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AN INVESTIGATION ON THE VALUE OF THE INDENTATION TEST FOR STEEL RAILS.

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(Read before the General Section, December 13th, 1906.)

This paper is the result of some experiments conducted during the year 1905-06 in the Civil Engineering Testing Laboratory of McGill University, with a view to determining the value of the indentation test for steel rails in regard to the essential qualities desired in service. These qualities are usually determined by subjecting the specimen to a series of separate tests, including transverse, tension, and impact, in addition to the chemical analysis made from time to time to ascertain the proportion of carbon, silicon, manganese, sulphur, phosphorus, and any other elements which might affect the rail one way or another.

A study of this particular method of testing steel rails was suggested to the Author by watching indentations made on a large number of steel rail sections in the Testing Laboratory of the University, under the direction of the Chief Engineer of the Canadian Pacific Railway Company. These tests were made with a spherical punch .75" in diameter, with a load of 100,000 lbs. supplied by the Emery testing machine for a period of 10 seconds after commencing to load, in the manner expressed in Fig. 1.

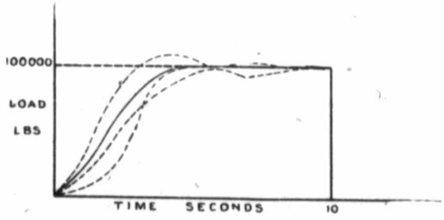


Fig. 1

The indentation was measured from the centre surface of the rail with an instrument reading to one-thousandth of one inch.

It is not known that any definite or satisfactory results were obtained from these tests, owing, probably, to the fact that the diameter of the indent at surface of specimen, or, in other words, the maximum diameter, should have been measured in addition to the identation, as it was afterwards found by the Author that this is the factor determining the relative hardness of the specimens; and also to the employment of the Emery machine instead of the Wicksteed, as the rate of loading by the Emery machine may vary over rather too wide a range for satisfactory results, there being a tendency to exceed the load desired in the effort to secure a balance. This feature in the loading by the Emery machine is illustrated by Fig. 1. Tests were made by the Author to determine this effect by applying loads as near as possible to rates of 5,000, 10,000, and 15,000 lbs. per second. For example, 100,000 lbs. would be applied at a fairly constant rate in 10 seconds and then dropped, 80,000 lbs. for 8 seconds, etc.

It may readily be seen by referring to curves 1, 2, 3, 4, and 5, how the rate of loading may affect the indentation made. It should be understood, however, that this effect is not so marked with an increase of time. For example, a certain indentation may be obtained by applying a load of 100,000 lbs. in 10 seconds; little or no difference might be found after holding the load on for 5, 10, or possibly 20 seconds, as a certain projected area of indent may have been reached for that load and rate of loading, after which the metal would refuse to flow. It is in the rate of loading while the metal is flowing that a considerable difference may be obtained.

Having ascertained the difficulties in the use of the Emery machine for indentation testing, it was decided to use the Wicksteed machine for the indenting of the rolled steel bars which had been prepared especially for this investigation by the Nova Scotia Steel Company. They were 2.5" × .75" × 6' in size, and were marked as follows:

1154 — .10% C.
1154 — .10% C.
2150 — .20% C.
2150 — .20% C.
1 — .30% C.
2 — .30% C.
1196 — .40% C.
1196 — .40% C.
2122 — .54% C.
2122 — .54% C.
1063 — .62% C.
3 — .75% C.
4 — .75% C.
5 — .90% C.
5 — .90% C.

The percentage carbon, as above stated, was checked at the College by the method of colour analysis with the following results:

1154 — .11% C.
2150 — .19% C.
2 — .25% C.
1196 — .42% C.
2122 — .66% C.
1063 — .64% C.
3 — .80% C.
5 — .96% C.

It may be seen that they agree fairly closely with the percentages marked, with the exception of 2 — .30 C. and 2122 — .54 C., these appearing by subsequent test to agree very closely with the 2150 — .20 C. and 1063 — .62 C. As the method of colour analysis, however, is not as satisfactory as a full chemical analysis, which was out of the question for all the specimens in the time available, these bars were not given as great importance as the others in the plotting of the curves.

A piece 18" long was cut off from each specimen for the tension test. The remaining lengths were then subjected to transverse test, resting flat on supports 40" apart, the load being applied at the centre by the Emery machine bearing the bar down to the point of yielding. The deflection curves obtained for the different specimens are shown on curve 33 with the relative condition of yielding. It may be observed on reference to this curve that some difficulty would be experienced in determining the point of yielding, particularly for the higher carbons, and it may be here noted that the values tabulated farther on were obtained from curve 33 by drawing a line parallel to the higher carbons, cutting the yield point of the curves at a distance of .1" from their straight course.

The value of Young's Modulus was then determined both from values between certain loads and also from the curves plotted, the latter being taken with respect to consideration of the different specimens in the different tests. In plotting the curve through these values it was seen that a constant value of E might be found for the steel specimens of different carbons. The tension specimens were then broken in the Wicksteed machine, the higher carbon pieces having to be split or planed down for the purpose.

It was difficult to obtain accurate stress strain curves up to the elastic limit, owing to the bars slipping in their grips. Careful note was made of their respective yield points and maximum loads, the latter values being uncertain, however, in the case of the .75 and .90 carbon specimens owing to their having broken inside the grip. The stress strain curves obtained after the yield point had been reached are shown on curve 34. For the indentation tests the pieces tested transversely were employed.

In addition to the .75" diameter spherical punch three other types were made, a 60° cone, a 90° cone, and a paraboloid having in a plane through its axis a curve of the value $y = \pi x^2$, this value being desired in order that a measure of the indentation would also be a measure of the projected area of indent at the surface of the specimen, it being found that this is the necessary factor in determining the relative degree of hardness of different specimens.

It was found, however, impossible to maintain the initial shape of any of the punches under the severe conditions of the harder specimens, and while the depth of the indentation was measured, it was done more with a view to checking the maximum diameter of the indent, or as a means of noting any slight variation in diameter hard to distinguish by a scale.

Considerable difficulty was experienced in obtaining the proper temper of these punches. They were made from Novo steel, turned to the required shape and tempered by heating in covered crucibles to a white heat, then plunging in thick oil and drawing out by heating again to a dull straw colour.

In the drawing out process they appeared to lose temper, there being apparently some difficulty in obtaining just the proper degree of reheating.

Several were not drawn out, but failed soon by cracking. Reference to curves 18, 20, and 21 will show the original design of these punches and their change in shape after the stated times of service.

It would seem that the sphere and paraboloid tend to retain their original shape much better than the cone, due to the point of the cone being under much more severe conditions of stress than the other two.

It may also be observed that the tendency of the cone curve is to gradually approach that of the paraboloid, while the paraboloid would tend to assume the spherical shape. This condition is exemplified farther on in the values of the hardness factor.

The term "Hardness Factor" should be here explained as the value obtained by dividing the projected area of indent at surface of specimen into the load applied, giving, in this case, the value of the hardness factor in pounds per square inch; for example, an area of .2 sq. inches obtained with, say, a .75" sphere, under a load of 80,000 lbs., would give a hardness factor of 400,000 lbs. per sq. inch; with a load of 40,000 lbs. an area of .1 sq. inch would be expected, though the value will be slightly more, as will be noted and discussed farther on.

It will thus be seen that careful measurement of the maximum diameter is necessary, as the area, and, consequently, the hardness factor would vary as the square of the diameter.

The Wicksteed machine was employed throughout the indentation test for these bars, and was found to give much more satisfactory results than the Emery machine, a uniform loading being obtained by setting the weight at the desired position and floating the lever arm by the hydraulic pressure from the accumulator, the load being thus never exceeded, while the rate of loading may be made fairly constant by watching the hydraulic pressure gauge.

Two indentations were made with each punch for each bar at loads of 40,000, 60,000, 80,000, and 100,000 lbs.

The 60° cone failed after a few trials, and further experiments with this type were not considered advisable. The results obtained with the .75" D. sphere, the 90° cone, and the paraboloid may be found tabulated farther on.

Load-area curves for the different specimens are shown, plotted from the values obtained from load-indentation curves. The respective values of the hardness factors are shown on curves 38, 39, and 40. It will be observed that the hardness factor rises slightly with the load, the rise in the curve being more pronounced in the harder specimens of higher carbons, though several of the lower carbon specimens appear to have curves rising considerably with the load, but this may be explained by the fact that particularly in the case of the .10% carbon the flow of metal tended to cease on the punch approaching the under side of the bar, when with a deeper bar it would have continued flowing.

It is believed that the slope of this hardness factor load curve bears a definite relation to the percent elongation in the tension test, the harder and less ductile the specimen the greater the slope. With the specimens at hand it was not possible to investigate this relation more fully. Again, the area obtained in the use of the different punches under the same load would vary slightly with the co-efficient of friction between the surface of the punch moving along and against the surface of the specimen, the effect of the friction would vary with the shape of the punch, and the co-efficient would vary with the degree of hardness of the punch relative to the specimen indented. This effect may be seen on referring to the indentation test sheets farther on, where, in the use of two different punches in the case of the cone and paraboloid in obtaining four indentations for one load, a distinct difference may be noted in the results obtained in the two cases, due in a large measure to the difference in the friction co-efficients of the two punches of different hardness.

It is the purpose of the Author to take up at a later period a more careful study of these effects, dwelling in particular upon the theory of these experiments in regard to the flow of solids.

Curves 41 and 42 serve to indicate the relation between the yield point, maximum load, percent reduction in area, and percent extension in the tension test to the hardness factors obtained by the indentation test with the different punches. The values of the hardness factors obtained by the 90° cone and paraboloid are almost identical, while those obtained by the .75" D. sphere are lower.

It was intended to experiment also with a sphere .5" in diameter to determine more definitely the relation of the hardness factor to the diameter of the indenter. It was found impossible, however, to obtain this punch in time for service, but it is certain that it would give a higher value of hardness factor than the .75" diameter sphere, as seen in the higher values obtained in the case of the paraboloid.

From the curves the yield point appears to vary directly as the hardness factor, .150 of its value in the case of the .75" sphere, and .143 in the case of the cone and paraboloid, and probably very close to this value in the case of a sphere .5" diameter. The maximum load curye is a straight line up to a hardness factor of about 425,000 lbs., then bends over to meet the yield point for higher carbons.

The percent reduction in area curve may also be fairly taken as straight from 200,000 lbs. hardness factor — .10% carbon steel — to 450,000 lbs. hardness factor — about .70% carbon steel, having a value of about (59 — .000109 H) for the .75" sphere and (61 — .000111 H) for the 90° cone and paraboloid, H being the hardness factor in each case. Refer to curve 44 and curve 45 for tabulated results.

Coming now to the relation between the percentage carbon and hardness factor (curve 43), as obtained by the sphere, cone, and paraboloid, it would seem that, other conditions being equal, the percentage of carbon varies directly as the hardness factor for steel, running up to about .90%.

With a further increase of carbon a maximum hardness factor would soon be reached and the curves would then tend to bend down.

To illustrate the practical value of this relation it is interesting to refer to a test made on a piece of rail, broken while in service on the Grand Trunk Railway line and sent to the laboratory to ascertain, if possible, the cause of its failure. A traverse test was made, giving a normal value by Young's Modulus. Indentations were then made giving a value of 427,000 lbs. per sq. in. for a hardness factor, with a load of 80,000 lbs., using the .75 inch sphere, indicating from curve 43 a probable percentage of carbon present of about .68. A chemical analysis subsequently made gave from .66 to .70% carbon, with .60% phosphorus, .78% manganese, and .07% silicon.

McGILL UNIVERSITY

Department of Civil Engineering—Testing Laboratory

INDENTATION TEST

Date.—February 15th, 1906. *Name of Observer.*—H. K. D.

Specimen.—80 lb. steel rail from Grand Trunk Railway Co. Broken while in place on line.

Indenter.—Sphere .75″ D. *Machine used.*—Wicksteed.

Method of Test.—Indentations made on top and bottom.

LOAD (Lbs.)	INDENTATION (Inches)	DIAMETER OF INDENT AT SURFACE OF SPECIMEN (Inches)	AREA OF INDENT AT SURFACE OF SPECIMEN (Sq. Inches)	HARDNESS FACTOR H (Lbs. per Sq. Inch)	REMARKS
60,000	.057				Bottom
	.057				"
	.055				Top
	.056	.425	.1418	427,000	"
80,000	.075				"
	.075				"
	.077				Bottom
	.079	.490	.1885	427,000	"
100,000	.101				Top
	.102				"
	.103				Bottom
	.103	.545	.2332	432,000	"

Although this may reasonably be termed an exceptionally close coincidence, yet an indentation test made on this specimen in the shops would have given a value of hardness factor to at least suggest the presence of a rather higher percentage of carbon than would be desired, or a condition equivalent to such, in regard to the other elements.

It is believed that Brinell, of Sweden, was the first to investigate this method of testing iron and steel, having published a paper on the subject about five years ago.

His term of "Hardness number" was obtained by dividing the area of the concave surface of the indent into the load instead of the area of the projection.

He also obtained the yield point and percent elongation by separate experiments, rather than direct reference to the hardness factor as herein attempted.

According to him no method purporting to determine hardness is to be considered suitable for practical use unless fulfilling the following requirements:

1. It must give trustworthy results.
2. It must be easy to learn and apply.
3. There should be no necessity for costly or time-wasting mechanical treatment of the material previous to testing.
4. The testing medium for forcing into the material should be cheap, easy to obtain, incapable of altering its shape, and of sufficient hardness.
5. The method should admit of testing finished articles as, for example, armour plates, rails, etc.
6. The testing results should be indicative of the absolute hardness of the material tested, defining the term "hardness" as the resistance offered by a solid substance to the entrance of another substance into it.

He found that a decrease in the size of the sphere gave higher values of hardness factor with more pronounced differences between the specimens of different carbons.

Also, that the value of the hardness factor for a given specimen rose slightly with the loads applied.

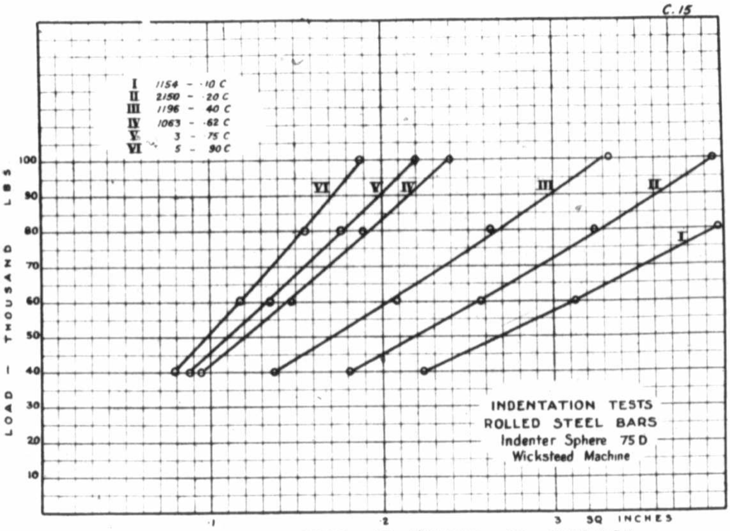
These results agree with those herein described, with the hardness factor obtained by dividing the load by the area of projection of indent, and it would seem that the hardness factor obtained in this manner would be simple and satisfactory for the testing of steel rails, while its relation to other factors in their manufacture could be better established in the plant than in the College laboratory.

In conclusion, on summarizing the results of this investigation it would seem that:

1. The hardness factor as herein obtained would be a satisfactory expression of hardness.
2. The yield point in the tension test may be expressed in terms of the hardness factor H. of the indentation test, the value of this expression being about .150 H. for a sphere .75" diameter and .143 H. for a 90° cone or paraboloid $y = \pi x^2$.
3. The percent reduction in area of the tension test for steel up to about .65% carbon may be expressed in terms of the hardness factor, the value of the expression being (59 — .000108 H) for a sphere .75" diameter and (61 — .000111 H) for a 90° cone or paraboloid $y = \pi x^2$.
4. The value of the expressions in (2) and (3) will vary slightly with the type of indenter and the manner of applying the load.
5. For the testing of specimens having a wide range of hardness the paraboloid $y = \pi x^2$ would be found very satisfactory.

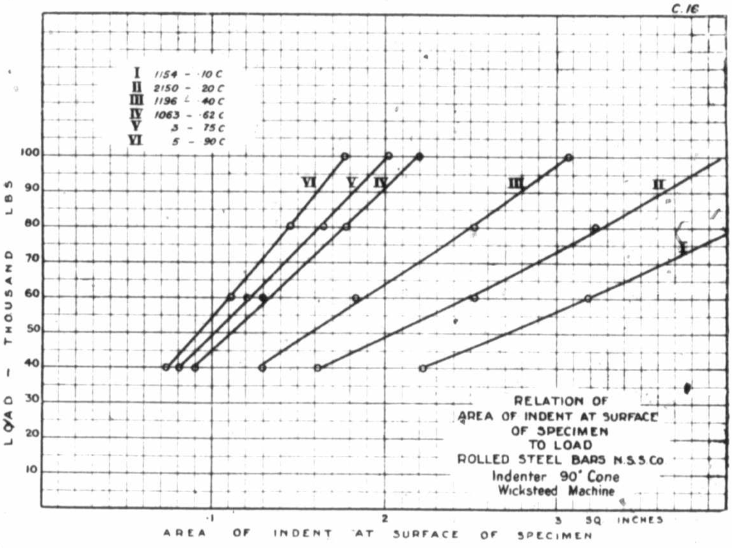
6. For the testing of steel rails hard steel balls of from .75" to .5" diameter would be found most suitable, using loads of 100,000 lbs. for the .75" diameter to loads of 50,000 lbs. for the .5" diameter indenter, and for the larger loads using a Wicksteed type of machine or one similar in principle of loading.
7. A higher value of hardness factor will be obtained in the use of a smaller sphere.
8. A higher value of hardness factor will be obtained by using the same sphere with a heavier load.
9. The slope of the load-hardness factor curve may be employed to obtain an expression for the ductile properties of the specimen.
10. The indentation test, when supplemented by other tests from time to time, would be a very convenient and practical method of inspecting the quality of an output of steel rails.

C.15



INDENTATION TESTS
ROLLED STEEL BARS
Indenter Sphere ·75 D
Wicksteed Machine

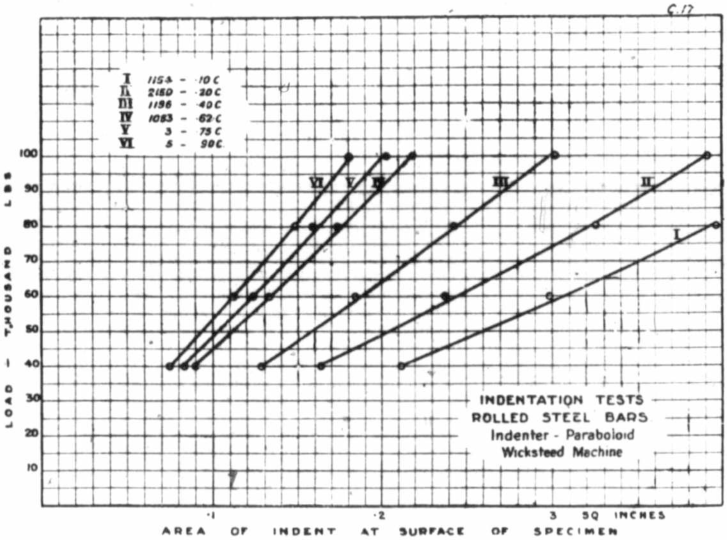
C.16



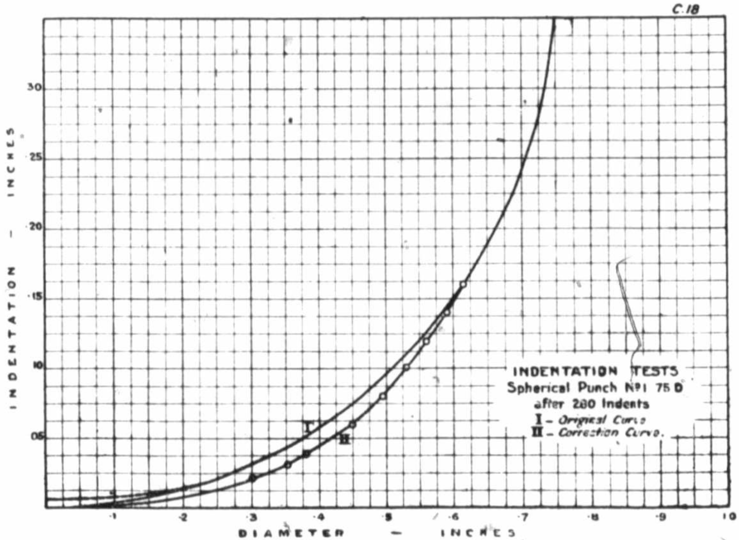
RELATION OF
AREA OF INDENT AT SURFACE
OF SPECIMEN
TO LOAD
ROLLED STEEL BARS N.S.S.Co
Indenter 90° Cone
Wicksteed Machine

L

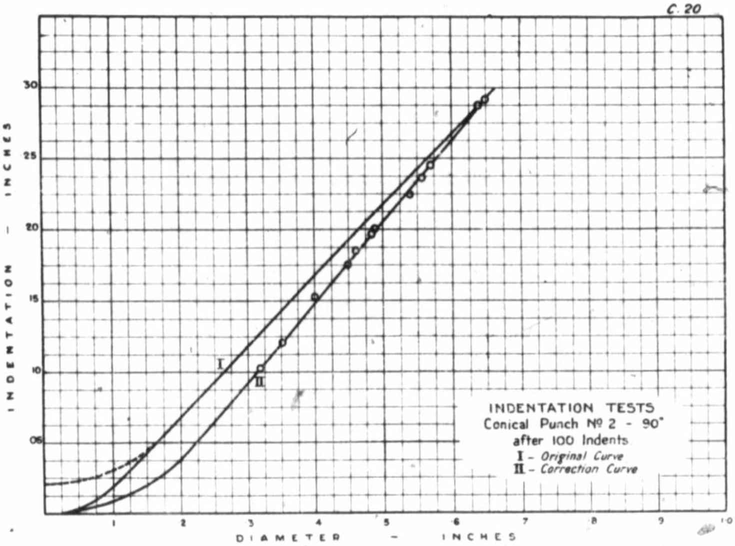
C.17


I 1154 - ·10 C
II 2150 - ·20 C
III 1196 - ·40 C
IV 1083 - ·62 C
V 3 - ·75 C
VI 5 - ·90 C
VI
V
IV
III
II
I
100
90
80
70
60
50
40
30
20
10
LOAD - THOUSAND LBS
·1
·2
·3 SQ INCHES
AREA OF INDENT AT SURFACE OF SPECIMEN
INDENTATION TESTS
ROLLED STEEL BARS
Indenter - Paraboloid
Wicksteed Machine

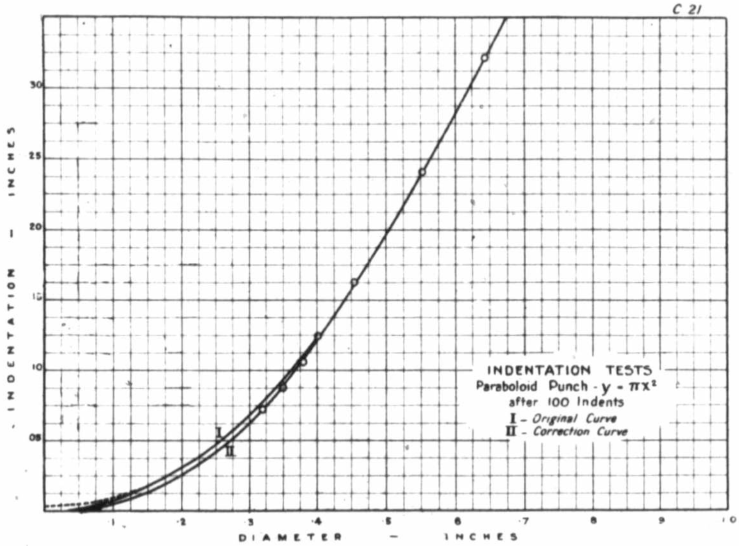
C.18


·30
·25
·20
·15
·10
·05
INDENTATION - INCHES
·1
·2
·3
·4
·5
·6
·7
·8
·9
1·0
DIAMETER - INCHES
I
II
INDENTATION TESTS
Spherical Punch Nº1 75 D
after 280 Indents
I - Original Curve
II - Correction Curve.

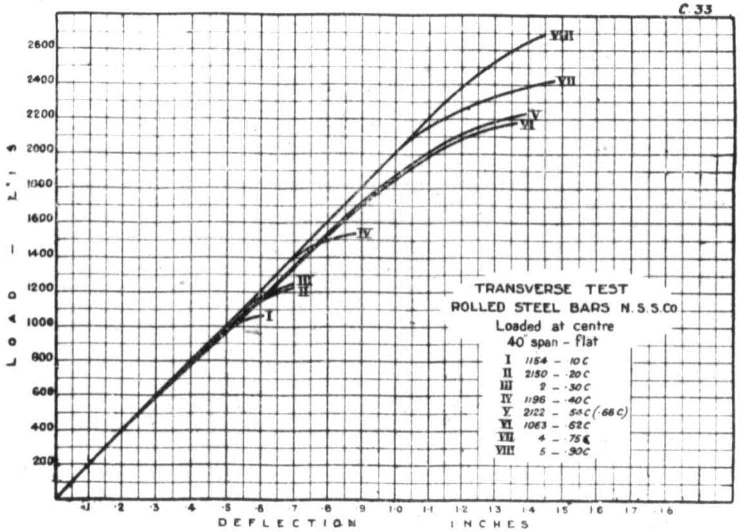
C. 20


INDENTATION TESTS
Conical Punch Nº 2 - 90°
after 100 Indents
I - Original Curve
II - Correction Curve
I
II
30
25
20
15
10
05
INDENTATION - INCHES
·1
·2
·3
·4
·5
·6
·7
·8
·9
1·0
DIAMETER - INCHES

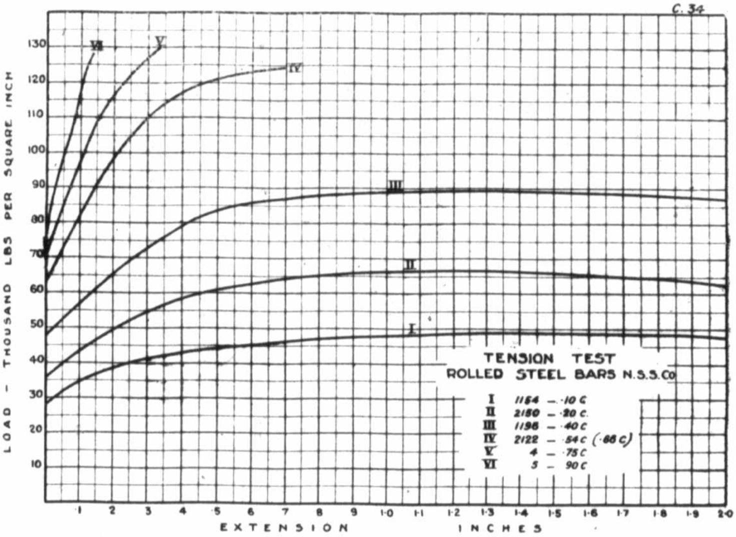
C 21


INDENTATION TESTS
Paraboloid Punch - y = πx²
after 100 Indents
I - Original Curve
II - Correction Curve
I
II
30
25
20
15
10
05
INDENTATION - INCHES
·1
·2
·3
·4
·5
·6
·7
·8
·9
1·0
DIAMETER - INCHES

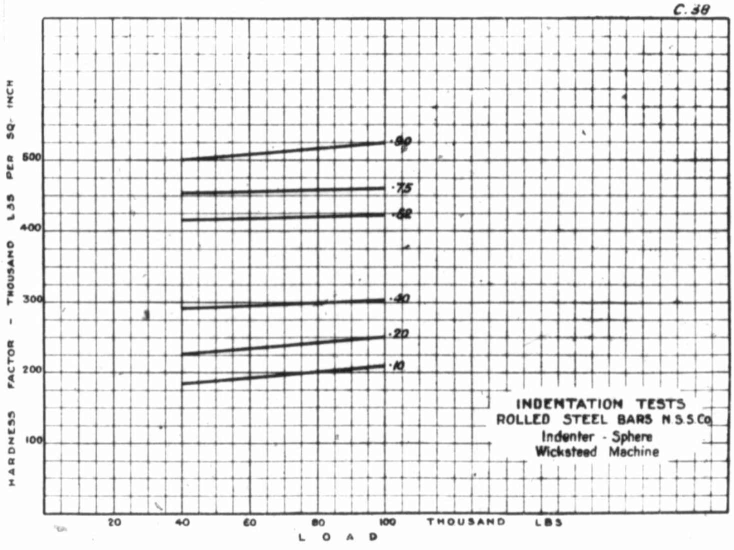
C. 33


TRANSVERSE TEST
ROLLED STEEL BARS N.S.S.Co
Loaded at centre
40" span - flat
I 1154 - ·10 C
II 2150 - ·20 C
III 2 - ·30 C
IV 1196 - ·40 C
V 2122 - ·54 C (·66 C)
VI 1063 - ·62 C
VII 4 - ·75 C
VIII 5 - ·90 C
VIII
VII
V
VI
IV
III
II
I
LOAD - L'bs
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
·1
·2
·3
·4
·5
·6
·7
·8
·9
1·0
1·1
1·2
1·3
1·4
1·5
1·6
1·7
·1·6
DEFLECTION INCHES

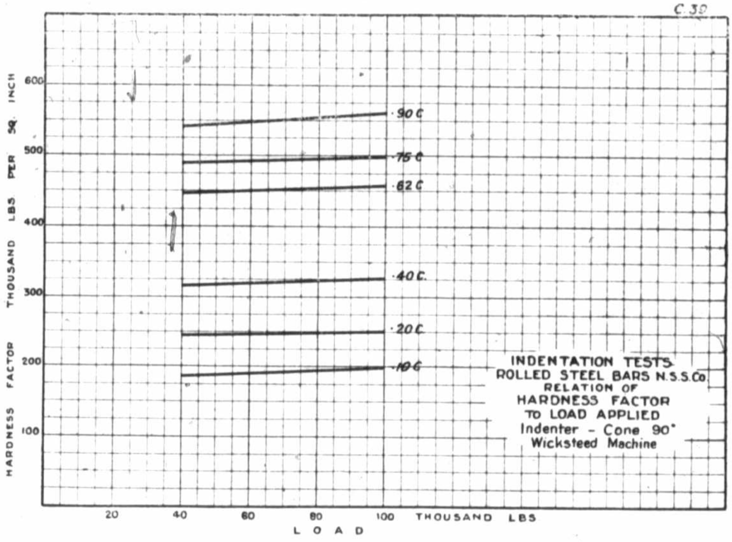
C. 34


TENSION TEST
ROLLED STEEL BARS N.S.S.Co
I 1154 - ·10 C
II 2150 - ·20 C.
III 1196 - ·40 C
IV 2122 - ·54 C (·66 C)
V 4 - ·75 C
VI 5 - 90 C
VI
V
IV
III
II
I
LOAD - THOUSAND LBS PER SQUARE INCH
130
120
110
100
90
80
70
60
50
40
30
20
10
·1
·2
·3
·4
·5
·6
·7
·8
·9
1·0
1·1
1·2
1·3
1·4
1·5
1·6
1·7
1·8
1·9
2·0
EXTENSION INCHES

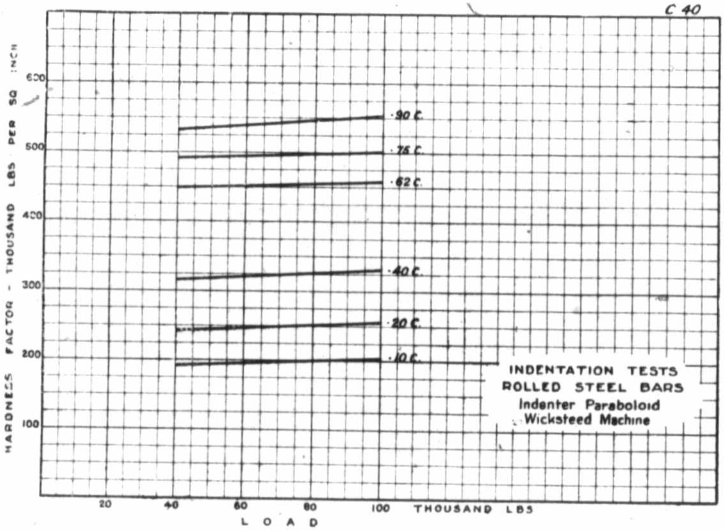
C.38


HARDNESS FACTOR - THOUSAND LBS PER SQ. INCH
500
400
300
200
100
20
40
60
80
100
THOUSAND LBS
LOAD
·90
·75
·62
·40
·20
·10
INDENTATION TESTS
ROLLED STEEL BARS N.S.S.Co.
Indenter - Sphere
Wicksteed Machine

C.39

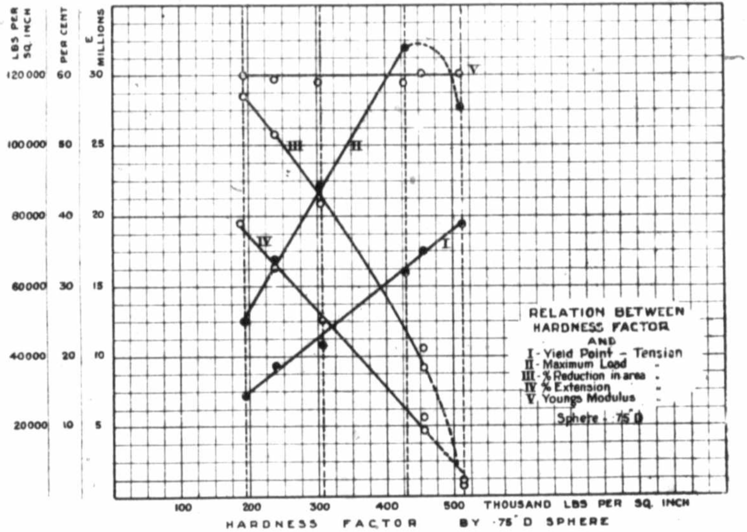

HARDNESS FACTOR THOUSAND LBS PER SQ. INCH
600
500
400
300
200
100
20
40
60
80
100
THOUSAND LBS
LOAD
·90 C
·75 C
·62 C
·40 C.
·20 C.
·10 C
INDENTATION TESTS
ROLLED STEEL BARS N.S.S.Co.
RELATION OF
HARDNESS FACTOR
TO LOAD APPLIED
Indenter - Cone 90°
Wicksteed Machine

C 40



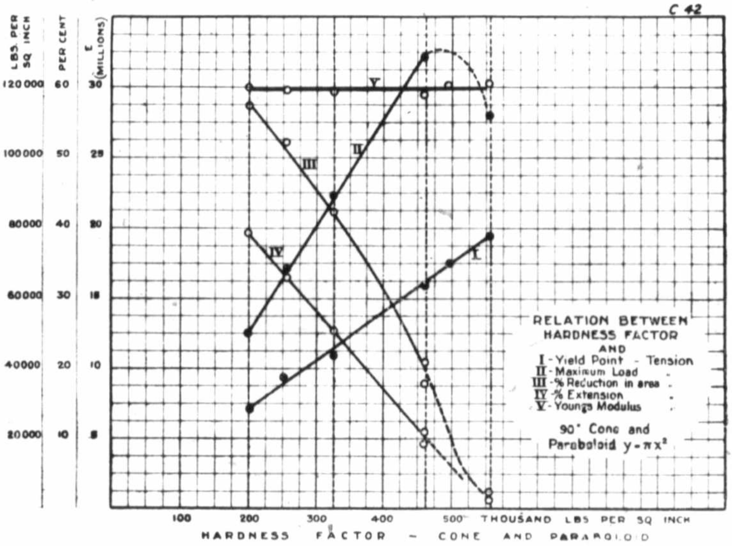
INDENTATION TESTS
ROLLED STEEL BARS
Indenter Paraboloid
Wicksteed Machine

C.41



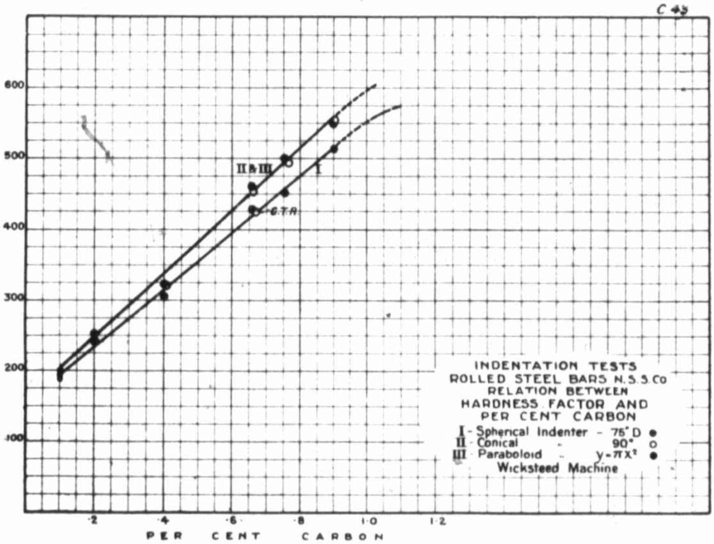
RELATION BETWEEN
HARDNESS FACTOR
AND
I - Yield Point - Tension
II - Maximum Load "
III - % Reduction in area "
IV % Extension "
V Youngs Modulus "
Sphere - ·75" D

C 42



LBS. PER SQ INCH
PER CENT
E (MILLIONS)
120000 60 30
100000 50 25
80000 40 20
60000 30 15
40000 20 10
20000 10 5
100
200
300
400
500 THOUSAND LBS PER SQ INCH
HARDNESS FACTOR – CONE AND PARABOLOID
I
II
III
IV
V
RELATION BETWEEN HARDNESS FACTOR AND
I - Yield Point - Tension
II - Maximum Load "
III - % Reduction in area "
IV - % Extension "
V - Youngs Modulus "
90° Cone and Paraboloid y = πx²

C 43



600
500
400
300
200
100
·2
·4
·6
·8
1·0
1·2
PER CENT CARBON
II & III
I
CTA
INDENTATION TESTS
ROLLED STEEL BARS N.S.S.Co
RELATION BETWEEN
HARDNESS FACTOR AND PER CENT CARBON
I - Spherical Indenter - 75° D ●
II - Conical - 90° ○
III - Paraboloid - y = πx² ●
Wicksteed Machine

RELATION BETWEEN { INDENTATION TENSION & TRANVERSE TESTS

CHARGE Nº	PER CENT CARBON	TENSION TEST				TRANSVERSE TEST		INDENTATION TEST HARDNESS FACTOR (for 80.000 lbs load) lbs. per square inch			REMARKS
		YIELD POINT lbs per sq. inch	MAXIMUM LOAD lbs. per sq. inch	PER CENT REDUCTION IN AREA	PER CENT EXTENSION	YIELD POINT FOR L = 40 in. lbs	YOUNG'S MODULUS E	SPHERE D = 75"	CONE 90°	PARABOLOID $y = \pi x^2$	
1164	·10	28 400	50,000	57·3	39·2	1050	30,000,000	195 000	190.000	200 000	
2150	·20	37,100	68.300	51·8	32·8	1250	29 450 000	240.000	245.000	255.000	
3	·30 (·25)	35.000	64 200	52·3	32·9	1250	30 800 000	245.000	245 000	255.000	
1190	·40	42.800	88.900	42·1	25·5	1500	29,000 000	305.000	325 000	325 000	
1063	·62	63.700	128,100	18·0	11·4	1950	28.600 000	430.000	450.000	455.000	
2122	·54 (·66)	62.700	126 000	21·0	9·2	2000	28.900 000	430.000	455.000	460.000	
4	·75	70 000	*101 600	*2·3	*1·5	2250	30 300,000	455 000	500.000	495.000	
5	·90	77 200	*111.700	*2·2	*1·2	2650	30 300 000	515.000	550 000	555 000	
		Mean of 2 trials	* Broke in clutch			Bars laid flat	from curves				

RELATION OF YIELD POINT AND PER CENT REDUCTION IN AREA TENSION TEST, TO HARDNESS FACTOR – H – INDENTATION TEST

CHARGE Nº	PER CENT CARBON	YIELD POINT				REDUCTION IN AREA				
		TENSION TEST	·150 H SPHERE ·73" D	·143 H CONE 90°	·143 H PARABOLOID $4 = \pi x^2$	TENSION TEST	(59-·000108 H) SPHERE 75" D	(61-·000111 H) CONE 90°	(61-·000111 H) PARABOLOID $y = \pi x^2$	
1154	10	28,400	27 800	27 200	28 700	39·2	38·0	39·9	38·8	NOTE – The values 150 H, 143 H, and (59-000108 H), (61-000111 H) are derived from curves C41 & C42 Nos I & IV respectively
2150	20	37,100	36 000	35 000	36,500	32·8	33·1	33·8	32·7	
3	·30 (·25)	35,000	36 700	35 000	38,500	32·9	32·5	33·8	32·7	
1196	40	47 800	45 700	46,500	46,500	25·5	26·0	25·0	25·0	
1063	62	63,700	64 400	64 400	65.000	11·4	12·6	11·0	10·5	
2122	·54 (·66)	62 700	64 400	65.000	65.800	9·2	12·6	10·5	10·0	
4	75	70 000	68.300	71 600	71 000	1·5 ?	10·0	5·0	5·5	
5	90	77 200	77 100	79 700	79.200	1·2 ?	3·3	—	—	