THESIS

a) An Investigation of the Relation Between the Tensile Strength and (Brinell) Hardness of Non-Ferrous Alloys.

b) A Design of a Fatigue Testing Machine for a College Laboratory.

by

Raymond Fuller Call

Class of Nineteen Hundred and Fifteen.

THROOP COLLEGE OF TECHNOLOGY
Pasadena, California

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A) An Investigation of the Relation between the Tensile Strength and (Brinell) Hardness of Non-Ferrous Alloys.

Look up references under classification.

A - An Investigation of the Relation between the Tensile Strength and (Brinell) Hardness of Non-Ferrous Alloys.

The object of this investigation was to determine if any relation existed between the tensile strength and (Brinell) hardness of non-ferrous alloys, and, if a definite relation was found, to see how it agreed with the one known to exist in iron and steel. A comparison between the Brinell hardness numbers and the Scleroscope numbers was made with a view of determining the relation existing between these two hardness values.

Before going further I wish to clear up any confusion as to what is meant by the hardness of metals. It is not however within the scope of this paper to trace out the many methods which have been devised for determining hardness; it will suffice to say that the methods employed have been the outgrowths of attempts to obtain data with some particular idea in view. At the present time the best definition of hardness is as follows:- "Hardness is understood to be a state of rigidness in a body which imparts to it the power to resist penetration and necessarily deformation."

The specimens under investigation consisted of an alloy of aluminum, copper, and zinc; the percentage composition as well as the best treatment of the alloy are unknown, these facts remaining a secret with the Griffith Machine Co. of Los Angeles, who kindly furnished the specimens in connection with some experimental work they were carrying on with this alloy. Several samples of an aluminum alloy were secured from Mr. Miller, of the Miller Carburetor Company, Los Angeles. Four bronze samples were tested but the main work was confined to the aluminum specimens.

For the tension tests a Riehle Bros. Universal testing machine of 30,000 lbs., capacity was used, while for the hardness test a Brinell machine of 3,000 kilograms capacity was employed. This Brinell machine was only recently installed in the testing materials laboratory and is manufactured by the Aktrebologet Alpha Company of Stockholm, Sweden. The ordinary Shore Scleroscope with the magnifying hammer was used for finding the scleroscope numbers.

The specimens were machined to the standard dimensions recommended by the American Society of Testing Materials; the load was applied continuously until failure occured. Two sections were then prepared for the Brinell test, one section was cut just below the tension break, the other where the fillet joined the threaded end. The object of taking two sections was to see if the section where failure occurred showed a different hardness than other portions of the metal; both sections were polished with emery cloth so that the indentation could be easily measured. Two loads were applied, one of 500 kilograms the other of 1000 kilograms, the heavier load being applied to the indentation made by the 500 kilograms pressure. A previous test on mild steel showed that no error was introduced by such procedure. (See Data Sheet No. 1) Both loads were applied for 30 seconds, this being the period recommended for soft material; in no case did the depth of the indentation exceed 1/7 of the total thickness of the specimen; and the center of the impression was always 2-1/2 times its diameter from the edge of the section. These last two conditions are recommended by Moore as a result of his investigation of the Brinell hardness test. In each case the indentations were measured across two diameters at right angles to each other; if a difference was found several readings were taken and an average value determined.

Results of Investigation.

Curves were plotted for each intensity of loading, hardness numbers as ordinates and tensile strength as abscissas. The ppints show the wide variation of the results. The only conclusion which can be drawn is that a general relation exists between the hardness and tensile strengths of this alloy but a variation of over 40% in the tensile strength showed the same hardness number under the 500 kilogram load. The general slope of each set of points is shown by the two straight lines; the two lines are practically parallel, showing that the two loadings gave uniform results.

The slope of the curve given by the bronze specimens was much steeper than that given by the aluminum specimens and is parallel to that found with steel; therefore it seems safe to say that bronze conforms to the same law as steel.

The tension breaks showed no tendency to neck down although several showed signs of failure below the plane of actual fracture: the breaks were in no sense cup shaped but were very rough and often showed a wide range of crystalline structure. Some sections were very porous, while still others were slightly fibrous, while still others were decidely crystalline, the crystals being easily seen with the naked eye.

Many of the indentations were elliptical, as much as two millimeters difference in the two diameters being observed. These elliptical impressions in steel are indications of irregular density or fluctuations in heat treatment and it seems reasonable to say that this same conclusion may be drawn in the case of non-ferrous alloys.

Many of the indentations had rough or flaky edges, this condition seemed to be confined to the specimens of decided crystalline structure.

The hardness numbers as found under the heavier loading, were all greater than those given by the 500 kilogram load; the variations in some cases is much greater than in others, the greater variation seeming to occur in the specimens of lower tensile strength. In regard to this variation of the hardness numbers, Mr. V. Skillman, in an address before the American Institute of Metals, September 7, to 11, 1914, on "The Brinell Hardness Testing of Non-Ferrous Alloys", has the following: - "It is evident that the hardness of a certain alloy cannot always be expressed by any one definite Brinell number. The best that can be said is that it usually has a hardness between certain limits depending much on the particular sample selected for test."

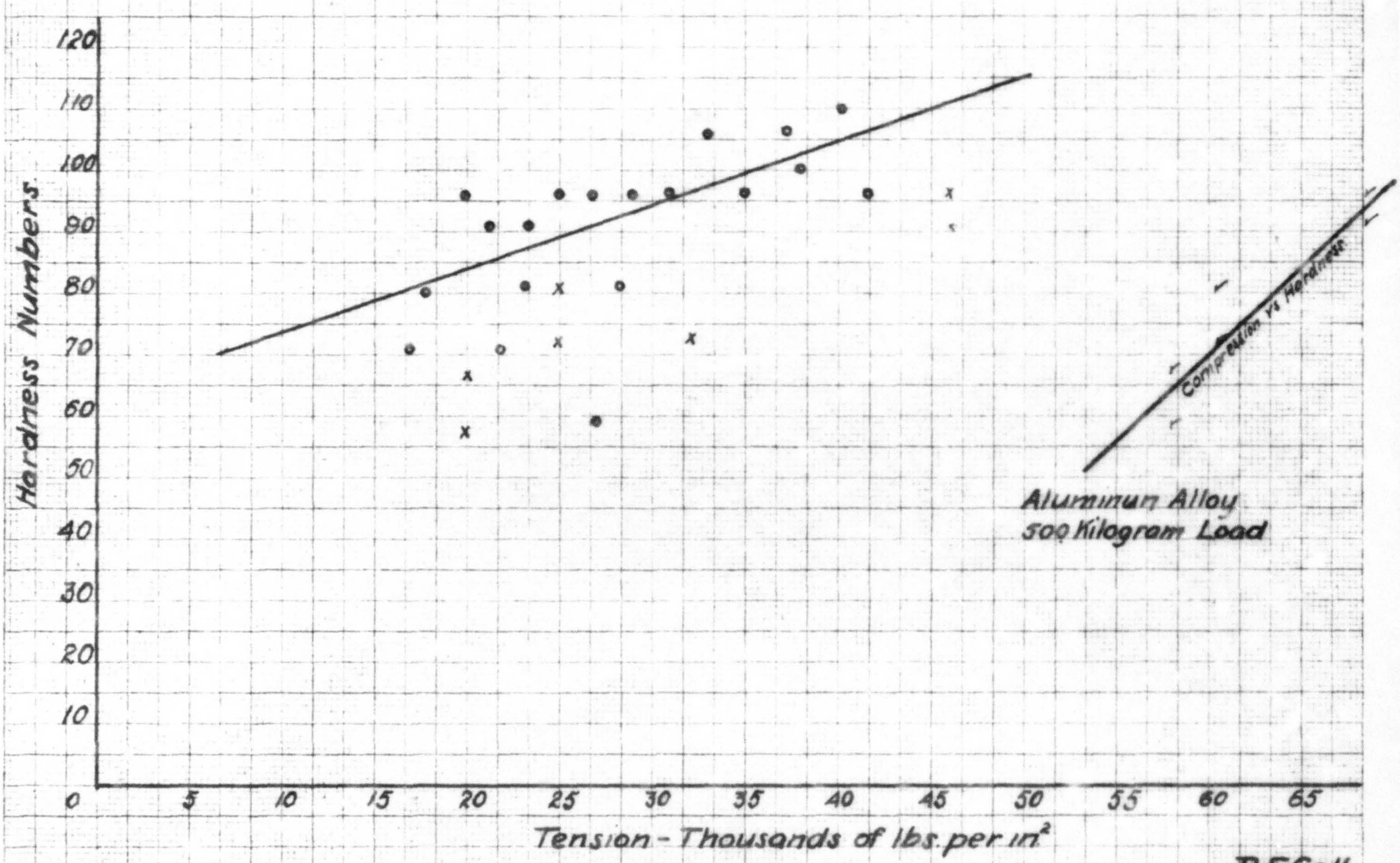
In general each sample was homogeneous, the hardness being the same at the threaded section as at the tension break; one case will show how the Brinell test will disclose any variation of hardness:- one specimen showed a hardness of 86 just below the tension break, while at the threaded section the hardness was 127, a variation of 41 in not over 1 inch of length.

Brinell and Scleroscope Numbers.

The constant for the aluminum alloy by which the Brinell number must be divided to give the corresponding scleroscope value is 4.20. The specimens of low tensile strength gave a higher value than the average, while those of high strength gave a lower value.

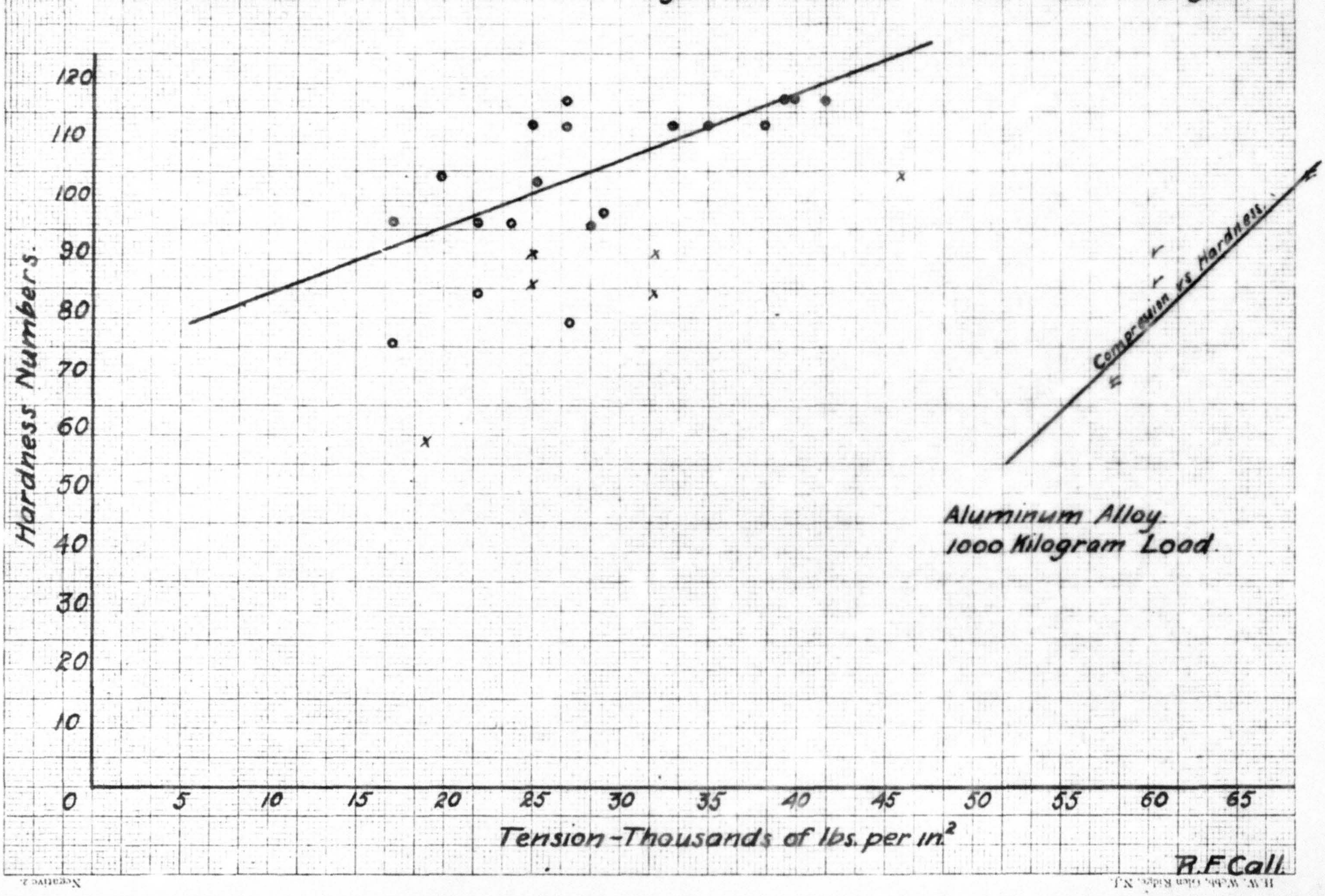
With the bronze specimens the value was fairly constant, the average being 3.54.

Relation Between the Tensile Strength and Hardness of Non-Ferrous Alloys.



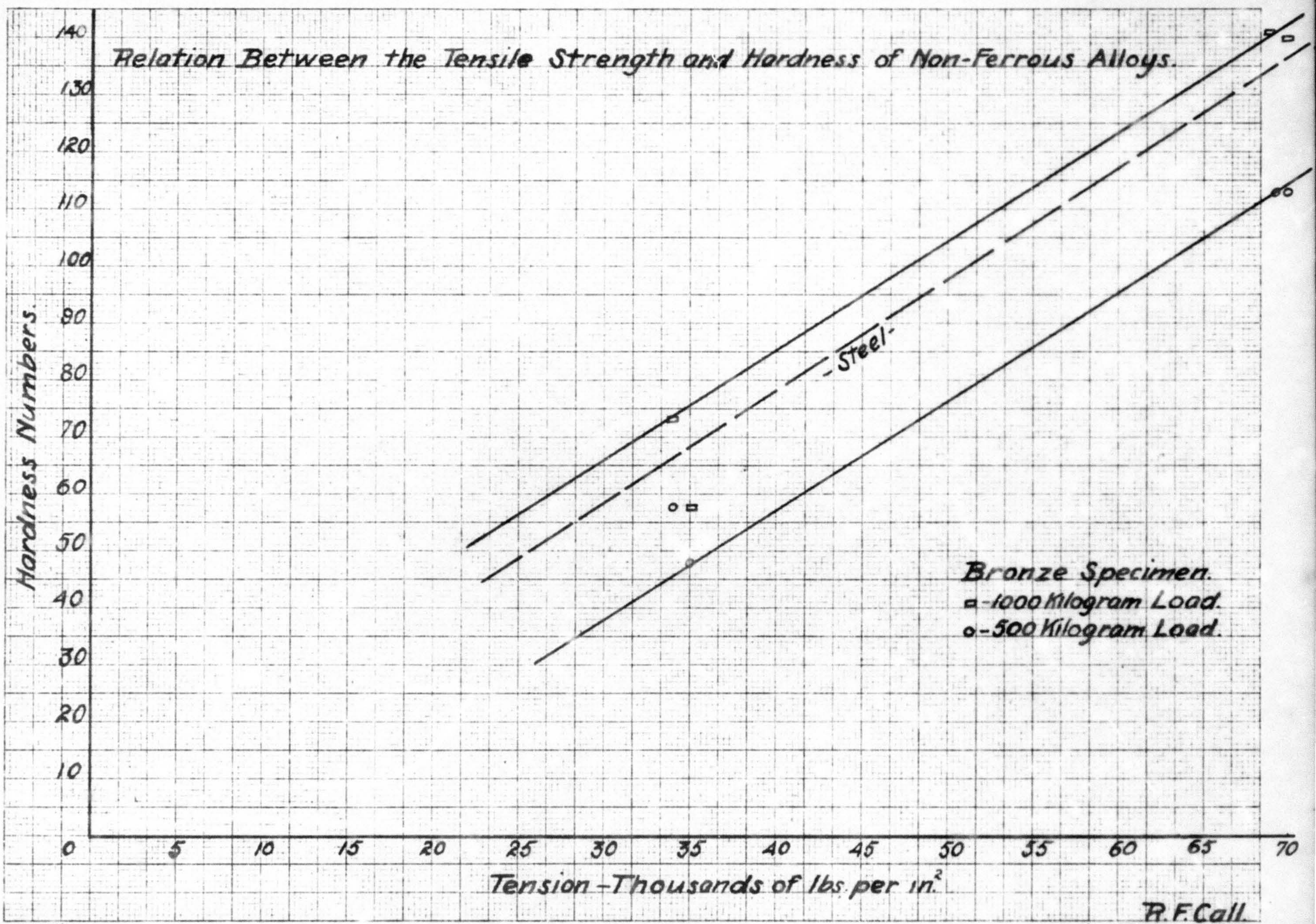
R.F. Coll.

Relation Between the Tensile Strength and Hardness of Non-Ferrous Alloys.



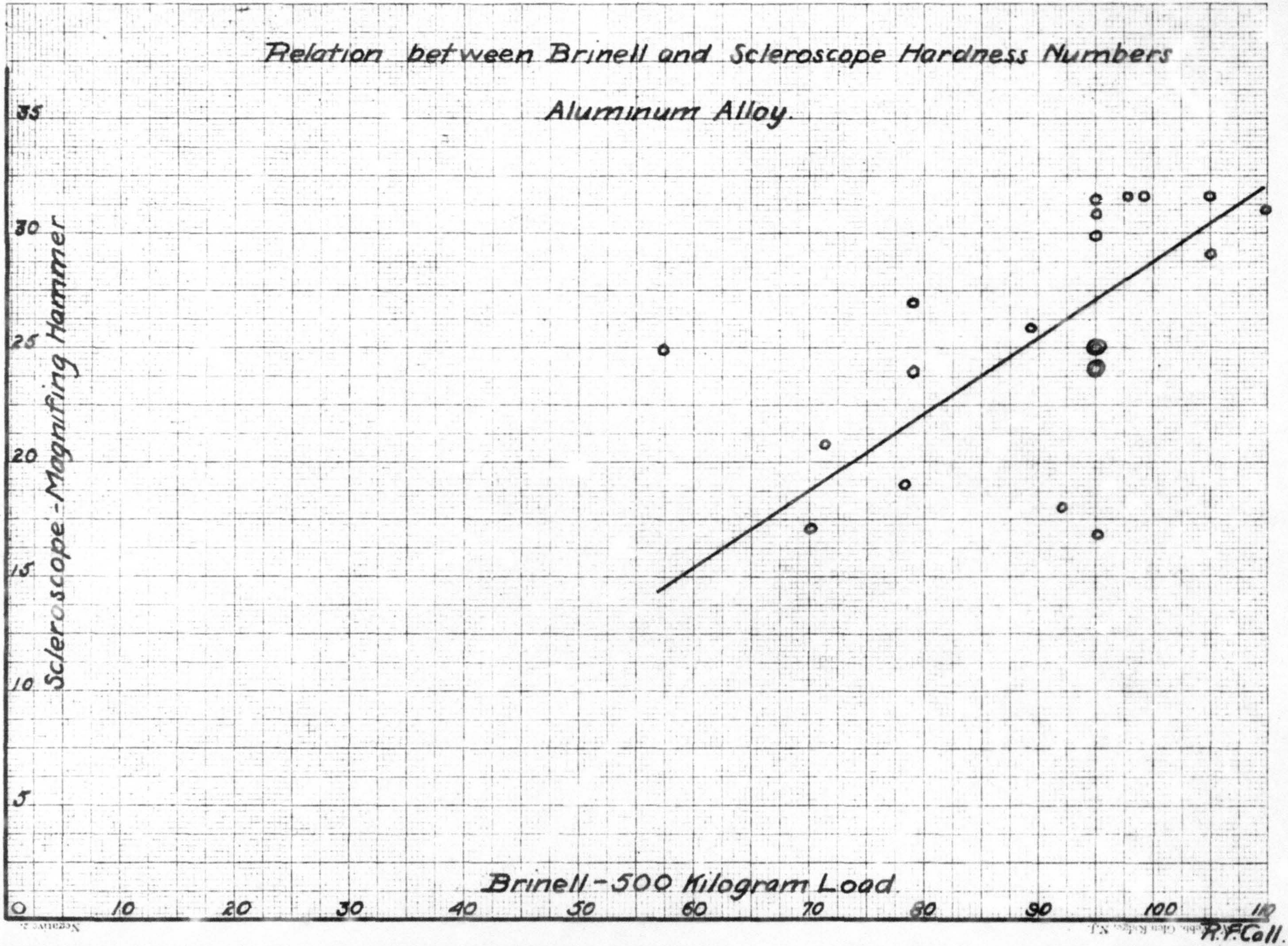
Negative 2.

H.W. Webb, Glen Ridge, N.J.



Relation Between the Tensile Strength and Hardness of Non-Ferrous Alloys.

Negative 2.
H. W. Webb, Glen Ridge, N. J.



Relation between Brinell and Scleroscope Hardness Numbers

Aluminum Alloy.

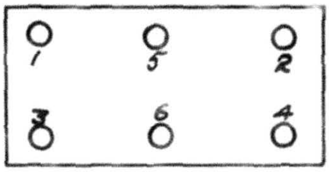
R.F. Coll.

MILD STEEL

Test to determine whether beginning with a light load successive heavier loads may be applied in the same indentation without introducing an error.

Number	Load	Diameter	Brinell Hardness
1	3000	4.65	152.5
2	3000	4.65	152.5
3	3000	4.65	152.5
4	3000	4.65	152.5
5	500	2.10	138.2
5	1000	2.90	144.5
5	1500	3.45	154.0
5	2000	4.00	151.5
5	2500	4.45	153.0
5	3000	4.65	152.5
6	500	2.10	138.2
6	1000	2.85	148.0
6	1500	3.50	149.0
6	2000	4.00	151.5
6	2500	4.50	145.0
6	3000	4.90	148.0

RELATIVE LOCATION of TESTS.



ALUMINUM SPECIMENS.

No.	Load	Dia.	Brinnel Hardness	Tension	Scleroscope Hardness	Brinnel / Scleroscope	Tension / Hardness
1	500	2.35	110.0	40,300	31	3.6	366
1	1000	3.25	117.5	40,300	31	3.8	344
2	500	2.40	105.9	33,300	29	3.6	318
2	1000	3.30	113.5	33,300	29	3.9	296
3	500	2.50	96.3	41,800	32	3.0	425
3	1000	3.25	117.5	41,800	32	3.7	356
4	500	3.20	58.8	27,000	25	2.4	460
4	1000	3.90	79.5	27,000	25	3.2	342
5	500	2.70	81.5	23,500	24	3.4	290
5	1000	3.60	96.4	23,500	24	4.0	244
6	500	2.70	81.5	28,300	27	3.0	346
6	1000	3.60	96.4	28,300	27	3.6	296
7	500	2.60	91.1	25,600	26	3.5	284
7	1000	3.45	104.0	25,600	26	4.0	248
8	500	2.95	70.7	17,000	17	4.2	245
8	1000	4.00	76.6	17,000	17	4.5	222
9	500	2.60	91.1	20,900	18	4.8	230
9	1000	3.60	96.4	20,900	18	5.1	216
10	500	2.75	79.5	17,500	19	4.2	220
10	1000	3.60	96.4	17,500	19	5.1	182
11	500	2.50	96.3	19,800	17	5.7	206
11	1000	3.40	104.1	19,800	17	6.1	190

ALUMINUM SPECIMENS.

No.	Load	Dia.	Brinell Hardness	Tension	Scleroscope Hardness	Brinell / Hardness	Tension / Hardness
12	500	2.50	96.3	24,800	30	3.2	256
12	1000	3.30	113.5	24,800	30	3.8	218
13	500	2.50	96.3	27,400	31	3.1	286
13	1000	3.20	117.6	27,400	31	3.8	234
14	500	2.50	96.3	35,200	31	3.1	362
14	1000	3.30	113.5	35,200	31	3.8	310
15	500	2.50	96.3	27,200	24	4.0	284
15	1000	3.30	113.5	27,200	24	4.7	240
16	500	2.45	99.5	38,000	32	3.1	382
16	1000	3.30	113.5	38,000	32	3.5	334
17	500	2.50	96.3	35,000	32	3.0	364
17	1000	3.30	113.5	35,000	32	3.5	312
18	500	2.50	96.3	29,000	24	4.0	302
18	1000	3.45	97.7	29,000	24	4.0	296
19	500	2.50	96.3	25,200	25	3.9	262
19	1000	3.30	113.5	25,200	25	4.5	222
20	500	2.58	70.8	22,400	21	3.4	314
20	1000	3.88	83.7	22,400	21	4.0	266
21	500	2.50	96.3	31,500	25	3.9	326
21	1000	3.35	107.5	31,500	25	4.2	294
22	500	2.40	105.9	39,300	32	3.3	374
22	1000	3.20	117.6	39,300	32	3.7	366

Average = 4.2

ALUMINUM SPECIMENS

No.	Load	Diameter	Brinell Hardness	Tension	Tension / Hardness
1	500	2.90	72.5	32,300	446
1	1000	3.80	83.7	32,300	386
1	500	2.80	73.0	32,300	442
1	1000	3.70	90.8	32,300	356
2	500	2.70	81.5	24,700	303
2	1000	3.70	90.8	24,700	272
2	500	2.90	72.5	24,700	341
2	1000	3.75	86.0	24,700	287
3	500	3.20	58.8	18,950	322
3	1000	4.00	69.4	18,950	273
3	500	3.00	67.5	18,950	281
3	1000	4.00	69.4	18,950	273
4	500	2.50	96.3	46,000	478
4	1000	3.40	104.1	46,000	441
4	500	2.60	91.1	46,000	505
4	1000	3.40	104.1	46,000	441

Compression Test

No.	Dia. of Specimen	Load	Ultimate	Tension	Compression / Tension
1	.5006	19,200	97,500	Specimen too short	
2	.501	11,960	60,700	24,700	2.46
3	.5008	11,440	58,000	18,950	3.06
4	.500	13,600	69,000	46,000	1.50

Above samples from the Miller Carburetor Co., Los Angeles, said to be the same alloy in varying proportions. There were four samples in each lot and the accompanying specimens are typical of their respective lots.

BRONZE SPECIMENS

No.	Load	Dia.	Brinell Hardness	Tension	Scleroscope Hardness	Brinell / Hardness	Tension / Hardness
1	500	2.35	113.5	69,000	38	3.0	615
1	1000	3.00	141.0	69,000	38	3.7	490
1	1500	3,70	136.0	69,000	38	3.6	511
2	500	2.30	113.3	69,500	38	3.0	615
2	1000	3.05	140.0	69,500	38	3.7	490
2	1500	3.65	137.5	69,500	38	3.6	511
3	500	3.55	48.8	35,400	16	3.0	740
3	1000	4.50	58.6	35,400	16	3.6	605
4	500	3.20	58.8	33,700	16	3.6	572
4	1000	4.10	74.0	33,700	16	4.6	455
					Average =	3.54	

ALUMINUM SPECIMENS

No.	Load	Diameter	Brinell Hardness	Tension	Tension / Hardness
1	500	2.50	96.3		
1	1000	3.50	99.4		
1	500	2.60	91.1		
1	1000	3.55	97.9		
1	500	2.60	91.1		
1	1000	3.50	99.4		
2	500	2.45	99.5		
2	1000	3.30	113.5		
2	500	2.45	99.5		
2	1000	3.30	113.5		
2	500	2.45	99.5		
2	1000	3.30	113.5		
2	500	2.45	99.5		
2	1000	3.20	117.6		
2	500	2.40	105.9		
2	1000	3.20	117.6		
3	500	2.50	96.3		
3	1000	3.40	104.1		
3	500	2.45	99.5		
3	1000	3.30	113.5		
3	500	2.50	96.3		
3	1000	3.35	107.5		
4	500	2.50	96.3		
4	1000	3.30	113.5		
4	500	2.50	96.3		
4	1000	3.40	104.1		
4	500	2.50	96.3		
4	1000	3.35	107.5		
4	500	2.50	96.3		
4	1000	3.40	104.1		
5	500	2.45	99.5		
5	1000	3.10	127.0		
5	500	2.40	106.0		
5	1000	3.20	117.6		
5	500	2.10	138.1		
5	1000	3.00	138.1		
6	500	2.50	96.3		
6	1000	3.35	107.5		
6	500	2.30	113.3		
6	1000	3.10	127.0		
6	500	2.50	96.3		
6	1000	3.40	104.1		
7	500	2.20	132.2		
7	1000	3.70	91.0		
7	500	2.20	132.2		
7	1000	3.70	91.0		

ALUMINUM SPECIMENS

No.	Load	Diameter	Brinell Hardness	Tension	Tension / Hardness
7	500	2.20	132.2		
7	1000	3.70	91.0		
7	500	2.20	132.2		
7	1000	3.70	91.0		
8	500	2.50	96.3		
8	1000	3.30	113.5		
8	500	2.45	99.5		
8	1000	3.30	113.5		
8	500	2.40	105.9		
8	1000	3.30	113.5		
8	500	2.50	96.3		
8	1000	3.30	113.5		
9	500	2.50	96.3		
9	1000	3.20	117.6		
9	500	2.65	86.0		
9	1000	3.30	113.5		
9	500	2.25	127.0		
9	1000	3.10	127.0		
9	500	2.30	113.3		
9	1000	3.10	127.0		
9	1500	3.70	134.0		
9	1500	3.70	134.0		
9	2000	4.20	135.1		
9	2000	4.30	130.0		
9	3000	5.25	127.0		
9	3000	5.20	131.5		
10	500	3.50	48.9		
10	1000	4.70	55.8		
10	500	3.50	48.9		
10	1000	4.75	53.0		
10	500	3.50	48.9		
10	1000	4.75	53.0		
10	500	3.50	48.9		
10	1000	4.50	58.4		
11	500	3.20	58.8		
11	1000	4.30	73.1		
11	500	3.25	57.8		
11	1000	4.20	69.2		
11	500	3.30	56.9		
11	1000	4.30	73.1		
11	500	3.30	56.9		
11	1000	4.30	73.1		
12	500	3.30	56.9		
12	1000	3.45	61.1		
12	500	3.30	56.9		

ALUMINUM SPECIMENS

No.	Load	Diameter	Brinell Hardness	Tension	Tension / Hardness
12	1000	4.50	58.4		
12	500	3.20	58.9		
12	1000	4.40	62.3		
13	500	3.00	67.6		
13	1000	3.70	90.8		
13	500	3.00	69.1		
13	1000	3.75	86.0		
13	500	3.00	69.1		
13	1000	3.75	86.0		
13	1500	4.50	88.4		
13.	1500	4.40	96.3		
13	2000	5.20	87.2		
13	2000	5.20	87.2		
14	500	3.60	48.1		
14	1000	4.80	51.3		
14	500	3.60	48.1		
14	1000	4.80	51.3		
14	500	3.65	44.1		
14	1000	4.80	51.3		
14	500	3.50	48.9		
14	1000	4.80	51.3		
15	500	2.85	70.8		
15	1000	3.50	99.4		
15	500	2.65	86.0		
15	1000	3.60	96.4		
15	500	2.85	70.8		
15	1000	3.60	96.4		
15	500	2.80	79.5		
15	1000	3.60	96.4		
15	2500	5.40	99.5		
15	2500	5.40	99.5		
15	2000	4.80	102.5		
15	2000	4.80	102.5		
16	500	3.00	67.6		
16	1000	3.90	79.5		
16	500	2.90	72.5		
16	1000	3.90	79.5		
16	500	3.10	63.6		
16	1000	3.80	83.7		
16	500	2.95	70.7		
16	1000	3.80	83.7		
17	500	2.40	105.9		
17	1000	3.30	113.5		
17	500	2.50	96.3		
17	1000	3.30	113.5		
17	500	2.50	96.3		
17	1000	3.30	113.5		
17	500	2.50	96.3		
17	1000	3.40	104.1		

ALUMINUM SPECIMENS

No.	Load	Diameter	Brinell Hardness	Tension	Tension/Hardness
18	500	2.90	72.5		
18	1000	3.95	78.5		
18	500	3.00	67.6		
18	1000	4.00	69.4		
18	500	2.90	72.5		
18	1000	3.90	79.5		
18	500	2.95	70.7		
18	1000	3.90	79.5		
19	500	2.70	81.5		
19	1000	3.50	99.4		
19	500	2.70	81.5		
19	1000	3.60	96.4		
19	500	2.70	81.5		
19	1000	3.55	97.6		
19	500	2.70	81.5		
19	1000	3.55	97.6		
20	500	3.20	58.8		
20	1000	4.20	67.0		
20	500	3.25	57.0		
20	1000	4.10	74.0		
20	500	3.20	58.8		
20	1000	4.00	69.4		
20	500	3.10	63.6		
20	1000	4.00	69.4		
21	500	3.80	42.3		
21	1000	5.10	45.4		
21	500	3.80	42.3		
21	1000	5.00	45.0		
21	500	3.90	39.8		
21	1000	5.20	43.8		
21	500	3.90	39.8		
21	1000	5.20	43.8		
22	500	3.30	56.9		
22	1000	4.40	59.5		
22	500	3.00	67.6		
22	1000	4.20	69.2		
22	500	3.30	56.9		
22	1000	4.20	69.2		
22	500	3.10	63.6		
22	1000	4.10	74.0		
23	500	3.10	63.6		
23	1000	4.10	74.0		
23	500	3.20	58.8		
23	1000	4.20	69.2		
23	500	3.30	56.9		
23	1000	4.15	67.5		
24	500	3.20	58.8		
24	1000	4.40	59.5		

ALUMINUM SPECIMENS

No.	Load	Diameter	Brinell Hardness	Tension	$\frac{\text{Tension}}{\text{Hardness}}$
24	500	3.10	63.6		
24	1000	4.10	74.0		
24	500	3.30	56.9		
24	1000	4.10	74.0		
24	500	3.10	63.6		
24	1000	4.00	76.6		
25	500	2.70	81.5		
25	1000	3.40	104.1		
25	500	2.80	73.0		
25	1000	3.60	96.4		
25	500	2.60	91.1		
25	1000	3.50	99.4		
25	500	2.70	81.5		
25	1000	3.60	96.4		

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Brinnell Hardness Testing of Non-Ferrous Alloys, by V. Skillmann. Proceedings American Institute of Metals. September 1914. (See Files, in T. C. T. Library.) (Gives result of tests on different brass and bronze alloys)

Comparison of Hardness Testing Methods, by Ralph P. Devries. American Machinist. Vol. 35, page 648. (Comparison of five different methods.)

Brinell Hardness Tests. American Machinist, Vol. 41, pages 66 and 274. (Two short articles - one on the Brinell and Scleroscope Relation; other on details recommended to American Society of Testing Materials.)

Hardness Testing: - Mechanical Wear. by E. H. Saniter. American Machinist. Vol. 37, page 516. (Shows application of Brinell testing in determining relative wearing qualities)

See any standard text for further discussion of hardness.

A Design of a Fatigue Testing Machine for a College Laboratory.

I

It is a well known fact that metals will fail under loads of from 1/2 to 2/3 the ultimate strength when such loads are repeated or reversed many thousands or even millions of times; the number of reversals to cause failure depending on the intensity of the loading.

It has been commonly supposed that these repetitions of stress caused a general deterioration of the metal, this deterioration consisting of a gradual breaking down of the cohesive qualities of the separate crystals; for want of a better knowledge this type of failure was called "fatigue". It has since been proven that no general deterioration takes place, for tests on specimens closely adjacent to such planes of failure show no deterioration; and furthermore specimens subjected to so many repetitions that they are known to be near the breaking point, when subjected to the ordinary tensile test show no clear evidence of alteration of strength or ductility.

What then is the true nature of the fatigue failure of metals? The early investigators of this subject hinted at the true nature of the failure when they pointed out that the reversal of stress always picks out sections of weakness and that the deterioration was confined to such sections. Since then it has been proven by microscopic examination that the weakening is due to the slipping of the crystalline molecules along the cleavage planes.

These studies have shown that slip planes gradually appear, broaden out and then on massing together, develop into a definite crack; in many cases the first set of slip lines observed were not those along which final failure occurred. These slip planes are known to occur because of the presence of slight defects in the metal, this weakening action gradually extending its influence until complete failure occurs. Therefore a more truly descriptive term would be "the gradual fracture of metals."

Let us consider the crystalline structure of metals. The internal structure of a crystal is too far removed to be studied directly, but the agreement of many indirect methods has given a fairly clear conception of how the crystals are put together. Consider a cubic crystal as made up of successive layers of steel balls; there are two ways in which this type of crystal may fail: 1st - through a slipping along the successive layers, i.e. a shearing of the crystal; and 2nd - by a pulling apart across the planes between layers, i.e. failure by tension.

The important distinction between these two classes of failures is this: the tension break is a complete failure from the very beginning, while the shear failure may only consist in a partial slip of one layer on another, the crystals in no sense being broken but merely permanently distorted. The question immediately arises in cases of shear stresses, - How is the metal injured if only slipping occurs? There would be no injuring if it were not for the fact that during this slipping the layers interfere slightly, thereby tearing out minute particles of each other in the form of a fine amorphorous dust. This dust formed in the slip planes although of similar chemical composition differs in its physical qualities by being harder and stronger.

The action of this dust is two-fold -- 1st: as one layer slips over the other the increasing amount of dust formed retards the slip until a point is reached where it is easier to start a new slip along an adjacent parallel plane, this process may be repeated many times until a large proportion of the material has been affected. 2nd: The action of the dust is modified by the fact that adjacent crystals do not simultaneously change shape, the main action being to work on a few slip planes until enough dust is formed between them to wear the crystal in two. This causes the load to be carried on the remaining crystals with a corresponding increase of stress intensity and the increased stress intensity in turn destroys the next weakest crystal with a corresponding higher stress intensity. This cycle is repeated until the stress intensity on the remaining good material goes beyond the breaking point, and then complete failure occurs.

From the above explanation it is seen that the change in size of each crystal has been very small, or in other words, there has been no reduction in area of a specimen in fatigue failure. This fact has been proven in practice and is in direct contrast to the well known "necking" down of tension specimens.

Another pertinent fact which is revealed in this theory is that steel does not crystallize in service through reversal of stress or excessive vibration. For since there is no apparent change in the size of crystals these points of weakness must have originally been present in the steel, and since it is a well known fact that impurities will cause excessive crystallization, it can readily be seen that the presence of impurities is the basis of the trouble. The presence of slight imperfections on fatigue failures also strengthens this theory, for the presence of nicks, such as chisel marks, letter marks, or even prick punch marks may start a fracture, and it is well known that a polished axle will last much longer than one with the tool marks left on.

Professor Lanza treats this subject of cold crystallization of iron and steel under repeated stress as follows: "The most usual phenomenon which crystallization has to explain is, the crystalline appearance of the fracture of steel axles, when samples cut from other parts of the axles show a true fibrous fracture. The assumption being that the steel was originally fibrous but that crystallization has resulted from the repeated stresses. This assumption however does not conform to the well known law of chemistry, which states that crystallization can only take place from solution, fusion or sublimation. Thus anyone upholding the theory of cold crystallization must prove that either the material was originally fibrous and had not been overheated during its manufacture, or that it had not been overheated during its period of service.

One case might be cited to show the result of improper heating and working of the material. A slab of selected scrap weighing 200 lbs. was forged into a 3" by 3" bar. One end was properly heated and forged, the other half was exposed to a sharp flame, quickly bringing the material to a running heat, kept at this heat for some time, and then hammered lightly; the flame was again applied and the process repeated. The result of this test was, that while no difference was apparent in the appearance of the two sections, when cut and treated with acid so as to bring out the true crystalline structure, the end that was properly heated and forged showed itself to be a fair representative of the best quality of iron, while in the other end the crystallisation was strongly marked, the majority of the crystals being large and well developed. The author of this test concludes as follows,- "The fact is, all hammered iron or steel is more or less crystalline, the lesser or greater degree of crystallization depending altogether upon the greater or less skill employed in working the metal, and also upon the size of the forging".

A few facts governing the fatigue failure of metals will now be pointed out:-

1st. It is doubtdul if a direct tensile test of a piece of steel gives any very definite information of its capacity to resist alternating stresses.

2nd. The number of repetitions before rupture depends on the range of stress and not on the maximum stress.

Example: A specimen subjected +8 to -8 tons per sq.in. would endure the same number of reversals as one subjected to a range of +10 to -6 tons per sq. in.

3rd. Tension (+) to compression (-) stresses cause rupture quicker than a stress in a single direction.

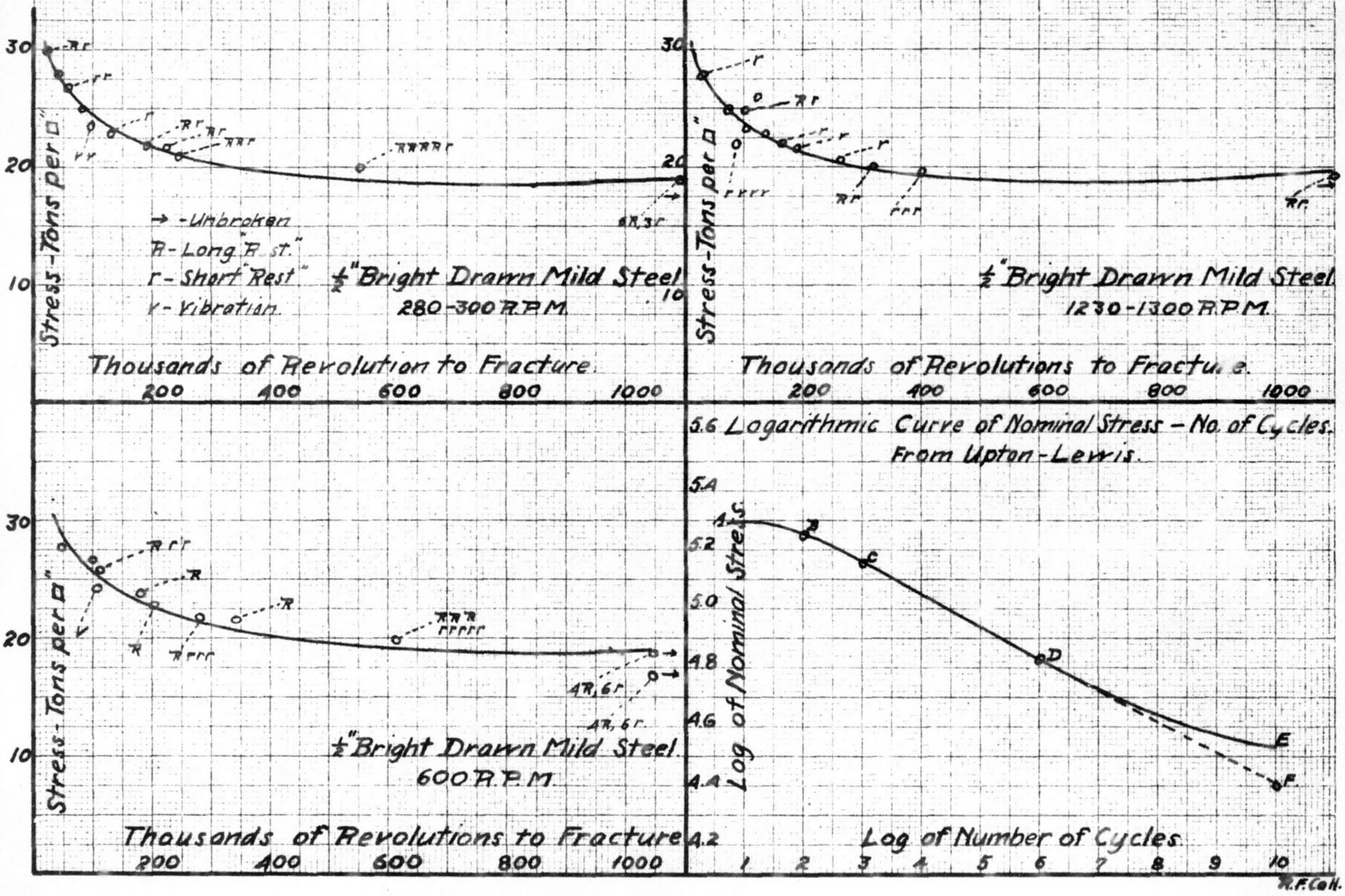
4th. Endurance is independent of the speed of alternations up to 2000 per minute, but falls off rapidly above this point. Same results at this higher value seem to indicate that the cause is increased vibration (rather than speed of alternations).

5th. Rest does not rejuvenate either with or without the load left on. See Curve Sheet. Burr, however, points out that if the load during rest is too near the ultimate breaking point, failure will occur. Tests on beams of the cantilever type prove this fact.

6th. Failure occurs in the ferrite grains and not in the cementing material. In steel, failure occurs in the ferrite rather than the pearlite grains. In other words a true fatigue failure goes through and not around the crystals.

7th. By plotting a curve to logarithmic scale, stress in ~~the~~ lbs. per sq. in. as ordinates and number of reversals as abscissas, H.W. Webb, Glen Ridge, N.J. Negative 2.

Effect of Rests on the Total Number of Revolutions to Cause Fracture.
From Eden, Rose and Cunningham



a curve is found which approximates a straight line. (See Curve Sheet No. 1). This point has been vigorously attacked, but the fact still remains that within reasonable limits the engineer may consider the portion C E (as dotted line D F) as a straight line. (See Curve Sheet)

8th. There is no break in the stress - repetition curve where it passes through the elastic limit. (Elastic limit having previously been determined by a simple tension test.)

9th. Number of applications of a load to produce failure depends upon:-

- a - The number of shear slips caused at each application.
- b - The number of crystals affected by these slips.
- c - Ratio of the number of these crystals to the total number,
- d - The percentage of crystals that must be put out of commission before failure occurs.

The question naturally arises - Where does the factor of fatigue failure stand in the present production of high grade iron and steel? The first systematic study of fatigue failure was made by Wöhler from 1849 to 1870 for the Prussian Government; these tests were continued after his death by Spangenberg. (See any standard text on Materials of Construction for a complete description of Wöhler's experiments).

For many years the laws governing fatigue failure were only of academic interest, and it has only been within the past 10 or 15 years that they have become of practical value. The demand for steels of higher working limits, less weight and material, has arisen recently because of the development of speed and weight of railway equipment. This demand has also been due in a large part to the rapid growth of the automobile industry, especially during the last three years when so much importance is given to the factor of light weight and high strength. Steels meeting these requirements of higher working strength and toughness have been rapidly developed, but the important consideration is, - of what use are these materials if they will not resist as many applications of their higher working stresses as the older materials did of their lower working stresses? And on this very important point engineers are not at present willing to commit themselves.

Professors Upton and Lewis frankly admit that up to the present time we do not know what are the laws governing the number of applications of a given stress intensity and kind of loading required to produce failure. And, most of all, there is no accepted and standard method of fatigue testing.

One illustration will show the value of a careful study of the laws of fatigue failure. In a paper delivered before the Institute of Naval Architects on "The Law of Fatigue Failure Applied to Crank Shaft Failures", the author, Mr. C. E. Stromeyer, used a formula with a factor of safety of only 1-1/2, whereas the common factor of safety had always been taken as 8. In the discussion following his paper his wisdom in using such a low factor was questioned rather sharply. The author justified himself by stating his interpretation of the true meaning of factor of safety as "a factor of ignorance", and he was positive that a person was justified in reducing this factor of safety in direct proportion as he increased his knowledge along any particular line.

I believe this one illustration points the way to a wider study and application of the laws governing fatigue failure, for above all, the engineering profession should welcome any means whereby their "factor of ignorance" can be lessened.

II

Before taking up the design of a fatigue testing machine for the Testing of Materials Laboratory, I will briefly outline four points.

1. Requirements of an adequate machine for fatigue testing.
2. Classification of different types of machines already used for fatigue testing.
3. Conditions to be met in designing a machine for the Testing of Materials Laboratory with a discussion of the adaptability of the above types -- their advantages and disadvantages under local requirements.
4. Details recommended for the design of the proposed machine.

Requirements of an Adequate Machine.

1. Test should give a reliable indication of the probable behavior of the material in service.
2. Test should be capable of detecting any injurious element in the material.
3. Influence of the strength of the material must be eliminated.
4. Test should require a minimum of time.
5. Test pieces should be of simple design and low cost.
6. Tests should be uniform, so that it will not be nec-

essary to go through a large number of trials in order to obtain an average result.

ALTERNATING IMPACT OR CONSTANT DEFLECTION

Type	Method of Loading. Description of Test.	Advantages	Disadvantages.
Landgraf Turner	Repeated impact which causes a deflection of sufficient amount to give the material a permanent set at every impact applied. Combined impact and deflection. Deflection changed by using various sets of dies.	Tests materials beyond their elastic limit, thereby giving a minimum of time. Two tests on each specimen. Eliminates question of inherent strength. Test pieces simple in design Low cost. Small power required.	Doubtful if the amount of deflection is constant because there is not any accurate method of adjusting the banner dies. Question of method of gripping specimen setting up unknown stresses. Seems to be generally agreed that this type gives rather a toughness test than true fatigue.
Cambridge	Specimen is reduced in area to insure break at fixed point. Specimen subjected to direct impact, supported on knife edges. Rotated 1/2 revolution between each blow. This machine really is a combination of the constant load type, for the blow struck is the same at every impact.	Force and frequency of the blows readily adjustable. Stress reversals accurately calculated. Small horse power required. Simple test pieces low in cost.	Rather complicated mechanism.

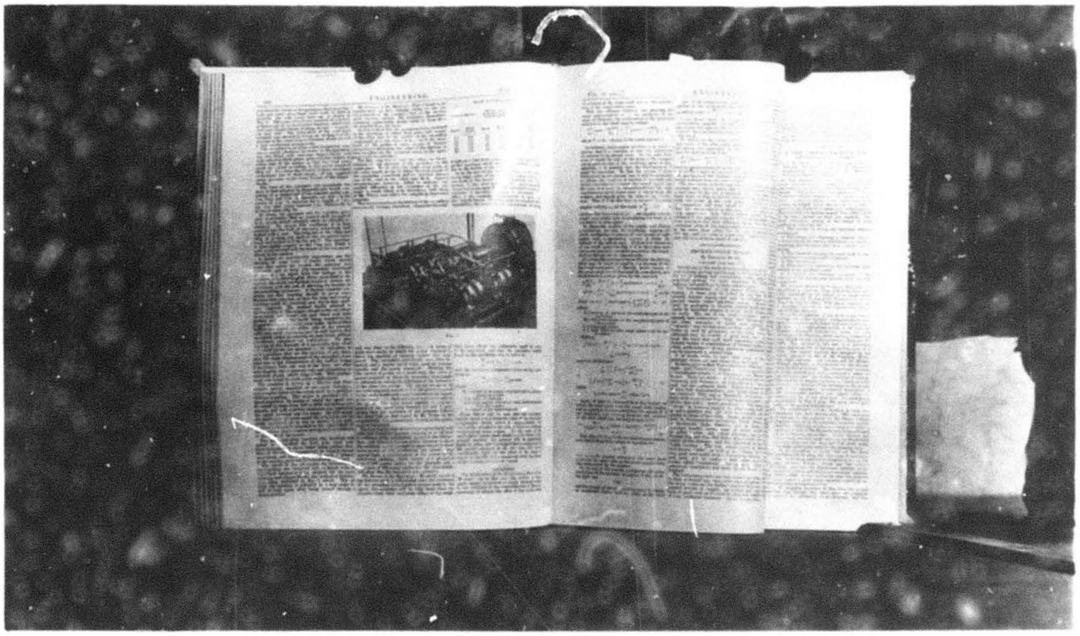
IMPACT

Type	Method of Loading	Advantages	Disadvantages
Olsen (Pendulum Type)	Pendulum type. Weight swung on radial arm, striking specimen which is gripped in upright position. Force of blow variable, depending on whether specimen is to be broken in one or several blows.	Simple specimen. Short time Very simple mechanism Speed of impacts same for all tests.	Question of gripping chucks influencing results.
Olsen (Freemont system)	Specimen notched and subjected to blow from weight falling vertically through known height	Simple specimen, low cost. Absolute amount of stress easily calculated. Speed of impact same for all tests.	Requires extreme height - 18 ft.
Upton-Lewis	Specimen deflected constant amount, by vibratory instead of rotary loading, the permanent deformation being measured by the resulting moment set up, this moment being measured by means of calibrated springs.	Simple specimen, short time. Simple and compact mechanism. Amount of deflection adjustable by changing throw of crank. Small power required. (Operated by hand if necessary.)	The only question might be one of gripping the specimen. This point however is always present in all types of fatigue machines.

REVOLVING BEAM OR CONSTANT LOAD

Type	Method of Loading Description of Test	Advantages	Disadvantages
White-Southern	Bending type, loaded as a cantilever. Loading accomplished by weights hung on ball bearings at ends of specimens. Intensity of loading variable depending on size of weights.	Comes nearer to meeting meeting the actual working conditions as found in practical work. Requires small amount of power.	Excessive cost of test specimen. Runs around $3 or $4 per specimen. Unless loading is carried up to or beyond the elastic limit, the time required is too long, often running several days or weeks.
Eden, Rose & Cunningham.	Reduced area of specimen subjected to a uniform load by means of suspended weights, hung on ball bearings.	Specimens of fairly simple design. Accurate means of adjusting and calculating stress intensity.	Test specimens require accurate forming. Cost rather high. Time required is rather long.
Wöhler's original experiments both in tension, compression, and in shear, were of the White-Southern type.			

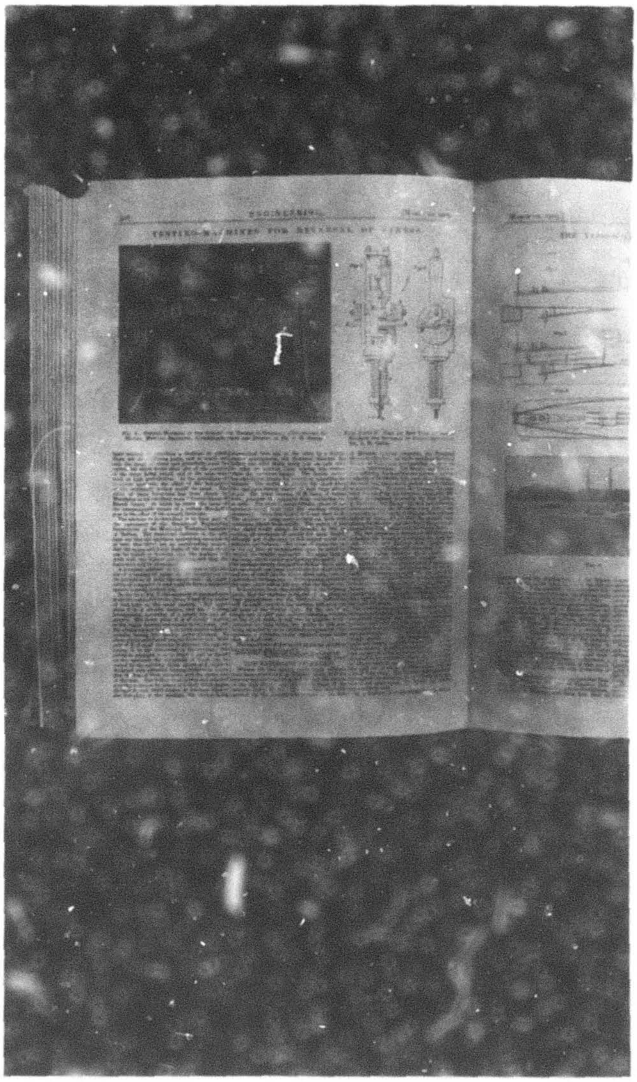
DIRECT LOAD TYPE. STANTON DESIGN.



DIRECT LOAD TYPE

Type	Method of Loading	Advantages	Disadvantages
Witton-Kramer. London Engineering, Vol. 94, page 805.	Stress applied in simple direction by means of the pull of an electromagnet, alternating current used, alternations depending on the frequency of the current. Reversals as high as 7,000 a minute are possible.	Requires a small specimen of low cost. Short time required. Machine very compact. Very little power.	Difficult to accurately measure the pull of the magnet. Machine has a decided tendency to wear itself out.
Stanton. London Engineering Vol. 79, page 201	Rotating crank causes periodic motion of a reciprocating mass by means of a connecting rod, the specimen under test forming the connection between the reciprocating mass and the crosshead. Complete machine made up of four cranks. Operates at high reversal, 2500 to 4000 per minute.	By using four cranks the machine is perfectly balanced. Four crank arrangement allows four different qualities of material to be tested under exactly similar stress conditions.	Harizontal motion of the masses involving frictional effects. Power required is high, a large proportion being used in overcoming friction. Rather complicated mechanism and oiling system.

EARLY DESIGN of Dr. J.H. SMITH.



DEAD LOAD TYPE

Type	Description of Test	Advantages	Disadvantages
Smith London Engineering Vol. 79 page 307	Stress reversals obtained by means of the inertia force of an oscillating weight moving in a vertical direction by means of a crank and connedting rod. This first machine of Dr. Smith's was designed in 1905.	Friction losses less than horizontal type. Six specimens tested at once - four in tension, two in shear. Machine does not require auxiliary balance weights. Harmonics will be eliminated.	
Smith London Engineering Vol. 88 page 105	Second machine of Dr. Smith's came out in 1909. Horizontal machine testing two specimens at once. Vibrating stresses set up by means of unbalanced weights mounted on a shaft, and specimens hung by means of a chuck.	Perfect balance of machine secured by placing unbalanced weights 180° apart on the main shaft. Machine descfibed has been in service for two years with practically no expense due to repairs, etc.	

III

The conditions to be met in designing a fatigue testing machine for the Testing of Materials Laboratory at Throop College of Technology, are different from those met in other lines of fatigue testing.

An adequate laboratory course for student investigation should require a minimum of time and should not involve excessive cost to the College.

The first and most important problem at Throop is one of time. Granting that all engineering institutions are confronted with a similar problem, the broad policy of Throop (namely, engineering plus the essential humanities) makes this saving of time doubly difficult. And in no course is the time element more important than in the testing of materials laboratory. When one considers that the time allotted to this course is only 90 hours, during which the student must cover a wide range of subjects, it is imperative that each test should be as short as is consistent with the subject under investigation; therefore it is essential that the fatigue test take a minimum of time. One example may be cited to illustrate the importance of the time element. A specimen was tested this year in the White-Souther machine, the piece was loaded up to 70% of the elastic limit and under this load ran continuously for 15 days; if they had made a check run, another 15 days would elapse, while if a third test was necessary still another two weeks would be required.

That is, a total of 45 days might be necessary before the test would be completed.

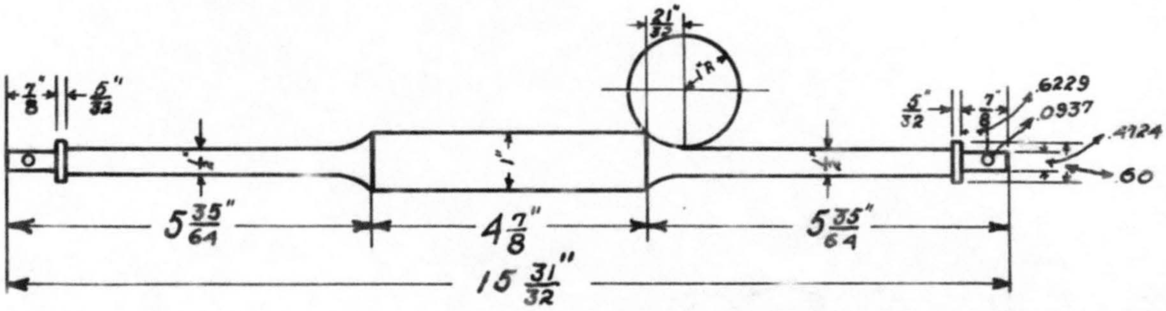
As a result of this excessive time required for a test in the White-Souther machine, the student's interest is more than likely to slacken, and when the test is finally completed, it will be hard for him to "line up" the results and come to the proper conclusions. This question would not be important in any but a college laboratory, but it is one which must be carefully considered in designing a fatigue testing machine for this class of work.

The item of expensive test specimens should be considered in the proposed design, for if many tests are conducted the cost of test speciment should be as low as possible. This question of costly specimens in mainly one of design.

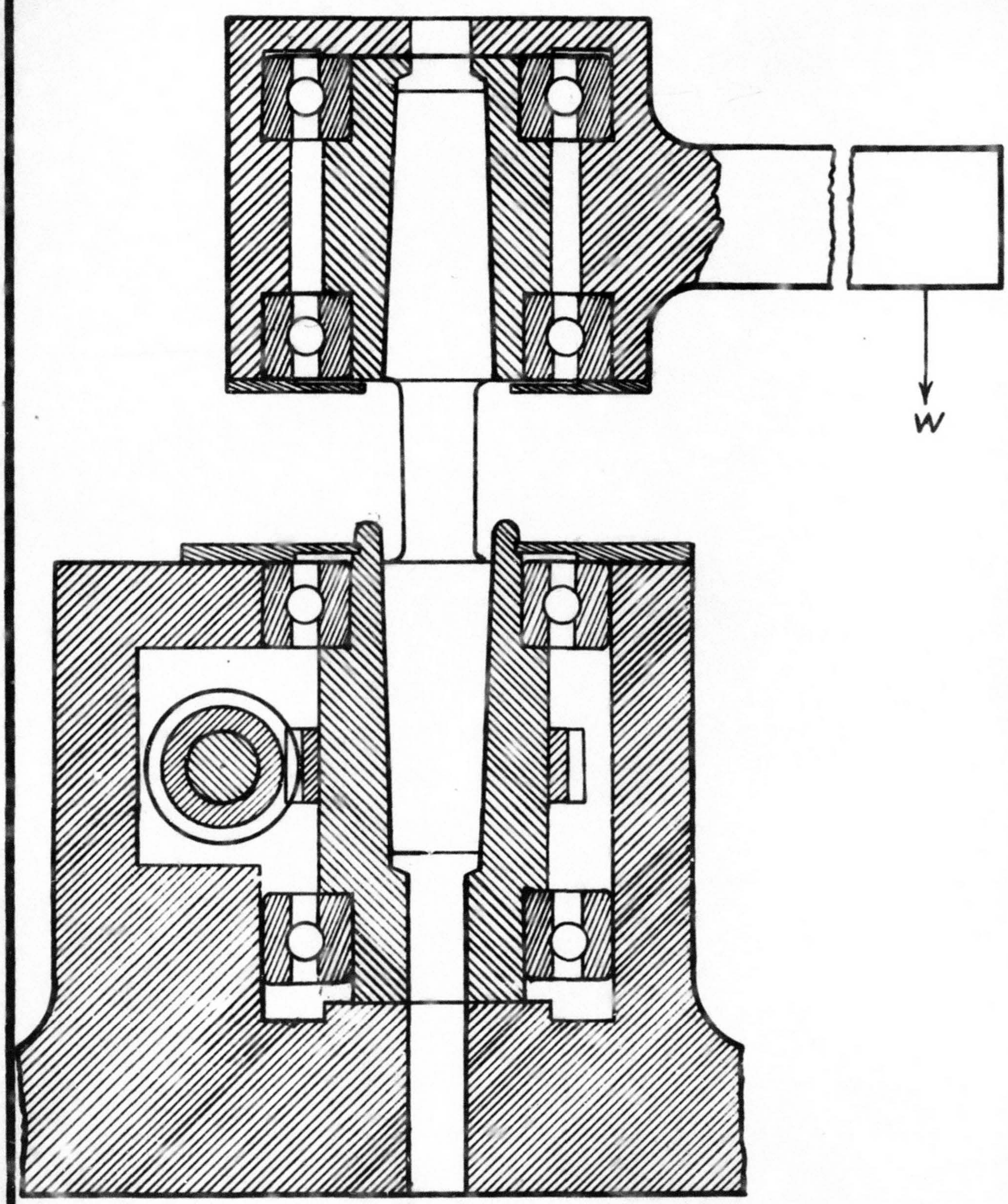
The following drawing of the standard specimen for the White-Souther machine is an example of poor design when considered from the standpoint of low cost.

STANDARD SPECIMEN.

WHITE-SOUTHER ENDURANCE TESTING MACHINE.



FATIGUE TESTING MACHINE.



R.F.CALL.

The above drawing works out very well on the drafting board, but several years' experience in preparing these specimens at Throop has shown many objectionable features. A few of the most important will be enumerated:

1st. The over-all length, 15-31/32 inches, requires a steady rest in machining the specimen.

2nd. There are several sections which must be very accurate, namely, the section which fits into the holding chuck, also the sections and shoulder carrying the ball bearings.

3rd. Practical difficulties of accurately machining a large radius fillet.

4th. Critical section occurs very close to the junction of the cylindrical portion and the fillet. This should be free from either tool or file marks, and this condition is hard to fulfill in practical work.

In comparision with the White-Souther specimen the Upton-Lewis test piece illustrates the simplest design possible, the only tools needed being a hack saw to cut off the proper length specimen.

IV.

Keeping in mind the load requirements I will next consider the advantages and disadvantages of the different classes of fatigue testing machines. The advantages and disadvantages of the individual machines of each class have been previously pointed out, but the classes as a whole possess certain features which should be pointed out. Also certain ones lend themselves to modifications along the lines needed at Throop College.

The chief advantage of the revolving beam class, seems to me to lie in the fact that this test closely approximates the conditions found in actual practice, namely car axles, line shafting, etc.; its great disadvantage is that unless the specimen is reduced in area, or the loading carried beyond the elastic limit, the time required is excessive, and the cost of test specimens is rather high.

The alternating impact type, that is, the single impact without subsequent bending, does not seem to me to come as near actual working conditions as is desired. It has the advantage, however, of using simple specimen and requiring short time. Dr. Stanton claims that the single blow method does not show any weakness which cannot be revealed in a careful static test. If this is true the single blow method would be at once eliminated from the discussion. Of the alternating impact type, the Upton-Lewis machine has the most points in its favor, but it does not adapt itself to more than one specimen at a time. This last however is not a great disadvantage in machines of this class, for the time required for testing with this method is always short.

The machines of the direct stress type are not adapted for local needs, and do not easily lend themselves to modification. The question of heavy reciprocating parts and the delicate balancing necessary eliminates them at once.

After considering the above points, it seems to me that the revolving beam types possess more features which can be adapted to local needs, and it will be along this line that the design will proceed.

IV.

The accompanying full size drawing shows one of the ten units of the proposed machine. The complete machine would not be over 5 ft. in length and it could be mounted complete with driving motor on one of the standard laboratory tables.

The specimen as loaded has a uniform bending moment over the reduced section. This is a very desirable feature as it allows the reversal of stress to pick out the weakest section instead of concentrating it at one point irrespective of the relative strength of that section.

The compressive stress due to the weight of the loading arm is negligible in comparison with that due to bending. For example, a load of 25 lbs. at the end of the lever arm giving a stress intensity of 50,000 lbs. per in. in the specimen.

The vertical thrust is carried on a plain bearing below the driving chuck. The ball bearing used are capable of an axial load of 50 lbs. which would be sufficient for every case except the load due to driving the specimens in place.

The speed counter is driven through a 100 to 1 reduction gear from the main driving shaft. Each unit has a separate counter attached to the dead end, which, when failure occurs, disengages the counter from the shaft.

The loading arms from alternate units are hung on opposite sides of the machine, this method assuring good balance of the whole machine.

The loading arm and yoke are not connected to the bottom of the machine. This allows each specimen to be removed when failure occurs.

The specimen is only 5-1/2 inches long, a Morse taper is used to hold it in the chucks.

Openings are left in both sections so that a knock-out pin can be used to remove the specimens when failure takes place.

Cover plates are provided to prevent dirt from getting into the ball bearings.

-Formulae-

Bending Moment: $M=\frac{pI}{e}$. where $M=P\ell$.

$P\ell=\frac{pI}{e}$ $\therefore p=\frac{P\ell e}{I}$ where $I=\frac{\pi d^4}{64}$, $e=\frac{d}{2}$

$\therefore p=P\left(\frac{\ell 32}{\pi d^3}\right)$ Putting $\frac{\ell 32}{\pi d^3}=2000$ $\ell=24.54''$=Lever Arm.

Therefore by multiplying the load P, applied at end of lever ℓ, by 2000, the resulting stress p (lbs./in^2) is found.

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