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A new prediction of the fatigue limit based on Brinell hardness and ultimate strength for high strength steels

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Abstract
Estimation of the fatigue limit based on the S-N curve means required many experimental tests; furthermore this required more time and high costs. In this study, several high strength materials of steels with their chemical composition, uniaxial mechanical properties, and fatigue limit are listed from previous studies. It was found that Brinell hardness numbers and mechanical uniaxial properties show a linear behaviour in relation to the fatigue limit of the materials were estimated. Correlations between fatigue limit and uniaxial properties were then investigated. Validity of the proposed correlation is examined and compared with other materials proposed and studied by the ASM international. Empirical correlations are founded that enable the evaluation of fatigue limits from the uniaxial properties. The proposed correlation was shown to provide a good reasonable approximations of the materials fatigue limit prediction for the selected materials.

Keywords: Fatigue limit prediction; Steels; Correlation; Brinell hardness; Ultimate strength.

1. Introduction

In industry, Most of the mechanical components undergo cyclic loadings which incite damage to material due to failure fatigue cracking mechanism; therefore fatigue characteristics of a materials are of extreme significance to the engineers of design. The materials selection is considered on the fatigue properties that are conducted in the laboratory by experiments, or the materials performance in operational conditions. A delegate number of trials are required in order to carry out laboratory experiments, which obviously increase the costs and time. Many efforts have been made by researchers to improve the correlations between the monotonic tensile characteristics and materials fatigue properties. These relationships are desirable, taking into consideration the time amount and the effort that necessary to achieve the characteristics of fatigue properties, related to the monotonic uniaxial tensile properties. The relationships between the properties of monotonic tensile and fatigue characteristics controlled by the constant strain have been investigated for the most commonly used steel types in the industry by Roessle and Fatemi, [1]. It suggests a method needing only the hardness and the elasticity modulus to evaluation the S-N behavior. The predictability of this procedure is assessed for a steels with a hardness ranging from 150 to 700 HP and related with a number of other methods suggested by others in literature. The method that suggested was presented to afford a good approximation of the S-N curve. Pavlina and Van, [2], provided a correlations to approximate the properties of the monotonic axial tensile strength of steel based on the hardness measurements of the bulk of steel covering such a large scale. The regression examination was used to determine the yield and tensile strength correlation of the values of the pyramid hardness to these steels. The aim of the study was to afford a relationships for estimating the yield and tensile strength based on bulk of hardness measurements.

In the structures are subject to heavy cyclic load, fatigue damage of materials, when plastic, is one of the most common failure mechanisms. Kunc and Prebil [3] described the elastic - plastic response of substances under cyclic load using the cumulative microstructure model of small deformities. The process of determining all physical properties of steel {42CrMo4 (ESO 683/1)} has been demonstrated in normalization with a hardness of 195HV and tempered with a hardness of 462HV, using the described material model. Also, Pavol and Ladislav, [4], found a correlation between simple hardness properties with a fatigue life respecting the hardening and softening states. The experimental materials have been selected from API 5L grade steels after different deformation expositions. Selection of materials in the industry that operates under high periodic load depend on fatigue tests conducted in the research laboratory, performance in operational conditions, or literature recommendations. In order to perform laboratory tests, many trials are needed, which obviously increases costs.

Martinez et al. [5], investigation was conducted to find a relationship between the toughness and the fatigue behavior of steels utmost usually used in the fabrication. The predicted correlation was adjusted to calculate the fatigue strength depend on the hardness of the charpy toughness, yield strength, ultimate strength, and material hardness. The conducted relationship shows fit very well with the data of the experimental fatigue. Casagrande et al. [6], estimated a good relationship between the hardness (Vickers) and the endurance fatigue. The limits of the fatigue for a four kinds of steels in a many different states (annealed, quenched and quenched/tempered) were calculated in different two methods, and the results were examined with the experimental values. A relationship between the Vickers number hardness and the estimated fatigue limits was appraised by measurements of the direct plastic deformation area, using an optical microscope. Several approaches have been suggested to evaluate the life strain curves of the tensile or stiffness data. Several methods have been discussed to evaluation the fatigue properties of hardness by Lee and Song [7]. Methods suggested, were applied successfully to evaluation the fatigue properties for aluminum alloys and titanium alloys. A new relationship of ultimate tensile strength with the hardness has been suggested for titanium alloys.

The main work of Gasko and Rosenberg, [8], was to review the possibilities of applying the interrelationships between the final tensile strength and the hardness of steel sheets in various structural situations. Experiments were carried out on advanced steels with structures consisting of ferrite and martensite. The present investigation developed a new correlation to predict the fatigue limit based on uniaxial properties, Brinell hardness number and the ultimate uniaxial tensile strength. Materials selected from the study of Roessle and Fatemi, [1], and Martínez et al. [5], to verifying the estimated correlation, the aim of the study was to seek and improve a procedure of prediction that allow computing the material properties under the circumstances of fatigue, through conducting tests for a short duration at low-costs.

2. Experimental materials

There are many researchers who have conducted experiments on various types of steel, where the use of these experiments in this research by knowing the mechanical properties of these materials. In the investigation of Roessle and Fatemi [1], find deformation controlled by strain and properties of fatigue for twenty steels normally used in the automotive manufacturing. The materials that used in the study were SAE 1141, SAE 1038, SAE 1541, SAE 1050, and SAE 1090 steels. Test methods identified by the ASTM Standard E8, [9] were conducted in the uniaxial tension tests. All strain amplitude fatigue tests were conducted permitting to the ASTM Standard E606, [10]. Table 1 shows the summary of the materials and properties that were studied, including material identification, endurance limit, ultimate strength, and Brinell hardness.

Moreover, Martínez et al., [5] studied the toughness of impact and the fatigue behavior of steels most normally employed in the industry. The steels tested were of the steel families AISI-SAE 4330M (chromium- molybdenum-nickel- M1, M2), 4138M (chromium-molybdenum steel-M3, M4), and 4140 (chromium molybdenum steel-M5).

Tensile stress tests, hardness and impact were performed with the aim of finding out the properties of the yield strength, ultimate tensile strength, Brinell hardness, elongation, and values of the absorbed energy. These experimental tests were carried out according to the specifications of ASTM A 370 [11]; Table 2 illustrates the results of the experiments. Fatigue tests were accompanied under the specifications of the ASTM E 739-91[12].

Table 1. Mechanical properties of the materials, Roessle and Fatemi [1].

Material / processing condition/ grain type	Brinell hardness	Ultimate strength, MPa	fatigue limit, MPa
SAE 1141 (AlFG), Normalized at 1650 °F, ferrite-pearlite	223	771	286
SAE 1141 (AlFG) Reheat, Q and T martensite	277	925	433
SAE 1141 (NbFG) Normalized at 1650 °F ferrite-pearlite	199	695	276
SAE 1141 (NbFG) Reheat, Q and T martensite	241	802	342
SAE 1141 (VFG) Normalized at 1650 °F ferrite-pearlite	217	725	287
SAE 1141 (VFG) Reheat, Q and T martensite	252	797	332
SAE 1141 (VFG) Normalized at 1750 °F ferrite-pearlite	229	789	296
SAE 1038 Normalized at 1650 °F ferrite-pearlite	163	582	222
SAE 1038 Cold size-form ferrite/pearlite	185	652	241
SAE 1038 Reheat, Q and T ferrite/spher., pearlite	195	649	248
SAE 1541 Normalized at 1650 °F ferrite-pearlite 180	180	783	228
SAE 1541 Cold size/form ferrite-pearlite	195	906	315
SAE 1050(M) Normalized at 1650 °F ferrite-pearlite	205	821	159
SAE 1050(M) Hot forge, cold extrude ferrite (ferrite)	220	829	369
SAE 1050(M) Induction through- hardened martensite	536	2360	717
SAE 1090 Normalized at 1650 °F pearlite	259	1090	350
SAE 1090(M) Hot form, accelerated cool pearlite-martensite	357	1388	417
SAE 1090 Hot form, Q and T martensite	309	1147	328
SAE 1090 Hot form, bainite	279	1251	337
SAE 1090(M) Hot form, accelerated cool pearlite/martensite	272	1124	401

Table 2. Mechanical properties of the materials, Martínez et al. [5].

Material	Brinell hardness	Ultimate strength Mean value, MPa	Fatigue limit, MPa
M1	336	1064	441
M2	321	976	403
M3	287	917	352
M4	312	1018	383
M5	245	795	310

All data of the materials that were listed in the Tables 1&2 will be considered in this study to assist in finding the correlation between the limits of fatigue and the mechanical properties, ultimate uniaxial tensile strength and Brinell hardness.

3. Theoretical approach

Sampling failure was clarified as the limit at which the upper limit load was reduced by about 50% due to cracks presented, as suggested by the ASTM Standard E606, [10].

This is related on the statement that an rise in the toughness of the materials have a tendency to to reduce the opportunity of the beginning and the spreading rate of cracks. Once a crack begin to grow an deformation area surround the crack tip increases the cycles number needed for the starting and spread, consequently the material fatigue properties of the material is increased. As has been distinguished in the introduction, there are a total of estimation techniques; Roessl and Fatemi's method, [1], provides relatively good results for steels. It was found that a least squares fit over the data with a correlation coefficient [13] R^2 equal to 0.91 results in the resulting relationship, see Figure 1

$$S_f = 1.43\,HB \tag{1}$$

For the steels with hardness lower than 500 HB, the correlation coefficient was employed between the results of Eq. (1) and the experimental fatigue limit.

Stephens et al., [14] have concluded that the fatigue limit was a constant value and the reason was thought to be because of the inclusions role. Roessle and Fatemi provided a plot for the fatigue limit vs. the ultimate tensile strength; see Figure 2, for high strength steels. It has been concluded that the fatigue limit approach was highly related with the dimension and diffusion of inclusions and other impurities.

A fit over data with ultimate tensile of S_u less than of equal1400 MPa were estimated to be correspondent. Therefore, the correlation coefficient of $R^2=0.86$ was founded as follows:

$$S_f = 0.38\,S_u \tag{2}$$

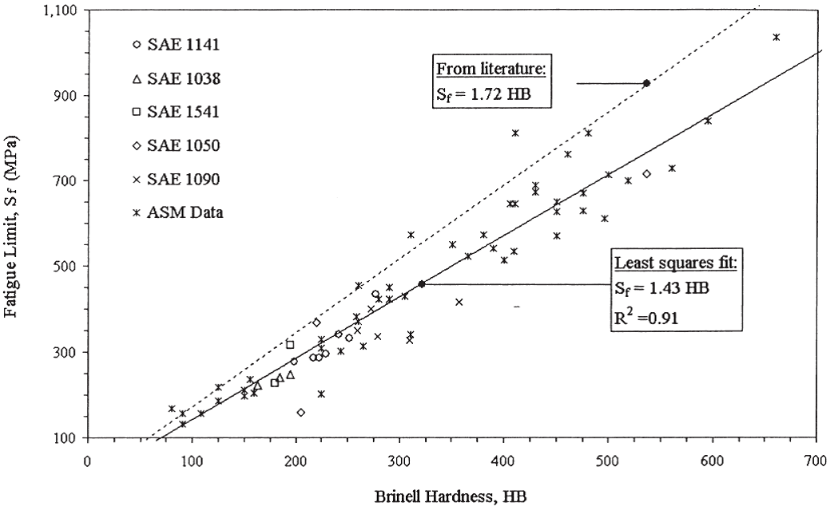


Figure 1. Fatigue limit vs. Brinell hardness [1].

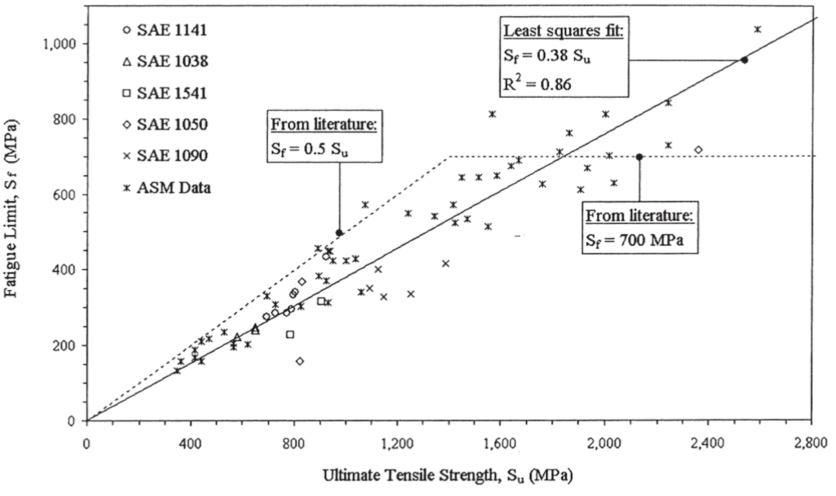


Figure 2. Fatigue limit vs. ultimate tensile strength, [1].

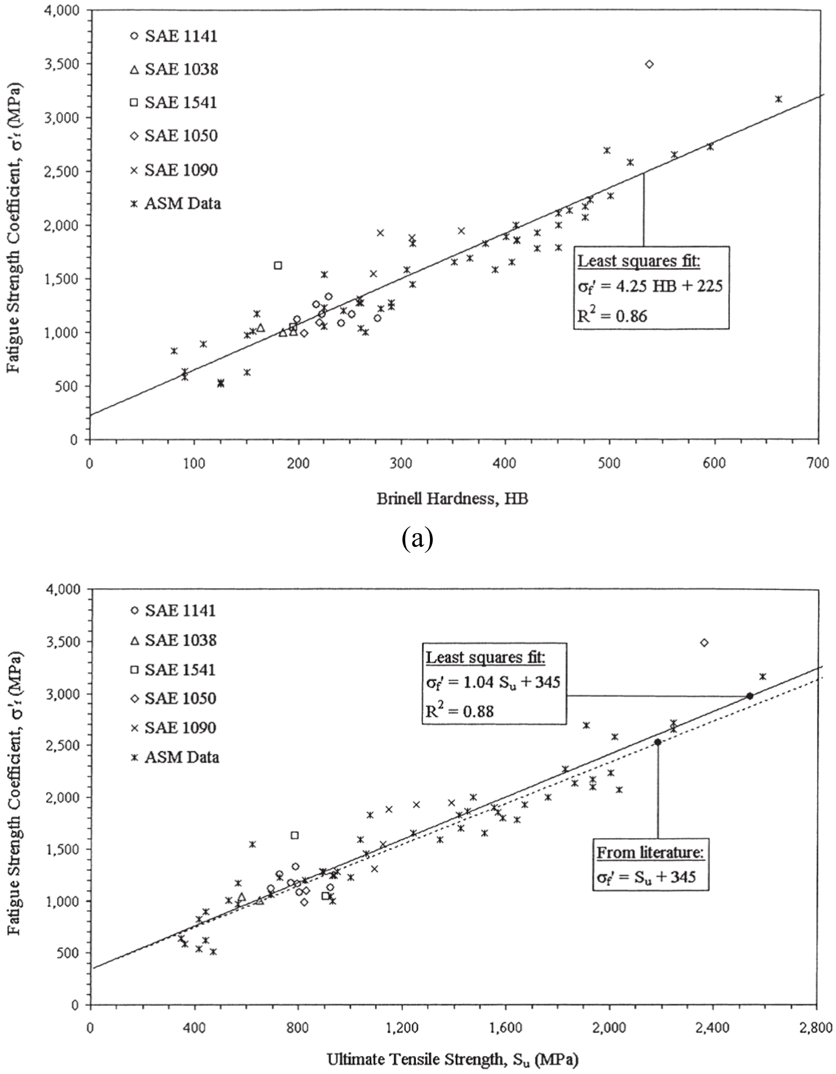
Moreover, the coefficient of the fatigue strength, S'_f, has been found to be more related with the Brinell hardness and uniaxial tensile ultimate strength of the steel as indicated on the figures of fatigue strength coefficient with the number of Brinell hardness and ultimate strength, Figure 3 (a and b). These figures show reasonably good least squares fits for the data, described by:

$$S'_f = 4.25\,HB + 225 \tag{3a}$$

$$S'_f = 1.04\,HB + 345 \tag{3b}$$

The fatigue limit was calculated from Basquin's equation, by means of $N_f=10^6$ cycles

$$\frac{\Delta S}{2} = S'_f(2N_f)^b \tag{4}$$



(a)

(b)

Figure 3. (a) Coefficients of the fatigue strength with Brinell hardness, (b) Fatigue strength coefficients with ultimate tensile strength, [1].

Martínez et al., [5] obtained a relationship between the impact material toughness and the fatigue properties of the fatigue of steels mainly usually used. The steels tested by Alexander Martínez et al. were the steels AISI-SAE 4330M (M1, M2), 4138M (M3, M4) and 4140 (M5) with different heat treatments (normalized and tempered, tempered and quenched). Tests were conducted to determine the chemical composition, impact Charpy test, and evaluated mechanical strength of the materials. Depend on the data founded, equations were cleared that relate the fatigue limit for these steels to their monotonic mechanical properties and to the impact energy value that found in the Charpy test.
The equations calculated were as follows:

$$\begin{aligned} S_f &= 0.17\,CVN + 2.59\,HB - 041\,S_u\,, with\ R = 95\% \\ S_f &= 0.13\,CVN + 7.49\,C_p + 0.37\,S_u\,, with\ R = 90\% \\ S_f &= 1.35\,CVN - 791.03\,S_y/S_u + 3.27\,HB\,, with\ R = 97\% \end{aligned} \tag{5}$$

where: Cp= Chemical composition (the sum of the percentage of alloying elements C+Mn+Ni+Cr+Mo+ V+Nb), Su= Ultimate tensile strength (Mpa), Sy=Yield strength (Mpa), CVN= Impact Charpy toughness (Joules), Sf= Fatigue limit (Mpa).

It can be observe from these equations that the good effects were found in the values of the hardness, material toughness, and in the summation of the elements of alloying percentages: (C+Mn+Ni+Cr+Mo +V+Nb) in the steel, which try to rise the performance of the material properties and fatigue, preferring, in addition, the value of impact toughness.

4. Results and discussion

A new correlation of the fatigue limit is proposed for the high strength steels. This correlation funded from a careful reference of previous studies with considerations of limiting the mechanical properties adopted. A results analysis was used to determine the relationship of the fatigue limit based on the tensile ultimate strength and Brinell hardness values from the data given in the investigations of researchers [1, 5], which were listed in Tables 1 and 2.

These data were then used to analyze the relationship between many various monotonic and fatigue properties. In terms of fatigue behavior, there was a direct correlation between the value of the fatigue limit and the mechanical properties found in this study, which was a linear best fit through the data with a correlation coefficient of R=92% that can be written as:

$$S_f = 1.3\,HB + 0.02\,\sigma_u \tag{6}$$

Figure 4 shows the regression data related the predicted fatigue limit, Eq. (6) and the experimental fatigue limit for the steels which their mechanical properties are listed in the Table 1 and Table 2. It can be concluded that the estimated correlation gives a reasonable results of prediction for the fatigue limit. The steels in the figure have a Brinell hardness numbers were enclosed by 163-536.

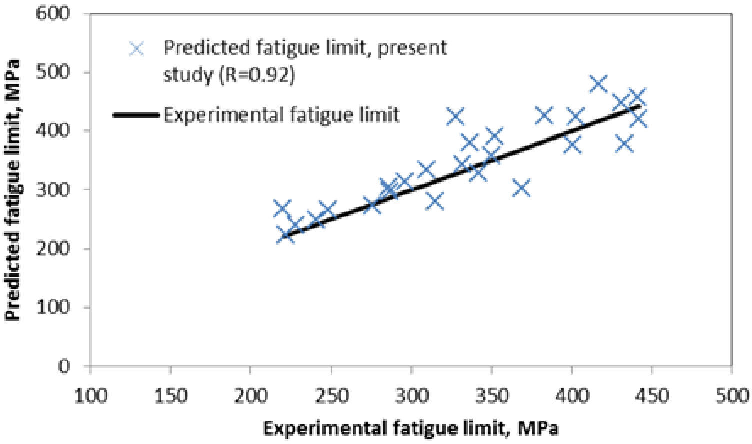


Figure 4. Prediction of the fatigue limit by the proposed method.

The correlation coefficient of the best prediction, Eq. (6), is found to be = 92%. Eq. (1) and Eq. (2) were employed for the materials have a mechanical properties are listed in Table 1 which then give a correlation coefficient of R= 95% and R= 93% respectively. Furthermore by employing Eq. (3a) and Eq. (3b) with Eq. (4) on the materials listed in Table 2, the resulting data of the fatigue limit give a correlation coefficients of R=91% and R=88% respectively. Table 3 shows and compares the correlation coefficients between the resulting data for a comparison, Eq. (6) found in the present study, gave a good convergence for all the data listed in Tables 1 and 2.

Eq. (6) is the best prediction for the fatigue limit based on Brinell hardness and the ultimate tensile only for the selected materials. The effect of the chemical composition and the impact toughness, which have been considered in [5], are considered to include the Brinell number and the ultimate tensile strength of the steels. Eq. (6) can predict the fatigue limit for the steels, which depend on Brinell hardness and ultimate fatigue limit only. The concept of finding a prediction equation for fatigue limit was considered by many researchers. Casagrande et al. [6] estimated a good correlation of the fatigue limit based on Vickers hardness only, while in this study, the prediction equation takes into account the Brinell hardness and the ultimate strength. Also, relationships between the materials fatigue limit and the ultimate strength appeared weak, as concluded in [1] while in this study a strong relationship exists has been estimated between Brinell hardness and the ultimate strength with the fatigue limit.

Table 3. Correlation coefficients.

Equation employed	Data	R %
Eq.(1), Roessle and Fatmi	Roessle and Fatmi study, Table 1	95
	Martinez et al. study, Table 2	91
Eq. (2), Roessle and Fatmi	Roessle and Fatmi, Table 1	93
	Martinez et al. study, Table 2	88
Eq. (3a) and Eq. (4), Roessle and Fatmi	Martinez et al. study, Table 2	91
Eq. (3b) and Eq. (4), Roessle and Fatmi	Martinez et al. study, Table 2	88
Eq. (6), present study	Table 1 And Table 2	92

The predicted correlation, Eq. (6), has been employed for other types of steels to verify the validity and accuracy of the estimated correlation equation obtained in this investigation. These types of steels were investigated by ASM international, [15]. Table 4 presents the results obtained considering the correlation evaluated. Figure 5 shows the regression data between the predicted and the experimental values of the fatigue limit for the steels that were investigated by ASM international. It is shown that the predicted equation has an approximate intermediate position amongst the data, and it has shown a close fit compared with the values obtained from the experiments with a correlation coefficient of R=0.82. Figure 5 is developed from a careful study of the previous predicted correlation with the goal of a fatigue limit.

The predicted correlation equation gave a small amount of scatter in the data. As can be found from Table 5 and by comparing the experimental fatigue limit with the predicted value, the predicted equation has a reasonable agreement with the results and is conventional for the steels that were selected in this study.

Table 4. Mechanical properties of the materials investigated by ASM international, [15].

SAE steel grade	Brinell hardness	Ultimate strength (MPa)	Fatigue limit (MPa)
1045	390	1343	509.953
1045	450	1584	705.985
1045	500	1825	678.228
1045	595	2240	714.117
4142	380	1412	570.150
4142	450	1757	631.864

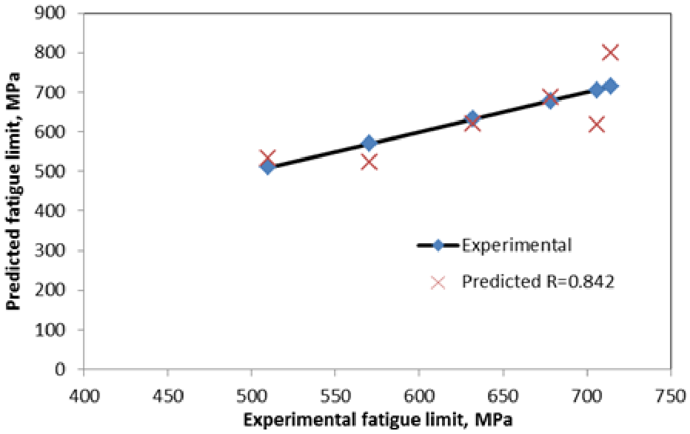


Figure 5. Verifying the estimated prediction of the fatigue limit by the proposed method.

Table 5. Comparison between experimental and predicted fatigue limits.

Experimental fatigue limit (MPa), ASM [15]	Predicted fatigue limit (MPa), present investigation
509.953	533.86
705.985	616.68
678.228	686.50
714.117	818.30
570.150	522.24
631.864	620.14

5. Conclusions

Comparing of the results that calculated and listed in Tables 3&5, the main conclusions can be given as below:

1- Correlations coefficient related the limit of fatigue and ultimate tensile appeared weak [1], while in this study a strong relationship be present related the Brinell hardness, ultimate tensile with the fatigue limit of steels has been estimated.
2- The estimated correlations allow for limitation of performance to the fatigue, based on very low rate tests, associated to the required to achieve a fatigue test.
3- Verifying the predicted fatigue limit equation, Eq. (6), for the selected materials shows a reasonable agreement and is more conservative for most of the steels that were selected.
4- The estimated correlation coefficients show good and acceptable results for the predicted equation, as seen in Table 3. Also, the equation gives a small amount of scatter in the data for the steels that were investigated by ASM international, see Table. 5.

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