ASSESSMENT OF FATIGUE PROPERTIES AND S-N CURVES FOR DIN EN 10283 ALLOY STEEL

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Abstract. *The scope of this study is to experimentally evaluate the stress-life curve, S-N, for the DIN EM 10283 type steel and determine the mean stress effects on its fatigue life. In that sense, 30 spécimen were experimentally evaluated under dynamic axial loads with stress ratios of -1, 0 and 1/3. Qualitative and quantitative tests were performed in order to evaluate the fatigue life and dynamic parameters of the material. Based on the obtained results it was possible to determine the parameters that describe the fatigue behavior of the evaluated material and obtain its S-N curves.In the evaluation of mean stress effects on fatigue life, Goodman, Gerber, Smith-Watson-Topper and Walker relations were tested in order to evaluate the validity of the use of such rules for the tested material. Based on the results it was possible to verify the Walker's relation makes it possible to evaluate in a consistent way the reduction effect on fatigue life due to the presence of mean stresses.*

Keywords*: Fatigue, SWT, Walker, Gerber, DIN EN 10283*

1. Introduction

One of the uses of DIN EM 10283 type steel is to assemble hydrogenators turbine blades. Despite the fact that these components are designed for infinite fatigue life conditions, it is relatively common to find fatigue cracks at the root of Kaplan and Francis turbine blades during inspections and maintenance routines. Recent reports released by maintenance and design specialists from the energy industry pointed the nucleation of fatigue cracks and even the presence of 150mm cracks after 10 thousand hours under working condition in Francis turbines. Considering that during fabrication, ultrasound and penetrating liquid tests are performed in order to identify the presence of cracks due to fabrication processes, the only plausible cause for the appearance of such defects is the fatigue phenomena. By simply evaluating the fabrication and mounting procedure, as well as the working conditions of such structural components, it is possible to verify that three fundamental factors for the appearance of fatigue are present: (*i*) presence of stress concentrators; (*ii*) residual stresses and (*iii*) relatively high levels of dynamic loads. In general, the techniques for estimating fatigue strength of structural components are well known and relatively reliable. However, for the correct use of such methods it is necessary to characterize in a consistent way the material mechanical behavior. In that sense, the main aim of this work is to estimate the mean stress effects on the fatigue strength and identify the most adequate model for estimating mean stress effects for this specific type of material.

1.1. Mean Stress Effects on Fatigue Life

Fatigue can be described as a permanent, progressive and localized degradation process of the material that can be observed in structural components subjected to load conditions that induce non permanent stresses and strains. This condition could induce the appearance of cracks and/or culminate in the complete fracture of the structural component after a sufficient number of load cycles. One of the most widely used methods in design applications and to describe fatigue life is the Stress-life, *S-N*, where the number of cycles to failure, *N*, is correlated to alternating stress present at some critical point of the component, S_a. Invariably, it is possible to verify that a power relationship can be used to adequately fit experimental data correlating alternating stresses and number of cycles to failure between 10^3 and 10^6 cycles, as expressed in Eq. (1) where A and b are, respectively, the constant and the curve exponent.

$$S_a = A \cdot N^b \tag{1}$$

Under real conditions, structural components are subjected to complex types of loads that can, after the identification and counting of the load cycles, be represented by a defined load sequences with constant amplitudes. In that sense, it is possible to define the following parameters used to quantify these types of loads:

Mean stress, S_m, representing the mean stress level assessed at the analysis point, estimated by Eq. (2).

$$S_m = \frac{S_{\max} + S_{\min}}{2} \quad (2)$$

Alternating stress, S_a, representing the stress variation around the mean stress and calculated by Eq. (3).

$$S_a = \frac{S_{\max} - S_{\min}}{2} \quad (3)$$

Load ratio, R, used to characterize the mean stress, being define by Eq. (4).

$$R = \frac{S_{\min}}{S_{\max}} \quad (4)$$

By analytically manipulating and combining equations (2) to (4), the mentioned parameters can be related and described as represented by Equations (5)

$$S_a = \frac{S_{Max}}{2} \cdot (1 - R) \quad (5.1) \qquad S_m = \frac{S_{Max}}{2} \cdot (1 + R) \quad (5.2) \qquad \frac{S_a}{S_m} = \cdot \frac{(1 - R)}{(1 + R)} \quad (5.3)$$

Defining load types that assume (S_m, S_a) = (0, S_{ar}) as a standard condition in order to determine S-N curve parameters, Eq. (1) can be represented in the form of Eq. (6) where σ'_f e b are material constants determined based on test results obtained for null mean stress conditions.

$$S_{ar} = \sigma'_f \cdot N^b \quad (6)$$

For different types of steel, the *S-N* curve parameters can be empirically obtained by considering their particular ultimate strength, S_{rt} (Dowling, 1998).

1.2. The Goodman and Gerber Relations

A common approach to evaluate the mean stress effect on fatigue life is by analyzing diagrams of S_m *versus* S_a. In that sense, several combinations of mean and alternating stress, (S_m, S_a), that cause fatigue failure of the specimen when subjected to N cycles of constant amplitude load are plotted for a specific fatigue life. The most used models to represent this mean stress effect are the ones proposed by Goodman and Gerber. The description of the relations between alternating and mean stress described by such models can be done by means of Eq. (7).

$$\frac{S_a}{S_{ar}} + \left(\frac{S_m}{S_{rt}}\right)^{\alpha} = 1 \quad (7)$$

where S_{ar} is the fatigue strength limit for a specific number of cycles, N, based on the conditions defined for the use of Eq. (2), S_{rt} is the ultimate strength for the material and α is equal to one for the linear relation of Goodman, and two for the parabolic expression of Gerber.

Algebraically manipulating Eq. (7) it is possible to determine the fatigue strength limit of the material when subjected to loads described by an alternating stress S_a and mean stress S_m, resulting in Eq. (8).

$$S_{ar} = \frac{S_a}{1 - \left(\frac{S_m}{S_{rt}}\right)^{\alpha}} \quad (8)$$

In the models proposed by Goodman and Gerber, Eq. (7) defines the limits of the fatigue failure region for a specific fatigue life, N. If the point representative of the stress cycle, (S_m ,S_a), ou (R, S_a), is located in the region between the Cartesian axes and the representative curves, there should not be failure based on such criterions. The graph shown on Fig. (1) exemplifies the behavior of the discussed models, the lines indicating hypothetical tests assuming load ratios of magnitude 0 and -1 and, as well as the geometrical places of the pair (S_m ,S_a) that represents the limits of failure.

1.3. The Smith-Watson-Topper (SWT) and Walker Relations

At the end of the sixties, Smith-Watson-Topper (Smith, 1970) proposed the empirical relation presented in Eq. (8) as an attempt to quantify the mean stress effect on fatigue life, where $\Delta\varepsilon/2$ represents the alternating strain and E the Young modulus of the material.

$$S_{Max} \cdot \frac{\Delta\varepsilon}{2} = \frac{\left(\sigma_f^{'}\right)^2}{E} \cdot (N)^{2 \cdot b} \quad (8)$$

Rearranging this last relation to a similar form present in Eq. (6) it is possible to obtain the expression as follows:

$$\sqrt{S_{Max} \cdot \frac{\Delta\varepsilon}{2} \cdot E} = \sqrt{S_{Max} \cdot S_a} = \sigma_f^{'} \cdot (N)^b \quad (9)$$

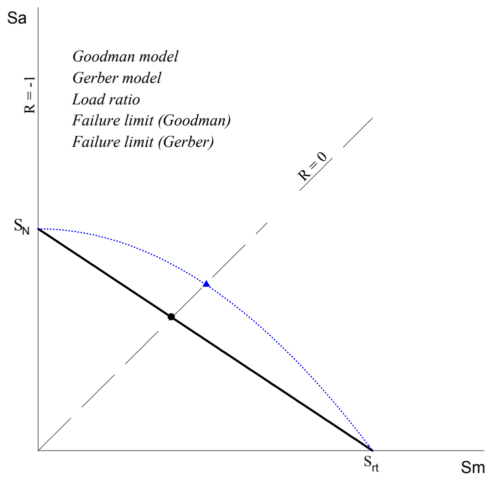

Figure 1. Representation of Mean stress *versus* Alternating stress diagram.

Based on equation (9) it is possible to directly correlate the fatigue strength limit, S_{ar}, to the parameter that describe the load, as expressed in Equations (10).

$$S_{ar} = \sqrt{S_{\max} \cdot S_a} \quad (10.1) \qquad S_{ar} = S_{\max} \cdot \sqrt{\frac{1-R}{2}} \quad (10.2) \qquad S_{ar} = S_a \cdot \sqrt{\frac{2}{1-R}} \quad (10.3)$$

Using the same philosophy adopted by Smith-Watson-Topper, Walker (Walker, 1970) proposed the relation presented in Eq. (11) to quantify the fatigue strength limit, S_{ar}, where the parameter γ is a constant characteristic of the material.

$$S_{ar} = S_{\max}^{1-\gamma} \cdot S_a^{\gamma} \quad (11.1) \qquad S_{ar} = S_{\max} \cdot \left(\frac{1-R}{2}\right)^{\gamma} \quad (11.2) \qquad S_{ar} = S_a \cdot \left(\frac{2}{1-R}\right)^{1-\gamma} \quad (11.3)$$

It is a common approach to represent the characteristic curve of the Smith-Watson-Topper and Walker relations using the ratios S_m/S_{ar} as the X axis and the ratio S_a/S_{ar}, as the Y axis, resulting in a singular tendency curve. Figure (2) illustrates the typical behavior of the curves representative of the described models.

2. Materials and Methods

2.1. Materials and Preliminary Tests

The material used in the development of this research was the DIN EN 10283 steel alloy, kindly supplied by a turbine specialist industry. This type of steel is used in the manufacturing of structural components that request a high mechanical and corrosion resistance, being used in hydraulic turbine blades and other components. The mechanical and chemical properties of the used material, given by the manufacturer, are presented in Tables (1) and (2).

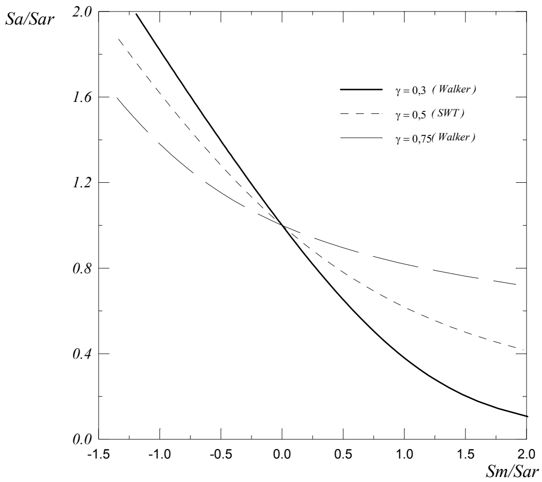

Figure 2. Walker e SWT models representative curves.

The specimens were manufactured from three round bar samples of the material without the specification of the heat treatment they were subjected. The bars presented regions characteristic of the use of high heat input cutting instruments that were not used to assemble the coupons or perform the tests. The parts of interest, supposedly not heat affected, was cut using a oil refrigerated saw to avoid creation of new heat affected zones. Therefore, in order to determine the mechanical properties and identify the manufacturing heat treatment, hardness tests were performed in samples of these bars. To determine if the bars were all subjected to the same heat treatment, hardness tests were performed in three samples of each bar. Such results are presented in Table (3), as well as its statistical characterization.

Table 1. Chemical Composition (%)

C (Max)	Mn (Max)	Si (Max)	Cr	Ni	Mo (Max)	P (Max)	S (Max)
0.06	1.00	1.00	12.0 – 13.5	3.5 – 5.0	0.70	0.035	0.025

Table 2. Normalized mechanical properties

S_{rt} (MPa) (Min)	S_y (MPa) (Min)	R.A. (%) (Min)	Elongation(%)	Charpy (0o) [J] (Min)
900	830	12	35	35

Table 3. Brinell hardness test results.

Test	Round bar		
	A	B	C
Mean	310.7	315.7	313.3
Deviation	4.0	4.6	7.5
CV (%)	1.3	1.5	2.4

In attempt to identify the existence of significant variations between tests results, variance analysis were performed, testing the hypothesis that the mean values of two distinct measurements are equal. Based on the results of such tests it is possible to assure or not if the samples present the same hardness. Once verified that the samples are statistically identical, it is possible to adopt as the mean value of hardness, the value of 313 HB. With such results it is possible to estimate the material yield strength, S_y, and ultimate strength, S_{rt}, based on the following correlations found in the literature.

$$S_y = 3{,}62HB - 206{,}8[MPa] \;\Rightarrow\; S_y = 962[MPa] \quad (12)$$

$$S_{rt} = 3{,}5HB[MPa] \;\Rightarrow\; S_{rt} = 1079[MPa] \quad (13)$$

Simple tension tests were used to validate the former estimates of the material yield strength and ultimate strength. In that sense, two tensile specimens were assembled based on NBR 6673. The tests were performed with two millimeters per minute, with displacement control, in a MTS 810 universal testing machine. Based on such tests it was possible to determine the material characteristics presented on Table (4)

Table 4. Mechanical properties obtained form simple tension tests.

Ultimate strength, S_{rt} (MPa)	Yield strength, S_y (MPa)	Young modulus (GPa)
890	637	209

2.2. Fatigue tests

The fatigue tests under axial loads were performed in a MTS 810 universal testing machine. With that purpose, 42 specimens were assembled. As recommended by norms ASTM / E 468-90 [ASTM, 1990] and ASTM E - 739/91 [ASTM, 1991], the minimum number of specimens necessary to obtain a standard *S-N* curve depends on the type of testing program intended. In this research, the program used had the purpose of determining critical design values and, as suggested by the norm, a minimum number of 12 specimens were necessary with a reproduction of the tests between 50 and 75%. Therefore, for a preliminary analysis of S-N curve, 2 specimens associated to each one of 5 stress levels were tested. In the three levels where a higher dispersion of the results was observed, the tests were replied, guarantying a replication of 58%. The levels of stress used in the fatigue tests are presented on table (5).

Table 5. Stress levels used to determine S-N curves.

R	S_a/S_{rt} (%)				
	1º	2º	3º	4º	5º
-1	46.89	49.44	52.06	57.22	63.58
0	28.31	31.41	36.62	37.81	43.63
1/3	21.89	23.97	27.43	28.20	31.97

The S-N curves were obtained considering the complete fracture of the specimens under cyclic conditions by repeating the process for different load magnitudes. The stress that correlates to an infinite life is defined as fatigue limit or endurance limit, reserving the term fatigue strength to the stress correlated to a specific finite life. In order to evaluate mean stress effects, S-N curves were assembled based on load ratios, *R*, of -1, 0 and 1/3. The test conditions for R=-1 were defined based on empirical relation described by Dowling (1999), resulting in the expected behavior of the S-N curve.

3. Results and Discussions

The results of fatigue tests for the 5 stress levels described previously are presented on Table (6). Based on these results it is possible to verify a significant dispersion on fatigue life.

S-N diagrams are presented in Figure (3). The experimental achievement of the endurance limit, S_n, was performed using the parallel projected method, described by Sheng (2001). The great advantage of this method consists the need for a few number of specimens. Basically, This method consists in achieving S-N curve for the material and estimating the fatigue strength limit considering a extrapolation of the fatigue curve for life identified as infinite fatigue life.

Table 6. Statistical behavior of fatigue life of the tested specimens.

	S_a/S_u (%)				
	46.9	49.4	52.1	57.2	63.6
Mean	9.63E+05	3.51E+05	1.62E+05	8.03E+04	9.38E+03
Deviation	5.46E+05	5.73E+04	6.36E+04	2.63E+04	***
CV (%)	56.7	16.3	39.1	32.7	***

Based on the values of mean lives, the equation that best describes the experimental results can be represented by Eq. (14).

$$S_{ar} = 1040.23\text{N}^{-0.0665865} \tag{14}$$

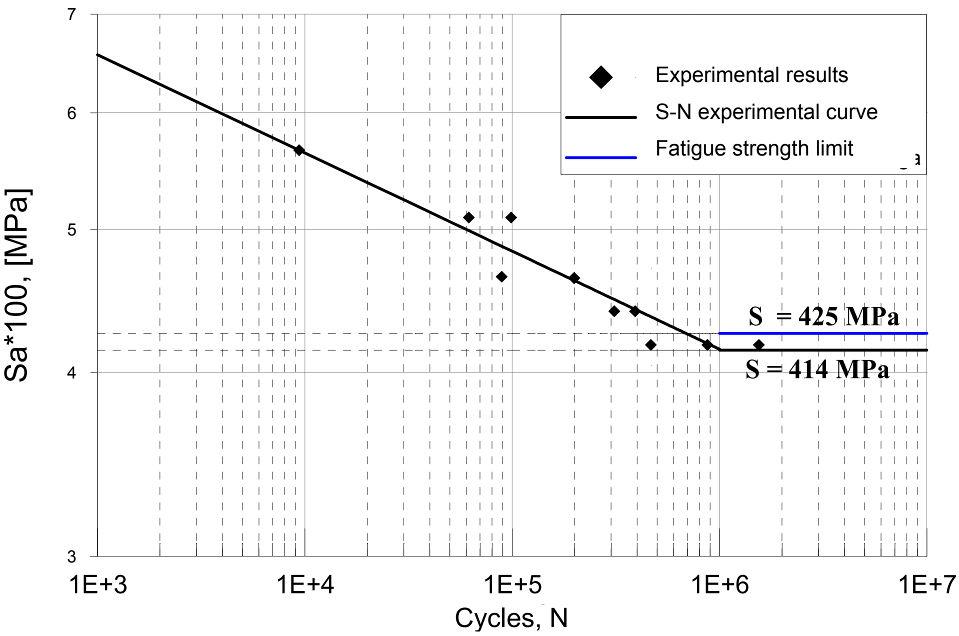

Figure 3. S-N curves for R = - 1.

Considering the relatively high degree of dispersion of the experimental data, it becomes interesting to determine the curves that define the confidence limits of such results. The graph presented on Fig. (4) shows the medium experimental fit, as well as the upper and lower 95%.confidence limits. By means of this analysis it is possible to evaluate the mean value of 414 MPa for the fatigue strength limit, with a minimum value of 377 MPa.

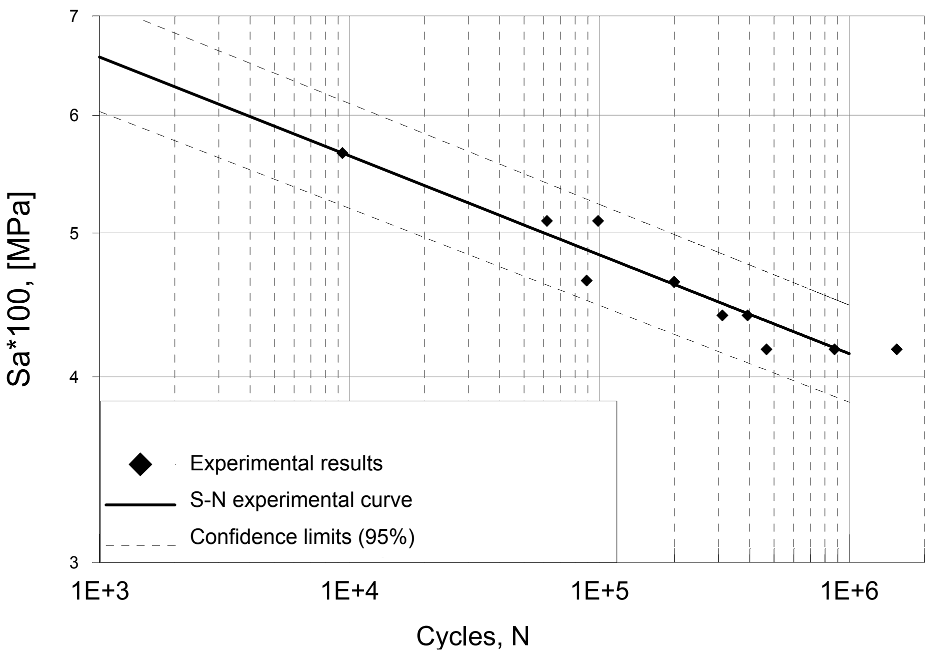

Figure 4. Confidence limits of S-N curve for R = - 1.

3.1. Mean Stress Effect

As described earlier, in order to evaluate the mean stress effect on fatigue life, tests involving load ratios of 0 and

1/3 were used to assemble *S-N* curves, additionally to the standard tests. The fits for the results obtained for such tests are presented on Fig. (5).

Based on the mean lives, the relations that best describe *S-N* curves for load ratios of 0 and 1/3 are represented in equations (15) and (16), respectively.

$$S_a = 953{,}15N - 0{,}09263 \quad (R = 0) \tag{15}$$

$$S_a = 719.51N^{-0.0975} \quad (R = 1/3) \tag{16}$$

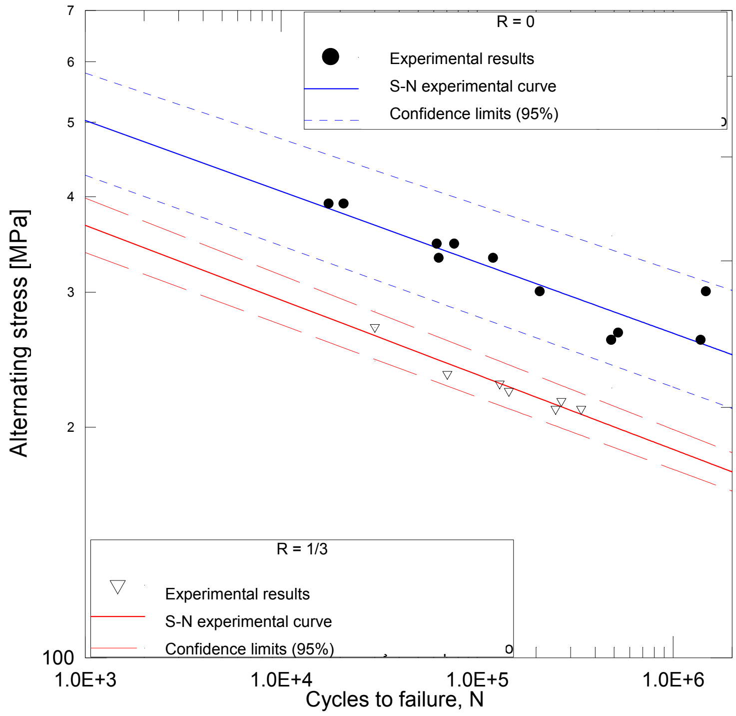

Figure 5. Stress *versus* life curves exemplifying the mean stress effect.

The mean and minimum values for the fatigue strength limit considering load ratios of 0 and 1/3 are presented on Tab. (7). Based on these results it is possible to verify that the fatigue strength limit for R=0 and R=1/3 are respectively 1.5 and 2.2 times the value for R=-1.

Table 7. Effect of load ratio on the fatigue strength limit.

Load ratio, R	-1	0	1/3
Mean strength [MPa]	414	265	186
Minimum strength [MPa]	377	225	173

3.2. Mean Stress *Versus* Alternating Stress Diagrams

The achievement of mean stress *versus* alternating stress diagram was performed in attempt to compare the reliability of the Goodman, Gerber, SWT and Walker empirical models concerning their capacity to describe the mean stress effects on fatigue life for DIN EN 10283 steel alloy. Therefore, the curves that represent the above models were plotted in the same graph as the experimentally obtained data for load ratios of -1, 0 and 1/3. On figure (8) are presented the normalized mean stress *versus* alternating stress diagram comparing the experimental results and the Goodman, Gerber, SWT and Walker curves. Considering the results presented on Fig. (6) it is possible to verify that: (i) Walker's model presents a good degree of consistency in its predictions of fatigue failure for all three analyzed load ratios; (ii) the use of the Goodman empirical model results in predictions of failure for level of stress less intensive the experimentally observed ones, resulting to be a conservative model in most of the analyzed cases. Such characteristic showed to be more intense for less expressive lives. (iii) when using Gerber and SWT models, the predictions of fatigue failure are non conservative with respect to the experimental data for all the analyzed situations.

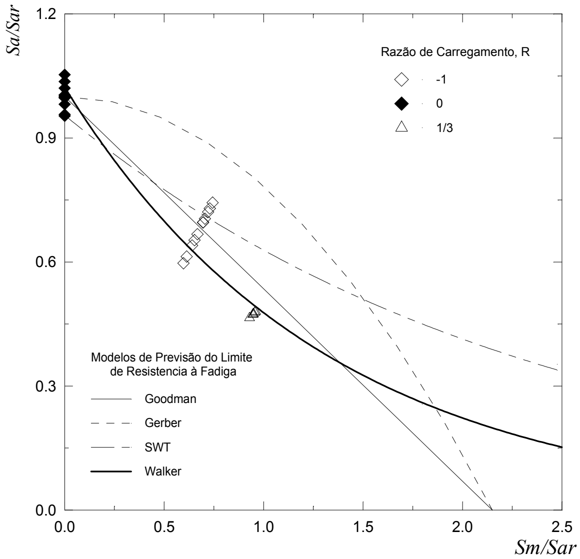

Figure 6. S_m x S_a diagram for the DIN EN 10283 steel alloy.

6. Conclusions

This scope of this research was to determine the fatigue behavior of DIN EM 10283 alloy steel, as well as to evaluate the mean stress effects on fatigue life. In that sense, S-N curves were experimentally determined for loading ratios of -1, 0 and 1/3. Such results were used to determine the fatigue strength limit of the material and to evaluate the mean stress *versus* alternating stress diagrams. In the evaluation of the mean stress effects, the Goodman, Smith-Watson-Topper and Walker relations were also used. By means of the obtained results it is possible to conclude: a) the fatigue endurance limit for the evaluated material is 414 MPa, value statistically similar to the one obtained form empirical models; b) Fatigue life is significantly affected by the presence of mean stresses and a reduction around 50% was observed for the analyzed load ratios; c) Gerber and SWT models for fatigue life prediction showed to be non conservative, what makes its use non-recommended for this material; d) The use of Goodman and Walker empirical relations resulted in prediction of fatigue failure on the conservative side when evaluating this material.

7. References

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8. Responsibility notice

The authors are the only responsible for the printed material included in this paper.

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