THE EFFECT OF MEAN STRESS ON THE FATIGUE BEHAVIOR OF ASTM A743 CA6NM ALLOY STEEL

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Abstract.*The objective of this work is to evaluate the effects of mean stress on the fatigue behavior of ASTM A743 CA6NM alloy steel. It is used in several hydrogenator turbine components. In order to achieve it, 33 specimens were experimentally evaluated under axial loads with stress ratio of - 1 and more 60 specimens were tested under stress ratio 0, 1/3 and 2/3. Based on the obtained results it was possible to determine parameters that describe the fatigue behavior of the evaluated material, obtain its S-N curves, its endurance limit and its scatter bands. In the assessment of the mean stress effects of fatigue life, Goodman, Gerber, Walker and Kwofie's relations were tested in order to evaluate the validity of the use of such rules for the tested material. According to the obtained results it was possible to verify that Goodman and Gerber's relations do not model correctly the reduction effect fatigue life and presented high scatter. The predictions of Walker and Kwofie's relation are consistent and the Walker's relation presented smaller scatter than Kwofie's relation. Walker's relation makes it possible to evaluate in a consistent way the effect of the presence of mean stresses on fatigue strength.*

Keywords*: Fatigue, Goodman, Gerber, Walker, Kwofie, ASTM A743 CA6NM*

1. INTRODUCTION

The ASTM A743 CA6NM alloy steel is used in several hydrogenator turbine components. In spite of these components be designed for infinite fatigue life, fatigue cracks usually are found at the root of turbine blades. The development and the propagation of those cracks are associated to the fatigue process. Fatigue is a permanent, progressive and located process of structural degradation that happens in a material under stress and strain dynamic conditions. This failure process depends strongly on the stress levels that activate in the most loaded points of the structure, on the presence of residual stresses, on the geometric details and on the material. These conditions can develop crack growth and it can culminate in fracture of the structural component after a certain number of cycle loads. This phenomenon is common in axes' flaws, blades and rotors. Starting from the production, assembly and operation, conditions of these components indentified that residual stresses are fundamental factors to cause the fatigue. The procedures to estimate the endurance limit of structural components are much known and relatively reliable. However, the use of these methodologies demands a solid characterization of the material. In that way, the present work aims to estimate the effects of mean stress in the fatigue strength and to identify the model to be capable to predict the strength of machine elements subject to complex loads, for the used material.

1.1. Basic relations of load characterization

The fatigue life is described by the Wöhler curve or *S-N* curve, Stress-life, where the number of cycles to failure, N, is correlated with the alternating stress, S_a. This method is a relation that can be well used to adjust appropriately experimental data in the sense to correlate the alternate stress and the number of cycles to failure between 10^3 and 10^6 cycles. This relation can be expressed as in Eq. (1), where A and b are the constant and the curve exponent, respectively.

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

Some practical applications and also fatigue tests in materials involve maximum and minimum constant level stresses that characterize the constant amplitude loads. The stress range, ΔS , is the difference between the maximum value and minimum value, Eq. (2). The mean stress, S_m, is the average between maximum value and minimum value, Eq. (3). The half of the range stress is called amplitude stress, S_a, Eq. (4). These are basic relations that characterize one load cycle.

$$\Delta S = S_{\max} - S_{\min} \tag{2}$$

$$S_m = \frac{S_{\max} + S_{\min}}{2} \tag{3}$$

$$S_a = \frac{S_{\max} - S_{\min}}{2} \tag{4}$$

And to describe the mean stress, a factor used to characterize the degree of symmetry of the load, load ratio, R, is defined by Eq. (5). The relation between S_a, S_m e R is expressed in the Eq. (6).

$$R = \frac{S_{\min}}{S_{\max}} \quad (5) \qquad\qquad S_a = \frac{1+R}{1-R}.S_m \quad (6)$$

The standard condition to determine the parameters of Wöhler curve is to assume alternating load, null mean stress. Thus, the Eq. (1) can be express in the form of Eq. (7). It is called Basquin's equation. Where σ'_f e b are material constants based in experimental results.

$$S_{ar} = \sigma'_f \cdot N^b \tag{7}$$

1.2. Mean stress effect predition Models

Initially, empiric models were proposed by Gerber (1874), Goodman (1899), Haigh (1917) e Soderberg (1930) to compensate the effect of mean stress in the high cycle fatigue strength. Gerber proposed a parabolic representation of the Wöhler's limit fatigue data on the graphic S_{max}/S_u *versus* S_{min}/S_u , Eq. (12). Goodman introduced a theoretical line to represent the evaluated fatigue data, Eq. (11). Haigh was the first to plot the fatigue data in the graphic S_a *versus* S_m. Since 1960, some models to determine the effect of mean stress have been proposed as improvement of the previous models. Fatigue tests indicate that the tensile normal mean stress should reduce the fatigue strength coefficient and that the compression normal mean stress should increase it (Lee *et al.* 2005).

In order to overcome the failure prediction's problem under load conditions with relatively low amplitude and relatively high mean stresses, Smith, Watson and Topper - SWT (Smith *et al.* 1970) proposed a model in which the equivalent stress to the endurance limit for the load ratio, $R = -1$, S_{ar}, is expressed in the Eq. (13). On this same year, Walker (1970) presented criteria similar to SWT, however using a factor γ that makes possible an adjustment of the curve in relation to the experimental data, Eq. (14). According to empiric considerations, Berkovits and Fang (Berkovits *et al.* 1993) and more recently Kwofie (2001) proposed widespread mathematical relations to describe the effect of mean stress on the fatigue behavior of endurance limit. Such model consists in the substitution of the Basquin's equation's constant, Eq. (7), for a function that will depend on the mean stress, S_m, on the limit of fatigue strength for the reverse load condition, S_{rt}, and on the ultimate strength, or yield strength, S_y. According to this model, the stress-life relation can be presented by Eq. (8).

$$\sigma_a = S_{ar} \cdot e^{\left(-\alpha \frac{\sigma_m}{S_{rt}}\right)} \tag{8}$$

Expressed in form of power series, the Eq. (8) can be expressed by Eq. (9):

$$\sigma_a = S_{ar} \cdot e^{\left(-\alpha \frac{\sigma_m}{S_{rt}}\right)} \cong \sum_{i=0}^{N} \cdot \frac{1}{i!} \cdot \left(-\alpha \frac{\sigma_m}{S_{rt}}\right)^i \tag{9}$$

Admitting that the argument of the exponential function tend to zero, $\alpha\left(\sigma_m / S_{rt}\right) \to 0$, the consequence is that the terms of superior order converge quickly to zero. In this specific condition, the Eq, (9) assumes the following form:

$$\sigma_a \cong S_{ar} \cdot \left(1 - \alpha \cdot \frac{\sigma_m}{S_{rt}}\right) \tag{10}$$

Starting from this last expression, one can verify with easiness that depending on the value of α, the widespread model will describe some models presented in the Tab. (1).

Table 1. Particular solutions of widespread Kwofie model

Hypotheses	Resulting Equation	Model	Equation
$\alpha = 1$	$\frac{\sigma_a}{S_{ar}} + \frac{\sigma_m}{S_{rt}} = 1$	Goodman	(11)
$\alpha = f\left(\frac{\sigma_m}{S_{rt}}\right) = \frac{\sigma_m}{S_{rt}}$	$\frac{\sigma_a}{S_{ar}} + \left(\frac{\sigma_m}{S_y}\right)^2 = 1$	Gerber	(12)
$\alpha = f\left(R, S_{rt}, \sigma_m\right) = -\frac{S_{rt}}{2 \cdot \sigma_m} \cdot ln\left(\frac{1-R}{2}\right)$	$\sigma_a = S_{ar} \cdot \left(\frac{1-R}{2}\right)^{\frac{1}{2}}$	SWT	(13)
$\alpha = f\left(R, S_{rt}, \sigma_m\right) = -\frac{S_{rt}}{\gamma \cdot \sigma_m} \cdot ln\left(\frac{1-R}{2}\right)$	$\sigma_a = S_{ar} \cdot \left(\frac{1-R}{2}\right)^{\gamma}$	Walker	(14)

2. MATERIAL AND METHODS

2.1. Material

The material used in the development of this research was the ASTM A743 CA6NM alloy steel, a stainless inox martensitic. This type of steel is used in the production of structural components that request high mechanical strength and that resist to the corrosion. The mechanical properties (Young modulus, E, tensile strength, S_{rt}, and yield strength, S_y) of the sample A and sample B are showed in Tab. (2).

Table 2. Mechanical properties of sample A and B

Sample	E (GPa)	S_{rt} (MPa)	S_y (MPa)
A	198	890	637
B	198	918	665

2.2. Specimen design

The specimens of the sample A were designed according to ASTM E 606-04 (ASTM, 2004) and sample B starting from ASTM E 466-96 (ASTM, 2002). These standards specify the main dimensions. In this work three different specimens were used: specimen for sample A, Fig. (1); specimen 1 for sample B, Fig. (1) and specimen 2 for sample B, Fig (2). Tab. (3) shows the respectively data.

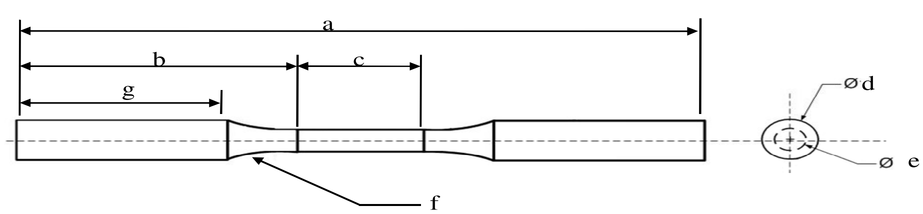

Figure 1. Specimen 1 for sample A and B

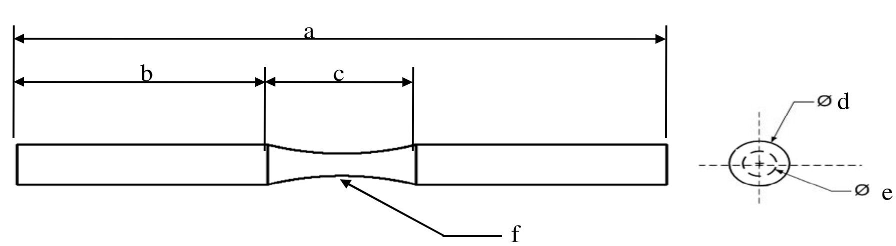

Figure 2. Specimen 2 for sample B

Table 3. Specimen data

Specimen / Sample	a (mm)	b (mm)	c (mm)	d (mm)	e (mm)	f (mm)	g(mm)
1 / A	151,42	63,71	24,00	10,00	6,00	48,00	50,00
1 / B	151,13	61,57	28,00	12,00	7,00	28,00	50,00
2 / B	152,40	58,87	34,66	12,50	7,00	56,00	

2.3. Fatigue tests

The fatigue tests under axial loads were performed in the MTS 810, universal testing machine. According to ASTM E 468-90 (ASTM, 1990) and ASTM 739-91 (ASTM, 2004), the minimum number of necessary specimens to obtain a curve *S-N* in order to determine the critical values of design is 12 specimens with reproduction of 50 to 75%. Then, for a preliminary analysis of the *S-N* curve, 2 specimens were tested for each one of the 5 chosen stress levels. In the three levels where larger scatter was observed the tests were reproduced, guaranteeing at least 58% of reproduction.

The *S-N* curves were obtained considering the total crack growth under dynamic loads, repeating the process for different stress levels. The stress related to the infinite life is defined as limit of fatigue. In order to evaluate the effect of mean stress, *S-N* curves were designed for the following ratio loads, *R*, -1, 0, 1/3 and 2/3.

2.4. Strategy for evaluation of mean stress models' adherence

The strategy used to evaluate models' adherence consists in the use of three parameters that characterize a fatigue test: mean stress, S_m, alternating stress, S_a, and the resulting life, *N*. According to Fig. (3), the application of the data which characterize the mean and alternating stress in one mean stress model allows to evaluate, through extrapolation of equation when $S_m = 0$, the equivalent fatigue strength according to specific model, called $S_{ar\ Model}$. In a similar way, the application of the value of resulting life, *N*, in the Basquin's equation allows to estimate a new value for the equivalent endurance limit, called $S_{ar\ Basquin}$ Then, if the prediction model was adherent to the experimental results, the values of $S_{ar\ Model}$ and $S_{ar\ Basquin}$ should be identical statistically. Tab. (4) shows a resume of the equations used to estimate the equivalent alternating stress, $S_{ar\ Model}$.

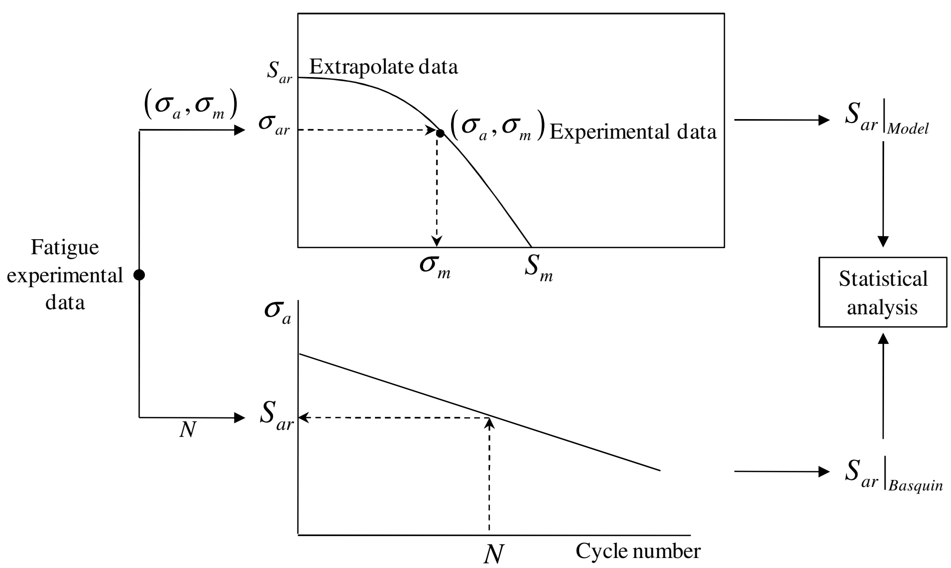

Figure 3. Strategy for evaluation of mean stress models' adherence

To estimate the exponents of the Kwofie and Walker's models, α and γ, respectively, the Eqs. (21) and (22) were used, respectively.

$$\sigma_a = S'_{f_{R=-1}} \cdot e^{\left(-\alpha \frac{\sigma_m}{S_{rt}}\right)} \cdot (N)^{b_{R=-1}} \tag{21}$$

$$\sigma_a \cdot \left(\frac{2}{1-R}\right)^{1-\gamma} = S'_{f_{R=-1}} \cdot N^{b_{R=-1}} \tag{22}$$

The estimate of parameters α and γ was accomplished using the Levenberg-Marquardt method (Gill and Murray, 1981). Tab. (5) shows the obtained results.

Table 4. Equations used to estimate the equivalent alternating stress

Model	Equation to estimate the equivalent alternating stress	Equation
Goodman	$S_{ar} = \dfrac{\sigma_a}{1-\left(\dfrac{\sigma_m}{S_{rt}}\right)}$	17
Gerber	$S_{ar} = \dfrac{\sigma_a}{1-\left(\dfrac{\sigma_m}{S_{rt}}\right)^2}$	18
Walker	$S_{ar} = \sigma_a \cdot \left(\dfrac{2}{1-R}\right)^{1-\gamma}$	19
Kwofie	$S_{ar} = \sigma_a \cdot e^{\left(\alpha \frac{\sigma_m}{S_{rt}}\right)}$	20

Table 5. Parameters that characterize Kwofie and Walker's models

Parameter	Expected value		Confidence intervals	
	Estimate	Standard error	Estimate	Standard error
α	0.407	0.019	0.346	0.468
γ	1.453	0.084	1.187	1.720

3. RESULTS AND DISCUSSIONS

3.1. Tests with ratio loading, -1

For the ratio loading equal -1, 11 specimens were used of sample A and 22 specimens of sample B. The Tables (6) and (7) show the statistic behavior of the estimated fatigue lives for such stress level.

Table 6. Statistic behavior of fatigue lives ($R = -1$) - Sample A

S_a (MPa)	417	440	463	509	566
S_a / S_{rt} (%)	46.9	49.4	52.1	57.2	63.3
Mean	9.63 e+05	3.51 e+05	1.99 e+05	8.03 e+04	9.38 e+03
Deviation	5.46 e+05	5.73 e+04	4.92 e+02	2.63 e+04	*
CV (%)	56.7	16.3	0.2	32.7	*

Table 7. Statistic behavior of fatigue lives ($R = -1$) - Sample B

S_a (MPa)	353	364	400	440	509
S_a / S_{rt} (%)	38.4	39.6	43.6	47.9	55.5
Mean	1.73 e+06	1.13 e+06	4.53 e+05	2.61 e+05	5.75 e+04
Deviation	5.49 e+05	8.82 e+05	8.32 e+02	1.09 e+03	9.74 e+03
CV (%)	31.6	78.1	18.4	0.4	16.9

3.2. Tests with ratio loading, 0

For the ratio loading, $R = 0$, 13 specimens were used of sample A and 14 specimens of sample B. Tabs. (8) and (9) show the statistic behavior of fatigue lives estimated for such stress level.

Table 8. Statistic behavior of the fatigue lives ($R = 0$) - Sample A

S_a (MPa)	260	265	300	332	347	391
S_a / S_{rt} (%)	29,2	29,8	33,7	37,3	38,9	44,0
Mean	6,2 e+05	5.3 e+05	1.8 e+05	9.3 e+04	7,0 e+04	1,9 e+04
Deviation	5.5 e+05	*	4.4 e+04	4,1 e+04	1,0 e+04	2.4 e+03
CV (%)	88,9	*	24,6	43,7	14,3	12,4

Table 9. Statistic behavior of the fatigue lives ($R = 0$) - Sample B

S_a (MPa)	260	265	300	332	347	391
S_a / S_{rt} (%)	29,2	29,8	33,7	37,3	38,9	44,0
Mean	7,9 e+05	1.7 e+05	2.0 e+05	8.8 e+04	9.7 e+04	2.7 e+04
Deviation	3.5 e+05	*	1.5 e+03	3.8 e+04	3.8 e+04	3.2 e+03
CV (%)	44,7	*	0.8	42.7	38.8	11.7

3.3. Tests with ratio loading, 1/3

For the ratio loading, $R = 1/3$, 7 specimens were used of the sample A and 7 specimens of the sample B. Tab. (10) shows the statistic behavior of the fatigue lives estimated for such stress level.

Table 10. Statistic behavior of the fatigue lives ($R = 1/3$) - Samples A and B

S_a (MPa)	197	200	211	216	223	228	235	270
S_a / S_{rt} (%)	29,2	29,8	33,7	37,3	38,9	44,0	26,0	29,0
Mean	4.9 e+05	3.5 e+05	4.0 e+05	2.7 e+05	1.5 e+04	1.3 e+04	7,1 e+04	3,4 e+04
Deviation	1.1 e+05	*	1.4 e+05	*	*	*	*	*
CV (%)	22.7	*	35,7	*	*	*	*	*

3.4. Tests with ratio loading, 2/3

For the ratio loading, $R = 2/3$, 19 specimens of the sample B were used. Tab. (11) shows the statistic behavior of the fatigue lives estimated for such stress level.

Table 11. Statistic behavior of the fatigue lives ($R = 2/3$) - Sample B

S_a (MPa)	133	135	140	141	143	148
S_a / S_u (%)	14.7	14.8	15.5	15.6	15.8	16.4
Média	8.7 e+05	7.8 e+05	4.4 e+05	3.7 e+05	2.0 e+03	6.2 e+01
Desvio	3.7 e+05	4.1 e+05	1.5 e+05	4.0 e+04	*	*
CV (%)	42.3	52.2	33.8	10.6	*	*

Based on the obtained results it is possible to verify a significant dispersion of fatigue life for all stress ratios tested.

3.5. Effect of the mean stress

The experimental data and its respective trend lines, for such ratio loading, are shown in Fig. (4) and the parameters that characterize the fatigue strength are resumed in the Tab. (12). The endurance limit, S`*f*, can be easily obtained through the parallel projection method (S-K Lin, 2001). Basically, this method consists in achieving S-N curve for the steel and estimating the endurance limit considering an extrapolation of the fatigue curve for life identified as infinite fatigue life.

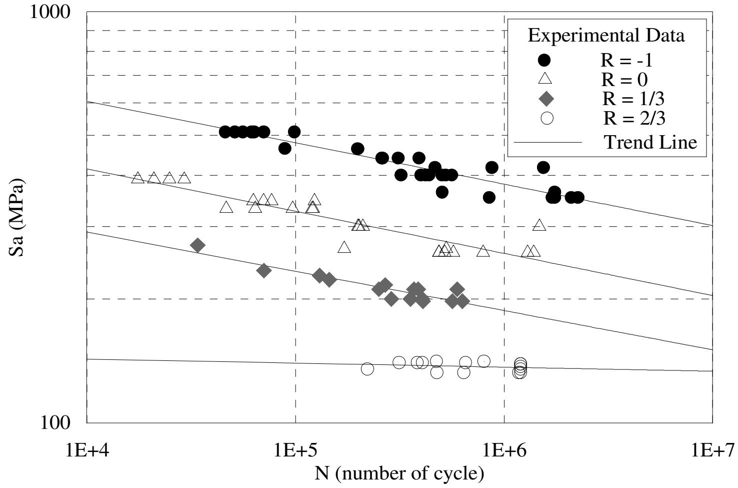

Figure 4. *S*-N curves about the effect of mean stress

Table 12. Parameters that characterize the *S-N* curves

R	Basquin's constant (A) [MPa]		Basquin's exponent (b)		Endurance limit (S`*f*) [MPa]	
	Mean	Standard error	Mean	Standard error	Mean	Standard error
-1	1406,9	102,9	-0,0941	0,0059	383,2	28, 0
0	996,8	146,8	-0,0962	0,0125	263,9	28,0
1/3	729,8	91,2	-0,0987	0,0101	186,7	23,3
2/3	152,3	7,4	-0,0077	0,0039	136,9	6,7

3.6. Models's adherence to experimental results

3.6.1. Goodman's model

Figure (5) shows the fatigue experimental data and the predictions based on Goodman's model. The results reveal low adherence. The trend line adjusts to Basquin's curve but reveal big scatter, as shown in Fig. (6). The confidence limits arrives to 300 MPa. In addition, for ratio loading of 2/3, the model predicts the possibility to apply, on average, stress levels around 34% superiors to real failure condition.

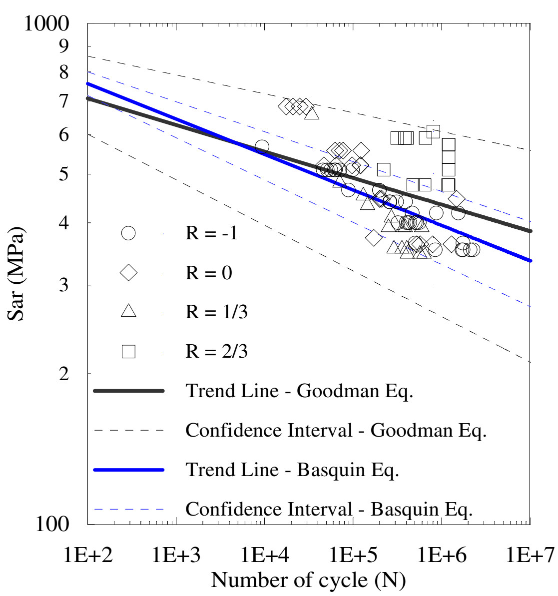

Figure 5. Goodman's prediction

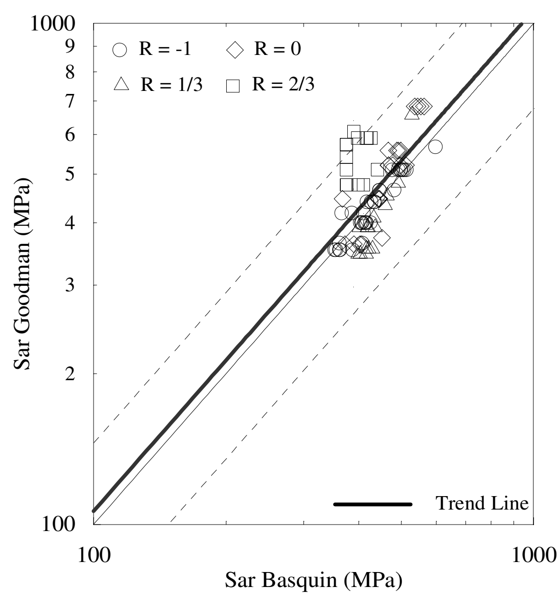

Figure 6. Goodman's scatter diagram

3.6.2. Gerber's model

Figures (7) and (8) shows the fatigue experimental data and the predictions based on Gerber's model. Based on the presented results, it is verified a relatively high scatter, approximately 300 MPa. The trend line of the predict results for this model is out of the confidence limits of the Basquin's equation. This model predicts the possibility to apply, on average, stress levels around 72% inferior to real failure conditions and it is extremely conservative.

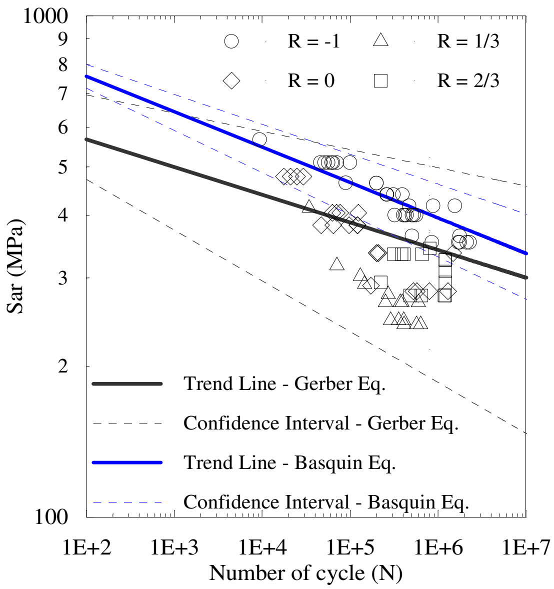

Figure 7. Gerber's prediction

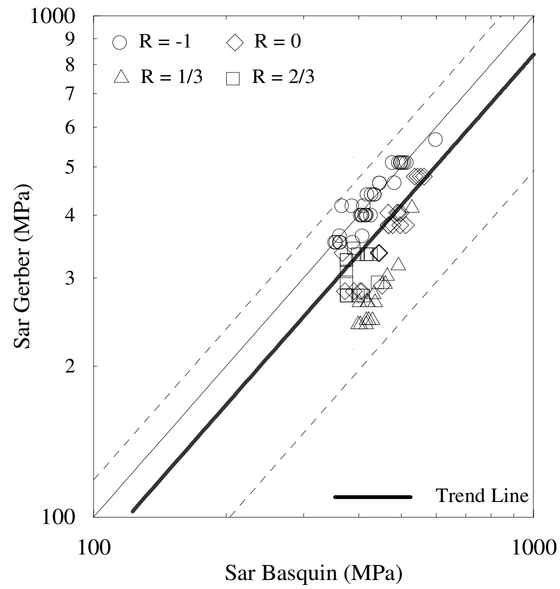

Figure 8. Gerber's scatter diagram

3.6.3. Walker's model

The fatigue experimental data and the predictions based on Walker's model are showed in the Figs. (9) and (10). The obtained results indicate that this model has a level of adherence significantly high to the experimental results because they were adjusted very well to Basquin's curve. In addition, the confidence intervals associated to both models have the same order of size, approximately 50 MPa.

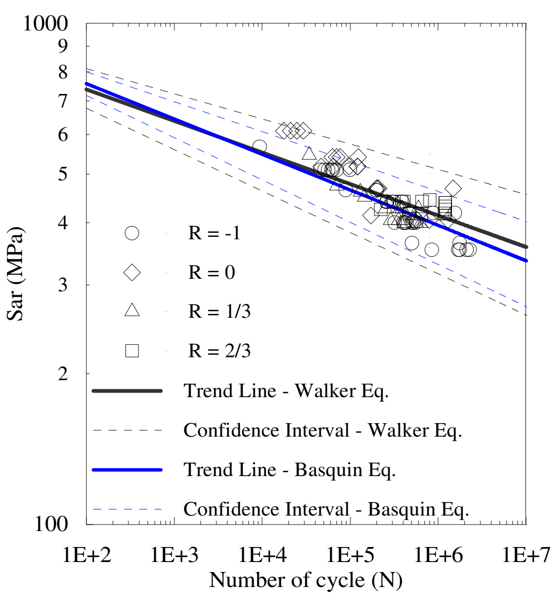

Figure 9. Walker's prediction

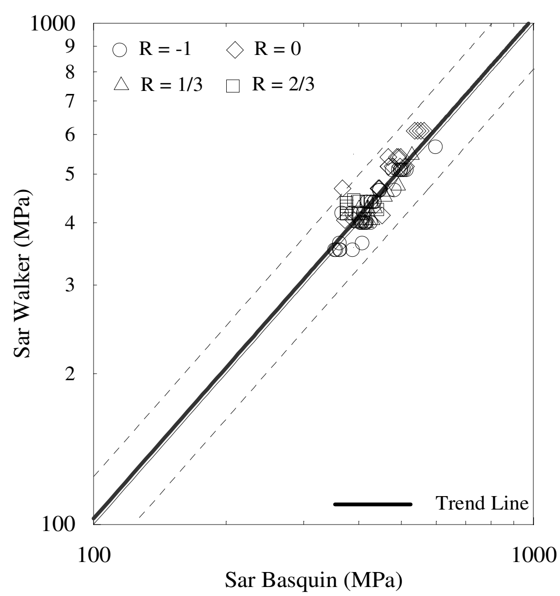

Figure 10. Walker's scatter diagram

3.6.4. Kwofie's model

The Figures (11) and (12) show the fatigue experimental data and the predictions based on Kwofie's model. Based on the results presented it is verified that in a way similar to Walker's model, Kwofie's model also presents a level of adherence expressively high. The obtained results were adjusted well by the Basquin's trend line. However, its confidence intervals are around 100 MPa, twice superior to the presented by Walker's model. In other words, Kwofie's model is less adherent.

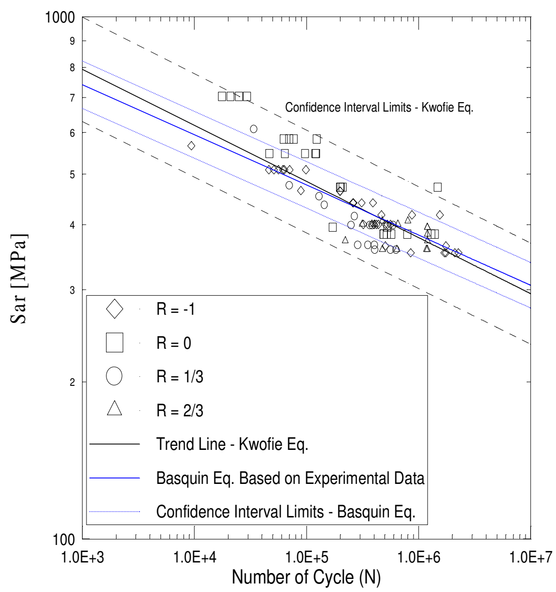

Figure 11. Kwofie's prediction

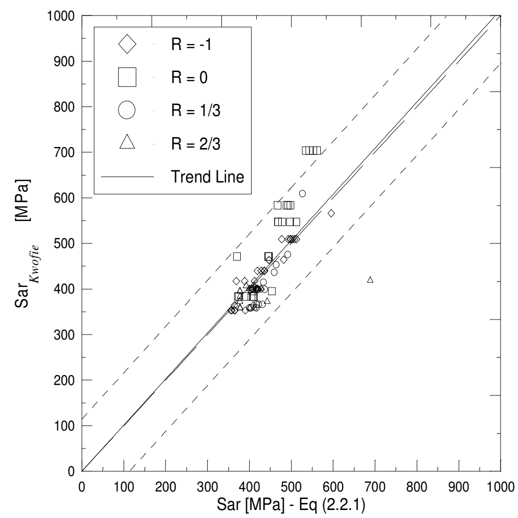

Figure 12. Kwofie's scatter diagram

4. CONCLUSIONS

The aim of this research was to evaluate the effect of mean stress of the fatigue behavior of ASTM A743 CA6NM alloy steel. In that sense, *S-N* curves were experimentally determined for loading ratios of -1, 0, 1/3 and 2/3. The results were used to determine the endurance limit of the material and to evaluate the comparative diagrams between Basquin's alternating stress and predictions of such model. The Goodman, Gerber, Walker and Kowfie's model were used to predict the mean stress effects. By means of the obtained results it is possible to infer: a) the fatigue strength limit for this alloy steel is 383 MPa; b) the fatigue life is strongly influenced by the presence of mean stresses, having a superior reduction around 50% in the endurance limit; c) Goodman and Gerber's model were shown inadequate to describe the mean stress effect on the fatigue strength, turning its use non-recommended; d) Kwofie's model presents a good prediction for the presence of mean stress but presents relatively high scatter; e) Walker's model was the best model to describe the effect of the mean stress on the fatigue strength of ASTM A743 CA6NM alloy steel.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

American Society of Testing Materials - "Manual of Fatigue Testing", 1949, Special Tech. Pub.
ASTM / E 468-90 - "Standard Practice for Presentation of Constant Amplitude Fatigue Test for Metallic Materials", 1990.
ASTM / E 739-91 - "Standard Practice for Statistical Analysis of Linear or Linearized Stress-Life (S-N) and Strain-Life (ε-N)", 1991.
Berkovits, A., Fang, D., 1993, "An analytical master curve for Goodman diagram data", Int J Fatigue, 15, pp. 173-80.
Gill, P. R., Murray, W., Wright, M. H., 1981, "The Levenberg-Marquardt Method" in Practical Otimization, London: Academic Press, pp. 136-137.

Kwofie, S., 2001, “An exponential stress function for predicting fatigue strength and life due to mean stresss”, Int J Fatigue, 23, pp. 829-836.

Lee, Y-L., Pan, J., Hathaway, R., Barkey, M. E., 2005, “Fatigue Testing and Analysis (Theory and Practice)”, Elsevier Butterworth-Heinemann, USA.

Lin, S-K., Lee, Y-L., Lu, M-W., 2001, “Evaluation of the staircase and the accelerated test methods for fatigue limit distributions“, International Journal of Fatigue, 23, p. 75-83.

Lipson, C. & Sheth, N. J., 1973, "Statistical Design and Analysis of Engineering Experiments", Mac-Graw-Hill Book Company.

Metals Handbook - "Properties and Selection: Irons and Steels", 1978, vol. 1, 9th edition, ASM International.

Norman E. Dowling, “Mechanical Behavior of Materials”, Prentice-Hall, 2nd edition, 1.

Smith, K. N., P. Watson, and T. H. Topper, 1970, “A Stress Strain Function for the Fatigue of Metals”, Journal of Materials, ASTM, Vol. 5, No. 4, 99. 767 - 778

Walker, K., 1970, “The Effect of Stress Ratio During Crack Propagation and Fatigue for 2024-T3 and 7075-T6 Aluminum”, Effect of Environment and Complex Load History on Fatigue Life, ASTM STP 462, Am. Soc. For Testing and Materials, West Conshohocken, PA, 1970, pp. 1-14.

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