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Pressure Vessel Research Committee

THE PLASTIC FATIGUE STRENGTH OF PRESSURE VESSEL STEELS

by J. H. Gross, D. E. Gucer, R. D. Stout

Lehigh University

208 Project Report

# THE PLASTIC FATIGUE STRENGTH OF PRESSURE VESSEL STEELS

By J. H. Gross,\* D. E. Gucer,\* and R. D. Stout\*

## Foreward

The investigation reported in this paper was sponsored and guided by the Fabrication Division of the Pressure Vessel Research Committee. Mr. P. R. Cassidy is Chairman and Mr. B. E. Rossi is Executive Secretary of the Pressure Vessel Research Committee. Mr. F. L. Plummer is Chairman of the Fabrication Division, while the project Steering Committee is composed of Mr. I. E. Boberg, Mr. L. C. Bibber, Mr. W. P. Gerhart, and Mr. A. R. Lytle.

## Introduction

In previous papers (1)-(2) a testing method was described for evaluating the resistance of steels to repeated loads in the plastic range. The effects of fabrication operations, such as cold working, welding, and heat treatment, were reported for several pressure vessel steels. Loading was restricted to the plastic range in order to produce failure in a range of cycles applicable to pressure vessel operation.

The present investigation was directed toward a comparison of plastic fatigue properties of a high strength Mn-Mo steel, ASTM A-302, Grade B, and a carbon pressure vessel steel, ASTM A-201. If higher strength steels are applied to vessels designed for increased stress levels, assurance is needed that the other mechanical properties of these steels will meet the requirements of service. In addition, this program was to parallel tests at the University of Illinois on larger hydraulic-loaded plate specimens and tests on model vessels at the Ecole Polytechnique, all on the same heats of A-302 and A-201 steels.

The following phases of the program were investigated:

1. Strain behavior in the specimen during cycling
2. Effect of surface preparation
3. Effect of temperature during testing

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(2)

4. Effect of welding and stress relieving
5. Tests under constant maximum loading instead of constant deflection
6. Influence of heat treatment and microstructure

These will be described and discussed in order.

### Testing Methods and Material

Tests at Constant Deflection. The details of the testing method have been presented previously. (2) The specimen, shown in Figure 1, was loaded as a cantilever beam in the machine shown in Figure 2. This machine is a cam-type loading device providing essentially constant deflection amplitude during testing. The specimen was sufficiently wide to set up 2:1 biaxial strains.

Tests at Constant Maximum Load. The investigations at the other cooperating laboratories utilize oil pressure pulses for cycling which constitute loading to a constant maximum pressure as opposed to the constant deflection characteristics of the machine of Figure 2. In order to determine whether the behavior of the steel under constant deflection is essentially the same or significantly different as compared to constant loading, a second machine was constructed, as shown in Figure 3. This machine is operated with compressed air, which furnishes loading by means of the opposing cylinders. The air pressure is controlled in a secondary tank, fed from the main tank, to plus or minus 0.5 pounds at levels varying from 50 to 100 pounds. The cycling is carried out at 100 cycles per minute by means of a synchronous motor operating a microswitch and in turn alternately activating three-way solenoid air valves. The loading is approximately square-wave in nature. When the specimen has cracked to an extent which allows the deflection to become one-half inch, limit switches stop the test. The results of tests carried out on this machine are presented in a later section.

Steels. The steels used for testing consisted of two heats each of A-302 and A-201 in 3/4 inch thickness. The analyses and tensile properties of these heats in the normalized and stress-relieved condition are given in Table I. The "standard" heats are those under test at Illinois and Ecole Polytechnique, available

in limited quantity. The "new" heats represent additional material needed for further tests.

#### Strain Behavior in the Specimens

One of the problems involved in fatigue testing in the plastic range is to express the severity of loading in quantitative and significant terms. The stress values used in elastic loading lose validity, while strain values possess certain ambiguities which are demonstrated later on.

In previous investigations, as a first approximation, the strain imposed on the initial tension cycle was used as an index of the loading range. It appeared desirable to study the strain produced throughout the test life of the specimen to permit the best choice of a criterion for indicating the severity of plastic loading. A second reason for such a study arose from the fact that specimens of unlike strength experience different strains at identical deflections. In general, greater strength results in lower strain in the test section.

Strains in the test section were measured with a Tuckerman optical gauge. The gauge length was 1/4 inch, centered at the minimum cross-section. Strains were measured at small increments of deflection during the first tension cycle and then were recorded from maximum tension to maximum compression at frequent intervals until the specimen developed a crack. Loads were also recorded on several of the tests by means of strain gauges affixed to the loading arm of the machine.

The relation between deflection, strain, and loads for the normalized and stress relieved A-302 and A-201 on the first tension cycle is shown in Figures 4 and 5. In the elastic range, the two steels behave nearly identically. Because of its lower yield strength, the A-201 commences large plastic strain at lesser deflections than the A-302. Thereafter, a given deflection induces greater plastic straining in the test section of the A-201 steel than in that of A-302. The loads required to deflect the specimen likewise differ between the steels, as to be expected from unequal tensile strengths.

Under cyclic loading in the plastic range, the resistance of the steel to failure can be expected to depend on the range of strain imposed throughout the test. The variation of strain with cycling is shown for the standard heats of two steels in Figures 6 and 7. The strain is expressed as that produced between the points of maximum tension and maximum compression. At high deflections, the strain range decreases noticeably during the first few cycles because of work hardening. After about 10 cycles, there is little change in the strain. At low deflection levels, the strain is nearly constant during the test. The sudden increase in strain toward the end of the test indicates the initiation of a crack in the gauge section.

It should be possible according to these data, to express the severity of loading fairly by the average straining range effective during testing. Representative values will be obtained by choosing the readings at 10 or 100 cycles. The relation of straining to deflection at 10 cycles for the two steels is indicated in Figure 8. At low deflections the two steels behave about alike, but at large deflections the A-201 is strained considerably more than A-302, much as was shown in Figure 4 for the initial tension cycle. The straining range after 10 cycles was chosen as the criterion to express the degree of loading. It should be noted however, that the conclusions reached in this paper would not be significantly altered if some other number of cycles were substituted, including the initial tension cycle. In Figure 9, strain ranges at 10 cycles are shown for the new heats of A-302 and A-201.

#### Effect of Surface Preparation

The influence of the surface characteristics on the fatigue endurance limit is well known. Cracks, discontinuities, tool marks, and similar surface irregularities lower the fatigue life seriously. Two questions therefore required consideration: (1) is the action of the surface as strong in plastic fatigue as it is in the elastic range; and (2) what relative sensitivity is shown by a high strength steel and a carbon steel to surface conditions.

A series of surface preparations, selected to furnish information on these points, included the following:

1. polished to a 3/0 finish by hand
2. ground to 50 G finish on a belt
3. scaled (by normalizing treatment)
4. scaled and pickled
5. notched 0.01 inch deep with a cutter 2 1/2 inches in diameter, 45° included angle and 0.01 inch tooth radius
6. punch-marked by a Rockwell diamond indenter to a depth of 0.017 inch at 1/2 inch intervals across the test specimen

All specimens except the polished series were stress relieved as the final operation before testing. The notch for condition 5 above was produced by lowering the milling cutter, without lateral movement, the required depth into the center of the test section. The resulting notch was about 3/8 inch long and was perpendicular to the axis of the specimen. Specimens for each condition were tested at four strain levels with triplicates at each level. The number of cycles to initiate the first visible crack was observed and also the number to cause failure of the specimen as indicated by loss of load carrying capacity.

The results of these tests are shown in Figures 10 and 11. The most favorable surfaces should be the polished and the ground ones. The points for these conditions lie at the top of the groups of data, that is, they show the largest cycles to failure. For the A-302 steel in Figure 10 the other conditions are fairly closely grouped at levels 30-40% lower than the polished series. The results for the A-201 are more scattered. The effects of scaling or pickling seem small, but the notches and punchmarks about halved the fatigue life.

A similar plot is shown in Figures 12 and 13 for the effect of surface preparation on the cycles to the first crack. The noticeable difference between these results and those of Figures 10 and 11 is that notches or punchmarks are highly effective in lowering the cycles to the first crack. This behavior is to be expected since cracking originates early in the vicinity of these stress-raisers. The life of the specimen after cracking is little affected by the surface preparation. Notice in the following table that the cycles between initial cracking and failure

were much the same for polished and notched specimens at all straining levels. Some of the scatter is due to the lower precision with which the cycles for cracking were determined:

Cycles Between Cracking and Failure

<u>Strain Level</u>	<u>A-201 Steel</u>		<u>A-302 Steel</u>	
	<u>Polished</u>	<u>Notched</u>	<u>Polished</u>	<u>Notched</u>
(1) lowest	40,000	18,000	20,000	30,000
(2)	20,000	16,000	10,000	14,000
(3)	6,000	7,000	4,000	5,000
(4) highest	2,500	1,800	2,000	1,600

Generally, one can conclude that the two steels respond in about the same way to surface variations. The high strength steel does not show a greater sensitivity to surface irregularities than the carbon steel. The influence of these variations in plastic fatigue is similar to that observed in elastic fatigue tests, except that it may be somewhat less marked in the plastic range.

Tests at Low Temperature

A cold chamber was installed on the fatigue machine for tests at low temperature. By means of dry ice, the test section could be held at about 0°F as compared to the 90-125°F temperature present in the section when it was tested in the open. Tests were run on both heats of A-302 steel in the normalized and stress-relieved condition.

The test data are shown in Figure 14. It will be seen that the results were essentially alike for 0°F and room temperature. This is to be expected since the strength of the steel changes very little in the temperature range covered.

Effect of Welding and Stress-Relieving

Specimens were prepared with longitudinal bead-weld deposited in accordance with the conditions prescribed in the correlation chart relating the projects at the three cooperating Universities. These welding conditions were as follows:

A-201 Steel	1/4" E7016	300 amps	12 in/min
A-302 Steel	1/4" E8015Q	300 amps	12 in/min. 350°F Preheat
	1/4" E12015	300 amps	12 in/min. 350°F Preheat



Both heats of A-302 and the new heat of A-201 were tested. All specimens were normalized before welding and were grooved and stress-relieved at 1150°F afterward.

As shown in Figures 15 and 16, welding raised the cycles to failure slightly at low testing strains. At high strain levels, the welded specimens tended to fall in performance slightly below the unwelded ones. The initial cracking showed an inclination to avoid the weld metal at low strains, but at high strains the weld metal generally initiated cracking. The specimens welded with E12015 were consistently better at high strain levels than those welded with E9015.

In general, the changes introduced by the welding operations were minor. When, as in these tests, the geometrical effects of weld ripples, undercut, and the like are removed by machining, the effects of welding followed by postheating appear small in these structural steels.

#### Tests at Constant Maximum Loads

The new heats of A-201 and A-302 steels were tested in the constant-loading machine. The effect of the loading level on the cycles to failure for the two steels is shown in Figure 17. The A-302 shows a much higher plastic fatigue strength than the A-201.

By the use of dial gauges, each loading level in the pneumatic machine could be connected with the amount of deflection of the specimen. The results obtained on the pneumatic machine could then be compared at equal deflections to those obtained on the cam machine. As indicated by Figure 18, the two types of testing show good agreement.

An attempt was made to produce failure in a specimen by loading it from one direction only. This method was intended to reproduce the type of loading in the Illinois specimen. At a pressure sufficient to bend the specimen initially to a high deflection, no failure was obtained after several hundred-thousand cycles. This result suggests that the Illinois plate specimen loaded as a diaphragm contains enough constraint to induce some reverse bending at its center.

### Influence of Heat Treatment

It is not at all clear what influence the metallurgical structure of the steel as influenced by heat treatment or cold work may have on fatigue resistance particularly in the plastic range of loading. Some early results of an investigation of this subject can be included here.

Metallurgical variations were introduced into the new heat of A-302 steel by subjecting fatigue specimens to the following preliminary treatments:

1. Annealing at 1650°F
2. Normalize at 1650°F, stress relieve at 1150°F
3. Normalize at 1650°F, prestrain 10% in tension
4. Water quench from 1650°F, temper at 400°F one hour
5. Water quench from 1650°F, temper at 1300°F one hour
6. Normalize at 2000°F, stress relieve at 1150°F (for coarse grain)

In addition to plastic fatigue tests, tension tests were made on specimens receiving each treatment. The results of tension testing are given in Table II. Also shown are the maximum straining range and the load imposed during fatigue testing.

The results of the plastic fatigue tests are summarized in Figure 19. Annealing, normalizing, cold working and quenching and tempering at 1300°F all produced relatively small variations in fatigue resistance despite the range of microstructure that they represented. The specimens treated to high strength (Treatment 4) showed a great superiority over the others at all straining levels. Again the importance of tensile strength even in fatigue tests involving relatively large plastic flow is demonstrated. Cold work raises the cycles to failure only at the lowest strain level, which is probably within the elastic range for this condition.

The effect of coarse grain was not shown in Figure 19 to preserve clarity. Normalizing at 2000°F produced a slightly harder structure than at 1650°F but little change in fatigue resistance except at the lowest strain level where the cycles to failure were raised about 20%.

Further tests in this field are planned.

Summary

The results of the investigation reported here can be summarized as follows:

1. When fatigue tests are conducted in the plastic range, the conditions of testing become ambiguous. The amount of straining per cycle is probably the most significant quantity to measure testing severity.
2. In bending fatigue, the amount of strain produced by a given deflection of the specimen will vary with the tensile strength of the steel and therefore must be determined for each analysis and condition of specimen.
3. The range of strain in the specimen changed with cycling. The strain range after 10 cycles of loading appeared to be a representative value at all levels of testing strain. This is the criterion of strain level adopted in the present investigation.
4. Surface irregularities can lower the plastic fatigue resistance markedly. Fabrication operations introducing scaling, pickling, punchmarking or other similar surface disturbances lowered resistance 10 to 50% as compared to a polished surface.
5. Ambient testing temperatures around 0°F did not alter the fatigue properties observed at room temperature.
6. When welding was followed by postheating, it produced a negligible change in plastic fatigue properties.
7. Heat treatment appeared to affect the fatigue resistance only when it also changed the tensile strength considerably.

References

1. "Repeated Load Tests on Welded and Prestrained Steels", by S. S. Tor, J. M. Ruzek, and R. D. Stout. The Welding Journal Res. Suppl. Vol. 17, No. 5, pp. 238-46 (1952).
2. Factors Affecting Resistance of Pressure Vessel Steels to Repeated Overloading" by J. H. Gross, S. Tsang, and R. D. Stout, Ibid., Vol. 18, No. 1, pp. 23-30 (1953)

TABLE I

TENSILE PROPERTIES OF PVRC STEELS  
 (Normalized at 1650°F-Stress Relieved at 1150°F)  
 0.05 inch diam., 2 inch gauge length

	<u>Yield Strength (.2% offset)</u>	<u>Ult. Tensile Strength</u>	<u>Red. of Area</u>	<u>Elongation (2")</u>
Standard A-201	37,300	59,000	67.7	40.0
	35,400	59,000	69.3	39.0
New A-201	35,900	57,000	70.3	39.0
	37,100	58,500	68.9	39.0
Standard A-302	64,600	87,200	65.1	27.0
	67,000	86,900	63.3	25.5
New A-302	59,500	79,500	66.7	28.0
	57,200	77,600	66.3	30.5

	<u>Chemical Analyses of PVRC Steels</u>					
	<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>	<u>Mo</u>
Standard A-201	0.114	0.38	0.017	0.034	0.20	--
New A-201	0.13	0.39	0.013	0.030	0.20	--
Standard A-302	0.16	1.44	0.026	0.032	0.27	0.43
New A-302	0.15	1.17	0.019	0.023	0.27	0.41

TABLE II

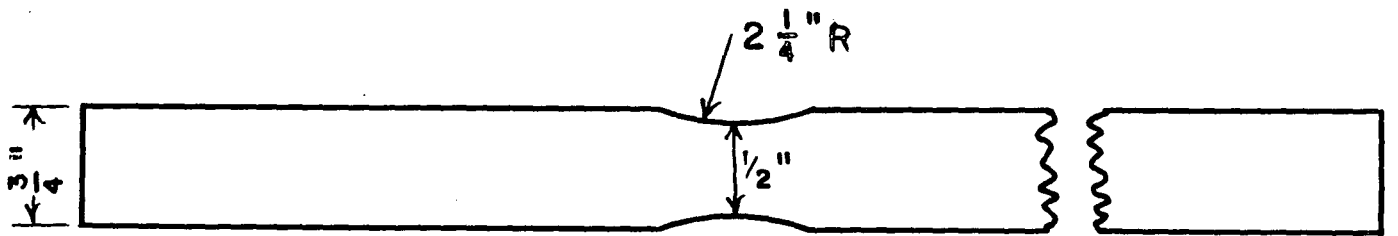
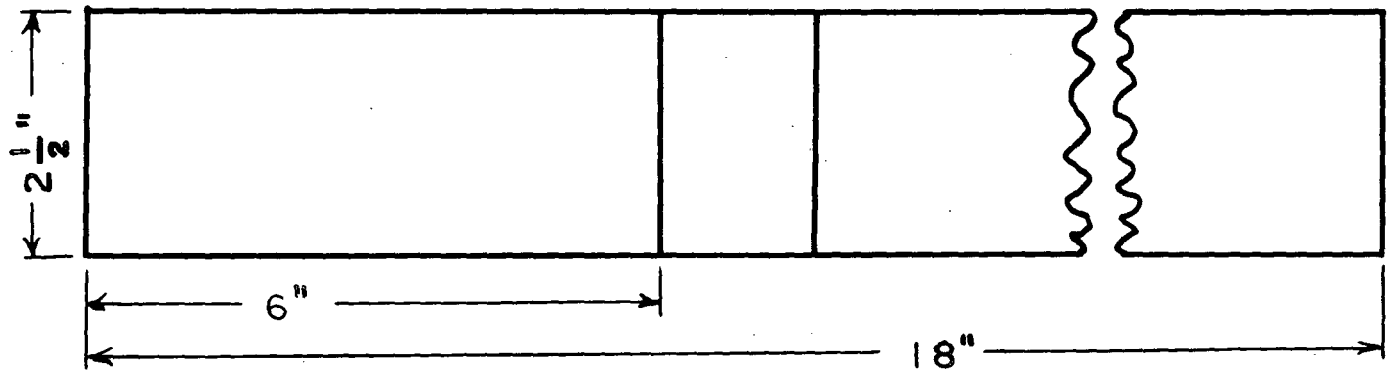
TENSILE PROPERTIES OF NEW A-302 STEEL TREATED IN VARIOUS WAYS

(0.505 diam., 2 inch gauge length)

<u>Treatment</u>	<u>Yield Strength (0.2% Offset)</u>	<u>Tensile Strength</u>	<u>% Elongation</u>	<u>% Red.Arca</u>	<u>Max. Strain at 10th Cycle in Fatigue Spec.</u>	<u>Max. Load at 10th Cycle in Fatigue Spec.</u>
Annealed 1650°F	50,000 psi	73,000 psi	31.8	61.5	1.62%	995 lb.
Norm. 1650°F, S.R.1150°F	58,000 "	78,500 "	29.2	66.5	1.57	1040 "
Prestrained 10%	90,000? "	90,000 "	17.5	63	1.22	1080 "
W.Q.1650°F, Temper 400°F	160,000 "	196,000 "	14	52	1.25	1800 "
W.Q.1650°F, temper 1300°F	74,000 "	92,500 "	27.5	72	1.22	1100

Fig. 1

Biaxial Plastic Fatigue Specimen



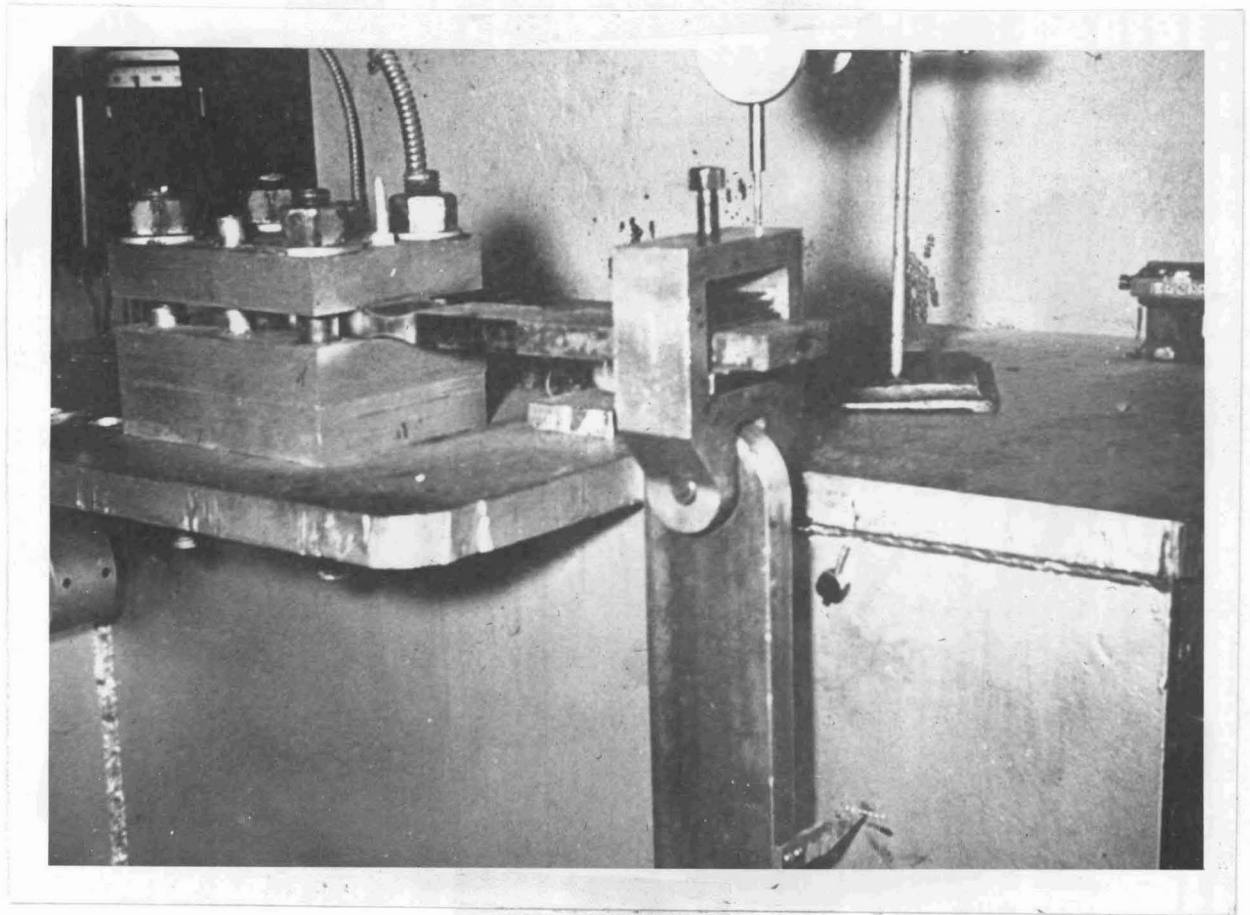


Fig. 2

Constant Deflection Fatigue Machine



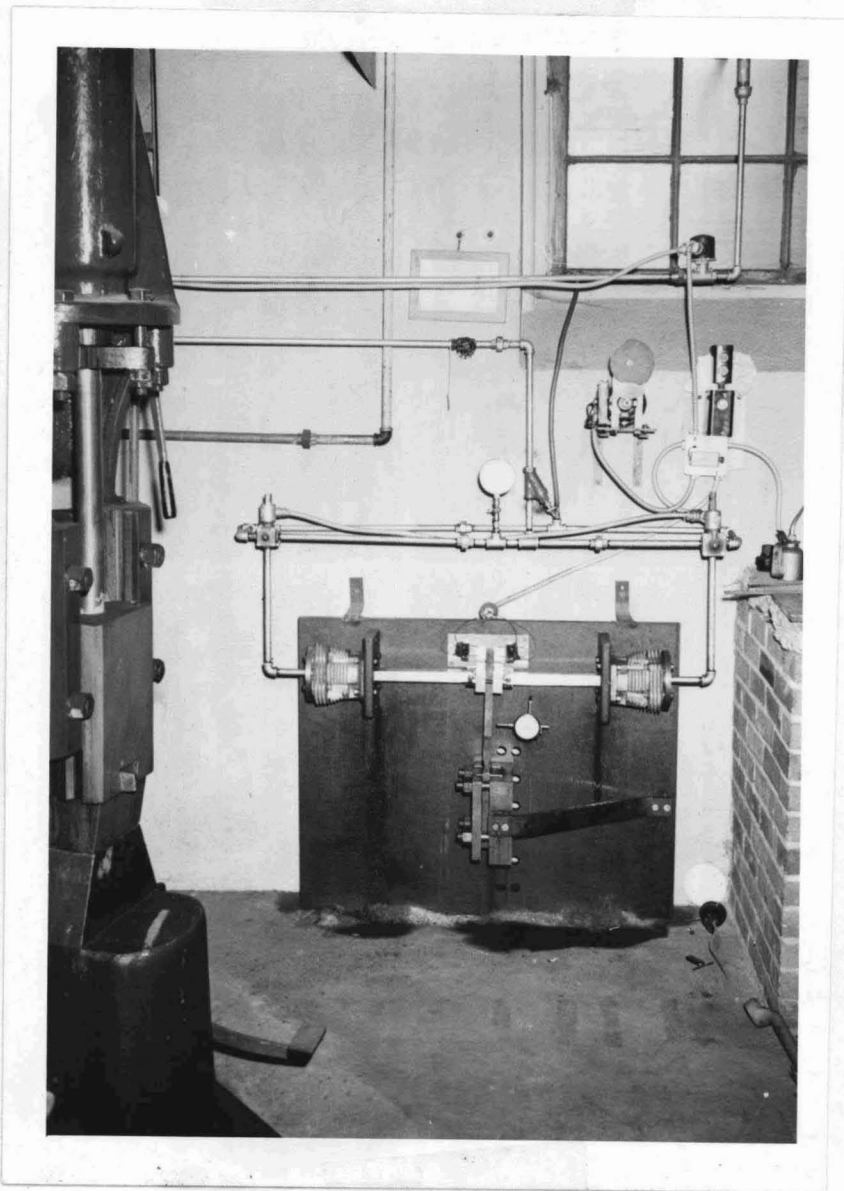


Fig. 3

Constant Load Fatigue Machine

Fig. 4

Strain Characteristics of A-302 and A-201  
Steels on First Tension Cycle

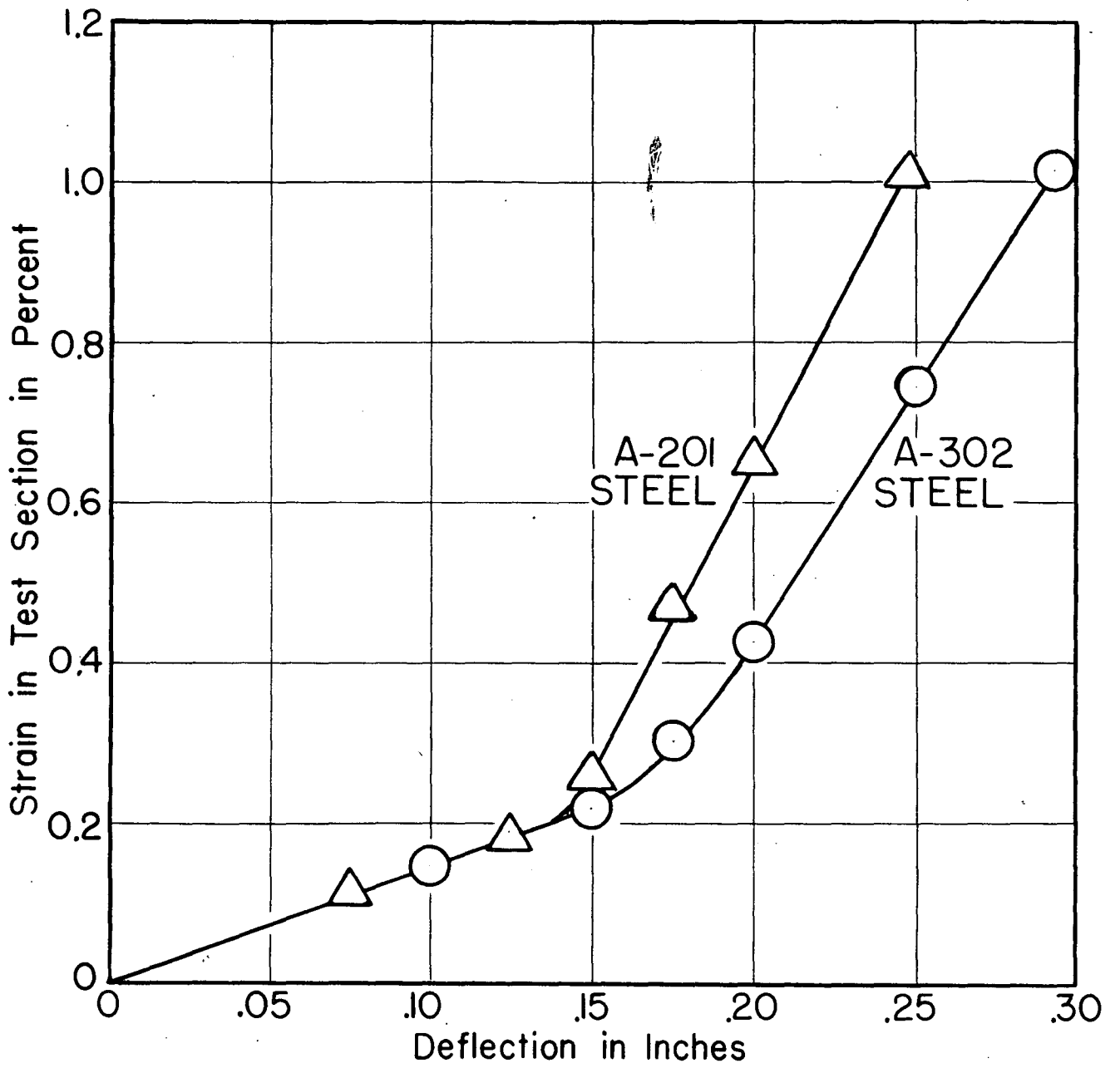


Fig. 5

Load-Strain Characteristics of A-302  
and A-201 Steels on First Tension Cycle

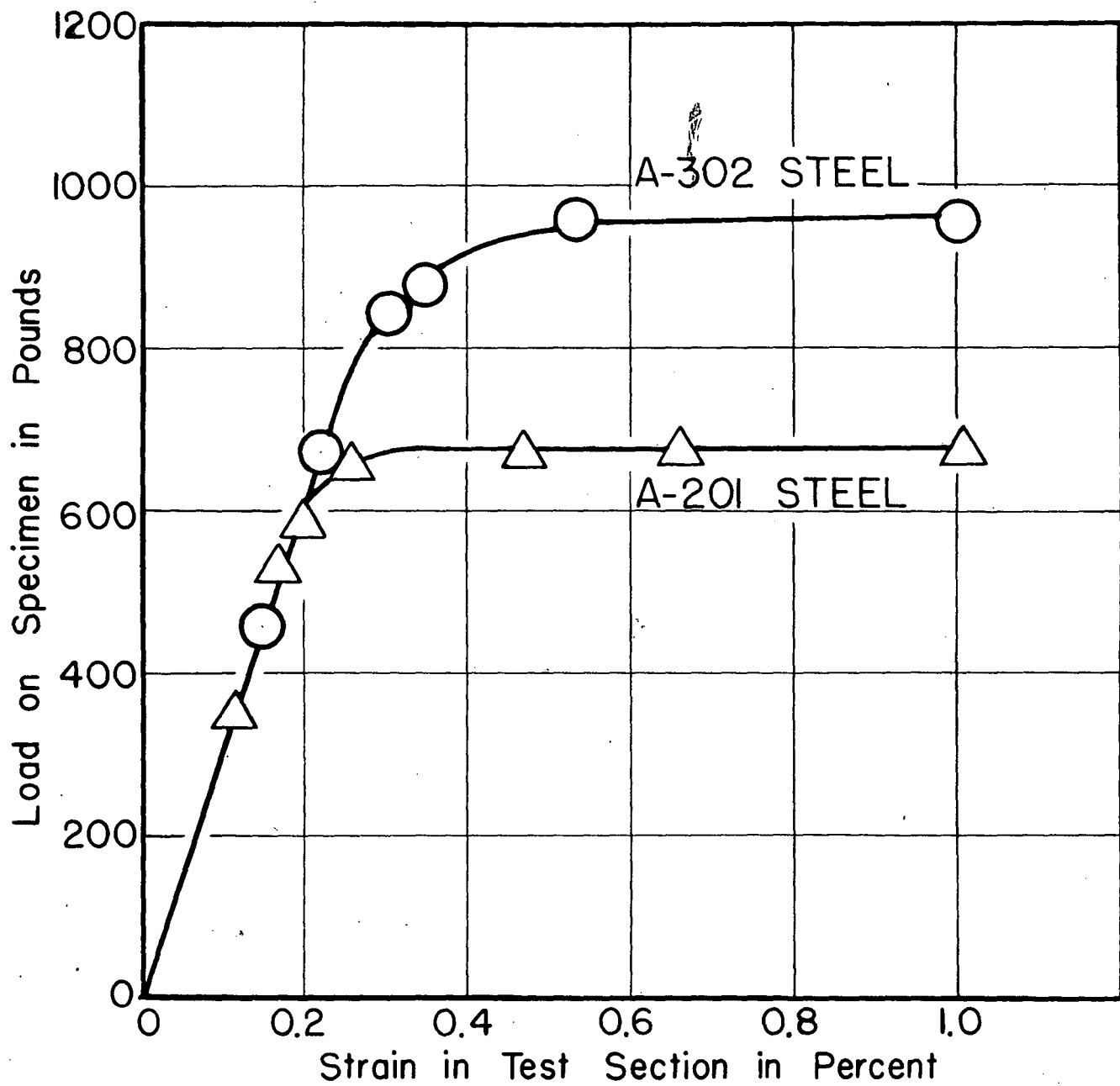
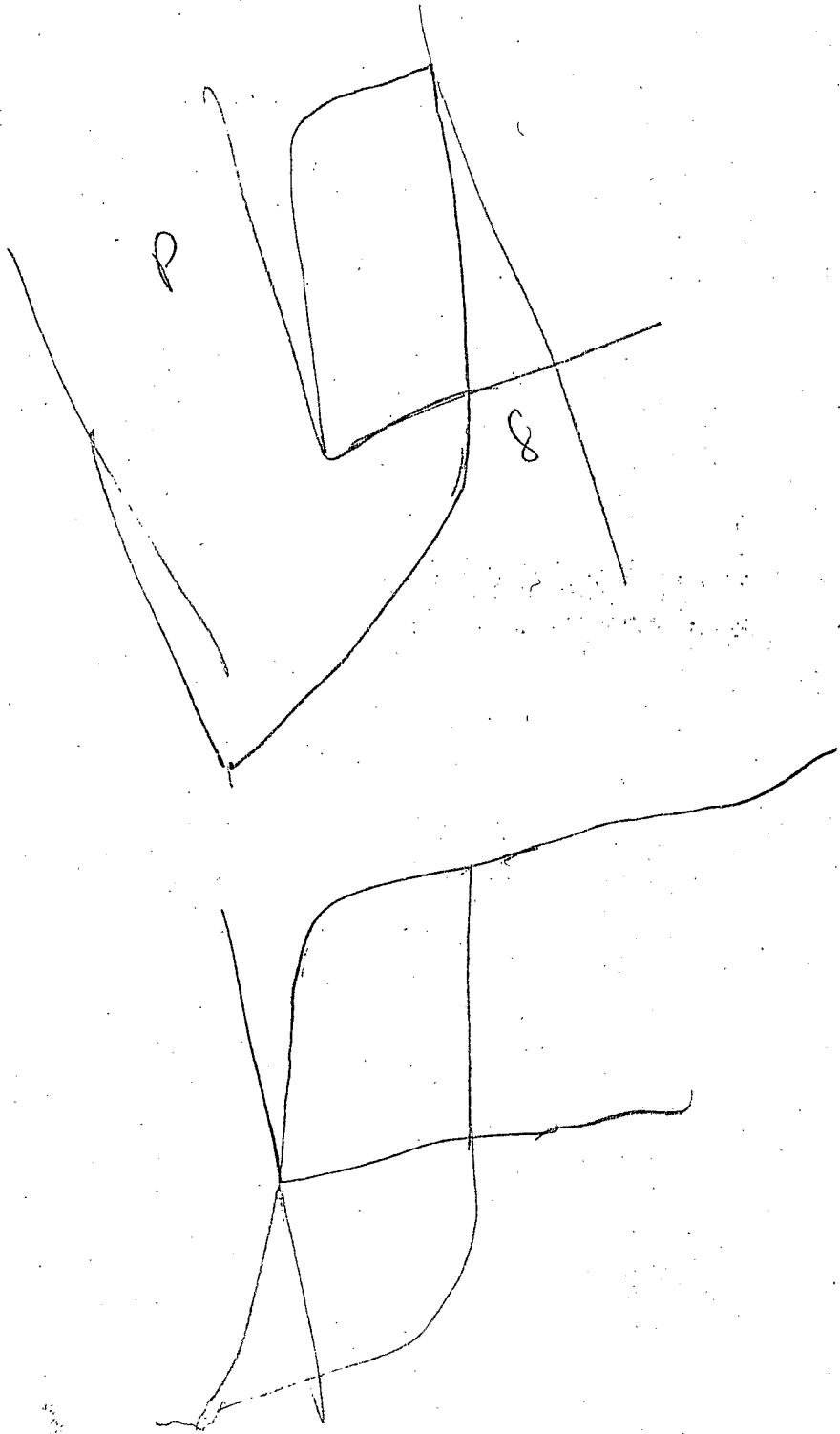


Fig. 6

Effect of Cycling on Straining Range Produced  
in A-302 Steel under Constant Deflection



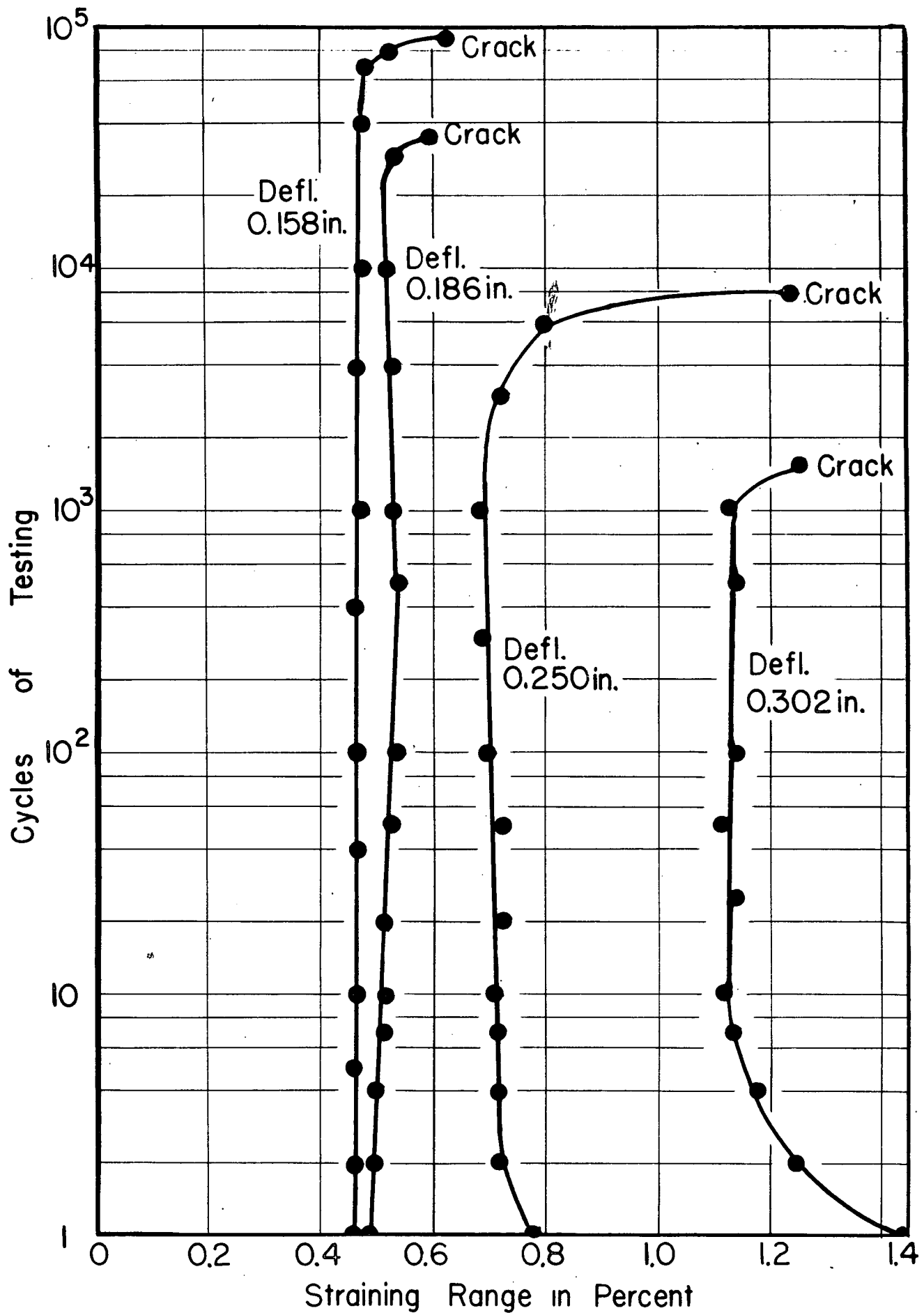




Fig. 7

Effect of Cycling on Straining Range Produced  
in A-201 Steel Under Constant Deflection

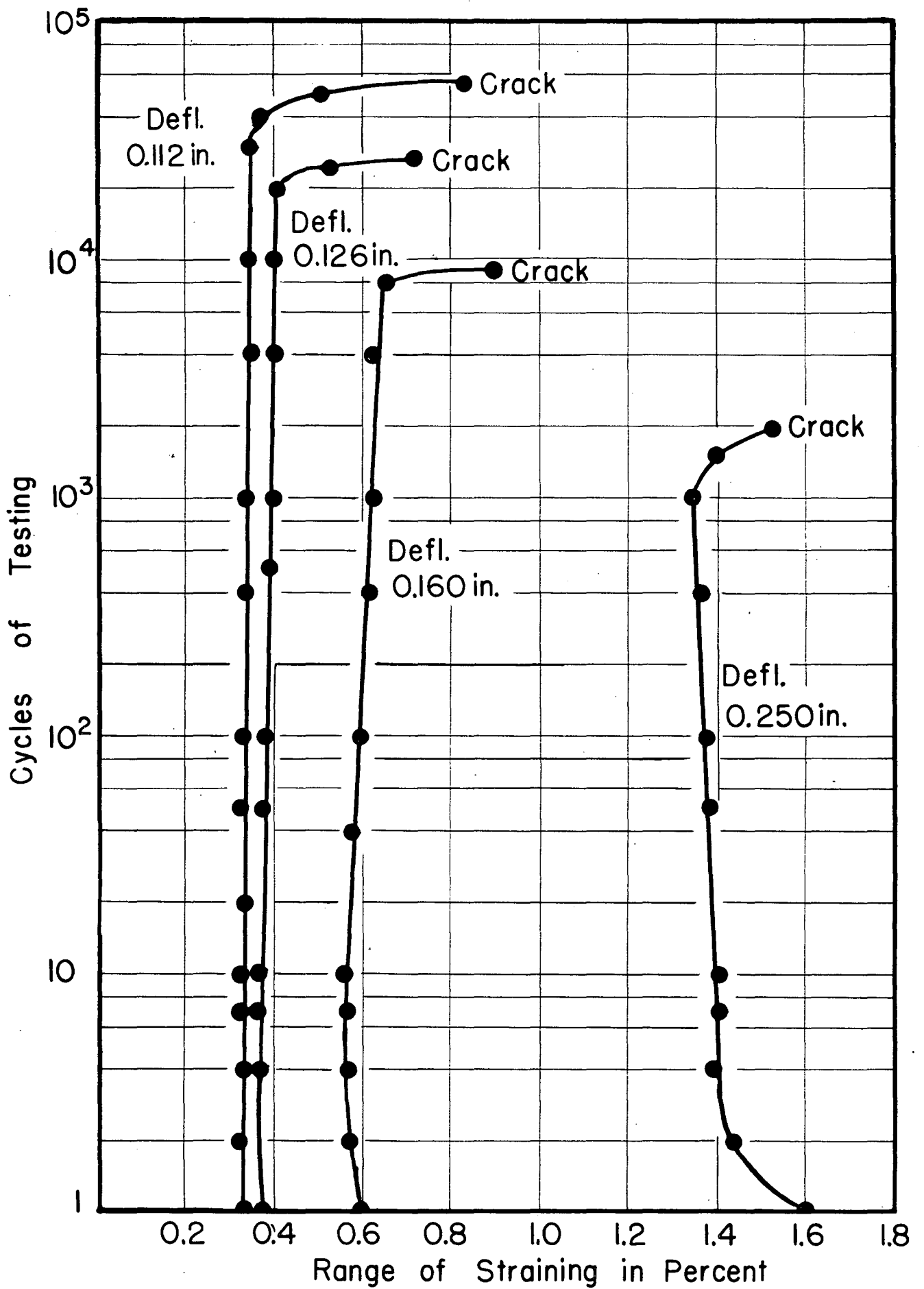


Fig. 8

Relation Between Deflection and the Range of Straining  
at 10 Cycles for the Standard Heats of A-302 and A-201 Steels

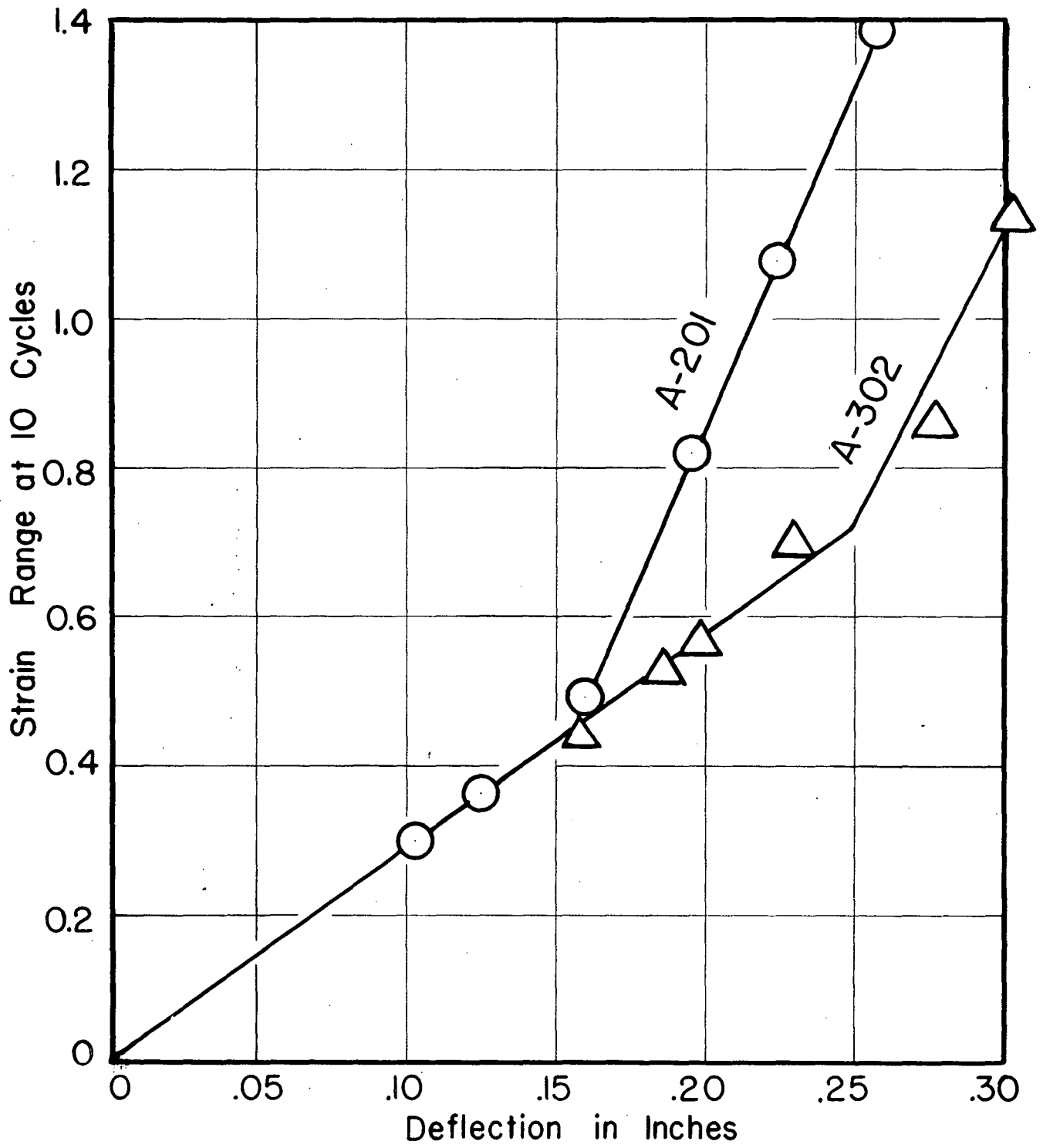


Fig. 9

Relation Between Deflection and the Range of Straining at 10  
Cycles for the New Heats of A-302 and A-201 Steels

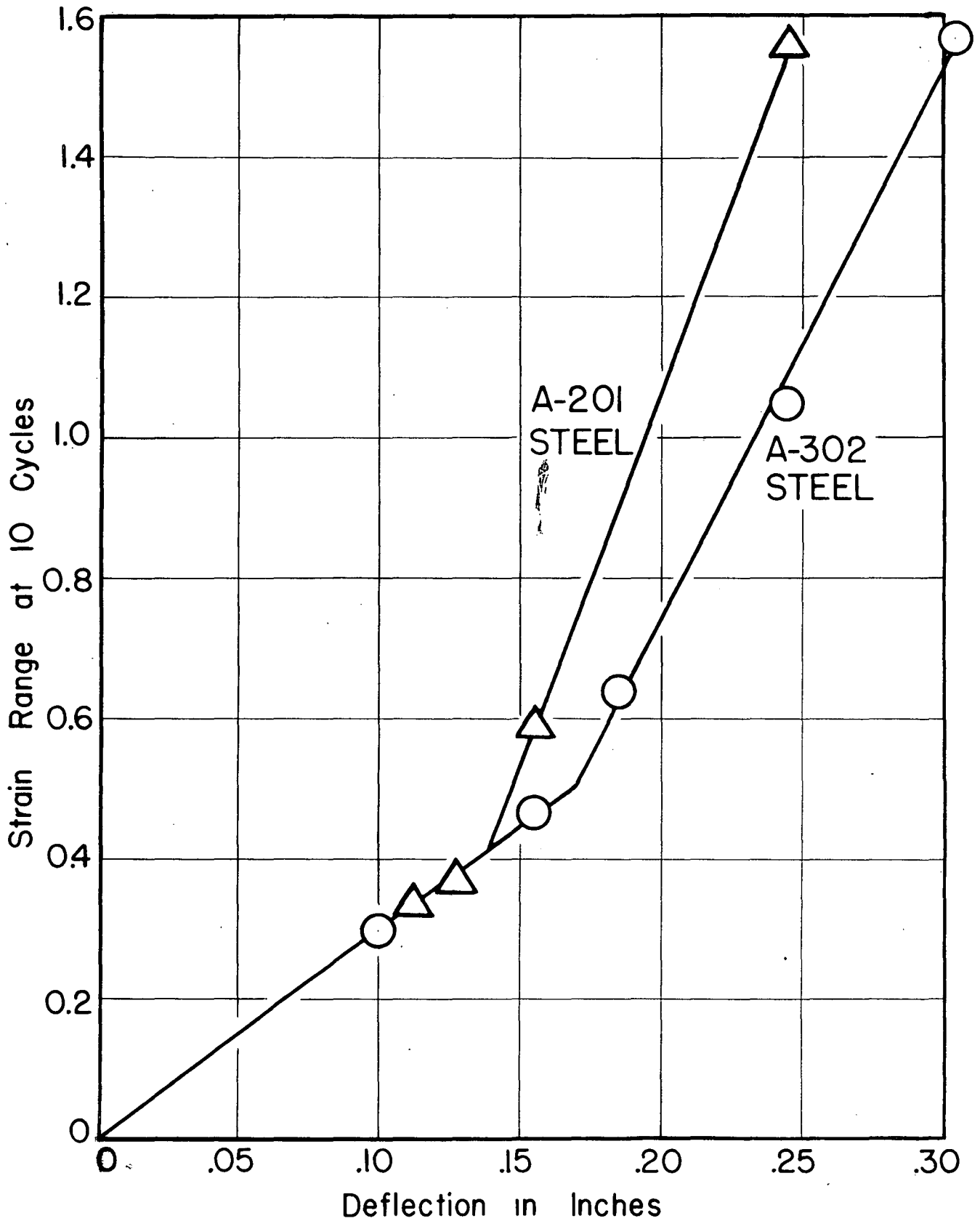


Fig. 10

Effect of Surface Preparation on the Plastic  
Fatigue Resistance of A-302 Steel

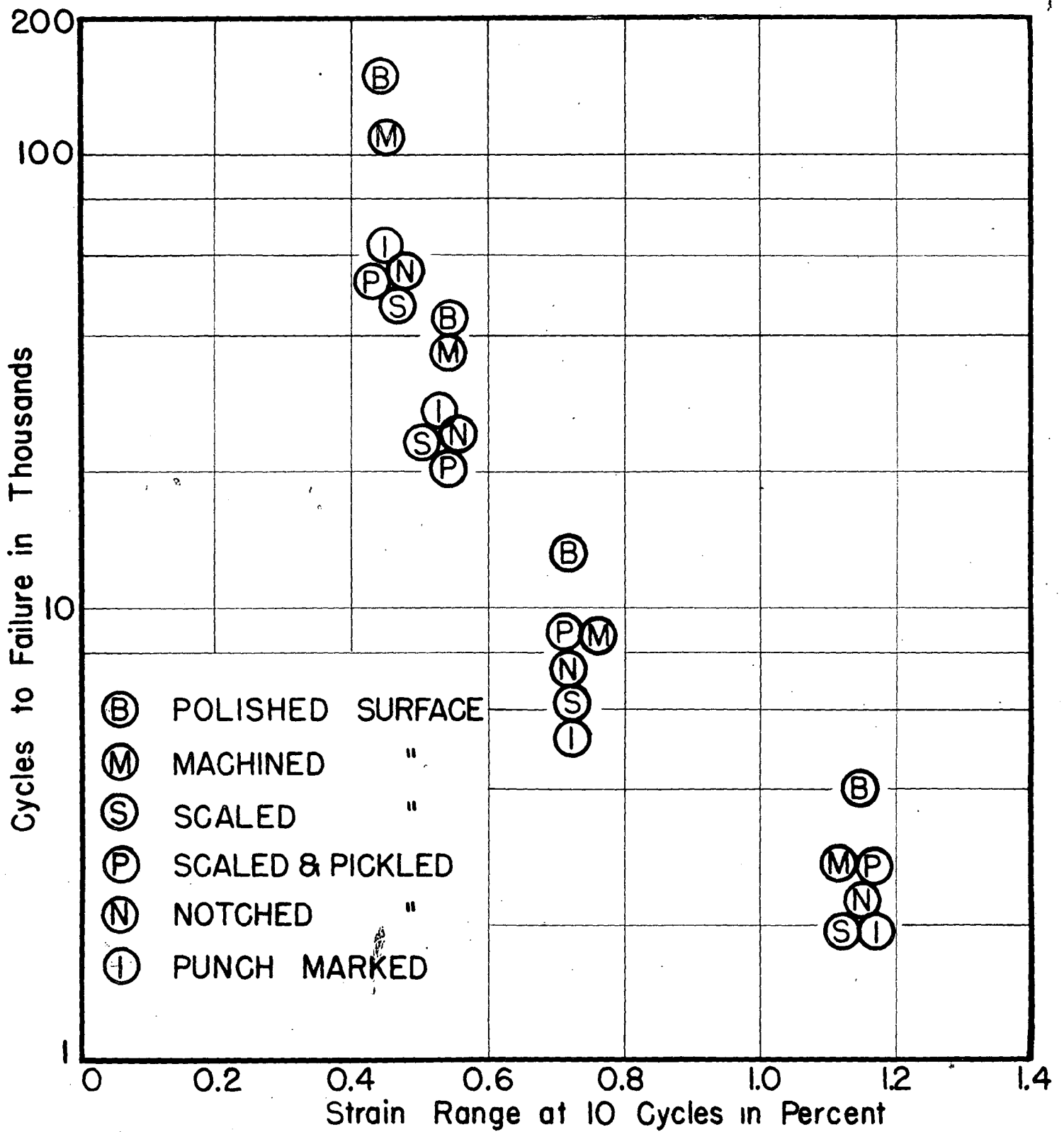




Fig. 11

Effect of Surface Preparation on the Plastic

Fatigue Resistance of A-201 Steel

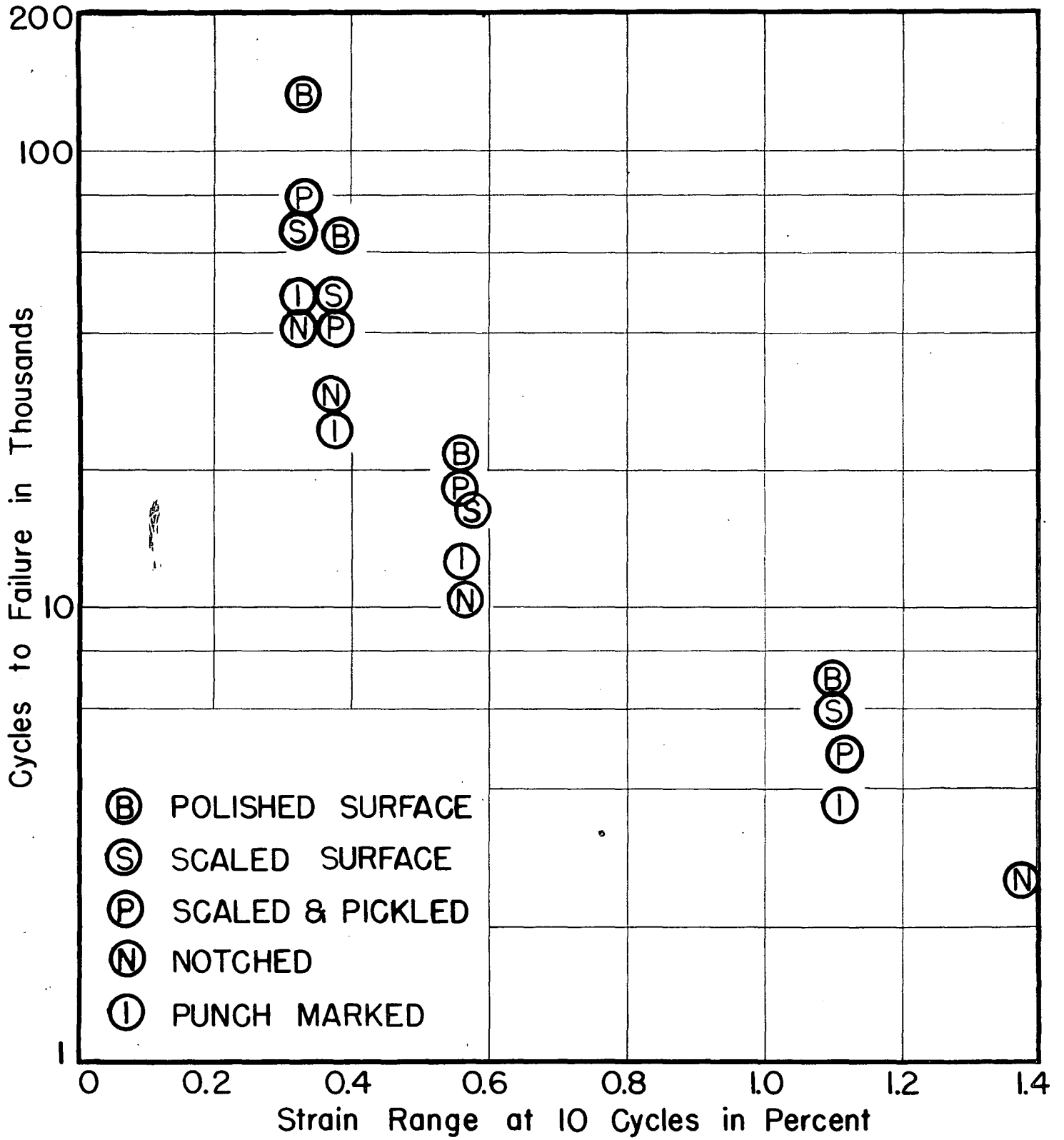


Fig. 12

Effect of Surface Preparation on the Incidence of  
Initial Cracking of A-302 Steel in Plastic Fatigue

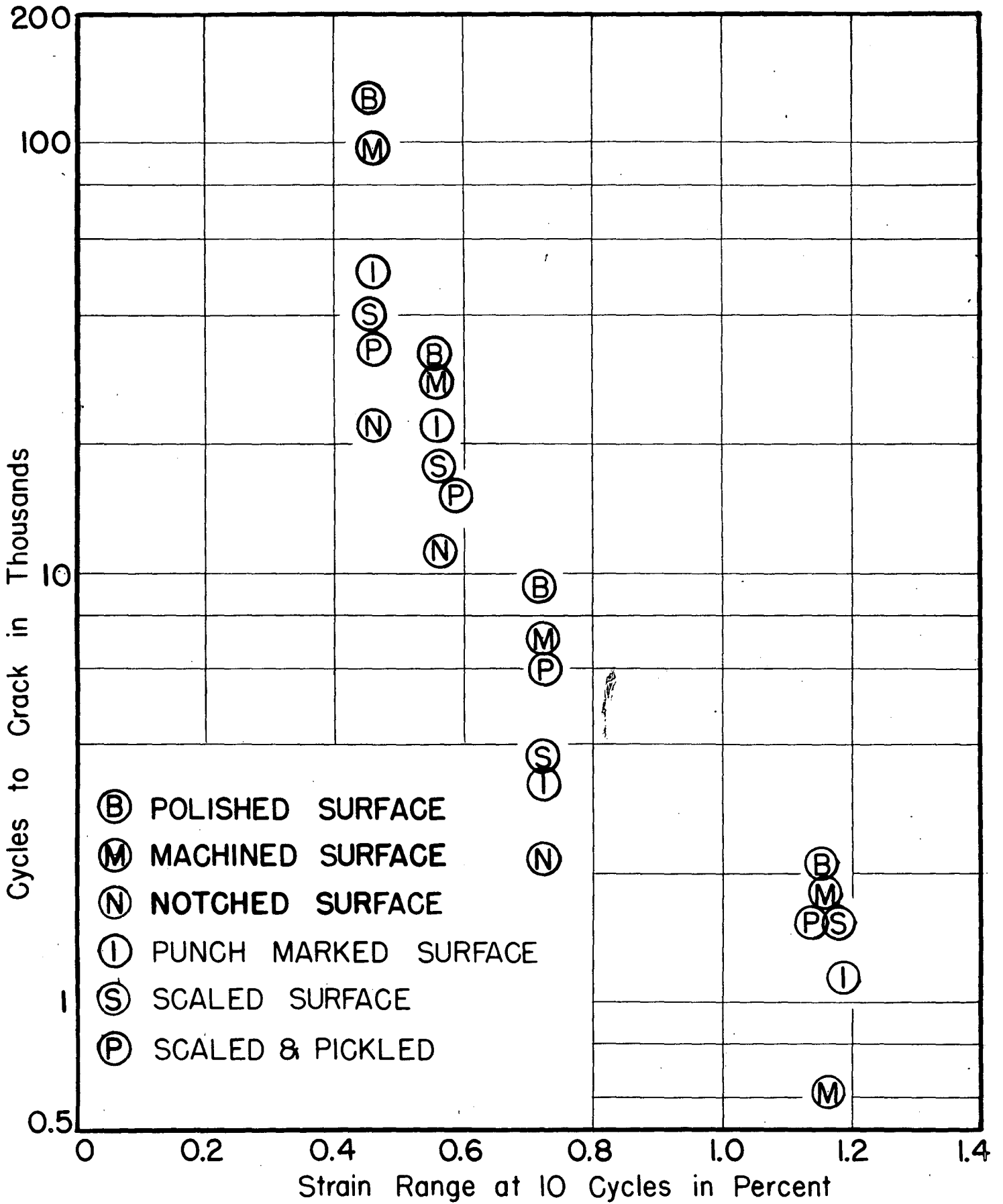


Fig. 13

Effect of Surface Preparation on the Incidence of  
Initial Cracking of A-201 Steel in Plastic Fatigue

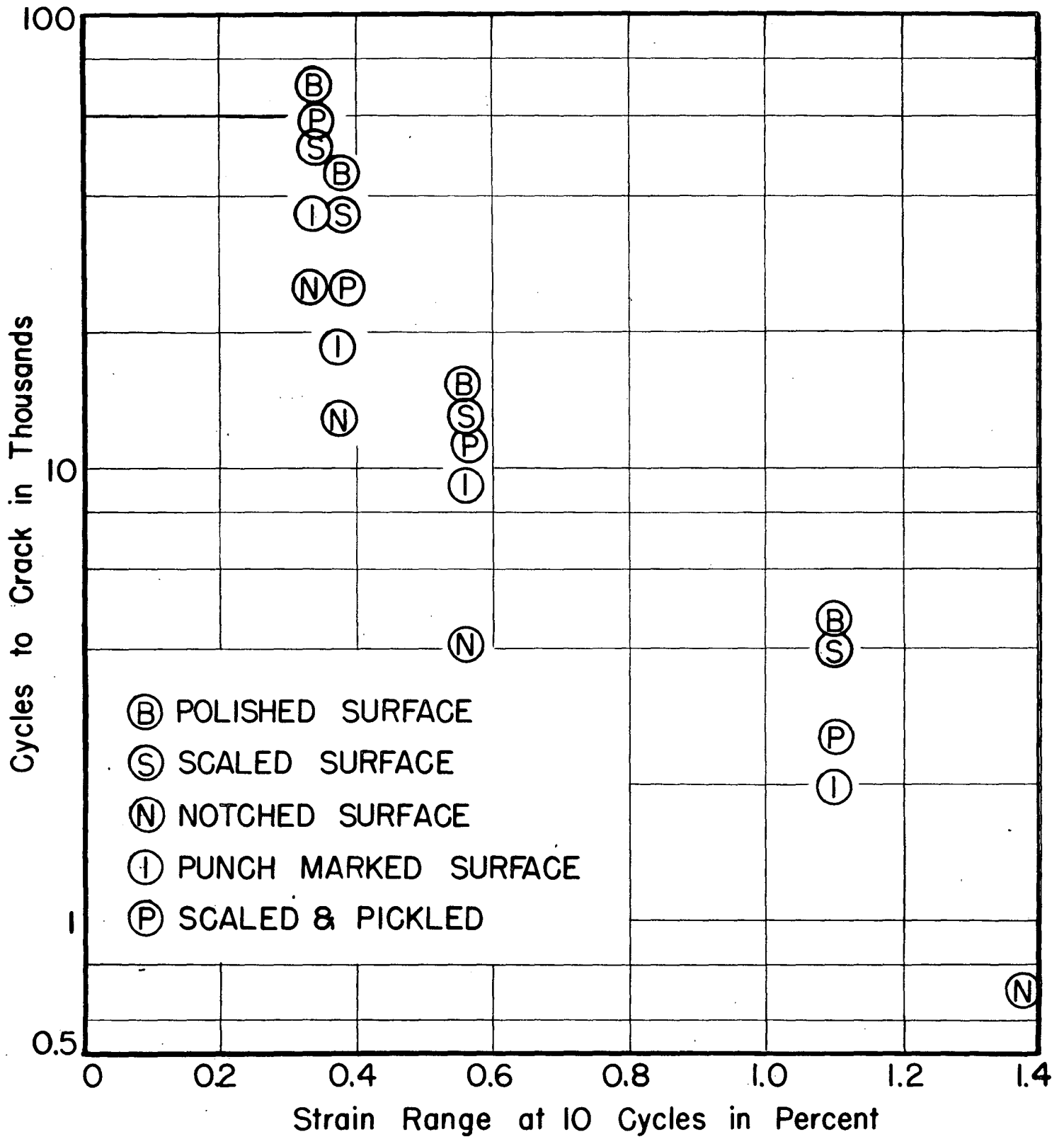


Fig. 14

Effect of Low Temperature on the Plastic  
Fatigue Resistance of A-302 Steels

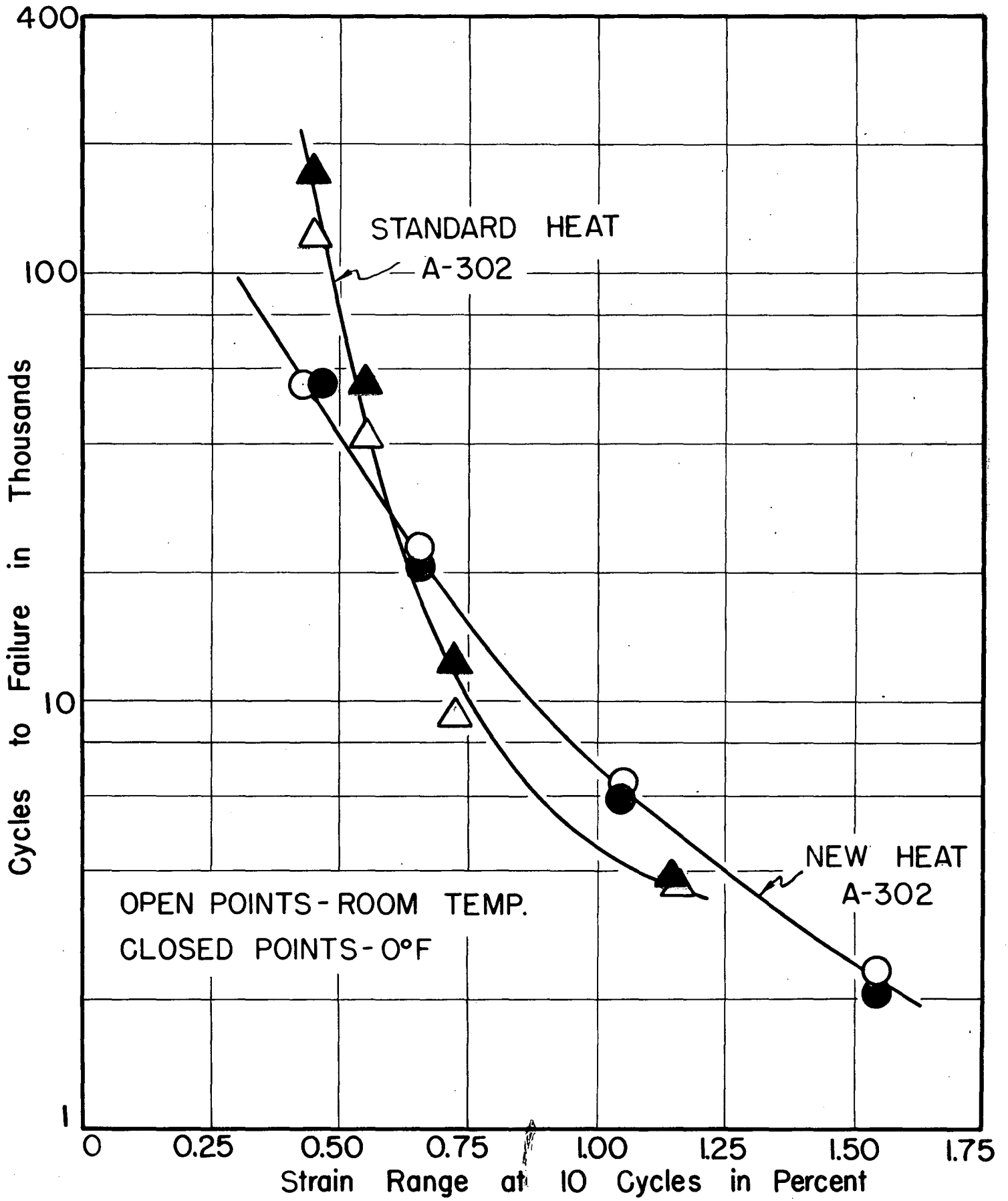




Fig. 15

Effect of Welding Followed by Stress-Relieving  
on Plastic Fatigue Resistance of Standard A-302 Steel

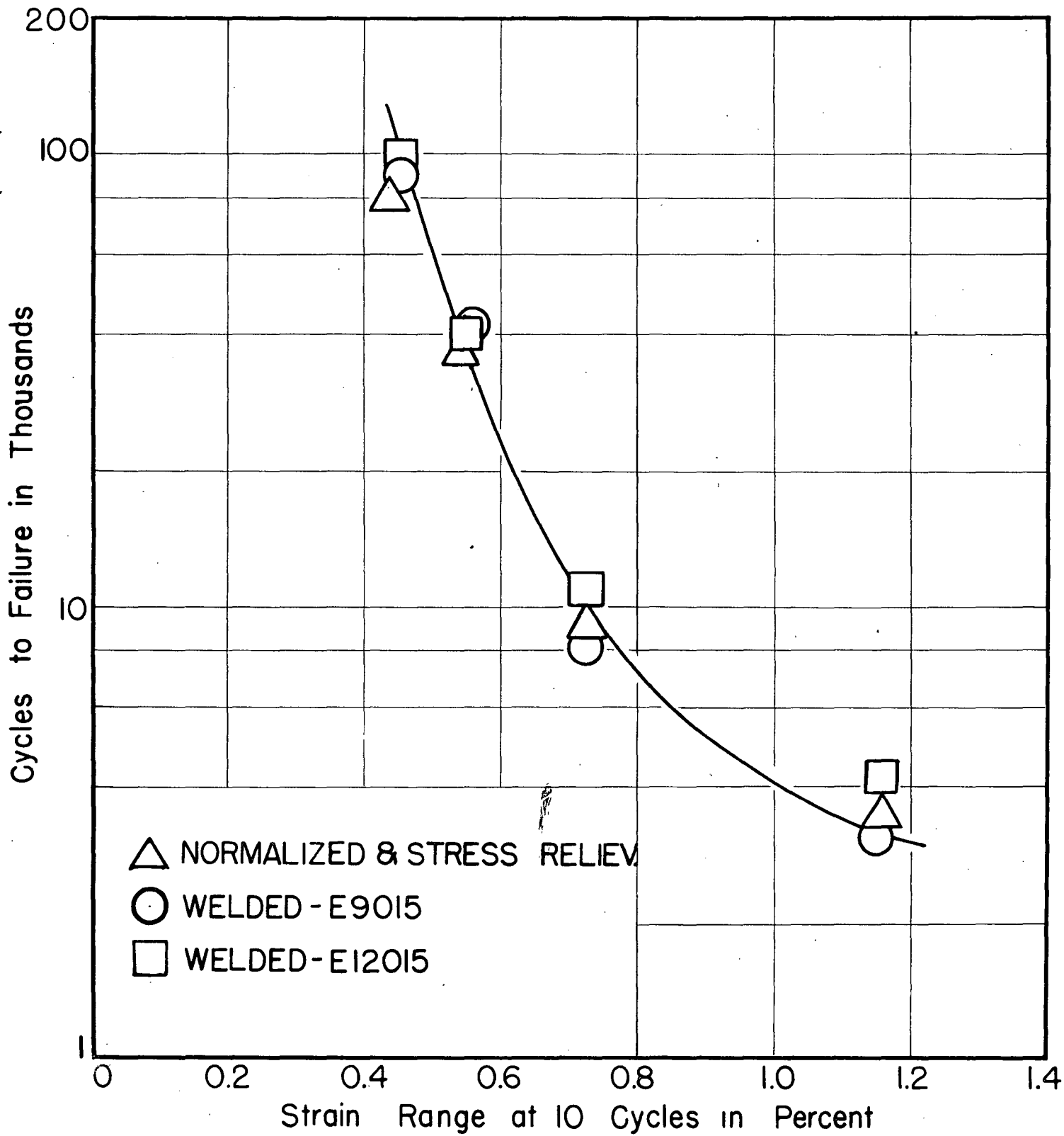


Fig. 16

Effect of Welding followed by Stress-Relieving on Plastic Fatigue  
Resistance of New Heats of A-302 and A-201 Steels

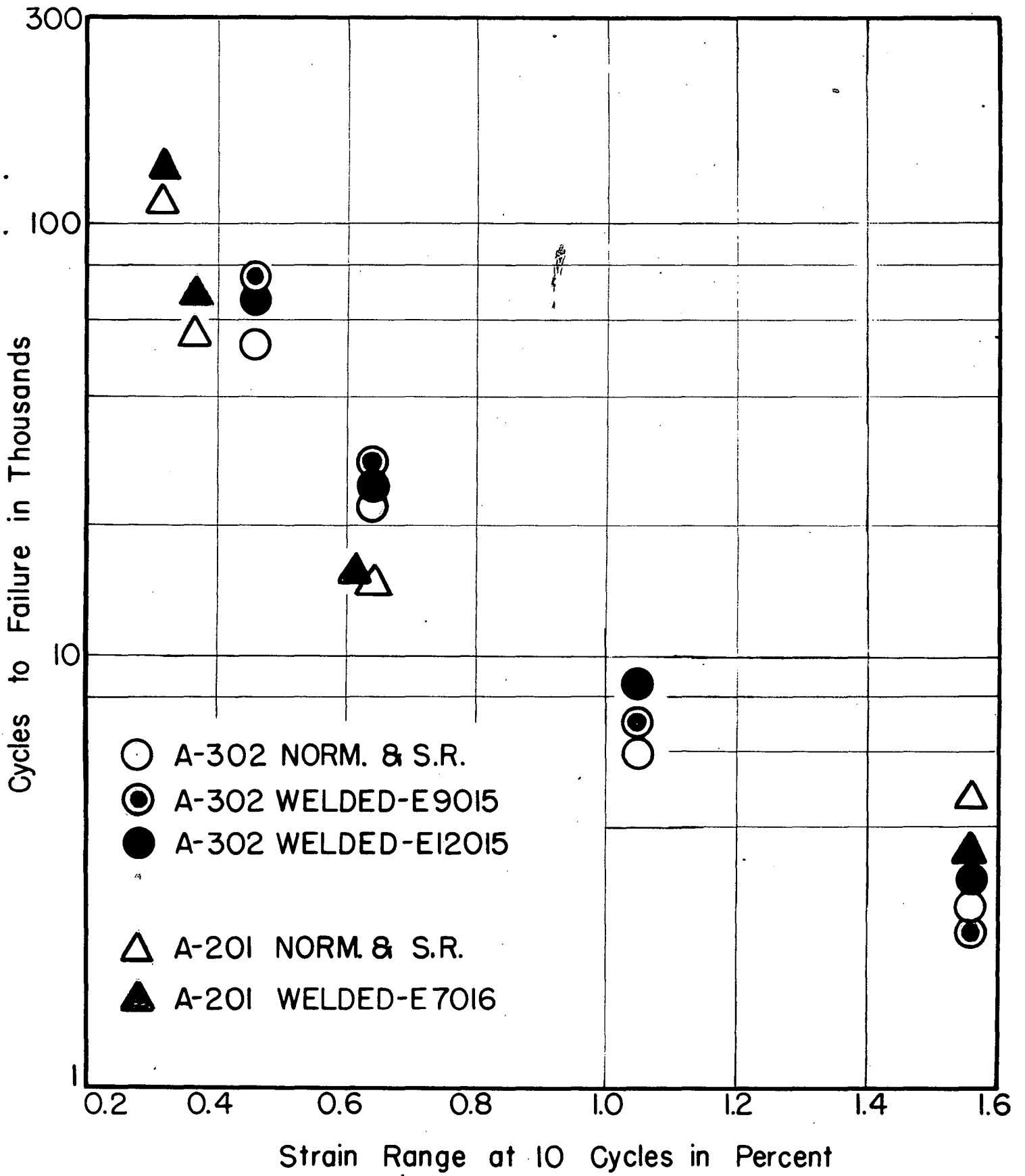


Fig. 17

Comparison of Plastic Fatigue Resistance of A-302 and  
A-201 Steels Under Constant Load Tests

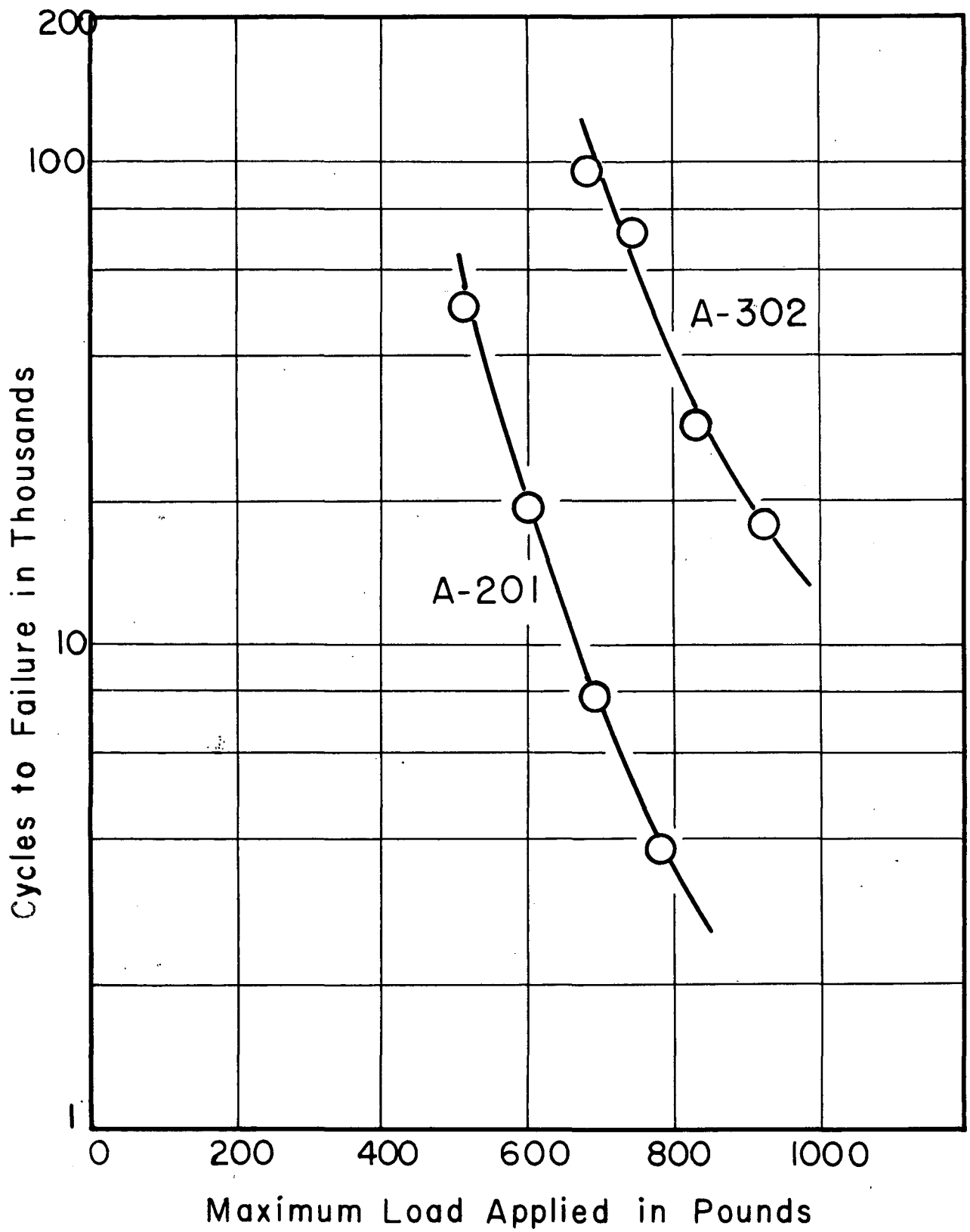


Fig. 18

Comparison of Constant Deflection and Constant Load  
Tests on New A-302 and A-201 Steels

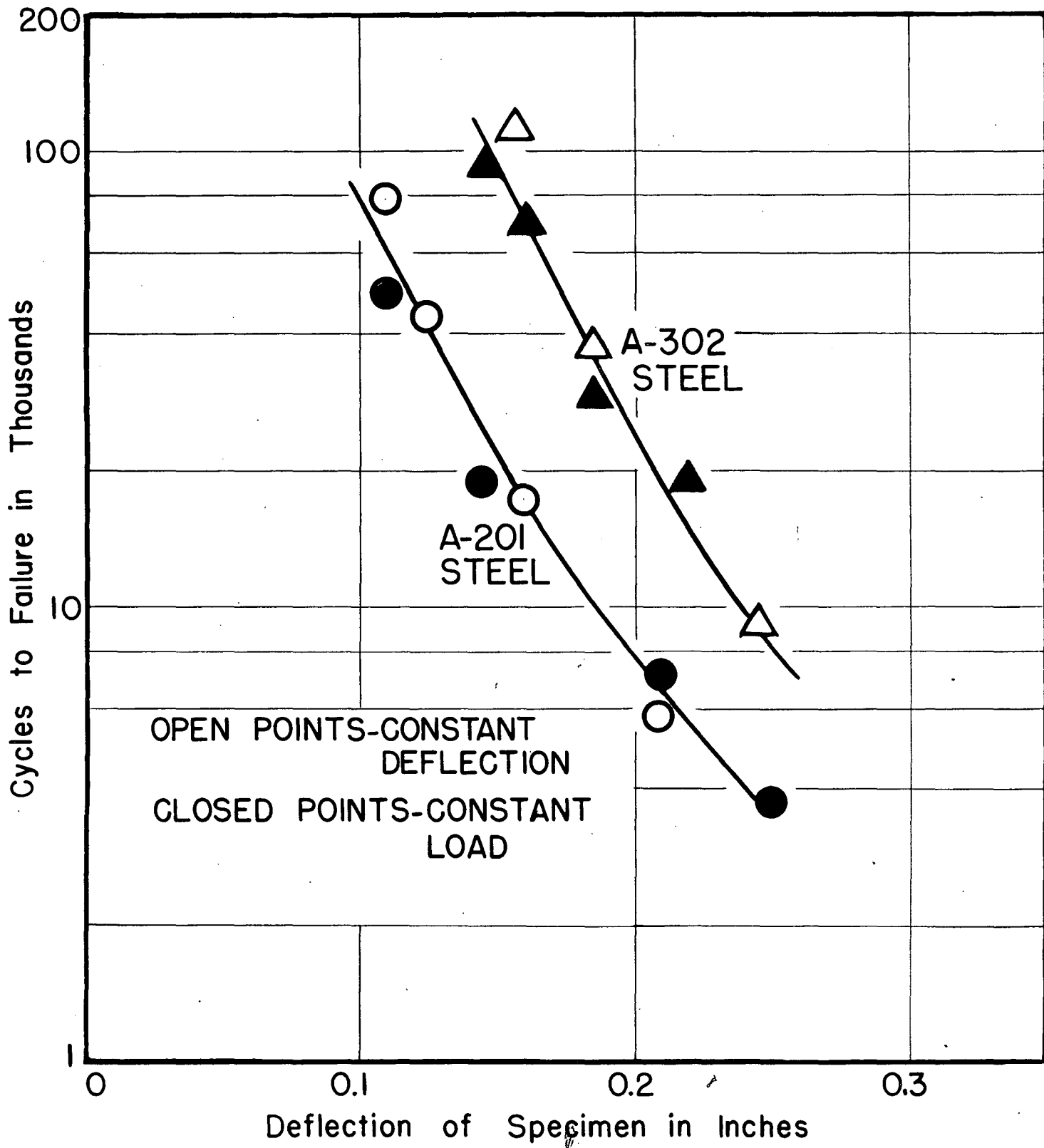




Fig. 19

Effect of Heat Treatment and Cold Work on Plastic  
Fatigue Strength of New A-302 Steel

