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MEAN STRESS EFFECT ON FATIGUE AND FRACTURE PROPERTIES OF ASTM A743 CA6NM ALLOY STEEL

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Abstract. *In fatigue problems, the mean stress effect is responsible of the component resistance when it is subject to load dynamic conditions. The purpose of this paper is to evaluate the effect of mean stress on the fatigue life behavior and on the threshold stress intensity factor of ASTM A743 CA6NM alloy steel. This material is a stainless inox martensitc steel commonly used in the hydrogenator turbine components design. Fatigue tests under uniaxial fully reversed conditions were conducted to estimate the endurance limit for several load ratio (R = -1, -2/3, -1/3, 0, 1/3 and 2/3) considering the Walker´s model to account the relation between amplitude and mean stress. Fatigue crack growth tests were used in order to determine the threshold stress intensity factor considering standard specifications for several load ratio (R = 0.05, 0.1, 1/3, 0.5 and 2/3) considering the Elber´s model. From the obtained results it can be possible to conclude that this material is considerably sensitive to the presence of the mean stress independently of the point of view: fatigue or fracture. The tests provided enough conditions to determine the parameters that describe the fatigue and fracture behavior of the evaluated material. The most important contribution of this work is to supply consistent information to electric sector, mechanical manufacturing and to support mechanic designers to select the best input data that can optimize the hydraulic components design.*

Keywords: *mean stress, fatigue, fracture, endurance limit, threshold stress intensity factor.*

1. INTRODUCTION

Typically, industrial products are designed against all kinds of failure. In practice, many mechanical components work in hard dynamic load conditions. The fatigue problem is known as the failure due to repeated loading. Fatigue failures can be lead to large financial losses. In electric sector, the loss of earning can reach the figure of millions of dollars. Among several other factors that influence the fatigue failure, the relationship between maximum stress and minimum stress, mean stress, is very important aspect to be investigated. Its effect can reduce the fatigue resistance of the structural components. This work is applied to specific stainless inox martensitic alloy steel usually used in hydrogenator turbine components: ASTM A743 CA6NM. The purpose is to characterize its main fatigue and fracture properties under mean stress effect.

2. MATERIAS AND METHODOLOGY

2.1. Material: ASTM A743 CA6NM alloy steel

The main standard chemical characteristics of the ASTM A743 CA6NM alloy steel tested are shown in the Tab. (1) shows the chemical composition of this material according to ASTM A 743/A 743M standard and the mechanical properties (Young modulus, E, tensile strength, S_{rt}, and yield strength, S_y) of the two samples analyzed are showed in Tab. (2). The presence of the elements Chromium and Molybdenum gives good properties while operating in severe conditions of corrosion.

Table 1. Chemical composition of ASTM A743 CA6NM (ASTM, 2003).

Chemical Element	%wt	Chemical Element	%wt
Iron, Fe	82,9~88,1	Manganese, Mn	$\leq$ 1,0
Carbon, C	$\leq$ 0,06	Phosphorus, P	$\leq$ 0,04
Chromium, Cr	11,5~14,0	Silicon, Si	$\leq$ 1,0
Nickel, Ni	3,5~4,5	Sulfur, S	$\leq$ 0,03
Molybdenum, Mo	0,4~1,0	-	-

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Table 2. Mechanical properties of ASTM A743 CA6NM (ASTM ,2003).

Mechanical property	Value
Modulus of Elasticity	201 GPa
Yield Tensile Strength, min	550 MPa
Ultimate Tensile Strength, min	755 MPa
Brinell Hardness, max	285 HB
Poisson Ratio	0,30

2.1 . Fatigue tests

2.1.1. Specimen design

The specimens of the sample A were designed according to ASTM E 606-04 (ASTM, 2004) and sample B according to ASTM E 466-96 (ASTM, 2002). These standards specify the main dimensions of the specimen for a uniaxial fatigue test. Three different specimen were used in these tests: an A sample according to specimen 1, Fig.(1) and a B sample according to specimen 1 and 2, Fig.(1) and Fig.(2). The Tab. (3) indicate the respectively data.

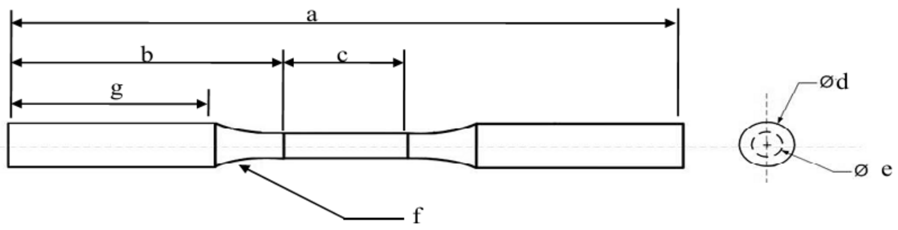

Figure 1. Fatigue specimen 1 for samples A and B

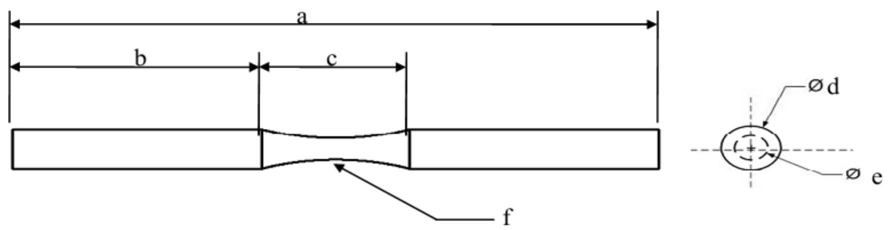

Figure 2. Fatigue specimen 2 for sample B

Table 3. Fatigue 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	-

2.1.2. Experimental Methodology

The fatigue tests under axial loads were performed in the MTS 810, universal testing machine. The standards ASTM E 468-90 (ASTM, 1990) and ASTM 739-91 (ASTM, 2004) define the minimum of 12 specimens with a reproduction of 50 to 75% that must be tested to obtain the S-N curves in order to determine the critical values of design. 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 uniaxial 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, -2/3, -1/3, 0, 1/3 and 2/3.

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2.1.3. Strategy for evaluation of mean stress models adherence

The strategy used to evaluate models adherence consists in to compare the endurance limit provided by Basquin equation and the endurance limit predict by Walker's equation. To perform this comparison the three parameters that characterize the fatigue test were used: mean stress, S_m, alternating stress, S_a, and the resulting life, N. The application of the data which characterize the mean and alternating stress allows to evaluate, through extrapolation of equation when $S_m = 0$, the equivalent fatigue strength according to specific mean stress model, called S_{ar} Model. In a similar way, the application of the value of resulting life, N, in the Basquin equation allows to estimate a new value for the equivalent endurance limit, called S_{ar} Basquin. After estimate these parameters, if the prediction model was adherent to the experimental results, the values of S_{ar} Model and S_{ar} Basquin should be identical statistically. The mean stress model used was the Walker (1970), with can be expressed by the Eq.(1) where R is the ratio load.

$$S_{ar} = \sigma_a \left(\frac{2}{1-R} \right)^{1-\gamma} \tag{1}$$

The exponent γ is coefficient to adjust the curve to the experimental data. The value of γ is on the Tab. (4).

Table 4. Parameter that characterize Walker's model

Parameter	Expected value		Confidence intervals	
	Mean	**Standard deviation**	**Lower Limit**	**Upper Limit**
γ	0,3658	0,004	0,3578	0,3737

2.2 Fracture tests

The tests were performed using Compact Tension Specimen (CT), showed in Fig. (3). The main dimensions are listed in Tab. (5).

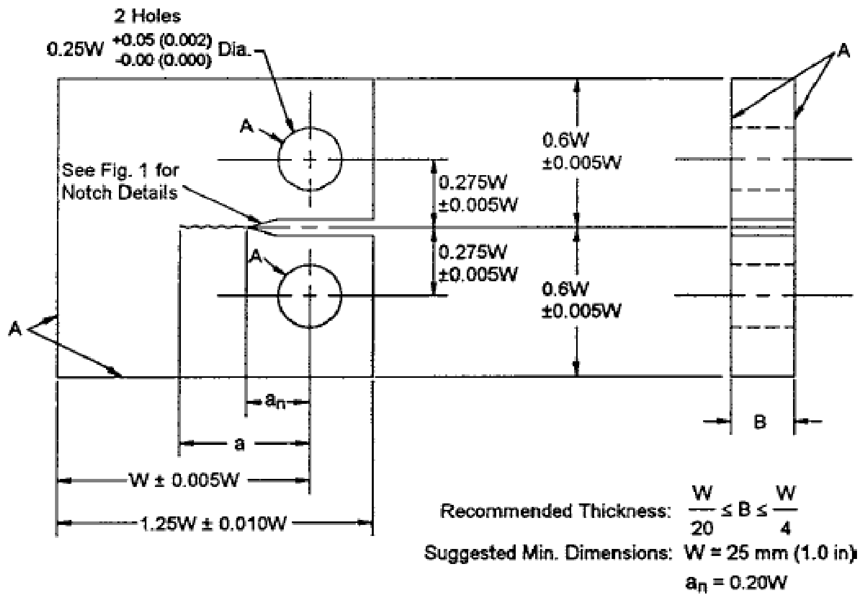

Figure 3. Scheme of compact tension specimen (ASTM, 2011).

Table 5. Main dimensions of the CT specimen.

Component	Dimension (mm)
W	50,0
b	12,5
a_n	10,0
D	12,4

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The fatigue crack propagation tests were performed in a MTS 810 servohidraulic machine, according to the ASTM E647 standard, at 25 Hz of frequency, controlling the decrease of ΔK. The crack length was measured by the compliance method using the bellow equation, Eq. (2):

$$a = \frac{1}{W}\left(C_0 - C_1.u_x + C_2.u_x^2 - C_3.u_x^3 + C_4.u_x^4 - C_5.u_x^5\right) \tag{2}$$

where a is the crack length, W is a characteristic length of the specimen and the constants $C_{0,}$ $C_{1,}$ $C_{2,}$ $C_{3,}$ $C_{4,}$ and C_5 where calculated by Saxena (1977). The value of u_x is obtained by the Eq. (3):

$$u_x = \left[\left(\frac{E\upsilon b}{P}\right)^{0.5} + 1\right]^{-1} \tag{3}$$

where E is the modulus of elasticity of the material, P is the applied load and v is the crack opening displacement, given by a clip gage, showed in Fig. (4), putt in a position inside the crack mouth.

Figure 4. Clip gage.

For each load ratio, the fatigue crack growth tests were replicated. The Tab. (6) shows the load ratios applied in each specimen tested.

Table 6. Specimen and respectively load ratio during test.

Specimen	Load Ratio, *R*	Specimen	Load Ratio, *R*
CP 01	0,10	CP 07	0,05
CP 02	0,33	CP 08	0,05
CP 03	0,50	CP 09	0,33
CP 04	0,66	CP 10	0,50
CP 06	0,10	CP 11	0,66

3. RESULTS AND DISCUSSIONS

3.1 Fatigue results

The experimental data and its respective trend lines, for such ratio loading, are shown in Fig. (5) and the parameters that characterize the fatigue strength are resumed in the Tab. (7). The endurance limit 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.

With the exception of the S-N curve for load ratio, R = -1/3, the other curves showed parallelism between them. Although the S-N curve for the load ratio, R = -1/3, cross the S-N curve for the load ratio, R = 0, the predicted value for the endurance limit for one million and two million cycles appears superior to that of R = 0, as expected . It's noted there is a change in the inclination of the S-N curves after curve of load ratio, R=1/3, in order to present a curve almost parallel to Life axis in the curve of load ratio, R= 2/3.

3.2 Model´s adherence to experimental results

The fatigue experimental data and the predictions based on Walker's model are showed in the Figs. (6) and (7). 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.

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Table 7. Parameters that characterize S-N curves

R	Basquin's constant (A) [MPa]		Basquin's exponent (B)		Endurance limit to 10^6 cycles [MPa]		Endurance limit to 2.10^6 cycles [MPa]	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
-1	1636.34	109.33	-0.1048	0.0055	384.60	26.51	357.35	26.76
- 2/3	1328.24	195.29	-0.0972	0.0117	346.87	19.29	324.28	20.40
- 1/3	1213.52	430.64	-0.1093	0.0272	267.89	23.91	248.34	26.01
0	1284.51	229.15	-0.1186	0.0147	249.57	28.11	229.87	28.80
1/3	563.79	91.3	-0.0785	0.0129	190.49	9.29	180.40	10.20
2/3	197.38	129.55	-0.0271	0.0497	135.66	16.63	133.14	19.05

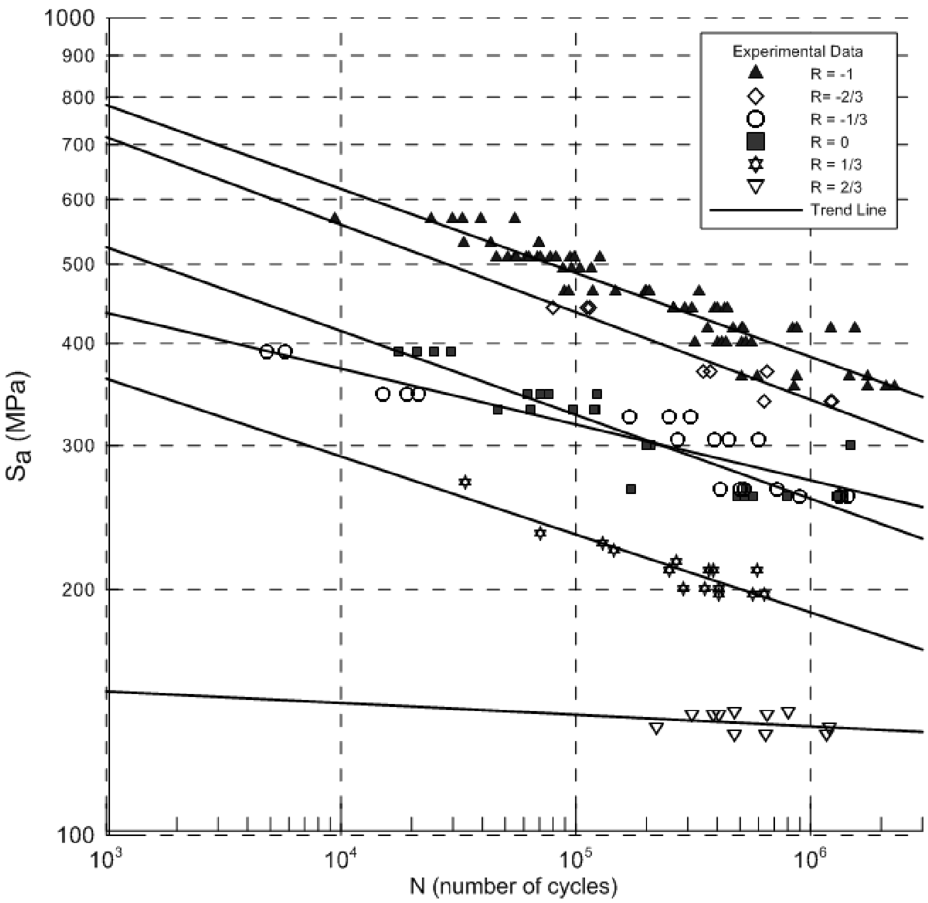

Figure 5. S-N curves about the effect of mean stress.

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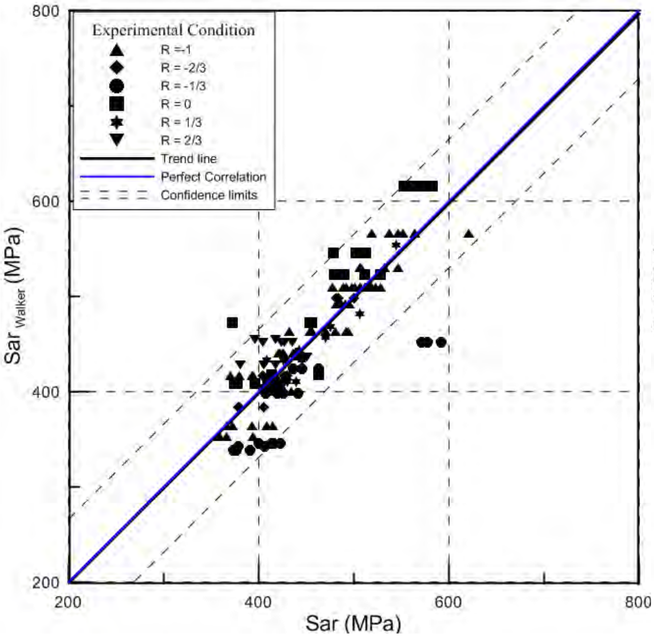

Figure 6. Walker's prediction

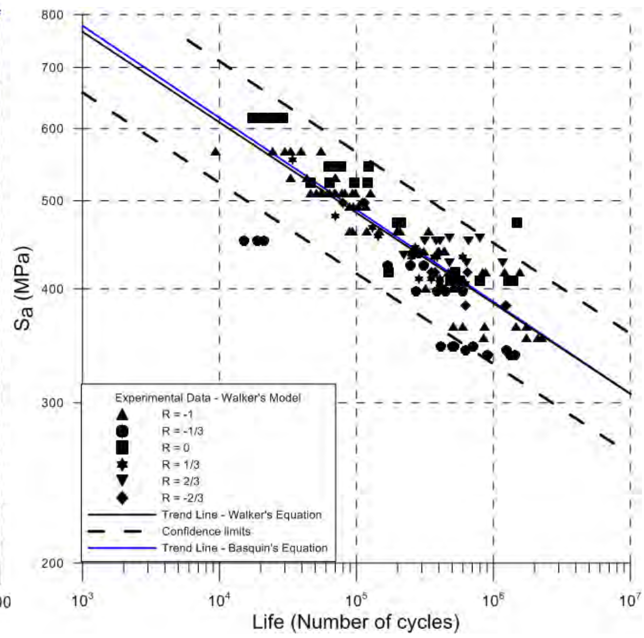

Figure 7. Walker's scatter diagram

3.3 Fracture results

The Fig. (8) shows the relationship between fatigue crack growth rate, da/dN, and the range of stress intensity factor, ΔK, at different load ratios.

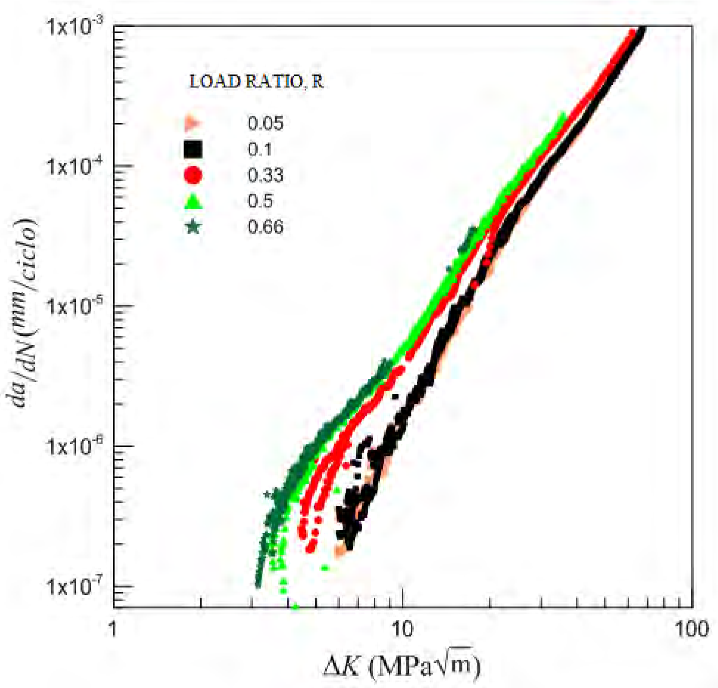

Figure 3. Graphic *da/dN versus* ΔK.

It can be observed that *da/dN* changes almost linearly with ΔK at all load ratios when *da/dN* is above 10^{-5}mm/cycle. In the loading –shedding process. the value of da/dN accordingly. However. for *da/dN* below 10^{-5}mm/cycle. *da/dN* varies nonlinearly with with ΔK. and ΔK reduces slowly. The larger the load ratio. the higher *da/dN*. The range of stress intensity factor at which the crack growth rate reached the value 10^{-7} mm/cycle was defined as the ΔK_{th}. The Tab. (8) shows the values ΔK_{th} for the 5 different load ratios studied.

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Table 8. Values of ΔK_{th} .

R	CP	ΔK_{th}		
		Avarege	Min limit	Max limit
0,05	7	5,67	4,63	6,94
0,05	8	5,39	4,76	6,12
0,10	1	5,57	5,27	5,88
0,10	6	5,39	4,54	6,39
0,33	2	3,43	2,76	4,28
0,33	9	4,73	2,49	8,99
0,50	3	2,85	2,24	3,63
0,50	10	3,98	2,78	5,72
0,67	4	2,87	2,58	3,19
0,67	11	2,79	2,60	3,00

4. CONCLUSIONS

Using the S-N curves obtained from the experimental data, it is possible to infer: a) the fatigue strength limit for this alloy steel is 384.60 MPa for a life of one million cycles and 357.35 MPa for a life of two millions cycles; b) the fatigue life is strongly influenced by the presence of mean stresses, having a superior reduction around 65% in the endurance limit; c) Walker's model is a good model to describe the effect of the mean stress on the fatigue strength of ASTM A743 CA6NM alloy steel.

Ten valid crack propagation tests were performed in order to evaluate the influence of the load ratio on the value of ΔK_{th} for the martensitic alloy steel ASTM A 743 CA6NM. The values of ΔK_{th} have been found for the following load ratios: 0.05; 0.1; 0.33; 0.5 and 0.66. It has been quantified that ΔK_{th} decreases while the load ratio is increased in interval of ratios analyzed.

The most important contribution of this work is to supply consistent information to electric sector, mechanical manufacturing and to support mechanic designers to select the best input data that can optimize the hydraulic components design.

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