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(North Carolina University Armor Fracture Size Effect Study, Progress Report No. 22)

SECOND REPORT ON TENSILE TESTS OF CLASS B ARMOR STEEL WITH SPECIAL REFERENCE TO SIZE EFFECTS.

NAVAL RESEARCH LABORATORY
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FORWORD

It is believed appreciation of the attached report will be improved by the following amplifying comments. As described in previous reports, the block of heavy Class B armor from which samples are being taken for this study is a fairly coarse grained Ni-Cr steel plate formed from a 200 ton open hearth heat poured into one ingot and reduced about 3-1/2 to 1 with forging under a press. Under such circumstances a close agreement of reduction of area values for small tensile bars taken from central regions of the plate is not expected.

The investigation is part of a larger program with the objective of studying such armor brittleness features as can be disclosed by slow speed bending or tensile testing from a size effect point of view. Previous work has now shown large size effects are present in steel of this type both under impact by projectiles and under slow speed testing. The size effects are only observed in association with deformation features which involve initiation and propogation of cracks.

Whether or not a "genuine" effect, an effect clearly outside experimental error, is disclosed frequently depends on the organization of the data. The maximum stress and reduction of area at this maximum stress both show size effect in the careful shoulder type tensile bar tests of this report with enough probability to satisfy most readers. The authors are cautious in their conclusions and the magnitude of the size effects shown are indeed quantitatively uncertain. In spite of the warning from the data of this report that the customary tensile bar test is poorly adapted to quantitative studies of rough fracture size effects, there remains some prospect that a grooved tensile bar, a different choice of size range, or both might result in a satisfactory tensile type measurement of fracture size effects. One benefit of such a development is that it might simplify general use for evaluating these properties in unknown material.

Regardless of the situation with respect to features associated with cracking and fracture, the cylindrical tensile bar is unquestionably well adapted to study of size effects in the plastic domain. The fact that careful tensile testing of this typical heavy armor material fails to show measurable size effects in the plastic domain is of fundamental importance.

G. R. Irwin

PROGRESS REPORT NO. 22

Copy ____ of 30.

August 28, 1943

To: Drs. Ross Gunn, G. R. Irwin, and A. E. Ruark

By: R. M. Trimble and P. E. Shearin

SECOND REPORT ON TENSILE TESTS OF CLASS B ARMOR STEEL WITH SPECIAL REFERENCE TO SIZE EFFECTS

Introduction

The purpose of this series of tests was to extend the investigation of size effect with a wider range of specimen diameters and with more accurately made specimens, tested in holders designed to apply the loads uniformly and axially.

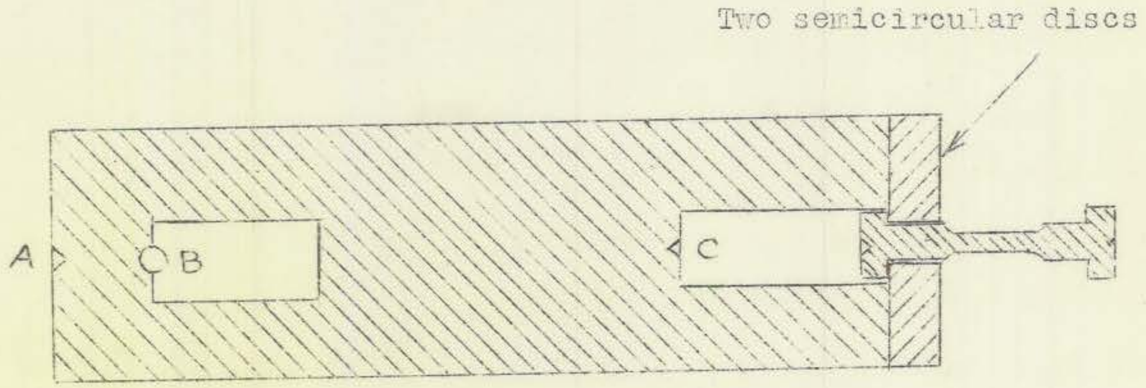
A former series of tests with threaded-end specimens with diameters of 0.2 in. and 0.4 in. was discussed in Reports No. 19 and 20 (Ref. 1 and 2) in which conclusions as to variations in mechanical properties, and as to size effect, were tentative because of the relatively small number of specimens. The flow curves were shown by plotting true unit stress against unit elongation. The specimens studied herein were made with shoulder bearings instead of threads and the flow curves are shown by plotting true unit stress against $(A_0 - A)/A$, where A_0 is the initial area and A the area at any given stress. This quantity is sometimes called "effective" reduction of area and we shall follow this practice although the name is not a good one. The former series of threaded specimen tests has been converted to this basis and plotted for comparison. The ratios of the length of the cylindrical portion of the specimen to its diameter are 4 and 1.875 for shoulder and threaded specimens, respectively. The size range now covered by both series is from 0.2 inch to 0.75 inch diameter. This means a factor of 3.75 in diameter or about 14.0 in specimen area.

With the new type holders described below the initial alignment of the specimen with the pulling axis, and the eccentricity of the specimen center, if any, can be tested and measured. This was not the case with the threaded holders. When threaded holders are used one cannot make any useful statement as to the origin of the spread of stress values for a group of specimens of given size and orientation. If most of the spread were due to defects of alignment and eccentricity, the use of the new holders should reduce it greatly. As a matter of fact, the new holders reduce the spread of the results but the improvement is not striking and the situation calls for careful discussion. (Sec. I). A chief advantage of the new holders in searching for size effects is that the magnitude of the experimental errors can be estimated on the basis of actual measurements with the specimen mounted in its holders.

I. EXPERIMENTAL DETAILS

1. The Holders.

One holder is shown diagrammatically, in section, below. The holder is made of 3-in. cold rolled steel turned on centers A and C. The ball, B, through which the load is applied, is adjustable laterally to have its center on the line of centers AC. The ball receives the load through a bearing block (not shown) with a spherical indentation preformed by the ball itself. The spherical area of contact subtends a central angle of about 90°.



The contact surfaces of specimen and holders are accurately ground perpendicular to the specimen axis with a tolerance of 0.0001 in. Before testing, the assembly of holders and specimen is mounted vertically on external centers (A,A) and rotated to determine the eccentricity of the specimen if any. The specimen may be adjusted laterally in the holders if necessary.

2. Preparation and Mounting of Specimens.

The specimens were prepared by lathing 0.008 in. over-size on body diameter with no tool marks as deep as 0.002 in. The diameter is then reduced by grinding longitudinally with a wheel of about No. 100 grit and a diameter of proper size to fit the fillet between body and shank. The reduction is accomplished by successive removals of material in decreasing depths of cut.

The shoulders are ground to finish, perpendicular to the specimen axis. Tests indicate that alignment of specimen in holders is good enough to relieve any doubts as to the uniformity of stress in the plastic domain; that is to say, any non-uniformities which are introduced by the holders or the geometric form of the specimens (deviation from perfection) should be small compared with those due to lack of homogeneity in the specimens.

Inspection of the literature would lead us to believe that these holders are at least as good as those used in the investigations of Docherty and Thorne (Ref. 3) and of Morrison (Ref. 4) which were carried out with the greatest care; but just as in the case of Morrison, the alignment attainable by machining the essential surfaces to a tolerance of 0.0001 in. will not prevent some falsification of the yield point of a substance showing a sharp break at the yield. To get such a yield stress it would be necessary to use multiple extensometers similar to the way worked out by Morrison.

However, if we are interested in the average stress over the specimen cross section at any specified point on the flow curve, small variations from perfect conditions of alignment and centering should not effect the results up to the point where cracks actually form in the specimen. As long as the material continues to work-harden there is a uniformizing action which tends to preserve correct alignment. If one side of the specimen undergoes slightly greater strain than the other this greater strain results in work hardening which checks its flow and allows the other side to catch up with it. Slight irregularities of strain over the cross section will not appreciably falsify the average stress, or the average elongation of a fiber parallel to the axis, or the reduction of area. In practice the reduced section is not truly circular and we allow for this by taking two sets of measurements of the diameter at the neck, in mutually perpendicular directions.

These ideas cannot be applied to a specimen which has begun to fracture. Any asymmetry of load on such a specimen will be expected to result in asymmetric fracture patterns under extremely asymmetric load; for example, cracking might commence far from the center. Afrer the onset of cracking, t e true average stress can no longer be obtained. That is, if we divide the load by the remaining area the number we get is not an average over the apparent section, but only an average over the unknown part which remains uncracked.

The reasoning above concerning the effect of asymmetry before incipient fracture leads to the idea that we need not distrust our flow curves for threaded specimens. Naturally the matter had to be subjected to experimental test by making tests with holders of the best possible construction, but the results in Figs. 186 and 187 do not support the idea that the values with threaded specimens are essentially inferior to those obtained with shoulder specimens. For this reason we believe that in considering size effects up to the point of incipient fracture, the threaded specimens should be included with the others.

3. Location of Specimens.

The mechanical and metallographic properties of the large block of Class B armor (4A443A1) from which the specimens were cut has been sufficiently described in References 1 and 2. For present purposes it will suffice to say that this 18 in. block shows a zone of tempered martensite extending about 3 in. from the original face and that the remainder is tempered bainite which is surprisingly uniform in hardness. Most of the specimens come from the bainite region. Their orientation is described by stating the direction of the specimen axis relative to a right handed coordinate system in which OX runs parallel to the length of the ingot and OZ is perpendicular to the original plate surfaces. Therefore, specimens with the symbols OX, OY, and OZ may be called longitudinal, transverse, and perpendicular, respectively.

4. New Method of Plotting.

Previously the tensile flow curves were plotted with true unit stress as ordinate and unit elongation as abscissa. Unless the neck always occurs midway between a pair of gauge points comparable curves for two specimens cannot be obtained. The revised method already mentioned in the introduction, eliminates the effect of position of the neck.

In going from the threaded specimens to the shoulder type the specimen shape was changed and it would not be practical to make any comparisons of the two on the basis of elongation, even if the ratio of gauge length to diameter were made the same in the two cases. This is true because the change in specimen shape causes a slight change in the distribution of the stress and strain along the specimen length.

On the long cylindrical shoulder-type specimen, in order to include the neck between a pair of gauge points, it was necessary to make multiple measurements of elongation. This was not done on the threaded series for since they were relatively short all breaks occurred between the single pair of gauge points. Measurements of area reduction were made throughout each test in all series, and it is obviously convenient to plot the flow curves against a variable closely connected with area reduction. The physical point involved is that we are interested in the conditions at or near the section which will finally break, not the conditions over a large length of the specimen, most of which is in a condition of deformation corresponding approximately to the maximum load.

The new method employs semi-logarithmic plotting paper in order to spread out the early stages of the flow for easy graphical study. The use of the variable $(A_o - A)/A$ results in a suitable spread and yields a curve which is nearly straight over a large region.

Figs. 186 and 187 show the flow curves for threaded and shoulder specimens, respectively. Direct graphical comparisons cannot be made between these two sheets. The reader will note that slightly different vertical scales are used and the number of cycles is not the same. However, size and directional effects are comparable in any group, and between groups.

II. TEST RESULTS

1. Table 1 shows the body of the data giving results in terms of maximum true stress, effective reduction at maximum true stress, and unit stress at maximum load. Percentage differences between results for large and small specimens are recorded to facilitate study of possible size effects. The method of recording load in the tests was the same as described in Report 19, viz. an interval of at least five minutes between application and reading of load was used throughout. This obviously detracts from the value of the first two properties mentioned above, since, more often than not, the final rupture takes place during the application of a load increment.

TABLE I. Effect of Size on Maximum True Stress, Effective Reduction of Area at Maximum True Stress, and Unit Stress at Maximum Load.

Region, Direction	Spec. No.	Diam. (in.)	Frac. Type	Max. Stress, psix10^{-3}	$(A_0-A)/A$ at max. stress	U.S. at Max. Load psix10^{-3}
	THREADED SPECIMENS					
Martensite OZ	123 I	0.4	R	123.0	0.2942	112.00
	123 Ia	0.2	R	126.0	0.4707	108.15
	Diff.			-2.4%	-37.5%	+3.5%
Bainite OY	D 8 I	0.4	CC	157.5	1.3720	107.76
	D 8 IA	0.2	CC	151.0	1.3705	105.42
	Diff.			+4.3%	+0.1%	+2.2%
Bainite OZ	123 II	0.4	R	119.0	0.3777	106.06
	123 IIa	0.2	R	114.0	0.3291	103.10
	Diff.			+4.4%	+14.8%	+2.9%
	SHOULDER SPECIMENS					
Bainite OY	221	3/4	R	124.82	0.5445	102.45
	211	3/4	R	119.16	0.4584	102.60
	232	3/4	A	120.45	0.3680	105.75
	Avg.			121.48	0.4570	103.60
Bainite OY	221a	5/16	R	124.30	0.4963	102.75
	221b	5/16	R	131.40	0.7379	103.70
	215	5/16	R	121.55	0.5075	102.30
	Avg.			125.75	0.5806	102.92
	Diff.			-3.4%	-21.3%	+0.7%
Bainite OZ	111	3/4	R	106.70	0.1901	102.55
	131	3/4	R	102.82	0.1473	100.20
	121	3/4	R	107.36	0.1164	no. max.
	Avg.			105.63	0.1513	101.38
Bainite OZ	111	5/16	R	119.50	0.4145	104.05
	131	5/16	R	103.08	0.1505	101.50
	121a	5/16	R	102.90	0.1528	100.90
	121b	5/16	R	116.25	0.3991	102.90
	Avg.			110.43	0.2792	102.34
	Diff.			-4.4%	-45.8%	-0.9%

R - Rough, A - angular, CC - cup and cone (or partial cup and cone)

The unit stress at maximum load appears to be of greater value. Although the maximum load does not always occur at the same value of reduction, the physical condition of the specimen is in a certain sense the same for all; namely, the effect of work hardening in portions which can still undergo plastic flow is in balance with the effect of reduced area and of any factors which work in a weakening direction.

The maximum load is arrived at not by simple inspection of the test data sheet, but by plotting, in the vicinity of the maximum, a curve of load versus area. The locus of the mid-points of chords of this curve is plotted and extended to cut the curve. The quotient of the coordinates of this point gives unit stress at maximum load. This property is independent of the nature of the fracture and the final stress and reduction.

2. No significant correlation was found between unit stress at maximum load and maximum true stress in the threaded series. However, as seen in Table 1, these comparisons depend on values for single specimens in each size pair. The ratio of these properties varied from 64% to 91% in these pairs.

In the shoulder specimen groups the averages of these ratios were as follows:

Group	(Unit stress at Max. load)/(Max. unit stress)	Difference
Large OY	0.860	
Small OY	0.818	+5.1%
Large OZ	0.968	
Small OZ	0.931	+4.0%

TABLE 2. EFFECT OF SIZE ON TRUE UNIT STRESS (p.s.i. x 10^{-3})
Fracture types: R - rough, A - angular, CC - cup, cone

SPECIMEN			Direction,	EFFECTIVE REDUCTION - $(A_0-A)/A$					Mean
Type	No.	Size	Frac. Type	0.02	0.04	0.08	0.16	0.32	Diff. %
Thd'd	123I	0.4 in.	OZ - R	87.9	96.9	106.4	115.1		
	123Ia	0.2 in.	OZ - R	85.1	94.3	103.8	112.0		
	Diff.%			+3.29	+2.76	+2.50	+2.77		+2.83
Thd'd	D8I	0.4 in.	OY - CC	73.2	87.2	99.9	109.2	119.5	
	D8Ia	0.2 in.	OY - CC	71.9	85.2	98.2	107.6	117.6	
	Diff.%			+1.81	+2.35	+1.73	+1.49	+1.62	+1.80
Thd'd	123II	0.4 in.	OZ - R	71.0	84.4	97.1	106.7	116.5	
	123IIa	0.2 in.	OZ - R	69.5	82.0	95.0	104.4	113.5	
	Diff.%			+2.16	+2.92	+2.21	+2.20	+2.64	+2.43
Shoulder	221	3/4 in.	OY - R	72.5	85.7	97.3	105.3	115.2	
	211		OY - R	72.1	84.5	96.6	105.1	115.0	
	232		OY - A	71.2	86.0	98.9	108.0	118.1	
	Avg.			71.93	85.40	97.60	106.13	116.10	
Shoulder	221a	5/16 in.	OY - R	73.7	85.5	97.9	106.3	115.8	
	221b		OY - R	72.6	85.0	97.4	105.9	115.4	
	215		OY - R	72.2	84.6	98.2	105.8	114.1	
	Avg.			72.83	85.03	97.83	106.00	115.10	
	Diff.%			-1.24	+0.44	-0.24	+0.12	+0.87	+0.01
Shoulder	111	3/4 in.	OZ - R	71.5	84.7	97.0	105.1		
	131		OZ - R	70.6	83.9	96.0	102.6		
	121		OZ - R	71.8	83.9	96.0	106.2		
	Avg.			71.30	84.17	96.33	104.63		
Shoulder	111	5/16 in.	OZ - R	70.5	83.3	97.3	106.4		
	131		OZ - R	69.9	82.8	95.5			
	121a		OZ - R	69.5	82.6	96.2	102.6		
	121b		OZ - R	70.3	83.3	96.2	105.4		
	Avg.			70.05	83.00	96.30	104.80		
	Diff.%			+1.78	+1.40	+0.03	-0.16		+0.76

TABLE 3. Effect of Size upon Unit Stress at Maximum Load.
(Arranged in Size Comparison Groups).

Region Direction	Spec. No.	Diam. (in)	Distance between centers (in)	U.S. at Max. Load p.s.i.x10^{-3}	Difference
	THREADED SPECIMENS				
Martensite OZ	123 I 123 Ia	0.4 0.2	7/8	112.00 108.15	+3.5%
Bainite OY	D 8 I D 8 Ia	0.4 0.2	5/8	107.76 105.42	+2.2%
Bainite OY	D 8 II D 8 IIa	0.4 0.2	15/16	107.05 103.20	+3.7%
Bainite OZ	123 II 123 IIa	0.4 0.2	7/8	106.06 103.10	+2.9%
Transition from Bain. to Mart. OX	D 6 I D 6 II D 6 IIa D 6IIIa	0.4 0.4 0.2 0.2	7/8 1-1/16 5/8	107.00 107.70 109.90 112.00	
	SHOULDER SPECIMENS				
Bainite OZ	121 a 121 121 b	5/16 3/4 5/16	1-3/16 1-1/8	100.90 no max. 102.90	--
Bainite OZ	111 111	3/4 5/16	1-1/4	102.55 104.05	-1.4%
Bainite OZ	131 131	3/4 5/16	1-1/4	100.20 101.50	-1.3%
Bainite OY	221 a 221 221 b	5/16 3/4 5/16	1-1/8 1-3/16	102.75 102.45 103.70	-0.8%
Bainite OY	232 215	3/4 5/16	2-9/16	105.75 102.30	+3.4%

3. Another criterion used in the search for size effect in plastic flow was the general position of the average flow curve for a given group. Ordinates of the flow curve were taken at a number of places and are shown in Table 2. The table shows the smaller spread of results in studies of the shoulder-type specimens.

On this basis both threaded and shoulder specimens show a slight average increase in unit stress as we go from small to large size.

4. Fracture types were all rough with one exception which has been labeled angular in accordance with a classification by Mehl and Wells (Ref. 5).

III. DISCUSSION

In searching for genuine size effects in the tensile test one must decide whether he will test a large number of specimens with ordinary precision, or a small number with the greatest precision which can be attained in a reasonable length of time. The choice depends on the homogeneity of the material. Little is known about the distribution curves for the various mechanical properties of a single large block of steel; data from different ingots or different heats cannot throw much light on this question. In making the program for the present investigation we were influenced by extensive cone-hardness profiles, running in all three principal directions in the block. These profiles showed that through the tempered bainite region the average deviation of the hardness from its mean value is only about 2%. Obviously a given uniformity of hardness is no certain guarantee that tensile stress properties will show the same uniformity, since the defects responsible for hardness variation may not be identical with the ones which determine variations of the tensile properties. Nevertheless, it seemed reasonable to make precise tensile tests on a relatively small number of specimens. The appearance of the curves in Figs. 186 and 187 is a fair justification of this procedure.

Now it is convenient to consider two general questions:

(A) Do the data show size effects in the mechanical quantities which refer to the fracture or incipient fracture? These quantities are (1) the maximum true stress, (2) the reduction of area at maximum stress, and (3) the elongation at this stress. We exclude the elongation from consideration for reasons stated earlier in the report.

(B) Do the data show a size effect of the true stress as the test proceeds from the yield point to the point where cracking is imminent; in other words, can size effect be detected in the domain of plastic flow? In particular, we must consider: (1) the true stress at maximum load, which does not occur at a constant value of the reduction and (2) the true stress at various values of the reduction.

Thus, there are four quantities to consider and Table 4 throws considerable light on their suitability as measures of size effect.

The larger the average deviations of a quantity from its mean value (or the larger the total spread around the mean value) the harder it will be to detect size effect with a limited number of specimens. We see from Table 4 that the average deviations for both sizes and both orientations of the specimens run as follows:

Maximum stress: 3.3%

Reduction of area: 18.0%

Stress at Max. Load: 1.0%

The deviations of the stress at given reductions are comparable with those of the stress at maximum load. This brief summary has limited utility in forming a picture of the situation since the fluctuations are generally smaller for the OY specimens than for the OZ specimens.

Table 4. Average Deviations and Total Spreads of Maximum Stress, Reduction of Area, and Stress at Maximum Load for Shoulder-Type Specimens. Values are in Per Cent.

Direction	Diameter	Maximum Stress		Reduction		Stress at Max. Load	
		Avg. Dev.	Total Spread	Avg. Dev.	Total Spread	Avg. Dev.	Total Spread
OY	3/4"	1.8	4.7	9.0	26.6	1.4	3.2
	5/16"	3.0	7.8	11.0	25.2	0.5	1.4
OZ	3/4"	1.8	4.3	14.6	42.1	1.2	2.3
	5/16"	6.7	15.0	37.4	76.7	1.1	3.1
Gen. Avg.		3.3	8.0	18.0	42.7	1.0	2.5

While we expect size effects to be largest in quantities characterizing the condition of the specimen at fracture, it is just these quantities which fluctuate most, blocking our attempt to find these size effects. On the other hand, in the domain before incipient fracture, the fluctuations of the true stress are small so that more precise statements about size effect can be made; but in this domain we expect the effect to be small from results of tests on notched bend specimens.

However, we should not take the attitude that these fluctuations are our foes in searching for size effect. According to present ideas, size effects are due to the presence of inclusions and other weaknesses; thus an increase of fluctuations of mechanical properties should be associated with an increase of size effects. We learn from Table 4 that the maximum stress is much more useful than the reduction of area in looking for size effects in the domain of the test bordering on actual fracture.

Also we may state, without going into details, that low values of the reduction can be correlated with areas of angular fracture or of brittle fracture on the broken specimens. After trying this idea out on all our shoulder type specimens, we have considerable faith in the utility of the fracture classification discussed by Mehl and Wells (Ref. 5). Of course these authors point out that there is only a rough correlation between low reduction and angular or brittle fracture, so that the subject does not permit precise discussion.

IV. CONCLUSIONS

The conclusions for this Class B armor steel are as follows:

1. Confining attention to shoulder-type specimens, the maximum true stress shows a size effect of the expected sign, in both the OY and OZ directions. The effect of increasing the diameter by a factor 2.4 is to lower the maximum stress 3.4% and 4.4% in these two cases respectively. The average deviations are sufficiently large (of the order of 2.4 and 4.3%, respectively) to block a definite assertion that the size effect is genuine. The remedy lies in making large numbers of tests, with lower precision. (Tables 1, 4).

2. The reduction of area at maximum stress fluctuates so greatly that this quantity is worthless in studying size effects in this steel. (Tables 1, 4).

3. The *true stress at maximum load* appears at first sight to show a positive size effect, but we are inclined to place our chief reliance on data obtained with shoulder type specimens, and when these are separately considered we find no evidence for a size effect as large as 2%. (Table 1, last column, Table 3, and Table 4).

4. The general positions of the flow curves support conclusion 3. These curves yield a multiplicity of independent comparisons of large and small specimens at values of $(A_0 - A)/A$ ranging from 2 to 32 per cent. There is no evidence for systematic development of a size effect as large as 1% (for specimen diameters in the ratio 2.4 : 1) as we pass over this domain. Also on taking averages of the values for various reductions, the mean size effect over the whole domain is only +0.01% for transverse specimens and +0.76% for perpendicular ones. In making these comparisons many experimental errors (such as errors in calibration of the testing machine) tend to cancel, but we do not believe the data give any evidence of a genuine size effect in plastic flow. (Table 2).

5. It appears quite certain that the tensile test is not well adapted to the study of size effects in armor steels. The bend test is much more rewarding.

Thanks are due Dr. George Irwin who suggested this problem and aided us by many helpful discussions.

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