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Empirical Relation between Leeb Rebound Hardness and Tensile strength for Austenitic Ductile Cast Iron

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Abstract: Rebound hardness is a popular onsite testing method to evaluate the hardness of heavy and massive metal parts and products. It is usually economical to do Leeb rebound testing where only one or very few items are to be produced because it is a non-destructive test. It is not economical to do destructive test such as tensile strength in this case. The aim of this study is to find the relation between leeb rebound hardness and tensile strength of the austenitic ductile cast iron, to rely on the leeb rebound test for measuring tensile strength to avoid the waste of material, and time in destructive tensile test. The tests were performed on a production of three groups of austenitic ductile cast iron covering a wide range of carbon equivalent (3.51 to 5.04%) using; carbon, silicon or nickel as alloying elements. The first group (A) having %CE ranging from 3.51 to 5.04 and the variable element was carbon. The second group (B) having %CE ranging from 3.86 to 4.64 and the variable element was silicon content, and the third group (C) having %CE ranging from 3.90 to 4.8 and the variable element was nickel. A mathematical relation was deduced to relate the tensile strength and Leeb Rebound hardness of austenitic ductile cast iron with regression coefficient R= 0.88.

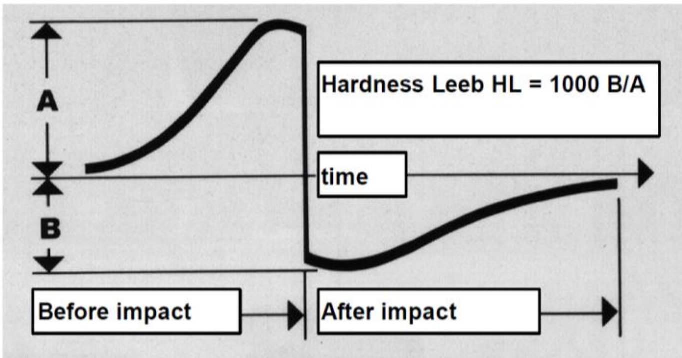
Keywords: Leeb Rebound, Tensile strength, Austenitic ductile cast iron, hardness test.

1. INTRODUCTION

Leeb hardness testing method was invented by Dr. Leeb in Switzerland at the end of 1970s, and has turned out to be a major breakthrough for hardness testing technology. The portable hardness tester developed can be applied at different positions of the parts and components over a wild testing range for it being compact and delicate, which is suitable for the testing hardness of the components with large scale and heavy-duty as well as those which have already been installed and cannot be disassembled.[1]

Rebound hardness testing evaluates the hardness of a test specimen by having an indenter, which is called a hammer or an impact body; strike a test specimen at a controlled velocity and measuring the height and velocity of its rebound. This is a widely used on-site testing method for evaluating the strength of large pieces of equipment and structures that are difficult to test with a stationary hardness tester [2].

Hardness testers using Leeb's method operate in a slightly different manner as compared to standard testing methods like Vickers, Rockwell or Brinell. The hardness is indirectly measured via the loss of energy of a so-called impact body a mass is accelerated to the surface of the test object and impinges on it at a defined speed, i.e. kinetic energy [3]. The impact creates a plastic deformation of the surface, i.e. an indentation, due to which the impact body loses part of its original speed – or energy. It will lose more speed by creating a bigger indentation and, thus, at softer material. Technically, this principle of measurement is implemented by means of an impact body which has a spherical tungsten carbide tip and which is impelled onto the test surface by spring force. The speeds after and before the impact are each measured in a noncontact mode. This is done by a small permanent magnet within the impact body which generates an induction voltage during its passage through a coil, with this voltage being proportional to the speed (Fig.1).



Fig(1) Voltage signal generated by the impact body penetrating through the coil. The signal is shown before and after the impact

HL = γ_R / γ_A.1000αVR/VA
Where ,
HL Leeb hardness value
γ_A: impact velocity
γ_R: rebound velocity
VA : induced voltage proportional to impact velocity
VR : induced voltage proportional to rebound velocity

Strength of metallic materials is the most important property for engineering calculations during the design, which deals with the behavior of solid objects subject to stresses and strains. The strength of the component is usually considered based on the maximum load that can be borne before failure is apparent.

With non-destructive testing (NDT) devices the measurements can be performed directly on the products, and structures and the strength can be estimated from the measured results.

Austenitic ductile cast irons are a series of nickel-bearing cast iron that contain from 18-36 mass% nickel, and have been treated with magnesium to bring about the formation of nodule graphite .These irons have tensile strength ranging from 55000 psi to 80000 psi (379 to 551 MPa) and elongations from 4 to 40% [4-6]. Castings made from this group of alloys have the following special properties:

(1) High resistance to erosion and corrosion,

(2) High resistance to heat and oxidation,

(3) High thermal sensitivity,

(4) Good machinability.

In addition, high strength and ductility are available over a wide temperature range The aim of this study is to deduce a relation between leeb rebound hardness and the tensile strength of the austenitic ductile cast iron experimentally to depend on the leeb rebound test for measuring the strength of the material to avoid the waste of material, and time in destructive tensile test.

2-Experimental

2.1-Material

three groups (A, B and C) were prepared in 90 –kg heats in a high frequency (1000 Hz) induction furnace using charges consisting of low sulphur, low manganese, and low phosphorous pig iron (Sorel metal) and steel scrap as shown in Table 1[7]. Necessary amounts of carbon, silicon, and nickel were added to yield a silicon content in the range of 1.63 to 5.31 mass%, carbon content in the range of 2.10 to 3.50 mass%, and nickel content in the range of 5.0 to 41.75 mass%. Desulphurisation procedures were not essential since the S-content of raw materials was within the permissible range (≤ 0.02%). The melts were superheated to 1773-1823 K. Magnesium treatment and inoculation was performed using sandwich technique. The ferrosilicon alloy containing 10% Mg was used in the spheroidising treatment. The heats were inoculated with 0.5 mass% of the charge with FeSi alloy 65% Si. The grain size of inoculants used ranged from 1.5 to 3 mm. Pure nickel was melted with raw materials to get austenitic ductile cast iron in the as cast condition. Tables 2,3 and 4 lists the actual chemical composition of all heats involved in this study of group A, B and C respectively. The melt was poured at a temperature ranged from 1620 to 1640 K, into two different moulds to produce specimens for both chemical analysis and tests. A half inch Y-block sand mould was used.

The % CE is calculated as follows:

$$CE = \%C + \left(\frac{\%Mn + \%Si}{6}\right) + \left(\frac{\%Cr + \%Mo + \%V}{5}\right) + \left(\frac{\%Cu + \%Ni}{15}\right)$$

Table 1 Chemical composition of the raw material used in the present study

Raw materials	Composition %						
	C	Si	Mn	S	P	Ni	Fe
sorel metal	4.0	0.1	0.1	0.0	0.0	0.0	bal
steel scrap	0.2	0.2	0.6	0.0	0.0	0.0	bal
Ferrosilicon	0.0	65.0	0.0	0.0	0.0	0.0	bal
Carboriser	100.0	0.0	0.0	0.0	0.0	0.0	0.0
Nickel	0.0	0.0	0.0	0.0	0.0	99.0	bal

Specimen No	Composition %				
	C	Si	Ni	Mn	Mg
A1	2.11	2.12	19.77	1.40	0.043
A2	2.31	2.07	19.44	1.40	0.041
A3	2.53	2.11	19.41	1.40	0.042
A4	2.71	2.08	19.70	1.40	0.050
A5	2.95	2.12	19.54	1.40	0.045
A6	3.16	2.14	19.41	1.40	0.053
A7	3.29	2.08	19.52	1.40	0.048
A8	3.42	2.16	20.02	1.40	0.059

Table 2 Chemical compositions of all specimens in group

Table 3 Chemical compositions of all specimens in group B

Specimen No	Composition %				
	C	Si	Ni	Mn	Mg
B1	2.50	1.63	21.54	1.34	0.047
B2	2.53	2.17	21.59	1.33	0.040
B3	2.52	2.76	21.90	1.32	0.042
B4	2.56	3.32	21.67	1.33	0.049
B5	2.54	3.89	21.86	1.34	0.051
B6	2.51	4.41	21.87	1.34	0.049
B7	2.53	4.92	21.65	1.33	0.038
B8	2.50	5.31	21.58	1.33	0.036

Table 4 Chemical compositions of all Specimens in group C

Specimen No	Composition %				
	C	Si	Ni	Mn	Mg
C1	2.90	1.86	4.99	1.77	0.045
C2	2.85	1.82	9.09	1.72	0.069
C3	2.79	1.84	13.50	1.48	0.061
C4	2.80	1.85	16.10	1.56	0.065
C5	2.83	1.75	19.80	1.71	0.051
C6	2.78	1.79	23.90	1.60	0.063

C7	**2.77**	**1.85**	**30.40**	**1.59**	**0.067**
C8	**2.91**	**1.83**	**34.70**	**1.39**	**0.062**

2.2 Tensile Test

Tensile properties were obtained from round specimens. Fig (2) shows the dimensions of a tensile specimen machined in accordance with ASTM-E8-2007[8]. Tensile test was performed on a computerised Instron universal testing machine .From each different %CE for each group, three tensile specimens were tested and the average results were taken. Tensile tests were performed at room temperature of (20°C) at a strain rate equal to $5.33 \times 10^{-5}\ s^{-1}$ up to fracture.

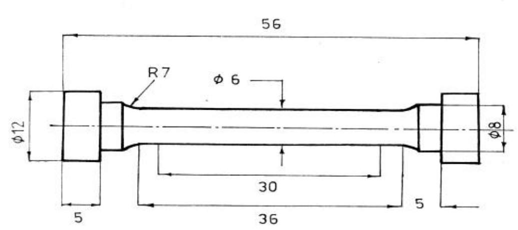


Fig 2 Dimension of the Tensile Test Specimen

2.3 Hardness Test

Hardness test was performed for each %CE. Three specimen for each from each CE% were tested by Equotip proceq Leeb rebound hardness tester shown in Fig (3).Each specimen was tested for leeb rebound hardness by taken ten measurements, for each group 24 sample was tested, total of 72 samples for the three groups .The test was done at 23 ºC .t

Fig (3) Rebound Hardness Tester

4. Statistical Analysis

4.1-The GRUBBS method

This method proposed for rejecting abnormal experimental data[9], in engineering experimentation a situation arises of obtaining a set of data in which one or more observations should be retained or rejected as being faulty

-The experimental data were arranged in increasing order: $x_1 < x_2 < x_3 < \ldots < x_{n-1} < x_n$

Where n is the sample size .

$$v^2 = \sum_{i=1}^{n}(x_i - \bar{x})2 \qquad (1)$$

$$v_1^2 = \sum_{i=1}^{n}(x_i - \bar{x}_1)2 \qquad (2)$$

$$v_n^2 = \sum_{i=1}^{n-1}(x_i - \bar{x}_n)2 \qquad (3)$$

If x_n is the suspect value, then the value v_n^2/v^2 was calculated. If this value is less than those in table of criteria for rejecting suspect observations (grubbs method) [9]

4.2-Normality Test (Shapiro-Wilk) test:

In mathematical statistics, normality tests are used to determine whether a data set can be modeled by normal distribution or not[10]. The importance of the normality tests concerning the tensile, and rebound hardness results can be understood since normality is an underlying assumption of many statistical procedures.

To see if the probability distribution of the rebound and tensile strength readings set of an individual test area can be described by normal distribution or not, the Shapiro-Wilk normality test was run on each population.

$$W = \frac{\left(\sum_{i=1}^{n} a_i x_{(i)}\right)^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \qquad (4)$$

Where:

X (i) (with parentheses enclosing the subscript index *i*) is the *i*th order statistic, i.e., the *i*th-smallest number in the sample.

a_i is constant given by table

The null-hypothesis of this test is that the population is normally distributed. Thus, if the *p*-value from Shapiro wilk [10] tables is less than the chosen, then the null hypothesis is rejected and there is evidence that the data tested are not from a normally distributed population; in other words, the data are not normal. On the contrary, if the *p*-value is greater than the chosen alpha level, then the null hypothesis that the data came from a normally distributed population cannot be rejected (e.g., for an alpha level of 0.05, a data set with a *p*-value of 0.02 rejects the null hypothesis that the data are from a normally distributed population). However, since the test is biased by sample size, the test may be statistically significant from a normal distribution in any large samples

5-Results and Discussion

5.1 Hardness Results:

The hardness test results are shown in table (5-7) for three material groups

Table 5: Rebound hardness of Group A

Heat No	A1	A2	A3	A4	A5	A6	A7	A8
%CE	3.51	3.69	3.91	4.1	4.34	4.55	4.67	5.04
	502	482	591	517	454	446	552	476
	508	490	553	524	464	460	551	470
	499	507	555	510	462	460	515	476
	512	499	562	484	471	453	505	469
	496	511	552	516	446	452	553	477
	504	499	599	515	457	461	559	468
	489	513	533	524	448	473	568	472
	485	500	562	489	452	461	557	471
	482	540	607	505	458	459	524	477
	558	521	553	507	456	459	553	471
Avarege	503.5	521	566.7	507	456.8	458.4	543.7	472.7

Table 6 Rebound hardness of group B

Heat No.	B1	B2	B3	B4	B5	B6	B7	B8
%CE	3.86	4	4.16	4.28	4.38	4.46	4.59	4.64
	518	447	468	458	465	467	456	430
	507	442	468	474	474	471	482	429
	509	456	480	463	477	489	481	440
	576	446	457	473	474	476	492	445
	529	447	460	453	487	479	499	430
	649	451	467	460	473	476	493	427
	640	447	452	463	473	472	483	428
	570	460	468	465	470	463	488	450
	573	464	444	463	476	480	474	440
	520	460	467	478	479	475	481	430
Avarege	559.1	452.0	463.1	465.0	474.8	474.8	482.9	434.9

Table 7: Rebound hardness of Group C

Heat No.	C1	C2	C3	C4	C5	C6	C7	C8
%CE	3.7	3.79	3.9	4	4.15	4.26	4.49	4.48
	620	615	502	441	464	425	411	452
	630	630	532	446	475	429	440	441
	635	589	511	468	441	421	451	442
	625	580	484	471	420	422	443	465
	600	617	488	459	446	439	455	454
	613	618	500	461	470	416	454	445
	599	624	509	471	440	417	460	456
	630	625	513	461	445	420	435	446
	625	620	520	460	469	419	442	460
	629	590	500	469	450	420	443	450
Average	620.60	610.80	505.90	460.70	452.00	422.80	443.40	451.10

The range of leeb rebound hardness of group A is between 456, and 567 HLD , for group B is from 452, to 559 HLD, and for group C is from 422, to 610 HLD.

5.2Tensile Test Results:

Tables (8-10) shows the results of the tensile test for the three groups

Table 8 Tensile test result of group A

Sample No.	A1	A2	A3	A4	A5	A6	A7	A8
UTS 1(Mpa)	530	520	445	470	450	481	440	390
UTS 2(Mpa)	515	511	432	458	442	476	438	382
UTS 3(Mpa)	512	490	415	454	431	469	432	374
Average (Mpa)	519	507	431	461	441	475	437	382

Table 9 Tensile test result of group B

Sample No.	B1	B2	B3	B4	B5	B6	B7	B8
UTS 1(Mpa)	509	513	501	504	510	470	435	425
UTS 2(Mpa)	492	510	494	499	495	463	433	420
UTS 3(Mpa)	485	498	490	499	489	455	424	415
Average (Mpa)	495	507	431	496	498	463	431	420

Table 10 Tensile test result of group C

Sample No.	C1	C2	C3	C4	C5	C6	C7	C8
UTS 1(Mpa)	641	582	510	499	461	348	354	334
UTS 2(Mpa)	634	573	497	494	459	342	349	328
UTS 3(Mpa)	625	564	483	487	451	336	345	320
Average (Mpa)	633	573	497	493	457	342	349	327

From the above results it is found that for group A, by increasing the tensile strength from 381 to 505 , the rebound hardness is increased also from 456 to 567, which mean that by increasing the tensile strength by 32%, the leeb rebound hardness is increased by 24.3%, for group B the tensile strength is increased from 420 to 507 Mpa, and the leeb rebound increased from 435 to 559 HLD which indicates that by increasing the tensile strength by 20.7%, the leeb rebound is increased by 28.5%, and for group C the leeb rebound hardness is increased from 422 to 620 HLD by increasing the tensile strength from 327 to 633 Mpa, which means that by increasing the tensile strength by 93.3% , the leeb rebound is increased by 46.9%.

5.3Statistical Analysis Results:

5.3.1Grubbs Method

Table 11 Grubbs method results for group A

Heat No	Suspect values		v_n^2/v^2		Critical values at confidence level 95%	Result	
	min	max	min	max		min	max
A1	482	558	0.877	0.205	0.4154	not reject	Reject
A2	482	540	0.73	0.475	0.4154	not reject	not reject
A3	533	607	0.76	0.65	0.4154	not reject	not reject
A4	484	524	0.57	0.85	0.4154	not reject	not reject
A5	446	471	0.74	0.558	0.4154	not reject	not reject
A6	446	473	0.62	0.667	0.4154	not reject	not reject
A7	505	568	0.58	0.836	0.4154	not reject	not reject
A8	468	477	0.77	0.809	0.4154	not reject	not reject

Table 12 Grubbs method results for group B

Heat No	Suspect values		v_n^2/v^2		Critical values at confidence level 95%	Result	
	min	max	min	max		min	max
B1	507	649	0.87	0.63	0.4154	not reject	not reject
B2	442	464	0.77	0.68	0.4154	not reject	not reject
B3	444	480	0.56	0.65	0.4154	not reject	not reject
B4	453	478	0.71	0.65	0.4154	not reject	not reject
B5	465	487	0.64	0.44	0.4154	not reject	not reject
B6	463	489	0.67	0.52	0.4154	not reject	not reject
B7	456	499	0.37	0.78	0.4154	Reject	not reject
B8	427	477	0.88	0.81	0.4154	not reject	not reject

Table 13 Grubbs method results for group C

Heat No	Suspect values		v_n^2/v^2		Critical values at confidence level 95%	Result	
	min	max	min	max		min	max
C1	599	635	0.64	0.84	0.4154	not reject	not reject
C2	580	590	0.62	0.83	0.4154	not reject	not reject
C3	484	532	0.71	0.59	0.4154	not reject	not reject
C4	441	471	0.54	0.87	0.4154	not reject	not reject
C5	420	475	0.57	0.77	0.4154	not reject	not reject
C6	416	439	0.88	0.31	0.4154	not reject	Reject
C7	411	460	0.32	0.82	0.4154	Reject	not reject
C8	441	465	0.79	0.61	0.4154	not reject	not reject

From the previous results, it was found that the value of v_n^2/v^2 is greater than the critical value at confidence level 95%, except for specimens A1, B7, C6 and C7. So these four readings 558, 456, 439 and 411 must be **rejected**

5.3.2Shapiro-Wilk normality test Results:

The results of Shapiro-Wilk normality test show that, for three groups all the results follow normal distribution.

5.4 Regression Analysis

Fig (4) shows the relation between rebound hardness and tensile strength of the austenitic ductile cast iron , the best fit equation is second degree polynomial equation 5

$$y = -0.00009x^2 + 1.9046x - 231.39 \quad (5)$$

THE REGRESSION COEFFICIENT R=0.89

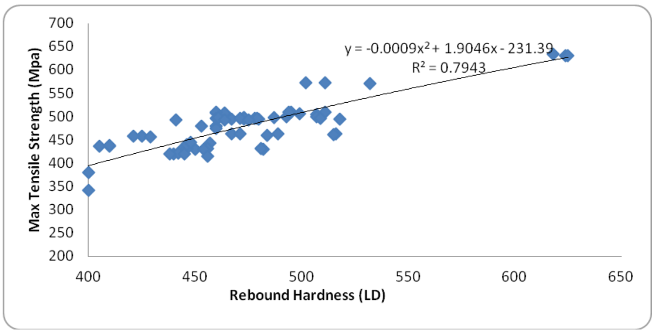


Fig (1) The relation between rebound hardness and tensile strength

The error between measured and calculated (from proposed equation 5) was measured as shown in table 14

Table 14 Curve fitting deviation from the average values

Sample name	Measured Tensile strength value	Calculated Tensile strength value	Error %
A1	505.0	507.1	-0.42
A2	506.0	519.9	-2.75
A3	430.0	454.0	-5.58
A4	461.0	519.2	-12.62
A5	441.0	458.2	-3.90
A6	478.0	466.5	2.41
A7	437.0	409.7	6.25
A8	382.0	392.0	-2.63
B1	498	526.1	-5.64
B2	508	470.6	7.35
B3	497	479.3	3.57
B4	496	487.9	1.64
B5	498	489.0	1.81
B6	463	486.7	-5.13
B7	431	483.8	-12.24
B8	420	446.4	-6.28
C1	631	642.0	-1.75
C2	572	530.1	7.33
C3	497	474.0	4.62
C4	493	469.1	4.84
C5	457	429.1	6.11
C6	342	390.1	-14.05
C7	422	459.7	-8.93
C8	327	336.7	-2.98

It was shown that the max error is 14%, only for sample C6, 75% from the readings have error less than 7%.

6. Conclusion

1. The leeb rebound hardness is on-site testing method for evaluating the hardness of large pieces of equipment and structures that are difficult to test with a stationary hardness tester.
2. The tensile test is a destructive test and it is not possible to use it to test large pieces, and products.
3. The relation between tensile strength, and leeb rebound hardness was studied experimentally on austenitic ductile cast iron, to find equation express this relation.
4. The best fitting equation which express the relation between tensile strength , and leeb rebound hardness for austenitic ductile cast iron is second degree polynomial equation with R=0.888 .
5. The equation is $y = -0.00009x^2 + 1.9046x - 231.39$, where y is the tensile strength, and x is leeb rebound hardness.

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