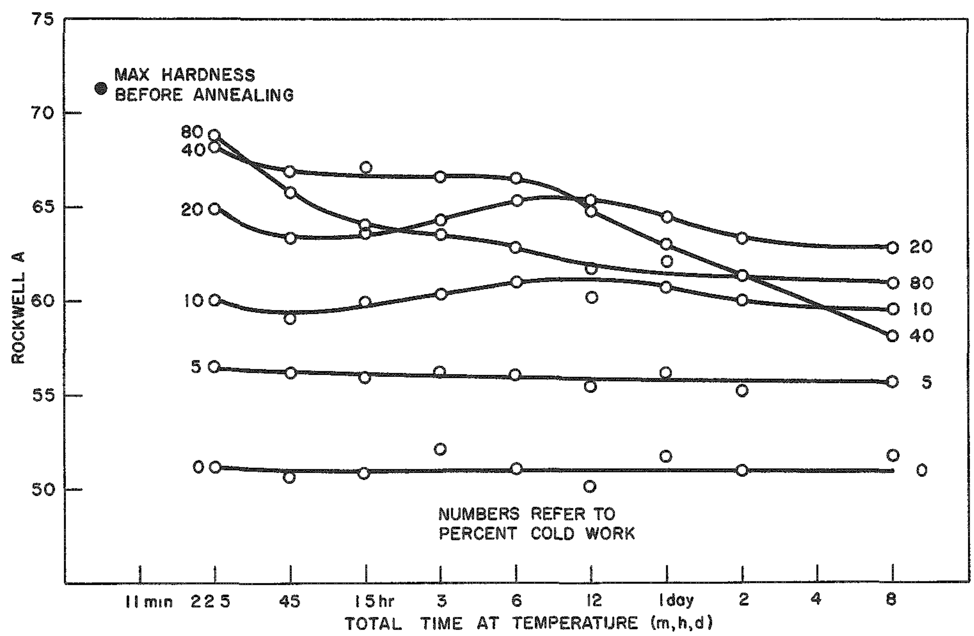

Figure 15. Effect of Pulse Annealing at 700°C on Hardness of Cold-worked Stainless Steel.

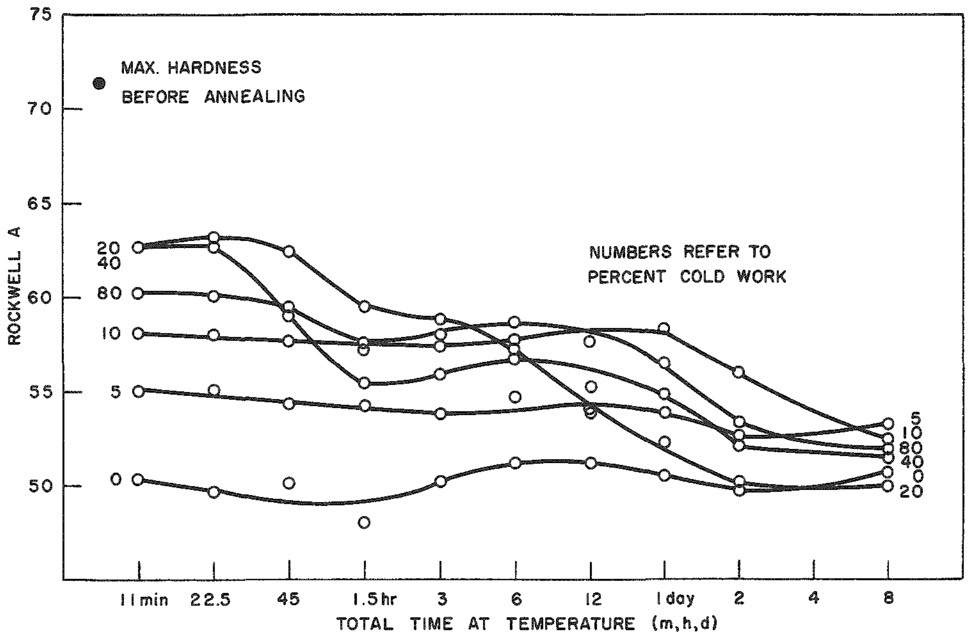

Figure 16. Effect of Pulse Annealing at 800°C on Hardness of Cold-worked Stainless Steel.

The pulse annealing results in stainless steel (Table XVIII and Figures 12-16) are much more complex than in nickel. There is first a minor trend for hardening, probably because of stress equalization. It occurs most noticeably in highly cold-worked specimens (above 10% reduction), and at periods of 6 hr at 400°C, 1.5 hr at 500°C, and 45 min at 600°C. Next there is a relaxation of stress back to the original as-rolled hardness. However, at high enough temperatures and times, the relaxation continues to lower hardness until it is counteracted by another hardening process, followed by final softening. The hardening is undoubtedly associated with the submicroscopic precipitation of a second phase, and the terminal softening correlates with agglomeration of the same, observed in metallographic specimens. The precipitated phase does not appear to be ferrite, a point discussed in the following section.

Effect of Pulse Annealing upon Magnetic Attraction

It is a well-known fact that the austenitic stainless steels are normally nonmagnetic as annealed, but that cold working causes precipitation of ferritic phases which are magnetic. In the case of ferromagnetic materials such as nickel, magnetic properties are usually lessened by the mechanical working.

In lieu of setting up a saturation magnet and its controls, it was decided to make comparative measurements as simply as possible with a small permanent magnet suspended on some weighing system. The Aminco-Brenner Magne-Gage, used extensively in industry to check thickness of coatings on magnetic base metals, appeared to have good potentialities for this use. In principle, it utilizes the pull needed to separate a freely suspended permanent magnet from the specimen to which it has been attracted. Usually, calibration is initially determined relative to the materials and coatings to be tested. In the present use, all readings were calibrated in grams of pull needed to separate a spherical point contact from a flat surface.

Hardness testing of pulse annealed specimens was accompanied by a parallel program of Magne-Gage testing on the same pieces. The data obtained are recorded in Table XIX. It will be seen that the as-rolled materials show the normal behavior mentioned above, and that the cold-work induced changes were reversed by the pulse-annealing program. In the case of the stainless steel specimens, it is interesting to observe that the appreciable ferromagnetism induced by the greatest degree of cold work was almost completely eliminated in three days at temperatures of 600-800°C. Evidently the residuals seen at 400-500°C indicate only that the reabsorption of ferrite at these temperatures would take a somewhat longer time than three days.

TABLE XIX

Effect of Annealing on Magnetic Attraction of Cold-worked Type A Nickel and Type 347 Stainless Steel

Type A Nickel			Type 347 Stainless Steel										
Cold Work (% RT)	Magne-Gage Pull (gram)		Cold Work (% RT)	Magne-Gage Pull after Indicated Temperature and Time (gram)									
	as-rolled			as-rolled	11.3 min	22.5 min	45 min	1.5 hr	3 hr	6 hr	12 hr	1 day	3 days
		1.5 hr					Annealed at 400°C						
0	3.84	3.84	0	0.03						0.02			0.02
5	3.70	3.72	5	0.03						0.02			0.03
10	3.60	3.67	10	0.03						0.02			0.02
20	3.45	3.55	20	0.05						0.05		0.04	0.04
40	3.33	3.44	40	0.25						0.23		0.12	0.12
60	3.36	3.39	60	1.56						1.57		0.78	0.78
80	3.33	3.49	80	2.02						2.27		0.72	0.79
		45 min					Annealed at 500°C						
0	3.80	3.86	0	0.03					0.00				0.04
5	3.76	3.74	5	0.02					0.00				0.04
10	3.57	3.70	10	0.03					0.02				0.04
20	3.40	3.59	20	0.06					0.03	0.02			0.05
40	3.38	3.55	40	0.36					0.24	0.22		0.14	0.15
60	3.34	3.54	60	1.16					0.72	0.72		0.32	0.32
80	3.33	3.59	80	2.14					1.28	1.32		0.40	0.43
		11.3 min					Annealed at 600°C						
0	3.82	3.91	0	0.03				0.02					0.06
5	3.72	3.80	5	0.04				0.02					0.07
10	3.57	3.81	10	0.04				0.02					0.06
20	3.41	3.81	20	0.05				0.02					0.04
40	3.35	3.74	40	0.34				0.08	0.08	0.06	0.07	0.06	0.06
60	3.37	3.69	60	1.10				0.36	0.24	0.20	0.20	0.10	0.05
80	3.35	3.77	80	2.26				0.34	0.33	0.30	0.27	0.08	0.04
		5.6 min					Annealed at 700°C						
0	3.76	3.98	0	0.03			0.02			0.06	0.11	0.12	0.06
5	3.65	3.93	5	0.03			0.02			0.08	0.16	0.20	0.07
10	3.37	3.89	10	0.04			0.02			0.07	0.13	0.19	0.05
20	3.40	3.91	20	0.06			0.02			0.07	0.15	0.18	0.07
40	3.41	4.16	40	0.25			0.03	0.02		0.08	0.12	0.19	0.08
60	3.35	4.08	60	1.64			0.08	0.06	0.06	0.05	0.13	0.14	0.08
80	3.34	4.13	80	2.12			0.06	0.04	0.03	0.04	0.13	0.16	0.04
		2.8 min					Annealed at 800°C						
0	3.83	4.05	0	0.03	0.02				0.02	0.16	0.23	0.26	0.24
5	3.62	3.98	5	0.03	0.02				0.02	0.08	0.22	0.26	0.14
10	3.63	3.96	10	0.03	0.03				0.03	0.08	0.16	0.23	0.18
20	3.48	4.10	20	0.07	0.03	0.02			0.02	0.10	0.18	0.24	0.16
40	3.37	4.10	40	0.26	0.03				0.02	0.13	0.16	0.20	0.14
60	3.35	4.11	60	1.18	0.03	0.02			0.04	0.10	0.16	0.15	0.10
80	3.30	4.07	80	2.10	0.03	0.02			0.03	0.03	0.17	0.17	0.06