Fatigue Limit Prediction Based on Hardness for Both Steel and Aluminum Alloys

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Abstract: The values of the fatigue limit of the substance represent how resistant it is to the worst of all that this material was Ferrous and non-ferrous. The values of this limitation can be inferred by creating a Wohler curve (S-N curve) is called and requires testing many samples that require a long time and a great effort to reach the final result. This research has created two athletic models for steel and aluminum alloys, without the need to create the Wohler curve (S-N curve) for these alloys. The two proposed models are (Fatigue limit = 1.30 x Steel Hardness (BH) for steel alloys) and (Fatigue limit = 1.85 x Aluminum Hardness (BH) for Al-alloys). The results obtained from these two models were compared with the results of the Heller curve for steel alloy (HRB400) and aluminum alloy (AA2017) by following the method of rotational bending loading and this comparison showed a very reasonable result. The results were also compared with results extracted from previous models, and it was found that the previous models gave a less accurate fatigue limit compared to the Wohler curve.

Keywords: Fatigue limit, steel alloy, Aluminum alloy, Brinell hardness, S-N Curve

1. Introduction
Finding the fatigue limit is a very important factor because it determines the permissible potential effort at which failure of the substance does not occur, and the fatigue limit is usually defined as the value of periodic stress applied to the material that cannot be caused by the values of the minimum stress of fracture or failure in this material. The steel alloy (HRB400) is a kind of low carbon steel and has been widely used in concrete bridges, which is also corresponding to Grade 60 steel bar in ASTM A615[1]. Aluminum alloy (AA 2017) was the first developed in the Al-Cu-Mg series, that used in chiefly in Aerospace components, structural applications in transportation and construction, machine products, screw, and fittings. This alloy has general characteristics as medium strength and ductility, good machinability, good formability, and fair resistance to atmospheric corrosion. In the aircraft industry, Fatigue limit for material used in the airframe industry, the nature of the aircraft's operation and its maneuvering limits should be taken into account, as well as the aerodynamic design of the wings and the tail group that bear significant stresses during the flight [2]. Przemysław and Janusz, 2016 [3]. The study presents two approaches to plotting an S-N curve based on the experimental results. The first approach is commonly used by researchers and presented in detail in many studies and standard documents. The model uses a linear regression whose parameters are estimated by using the least squares method. A staircase method is used for an unlimited fatigue life criterion. The second model combines the S-N curve defined as a straight line and the record of random occurrence of the fatigue limit. A maximum likelihood method is used to estimate the S-N curve parameters. The result gives good approximation, especially regarding the time required to plot the S-N curve.
Przemyslaw and Tomasz, 2017 [4], to calculate fatigue life in high-cycle region, the S-N characteristics for the material or construction element (depending on the calculation model employed) must be obtained. Due to this, analytical models are used for estimating the S-N fatigue curve. Since these methods bear significant error, hybrid models based on experimental data from hardness measurements were developed. Such evaluation is easy to perform, quick, and, most importantly, is a non-destructive examination. The paper presents two models for evaluating high-cycle fatigue characteristics, one of which is an own model. Both of these approaches are based on hardness measurement, and employ the relationship between hardness and tensile strength & fatigue limit. Kittima et al., 2017 [5] overall fatigue strengths and hardness distributions of the aluminum alloy similar and dissimilar friction stir welding (FSW) joints were determined. The local fatigue strengths as well as local tensile strengths were also obtained by using small round bar specimens extracted from specific locations, the relationship between fatigue strength and hardness for aluminum alloys was investigated based on the present experimental results and the available wide range of data from the references, to estimate the fatigue strengths of aluminum alloy FSW joints from the hardness measurements. It was also confirmed that the estimated fatigue strengths were in good agreement with the experimental results for aluminum alloy FSW joints.

Azzam, 2018[6] Estimation of the fatigue limit based on the S-N curve means required many experimental tests; It was found that Brinell hardness numbers and mechanical uniaxial properties show a linear behavior in relation to the fatigue limit of the materials were estimated. The proposed correlation was shown to provide a good reasonable approximations of the materials fatigue limit prediction for the selected materials.

Miloslav, 2018 [7], the contribution explains a possibility of using design S-N curves and design stress spectra for probabilistic fatigue life assessment of vehicle components. The design S-N curves can be considered on the basis of either experiments or using some standards. The design stress spectra can be generated theoretically, but it is more appropriate to derive them from the results of representative stress measurement during the characteristic operation of the vehicle. The resulting fatigue life distribution function is then a probabilistic interpretation of the service fatigue life of the vehicle component under consideration.

Nwokedi et al., 2018 [8], the study assessed the correlation between the tensile strength and hardness of each of steel and aluminum alternative ship hull construction materials in use in ship building in Nigeria shipyards. It also compared the hardness’s of aluminum and steel as well as their tensile strengths. It was found that a perfect strong positive correlation exists between the hardness and tensile strength of both steel and aluminum ship hull material types indicating that the hardness of each material increases as the tensile strength increases. The comparison of the tensile strengths and hardness’s of steel and aluminum materials in use for ship hulls in Nigeria each showed a significant difference in favor of the steel hull.

Telloa et al., 2020 [9], this paper presents a procedure developed to predict the fatigue life in components made of steel, based on the mechanical properties of the base material and Thermally Affected Zones (TAZs) owing to welding. Therefore, it is proposed A criterion for the adjustment of the exponent and the stress stroke of the fatigue life curve in welded joints is proposed in which the parameters that define the alternating stress versus the number of cycles to failure (S-N) curve are obtained exclusively from the ratio between the base material yield stress of a given steel and the strength of its Thermally Affected Zone.

The aim of this research is to rely on the hardness of the material to obtain the fatigue limit for two types of metallic alloys used in the manufacture of aircraft, which are (steel and aluminum) alloys and comparing it with the Wohler curve method, and with some references that have extracted practical mathematical equations to measure the fatigue limit, and this saves the economy in time and cost to obtain quick results.

1. Experimental Details:

2.1 The Specimens:

Each of the steel alloy samples (HRB400) and aluminum alloy (AA 2017) were received with bars and different lengths, and test samples were manufactured by CNC programmed lathe at the
Institute of Technology - Baghdad with the aim of obtaining high accuracy in the form of the sample, and to avoid any errors in the dimensions was performed the process of softening surfaces and obtaining good surface roughness in order to reduce the remaining stresses. Figure 1 shows the dimensions of the sample used in rotational bending tests.

![Figure 1. Fatigue Specimens (ASTM) According to (DIN 50100) Standard Specification [10].](image)

The chemical compositions as shown as in two tables (1&2) for steel alloy and aluminum alloy respectively.

| Table 1. The chemical composition of steel alloy (HRB400) |
|----------------------------------------------------------|
| Wt. % Max. | C | Si | Ni | Cu | Mn | P | Cr | S | V | Fe |
| Standard[11]| 0.16- | 0.4- | 0.01- | 0.02- | 0.14- | 0.01- | 0.01- | 0.03- | Bal. |
| Measured   | 0.17 | 0.41 | 0.02 | 0.03 | 1.42 | 0.01 | 0.02 | 0.01 | 0.04 | Bal. |

| Table 2. Chemical Components of aluminum alloy (AA 2017)|
|-------------------------------------------------------|
| Wt. % Max. | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti | Al |
| Standard [12]| 0.2-0.8 | 0.7 | 3.5-4.5 | 0.4-1 | 0.4-0.8 | 0.1 | 0.25 | 0.15 | Bal. |
| Measured   | 0.44 | 0.25 | 3.8 | 0.68 | 0.56 | 0.1 | 0.2 | 0.1 | Bal. |

2.2 Mechanical Properties
Tables (3&4) gives the mechanical properties of steel alloy (HRB400) and of aluminum alloy (AA 2017) respectively.

| Table 3. Mechanical Properties of steel alloy (HRB400) |
|--------------------------------------------------------|
| Material (HRB400) | UTS (MPa) | YS (MPa) | Elongation % | E (GPa) |
| Standard [13] | 630-650 | 465-495 | 20-23 | 200-210 |
| Measured | 630 | 470 | 21.5 | 206 |

| Table 4. Mechanical Properties of aluminum alloy (AA 2017) |
|----------------------------------------------------------|
| Material (AA2017) | UTS (MPa) | YS (MPa) | Elongation % | E (GPa) |
| Standard [14] | 380-425 | 230-275 | 25-28 | 70-80 |
| Measured | 400 | 265 | 26.3 | 75 |

The above analyses were carried out in the laboratories of the Ministry of Industry and Minerals and the Central Organization for Standardization and Quality Control in Baghdad, Iraq, and the average was taken for at least three readings.
2.3 Fatigue Testing Machine

Avery type 7305 rotary fatigue test was used as shown in figure 2, which works in reversed Bending by loading cyclic stresses of the type rotating bending, which are tension and compression stresses and are often close to practical reality.

![Fatigue Testing Machine (Avery Type 7305)](image1)

Figure 2. The Fatigue Testing Machine (Avery Type 7305)

2.4 Hardness Testing Machine

Use a Brinell Hardness testing and circular samples of the two alloys were examined by Hardness Testing Machine type (AKB-3000) as shown as in figure 4.

![Hardness Testing Machine type (AKB-3000)](image2)

Figure 4. Hardness Testing Machine type (AKB-

3. Experimental Results

3.1 Results of fatigue tests

3.1.1 Steel alloy test results

Wohler concluded the curve of the steel alloy, and the results were as shown in table (3) by charting the relationship between cyclic stresses and the number of cycles leading to fracture of the fatigue sample test, we get the figure 5 which represents the Wohler curve represented by the following equation:

\[ \sigma_f = 608 \times N_f^{-0.058} \]  

(1)

And from this equation we get a fatigue limit of 273 MPa by compensating \( N_f = 10^6 \).
Table 3. The relationship between loading stress and the number of cycles leading to fracture of the fatigue sample test.

| The Sample NO. | Loading Stress (MPa) | Number of Operating Cycles (Nf)*10^3 |
|----------------|----------------------|-------------------------------------|
| 1,2,3          | 400                  | 1.4                                 |
| 4,5,6          | 370                  | 4.2                                 |
| 7,8,9          | 340                  | 21                                  |
| 10,11,12       | 310                  | 100                                 |
| 13,14,15       | 280                  | 700                                 |
| 16,17,18       | 273                  | 1000                                |

3.1.2 Aluminum alloy test results

Results of aluminum fatigue test as shown in Table 4.

Table 4. The relationship between cyclic stress and the number of loading cycles leading to the breakdown of aluminum alloy tested on fatigue.

| The Sample NO. | Loading Stress (MPa) | Number of Operating Cycles (Nf)*10^3 |
|----------------|----------------------|-------------------------------------|
| 1,2,3          | 250                  |                                    |
| 4,5,6          | 225                  | 10                                  |
| 7,8,9          | 200                  | 29                                  |
| 10,11,12       | 175                  | 110                                 |
| 13,14,15       | 150                  | 550                                 |
| 16,17,18       | 142                  | 1000                                |

Figure 6 shows the relationship between cyclic stress and the number of loading cycles that represent the Wohler curve and through it we get the following equation:

$$\sigma_f = 557 \times N_f^{-0.099} \tag{2}$$

And from this equation we get a fatigue limit of 142 MPa by compensating Nf = 10^6.
4. Results of the Hardness measurement of alloys

The hardness of the alloys was measured by the hardness measuring device, the results were recorded for ten readings for each alloy, and then the average was taken, and the results were as follows:

| Metal       | Hardness (BH) | Applied force (kg) |
|-------------|---------------|--------------------|
| SA HRB400   | 217           | 750                |
| AA 2017     | 80            | 500                |

4.1 Previous Results

The results of the hardness test and the fatigue limit collected for different types of carbon steel alloys from different references as shown in Table (6).

| Reference     | Fatigue Limit (MPa) | Hardness (HB) | Reference |
|---------------|---------------------|---------------|-----------|
| AISI 1040 Carbon Steel | 165                | 127           | 20        |
| AISI 1050 Medium Carbon Steel CK45 | 212                | 163           | 19        |
| 0.14C% Hypo-Peristatic Steel (42CrMo4) | 325                | 250           | 21        |

The results of the hardness test and the fatigue limit collected for different types of aluminum alloys from different references as shown in Table 7.

| Metal            | Hardness (HB) | Fatigue Limit (MPa) | Reference |
|------------------|---------------|---------------------|-----------|
| AA7075           | 90            | 166                 | 15        |
| AA7021           | 105           | 194                 | 16        |
| AA 2024          | 148           | 273                 | 17        |
| AA 6061          | 165           | 305                 | 18        |
| AA2519-T62       | 204           | 377                 | 20        |
4.2 Accounts and Final Results

4.2.1 Steel Alloy (HRB400)

Through the results listed in Table (6), the relationship between hardness and fatigue limit is illustrated as shown in figure 7 and mathematical equations are extracted as a straight line that passes through most points using the process curve fitting method.

\[ \text{Fatigue limit} = 1.30 \times \text{hardness of steel (BH)} \]  

Figure 7. The relationship between hardness and the fatigue limit for steel alloys

4.2.2 Aluminum Alloy (AA 2017)

Through the results (Table 7) of Aluminum, the following equation was extracted:

\[ \text{Fatigue limit} = 1.85 \times \text{hardness of aluminum (BH)} \]  

As shown in figure 7 below

Figure 7. The relationship between hardness and the fatigue limit for aluminum alloys

4.3 Results comparison

Through the equations 3 and 4 the fatigue limit for both steel and aluminum can be extracted and compared to the practical results that we obtained from the, as follows:
5. Discussion
The aim of the research is to find a mathematical formula that can be used when there is a need to know the limit of fatigue for both steel and aluminum alloys of all types, particularly those used in aircraft manufacturing. Knowing the limit of fatigue of the material makes the engineer who wants to use the material in the field of dynamic movement dominating it variable loads over time knowing the permissible load before starting the projection of the lantern in the projection group, and that the projection is done by the projection group, and that from a dynamic load during flight it focuses on the wingspan of the plane and the tail group and the control surfaces that contain the two search materials. Our focus has been on obtaining mathematical equations with which we obtain a rapid initial estimate of the fatigue limit without referring to the construction of the Wohler Curve which requires more time to construct. The researcher extracted (19) a mathematical relationship to find the limit of fatigue for steel in a rapid manner, namely:

For Steel

\[ \text{Fatigue limit} = 1.75 \times \text{Hardened metal (BH)} \]  \hspace{1cm} (5)

Researcher (21) also extracted a mathematical equation, but it related to aluminum, which:

For Aluminum

\[ \text{Fatigue limit} = 1.60 \times \text{metal hardness (BH)} \]  \hspace{1cm} (6)

Results for comparison of fatigue threshold values are shown in Table (9) below:

| alloys    | Hardness (HB) | Fatigue limit (Wohler curve) (MPa) | Fatigue Limit (Equations) (MPa) |
|-----------|---------------|-----------------------------------|---------------------------------|
| HRB400    | 217           | 273                               | 282                             |
| AA 2017   | 80            | 142                               | 148                             |

6. Conclusions
1. A suggested model for both (steel and aluminum) alloys was obtained through which the fatigue limit for these two metals could be found, by measuring the hardness of the metal (HB) and without referring to the Wohler curve and testing a large group of samples. Using these simple equations above.
2. A Wohler curve can be dispensed only when the fatigue limit is required for the material, and not the life of the material (i.e. the number of loading cycles) is required by knowing the applied fatigue applied to it.
3. As a result of the comparison between the current model and previous models, the current model gave a good estimate compared to the fatigue limit derived from the Wohler curve.

7. References
[1] ASTM. Standard specification for deformed and plain carbon-steel bars for concrete reinforcement. ASTM A615/A615M-09, West Conshohocken, PA; 2009.
[2] AZoM, The state of scientific marketing survey, Aluminum AA 2017 Alloy (UNS A92017), Applications, May 27 2017.
[3] Przemyslaw Strzelecki and Janusz Sempruch, Experimental Method for Plotting S-N Curve With a Small Number of Specimens, Polish Maritime Research 4 (92) 2016 Vol. 23; pp. 129-137, 10.1515/pomr-2016-0079.
[4] Przemyslaw Strzeleckia, and Tomasz Tomaszewskia, Analytical models of the S-N curve based on the hardness of the material, 2 nd International Conference on Structural Integrity, ICSI 2017, 4-7 September 2017, Funchal, Madeira, Portugal.
[5] Kittima Sillapasa , Yoshiharu Mutoh, Yukio Miyashita and Nobushiro Seo, Fatigue Strength Estimation Based on Local Mechanical Properties for Aluminum Alloy FSW Joints, Materials 2017, 10, 186; doi:10.3390/ma10020186.
[6] Hassan, Azzam D. A new prediction of the fatigue limit based on Brinell hardness and ultimate strength for high strength steels. International Journal of Energy and Environment, vol. 9, no. 1, 2018, p. 77+. Gale.
[7] Miloslav Kepka(*), Miloslav Kepka Jr., Using Design S-N Curves And Design Stress Spectra for Probabilistic Fatigue Life Assessment of Vehicle Components, Proceedings IRF2018: 6th International Conference Integrity-Reliability-Failure Lisbon/Portugal 22-26 July 2018.
[8] Nwokedi, Theophilus C, Ndikom Obed C, Gbasibo Lawrence Addah, Odumodu Chigoez Uzoma, Ezewusi Kingsley and Olusegun Buhari, Measuring the Correlation between the Tensile Strength and Hardness of Steel and Aluminum as Alternative Ship Hull Construction Materials in Local Ship Yards in Nigeria, International Journal of Latest Technology in Engineering, Management & Applied Science (IJLTEMAS), Volume VII, Issue XII, December 2018 | ISSN 2278-2540.
[9] B. Ravi, Fabrication and Mechanical Properties of Al7075-SiC-TiC Hybrid Metal Matrix Composites , International Journal of Engineering Science Invention, Volume 6 Issue 10|| October 2017 || PP. 12-19.
Time and different Cold Plastic Deformation degree, Materials Research. 2019; 22(4): e20180598.

[18] G. Pitchayyapillai, P. Seenikannan, K. Raja and K. Chandrasekaran, Al6061 Hybrid Metal Matrix Composite Reinforced with Alumina and Molybdenum Disulphide, Advances in Materials Science and Engineering. Volume 2016, Article ID 6127624, 9 pages. http://dx.doi.org/10.1155/2016/6127624.

[19] Bandara, C.S., Siriwardane, S.C., Dissanayake, U.I., Dissanayake, R., (2016). Full range S-N curves for fatigue life evaluation of steels using hardness measurements. International Journal of Fatigue 82, 325–331. doi:10.1016/j.ijfatigue.2015.03.021.

[20] Robert Kosturek, Lucjan Snieżek, Janusz Torzewski and Marcin Wachowski, Low Cycle Fatigue Properties of Sc-Modified AA2519-T62 Extrusion, Materials 2020, 13, 220; doi:10.3390/ma13010220.

[21] Dazhi Pu, Guanghua Wen, Dachao Fu, Ping Tang and Junli Guo, Study of the Effect of Carbon on the Contraction of Hypo-Peritectic Steels during Initial Solidification by Surface Roughness, Metals 2018, 8, 982; doi:10.3390/met8120982