EFFECT OF SIZE ON OPTIMUM HARDNESS OF BOLTS

BY

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ABSTRACT

Notch-tensile properties have been investigated for a high-carbon steel. A method of finding the optimum hardness has been developed. The optimum hardness was found to lie in the lower hardness levels.

The size effect was also ascertained. In the brittle region, specimens of smaller size have higher optimum hardness and higher notch-strength, and vice versa.

To be used as bolts, the largest size for tough behavior for the steel tested is 3/4 inch in diameter.

CONTENTS

ACKNOWLEDGEMENTS

The writer wishes to express his sincere thanks to the following professors for their guidance to his graduate studies at the Colorado School of Mines: Professor H. Gordon Poole, Head of the Department of Metallurgy; Dr. J. D. Lubahn, Professor of Metallurgy; Dr. J. S. Rinehart, Professor of Mining Engineering; and Dr. H. T. Pinnick, Assistant Professor of Physics.

Dr. Lubahn has been very kind to teach the writer the theoretical concepts and the experimental methods of this thesis.

The writer is also indebted to the Atomic Energy Commission for sponsoring the project.

INTRODUCTION

In most structural applications, annealed steels are too soft for use, and therefore, they are often hardened by heat treatment or by other proper methods. With higher hardness, steels will have greater resistance to plastic deformation. But, when the hardness is too high, the steels will lose their toughness and become very brittle. Thus, each kind of steel must have a certain optimum hardness corresponding to its maximum utilization.

The strength of steels depends not only on the hardness, but also the brittle strength which decreases with increasing size of defects or depth of notch. For example, as the size of a steel bolt increases, the depth of the notch will also increase. Therefore, larger-sized specimens will have greater notch depth. It becomes apparent that for a given hardness, the maximum strength of a steel will vary with the size.

This investigation was (1) to evaluate the optimum hardness, and

(2) to ascertain the size effect. It is a part of the research program supported by the Atomic Energy Commission. The whole program is concerned with the determination of the strength limitations of metals.

The experimental procedure was first to heat treat several sizes of notch-tensile specimens to have the maximum obtainable hardness, and then to temper them to different hardness levels. The specimens were tested to failure. Next, the notch-strength values were correlated with the corresponding hardness to see in what manner the strength would change with the hardness.

The size effect became apparent when the notch-strength of different sizes of specimens were compared with each other. With reference to previous experimental facts, the data were analyzed and due conclusions were deduced.

SPECIMENS

Three different sizes of notch-tensile specimens were made for tests. Two adjacent notches were cut to simulate bolt threads. Only one of the notches was sharpened after tempering.

The specimens were made of D2 steel. This steel contains 1.5 percent carbon and 12 percent chromium. It is one of the steels to be studied for the entire research program supported by the Atomic Energy Commission. Detailed specimen dimensions are shown in Fig. (1). All specimens were heat treated to give tempered martensite.

Heat Treatment

For later use, a batch of disk-like samples was hardened and tempered at different temperatures. The hardness values were measured and plotted against the tempering temperature. This curve, Fig. (2), served as a guide for selecting temperatures for tempering the tensile specimens.

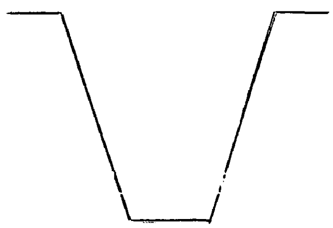
The specimens were hardened at 1,850°F, and were quenched in still air. For this hardening temperature, the specimens were necessarily protected from decarburization by packing in a box of cast iron chips. The hardened specimens were then tempered at various temperatures and air cooled (see Table 1). In all cases, a calibrated potentiometer was used to check the temperature; and the furnace temperature-controller was adjusted, when necessary, according to the potentiometer.

Notch Preparation

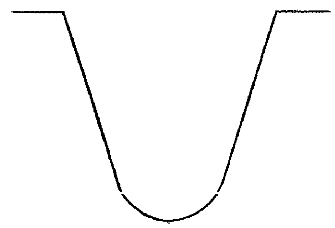
A notch is a stress raiser. It sets up localized concentration of stress. The severity of stress concentration depends upon the depth and the root-radius of the notch. Therefore, the dimensions of the notch must be controlled with great care.

To simulate bolt threads, the notch depth should vary with size of the specimen, that is, the larger the specimen, the deeper the notch. As the notch becomes deeper, the stress concentration factor increases. In order to determine the effect of absolute bolt size for a given relative notch depth, the notch depth should be kept in proportion to the specimen size. Hence, geometric similitude is necessary so as to fix a definite percentage of cross-sectional reduction by notching. The notch depth was chosen to be 10 percent of the specimen diameter (36 percent reduction of cross section by notching). This decision was made for two reasons: (1) the 10 percent notch gives low stress values, and (2) this notch depth is quite close to that of the usual bolt threads.

Some bolts were sectioned and the root-radius of their threads was examined. The shape of the thread-roots was found to be different from the truncated-V usually specified in handbooks. Rather, they had a round bottom. The difference is compared in the following sketch:



Specified thread root



Actual thread root

It was then decided that, to simulate the root configuration of bolt threads, the notch should have a round bottom with maximum root-radius of 5 thousandth of the specimen diameter. The root-radius of the notch of the specimens which were tempered above 1,200°F could be sharpened by an ordinary lathe tool. After each cut, the tool was measured by a microscope to insure that the root-radius was properly sharpened. Specimens tempered below 1,200°F were too hard to cut. In this case, a thin metal wire of suitable diameter was used to lap the root-radius of the notch. The sizes of the used wires are as follows:

Specimen diameter in.	Wire diameter in.
1/4	0.0026
1/2	0.0040
3/4	0.0065

The root-radius was measured by microscope after lapping. The lapping operation needed a longer time to sharpen the root-radius, but it gave very good results.

TESTING PROCEDURE

The specimens were first tested for notch-tensile strength. A section of each specimen was then cut and polished on both end-surfaces for hardness measurements. Afterwards, the same hardness samples were used for the compression tests.

Tension

As the specimens were not perfectly concentric during testing, two dial-indicator gages were used to measure the deflection. By a specially made fixture, the gages were mounted 180 degrees apart on clamps fastened to the specimen at the ends of the gage length. During testing, both gage readings were recorded at 1,000-pound load intervals for the 3/4-inch-diameter and the 1/2-inch-diameter specimens, and at 500-pound load intervals for the 1/4-inch-diameter specimens. The average of the gage readings was used for strain calculations. The arrangement is shown in Fig. (3).

Hardness

After the tensile test, a piece about 1 inch long was sectioned from the broken specimen. Both end-surfaces were carefully polished so that they were parallel and smooth. The sample was put on a Rockwell hardness tester. Several points on one surface were tested and the average of the readings was taken as the hardness value of the specimen. The Rockwell C scale was used for all tests.

Compression

In compression test, it was necessary to load the sample as concentrically as possible. For this reason, a movable half sphere was used for easy adjustment, Fig. (4).

Because the guideposts of the testing machine provided the crosshead with restriction against tilting, only one dial-indicator gage was needed to measure the crosshead motion and to record the deflection of the sample.

As mentioned above, the hardness samples were used for compression. But the sample length of the 1/4-inch-diameter size was cut comparatively shorter for compression test in order to avoid buckling. The approximate lengths of the compression bars are as follows:

Specimen diameter in.	Length of comp. bar in.
1/4	0.6
1/2	1.0
3/4	1.0

RESULTS AND ANALYSES

All tests gave normal results. But the tensile tests of the 3/4-inch-diameter specimens had a peculiar fashion of fracturing. In spite of the fact that the notch of each specimen was sharpened carefully and was cut purposely, before sharpening, about 0.02 inch deeper than the threads, the specimens did not break at the notch, but consistently broke at the last thread.

Because the specimens could not be loaded perfectly concentrically, they received a considerable amount of bending which caused them to break in the particular way. Fig. (5) and Table (2) give an example of this situation. Normally, both gages should always give readings indicating extension. On the contrary, one gage would often indicate contraction in the early part of the test, due to the bending effect. However, the average change in gage readings for each load interval was quite uniform.

That the specimens broke at the last thread was not considered to affect the testing results, for the important thing was to find the notch-tensile strength, and the thread, whose root-radius was found to be comparable with that of the notch, just served the very same purpose as the specially prepared notch. Testing results are shown in Table (1).

Use of Data

Although a hardness test is a convenient test of the deformation behavior of metals, it is not a direct measure of the strength itself. It was, therefore, very desirable to determine the yield strength of the specimens. The yield strength was obtained from the compression tests. An amount of 0.002 strain was chosen as a standard offset. The hardness value was then related to the yield strength as shown in Fig. (6), so that the yield strength of the specimens, heat treated to any hardness, can be found from this curve.

The notch-tensile strength of each specimen was plotted against its yield strength. The 0.002 inch plastic extension was used to determine the notch strength in case the tensile specimen malfunctioned by yielding. When the tensile specimens malfunctioned by fracturing, the notch strengths were obtained by dividing the breaking load by the cross-sectional area at the root of the notch.

Faired curves of the strength values for each size of the specimens were then established as shown by lines AA', BB', and CC' in Fig. (7). These lines represent the malfunction stresses by fracturing (S_{mff}). The notch-tensile strength, represented by the ordinate in this graph, is called the malfunction stress, S_{mal}, for it is this stress which caused the specimen to fail. A line through ABC was then drawn on the graph. This line represents the malfunction stress by yielding (S_{mfy}). The intersection Points A, B, and C separate the graph into two regions. On the right side, the specimens are frangible (fail by fracturing). On the left side, the specimens are tough (fail by yielding).

The line ABC was established according to the following criterion:

(1) The line should be straight and have a slope equal to the plastic constraint factor. This factor was determined by Sachs, Lubahn, and Ebert (1945) as

$$S_n/S_u = 1 + \%R$$

S_n = notch strength

S_u = unnotched strength

$\%R$ = percentage of reduction in area by notching/100

(2) There should not be frangible points to the left of it.

(3) The line should fit the points where tough behavior occurred.

However, the real situation is not so ideal, and the above criteria can not be all satisfied at the same time. Consequently, the line has to be drawn with best compromise. Hence, line ABC is established as

$$S_{mfy} = 1.13\ S_y \qquad (1)$$

where S_y = yield strength

1.13 = plastic constraint factor

According to the formula, the plastic constraint factor should be 1.36. The discrepancy may be due to the difference in definition of strength. Here the stress to generate 0.002 in plastic extension was taken as the malfunction stress, whereas the cited authors used the ultimate strength.

The lines AA', BB', and CC' were drawn by referring to the inverse square law (Winne and Wundt, 1958). This law requires that

$$S_{mff} = K \frac{1}{\sqrt{d}} \tag{2}$$

where d = specimen diameter

k = $f(S_y)$, a function of yield strength

let $$f(S_y) = mS_y + b$$

then $$S_{mff} = \frac{mS_y + b}{\sqrt{d}} \tag{3}$$

Taking logarithm of this equation,

$$\log S_{mff} = \log (mS_y + b) - 1/2 \log d$$

Differentiating log S_{mff} with respect to log d,

$$\frac{\partial(\log S_{mff})}{\partial(\log d)} = -1/2 \tag{4}$$

This means that for a certain yield strength level, the plot of log S_{mff} versus log d should have a slope of -1/2.

The faired curve in Fig. (8) shows that the data have a good agreement with this law.

The constants m and b in equation (3) can be determined by substituting from Fig. (7) values of S_{mal} and S_y which agree with equation (4) and also satisfy the data, on the average. By this curve fitting method, equation (3) is established as

$$S_{mff} = \frac{108,000 - 0.0802\ S_y}{\sqrt{d}} \qquad (5)$$

This equation represents the lines AA', BB', and CC' in Fig. (7). The intersection points, obtained by solving equations (1) and (5) will determine the optimum strength of a specimen of any size.

As an example, to find the optimum strength of a 6-inch bolt, solve equations (1) and (5) by substituting d = 6 and get

$$S_{mff} = 1.13\ S_y = \frac{108,000 - 0.0802\ S_y}{\sqrt{6}}$$

then

$$S_y = 38,000 \text{ psi}$$

This is the optimum strength of the 6-inch bolt. But this optimum strength cannot be reached by the D2 steel, because the lowest hardness after tempering is R_c 28.5, the corresponding yield strength is 110,000 psi. At this yield strength a 6-inch bolt will be brittle and will have a strength, according to equation (5), of 40,000 psi.

The above result is very significant. It means that, for D2 steel, the optimum strength of a 6-inch bolt cannot be realized because the bolt is too large. This fact brings out an interesting subject, namely the size effect.

Size Effect

Fig. (7) shows that the stress for malfunction by fracture decreases when the size increases. The faired stress lines have been drawn in such a way as to conform to the inverse square root law for every yield strength. The line for the smallest size lies on the top, that for the intermediate size in the middle, and that for the largest size at the bottom. Fig. (8) shows the size effect even more clearly. The faired log S_{mff} log size curve has been drawn as a straight line with a slope of -1/2. It indicates that for a certain strength level, the larger the size, the lower the malfunction stress. Furthermore, this curve can be constructed and used by extrapolation to predict the optimum strength of the specimen whose size is too large to test.

As to the size effect, it should be made clear here that the result of the above example does not mean that a 6-inch bolt of D2 steel cannot be used. It does mean, however, that the bolt of this size should be heat treated to have the lowest hardness level so as to best utilize the strength of the material. This fact leads to the discussion to the problem of optimum hardness.

Optimum Hardness

Fig. (7) shows that the specimens of each size have a general characteristic. As the yield strength increases the malfunction stress first increases to a certain level, then apparently starts to decrease rather slowly. All the faired curves AA', BB', and CC', were drawn as straight lines of decreasing slope. There is some indication, particularly in the case of line BB', that there is a maximum in strength near 225,000 psi yield strength, but the scattering precludes a definite conclusion.

With the data faired in this manner, the optimum hardness is at the line separating the tough and the frangible regions (points A, B, and C). The reasons that other possibly higher hardness values lying to the right of this line are not considered as optimum hardness are as follows:

(1) They are in the frangible region. Bolts heat treated to such hardness will fail by fracturing under possible circumstances of excessive eccentric loading or momentary overloading.

(2) They are not much higher than the chosen optimum hardness. Consequently, the gain in bolt strength is little.

By contrast, the advantages of locating the optimum hardness by the above method are now quite obvious:

(1) The bolt will have high strength, and yet it is not frangible.

(2) The bolt will be able to sustain possible overloading or eccentric loading by plastic deformation and still continue to perform its function.

Accordingly, from Fig. (7) and (6), the optimum hardness values, and the corresponding optimum yield strengths of the tested specimens are found as follows:

Specimen diameter in.	Optimum Hardness R_c	Optimum Yield Strength psi
1/4	41	167,500
1/2	33	122,500
3/4	28.5	102,000

The 3/4-inch-diameter bolt should be tempered to have the lowest obtainable hardness.

DISCUSSIONS AND CONCLUSIONS

There is considerable scattering of the data points in the graphs. It is believed that the scattering is due primarily to the bending effect in the tensile tests, and partly due to the slight variations of the root-radius of the notch. The scattering has caused some uncertainty in the exact location of the curves, and they have to be drawn with best estimates.

However, in spite of some scattering of the data, this investigation has furnished sufficient proof that

(1) The notch-tensile strength of the steel is sensitive to specimen size.

(2) The optimum hardness depends on size. Specimens of larger size should have comparatively lower hardness.

(3) When the hardness continues to increase beyond the tough-frangible boundary, the malfunction stress will tend to decrease, but the stress decreases very slowly, until high hardness is reached.

(4) For future experimentation in notch tension, two things should

be taken into consideration:

(i) The effect of bending: A special fixture should be used so as to eliminate the bending effect and to achieve pure tension.

(ii) The variations of notch root-radius: The root-radius of the notch should be all lapped by metal wire of suitable size. The lapping operation will insure the uniformity of the notch root-radius.

The above conclusions apply only to the D2 steel. They should also apply to other steels which can be heat treated to have frangible behavior, but the optimum hardness values may be considerably different.

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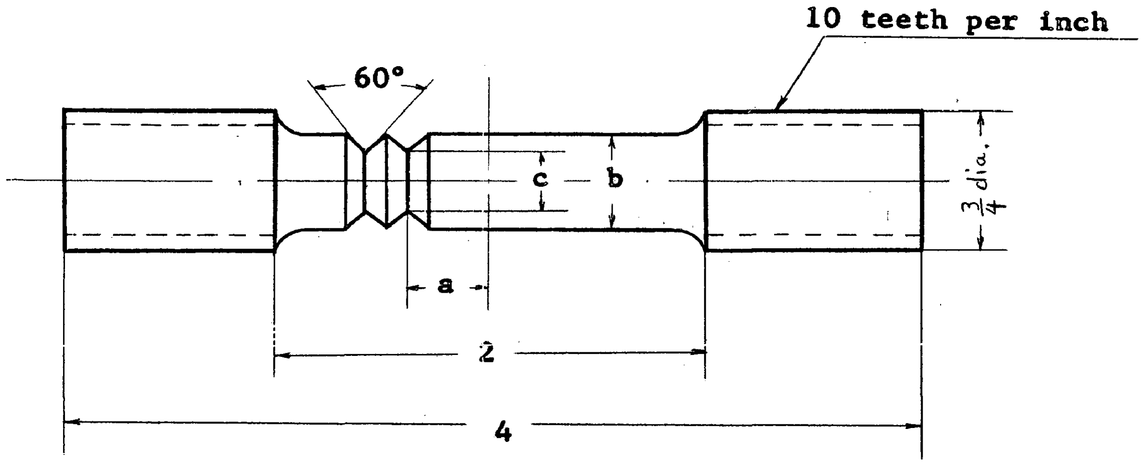
Winne, D. H., and Wundt, B. M., 1958, Application of the Griffith-Irwin theory of crack propagation to the bursting behavior of disks, including analytical and experimental studies: Trans. of Am. Society of Mechanical Engineers, v. 80, p. 1643-1658.



Dimensions in Inches

a	1/4	1/2	1/8
b	3/4	1/2	1/4
c	0.610	0.400	0.203

Fig. (1) Specimen Dimensions

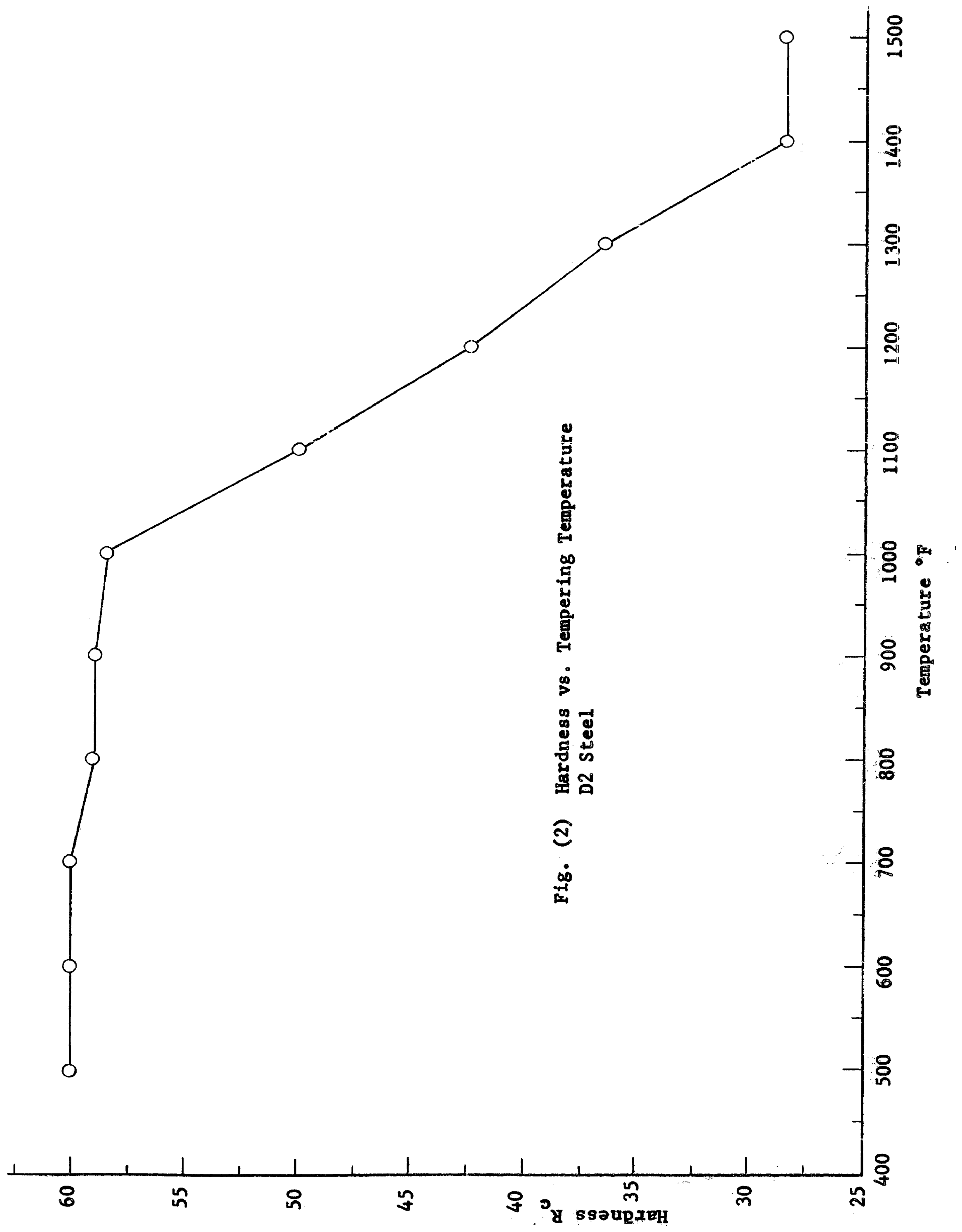
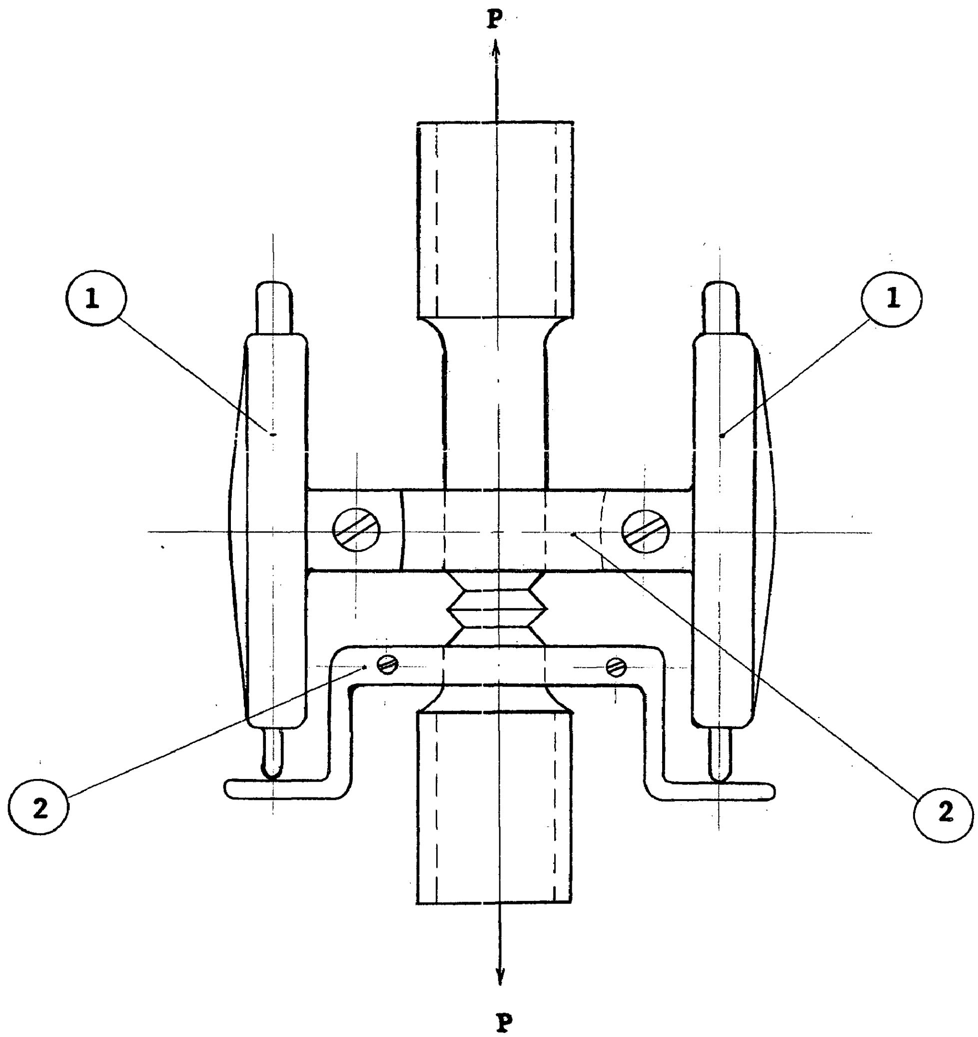


Fig. (2) Hardness vs. Tempering Temperature
D2 Steel

Specimen diameter in.	Tempering temperature F°	Hardness Rc	Breaking load lb	Notch root-radius in.	Notch diameter in.
1/4	500	60	5800	0.0013	0.204
	800	58.5	6000	"	0.205
	1100	49	5900	"	0.204
	1150	45	4640	"	0.202
	1200	42	6300	"	0.201
	1250	39	6000	0.0011	0.197
	1300	36.5	5400	0.0012	0.204
1/2	--	64.5	10700	0.0020	0.403 (Not tempered)
	500	60	17500	"	0.401
	800	59.3	17000	"	0.400
	1100	49	21500	0.0026	0.403
	1100	49	19000	0.0020	0.402
	1150	44	18400	0.0024	0.402
	1200	42	15800	0.0024	0.404
	1250	40	16000	0.0025	0.395
	1300	38.5	16000	0.0024	0.400
	1350	34	16700	0.0016	0.395
	1400	31	18000	0.0011	0.403
3/4	300	63.5	16600	*	*
	500	59	15500	*	*
	1200	42.5	31700	*	*
	1400	29.5	35900	*	*

* The 3/4-in.-dia. specimens were broken at the last thread. The root-radius of the last thread was found to be approximately 0.003.+

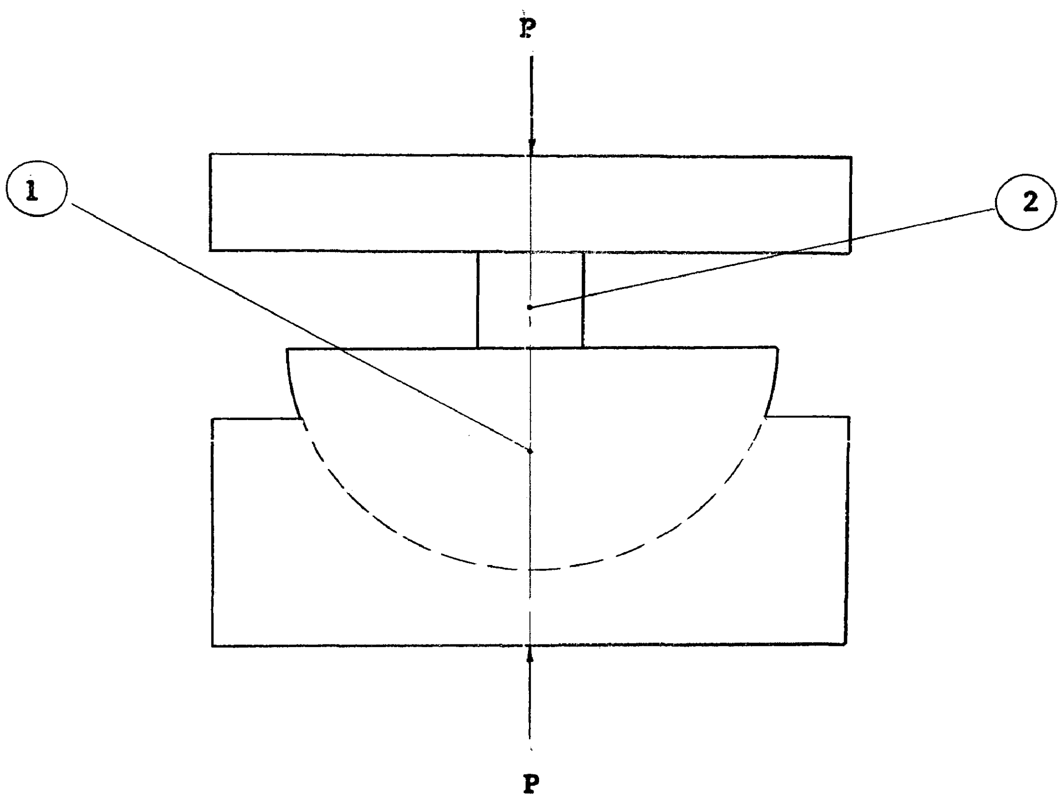
Table (1) Summary of Data



(1) Dial-Indicator Gages

(2) Fixtures

Fig. (3) Tensile Test Arrangement



1 Movable Half Sphere

2 Sample

Fig. (4) Compression Test Arrangement

Load 1000 lb	Gage 1 0.001 in	Gage 2 0.001 in	Gage Sum 0.001 in
1	6.2	10.7	16.9
2	6.0	10.8	16.8
3	5.6	11.1	16.7
4	5.2	11.3	16.5
5	4.9	11.4	16.3
6	4.7	11.4	16.1
7	4.5	11.4	15.9
8	4.3	11.4	15.7
9	4.1	11.4	15.5
10	3.9	11.4	15.3
11	3.8	11.3	15.1
12	3.7	11.2	14.9
13	3.6	11.1	14.7
14	3.5	11.0	14.5
15	3.4	10.9	14.3

Specimen broke at 15,800 lb.

Table (2) Data Sheet of Tensile Test, Illustrating the Bending Effect. 1/2-in.-dia. Specimen Tempered at 1200°F

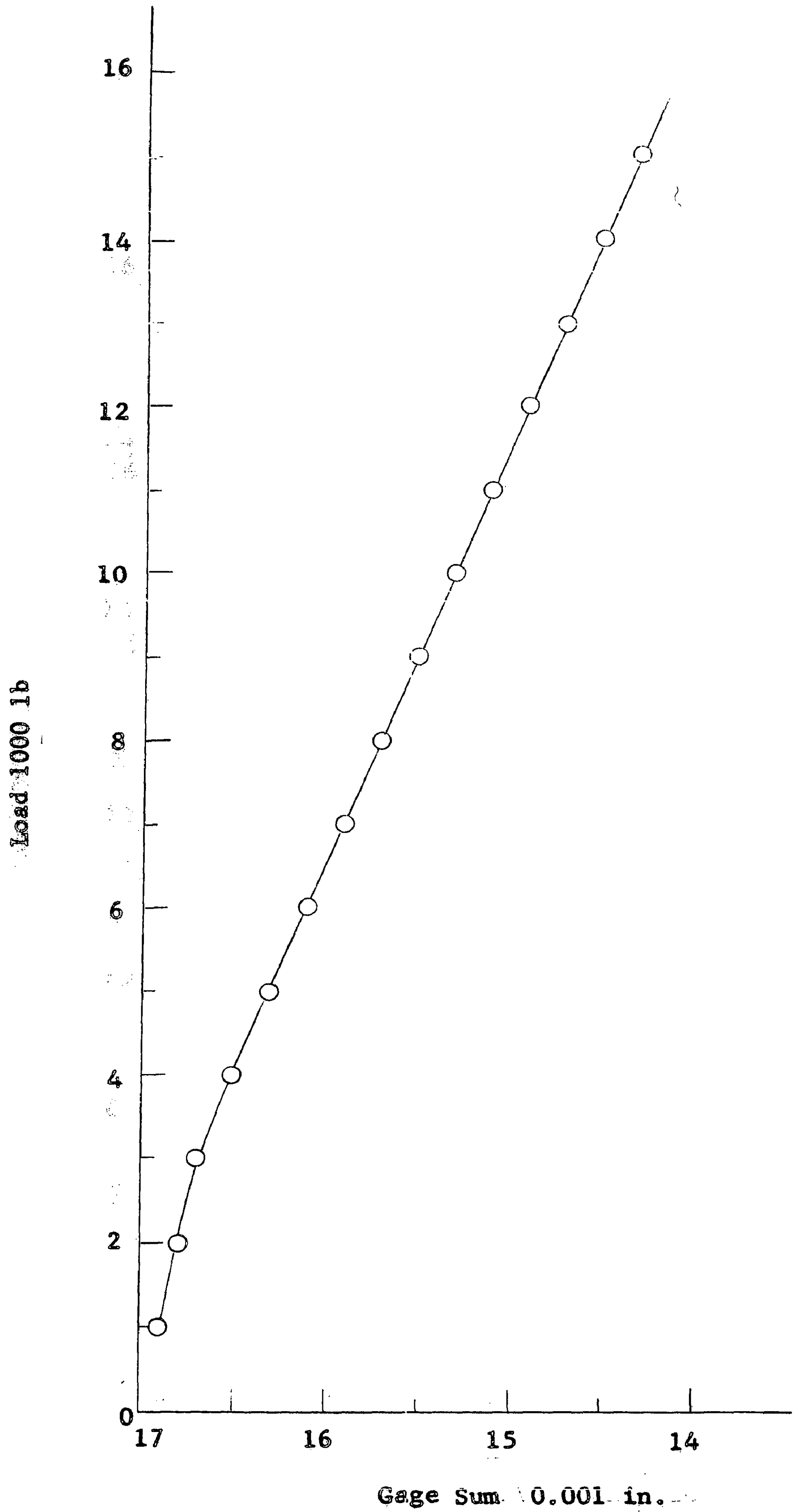


Fig. (5) Tensile Curve From data on Preceding Page

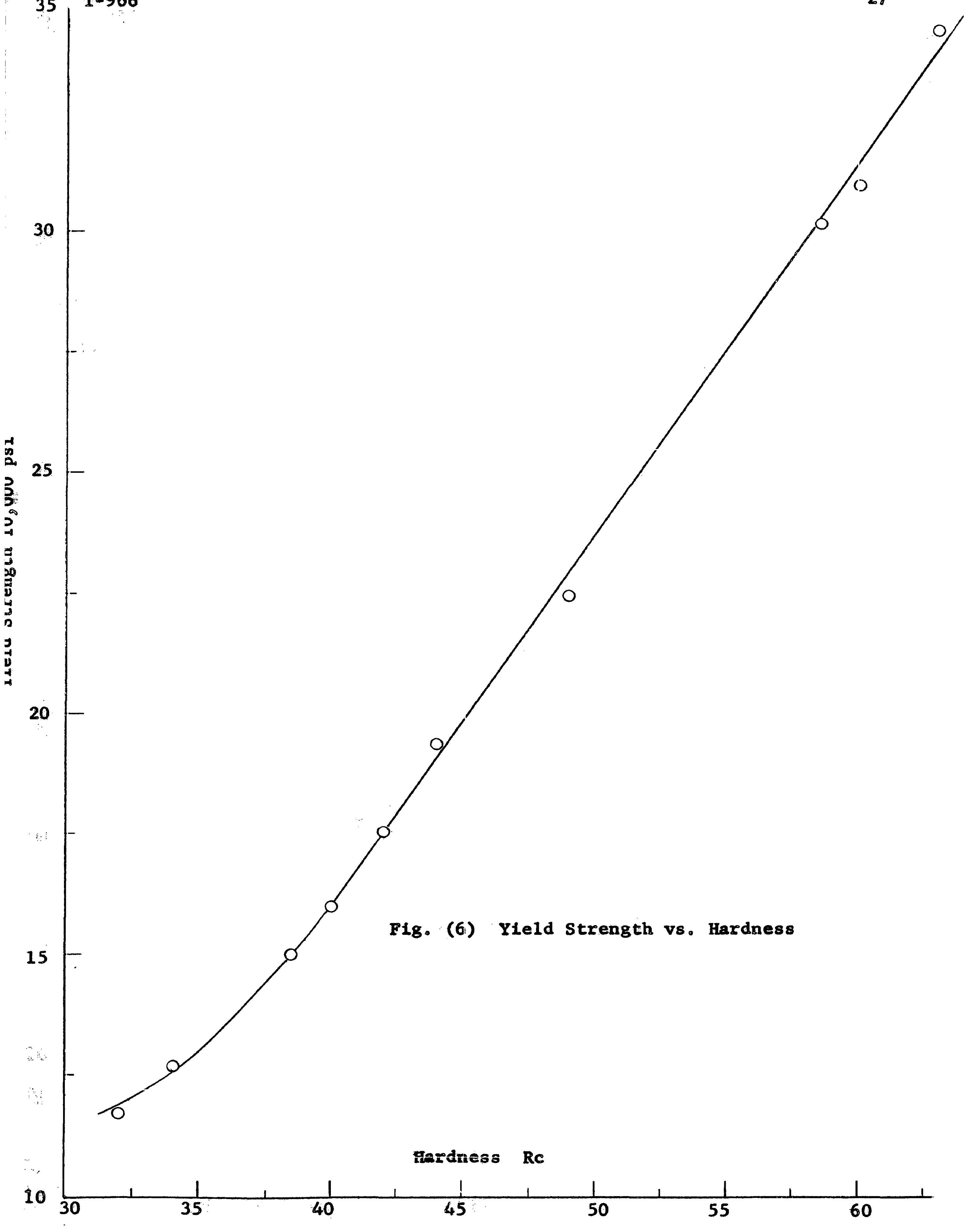


Fig. (6) Yield Strength vs. Hardness

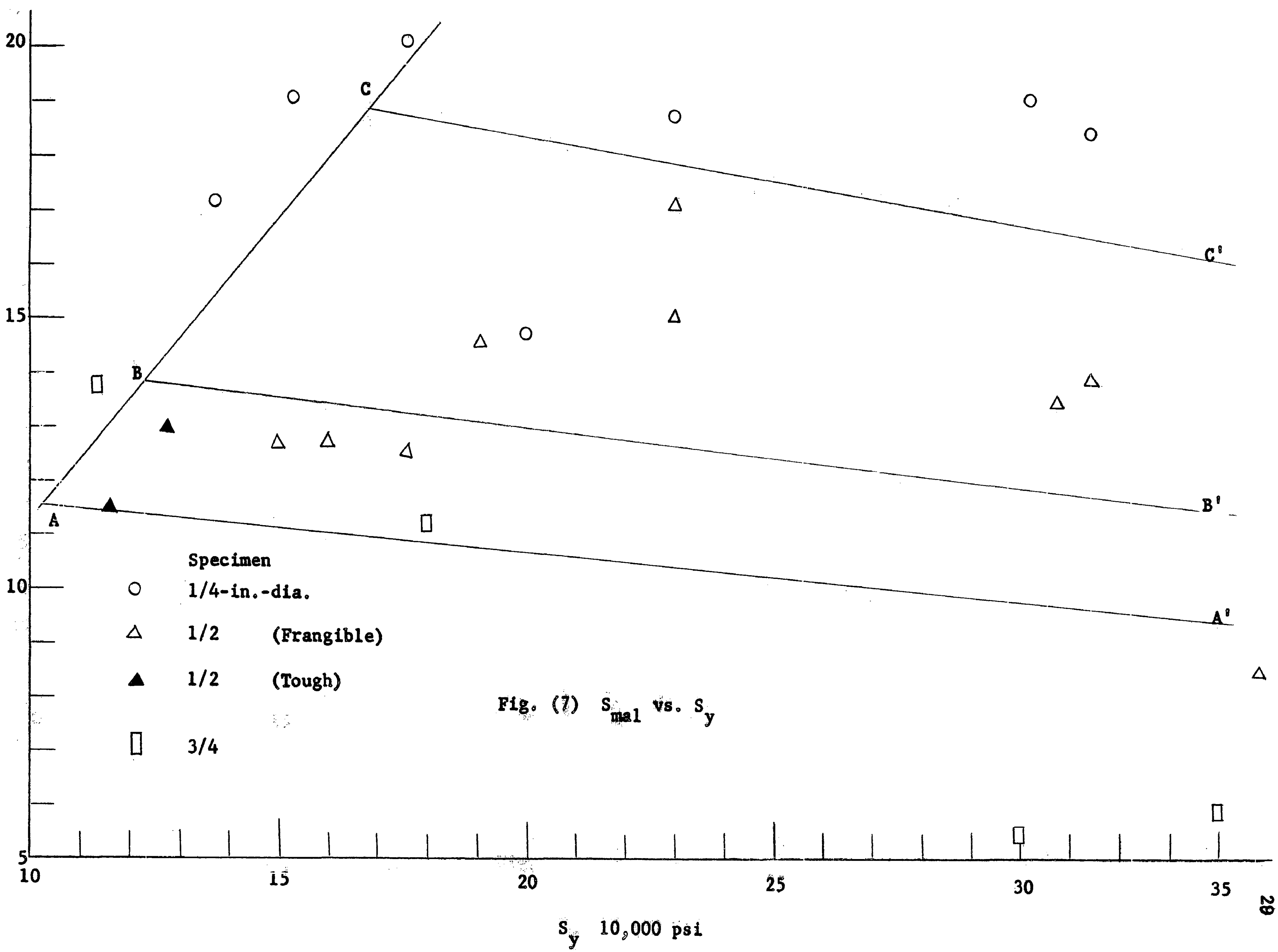
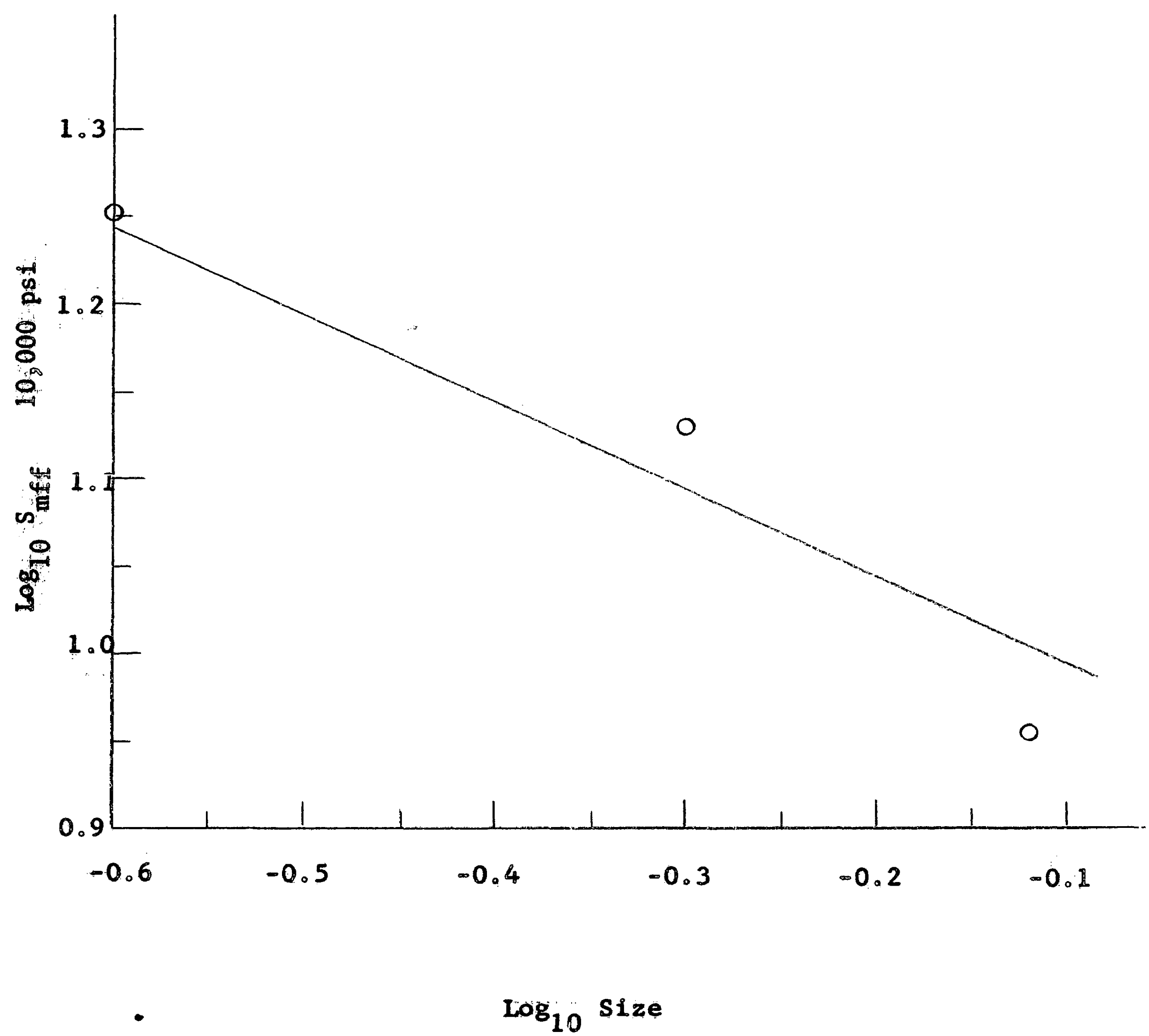


Fig. (7) S_{mal} vs. S_y



S_{mff} = Stress of malfunction by fracturing

Fig. (8) Log S_{mff} vs. Log Size