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DESIGN AND CONSTRUCTION OF A MACHINE FOR FATIGUE TESTS BY ROTATION AND FLEXION

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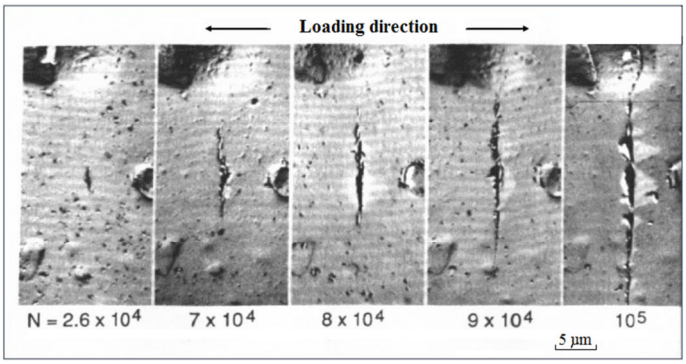
ABSTRACT

This work proposes the design and construction of a machine capable of inducing the fatigue phenomenon by associating the rotation and flexion movements in standardized test bodies, being able to be applied in several types of materials in order to verify their resistance. The machine has a simple and robust structure with immediate decoupling system after failure. This equipment was built to meet the needs of practice and research of the institution.

Keywords:. fatigue, flexion, rotation, fatigue failure, flexor fatigue.

INTRODUCTION

Fatigue is a type of mechanical failure, caused mainly by the application of loads that vary over time. Its main feature is a gradual process of nucleation and crack growth which can lead to component rupture. This cumulative and localized fracture process can be caused by low variations in service loads and can be quite slow, taking several cycles up to its failure. (Hibbeler, 2000). In general, fatigue cracks are nucleation in singularities or discontinuities in virtually all materials. Discontinuities may be superficial or internal to the material. The singularities can be structural, such as inclusions, particles of impurity or even geometric, such as scratches.(Rosa, 2002) and (Nascimento, 2011). One of the possible explanations for nucleation of fatigue cracks occur in most cases on the surface may be due to the fact that plastic deformation is easier on the surface and slippage of steps also occur on the surface, in addition to the fact that the maximum stress will always be positioned at some superficial point. (Shigley, 2005). Figure 1 shows the nucleation and propagation of a surface crack.



(a) Crack for flexion (adapted for Milfont and Oliveira, 2016)

(b) Crack for intrusion and extrusion

Fig. 1 - Nucleation phenomenon and propagation of a surface crack

FATIGUE RESISTANCE

And the ability of a material to withstand cyclic loading conditions. However, in the presence of a measurable plastic deformation, the materials respond differently to the cyclic deformation than to the cyclic stress. (Torres, 2003)

Cyclic loading will produce cyclic stresses which, in turn, will produce cyclic deformations. These deformations are elastic in a first moment, however, over time, small plastic deformations begin to appear starting from existing micro structural defects or geometric discontinuities of the material. These plastic deformations are permanent deformations and tend to increase over time and use of the equipment. Therefore, for fatigue failure it is necessary that three factors be applied simultaneously in the material: a) dynamic demands, b) tensile stress, c) plastic deformation. (Rosa, 2002)

The characteristics described below, are factors of great impact when the subject is the resistance to fatigue of materials:

- *Surface finish*: the better the surface finish the greater its fatigue strength.
- *Size of the piece*: these are inversely proportional quantities, that is, the larger the component, the lower its resistance to fatigue.
- *Temperature*: the metals present an increase in their resistance to fatigue with the decrease of the temperature.
- *Stress concentration*: all discontinuities such as notches, holes and grooves modify the distribution of voltages, causing an increase in localized voltages at certain points.
- *Microstructural effects*: the fatigue of steels occurs due to their microstructure as well as the level of impurities present. A tempered and quenched material has better fatigue characteristics than in its normalized / annealed state.

The limit of resistance to fatigue is determined from the following variables, they are: (Filho, 2010):

- S_f: Fatigue resistance limit for finite life of the test body cycles, where equations 01 and 02 define the boundary conditions.

$$S_f = 10^c . N^b \tag{01}$$

$$N = S_f^{\frac{1}{b}} . 10^{-\frac{c}{b}} \tag{02}$$

Were, $b = -\frac{1}{3} . log \frac{0,8.Sut}{Se}$ e $C = log \frac{(0,8.\ Sut)^2}{Se}$

- S_e: Fatigue resistance limit for infinite life of the test body $10^3 \leq N \leq 10^6$,where it is determined by equation 03..

$$S_e = k_a\ x\ k_b\ x\ k_c\ x\ k_d\ x\ k_e\ x\ k_f\ x \ldots x\ S_e \tag{03}$$

Where, S_e is the resistance limit of the fatigue element of the machine element, S_e' is the limit of resistance of the test body, k_a is the surface finish factor, k_b is the size or

dimension factor, k_c is the reliability factor, k_d is the temperature factor, k_e is the stress concentration factor and k_f is the factor for other effects.

The behavior of the fatigue can be seen in figure 02 below.

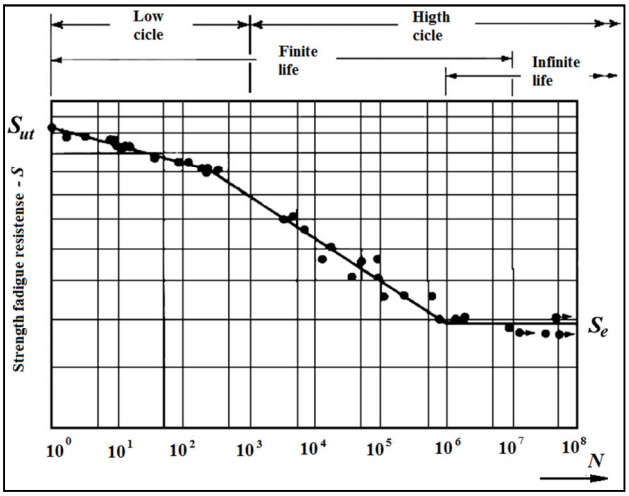


Fig. 2 - Curve S-N (adapted Rosa, 2002)

RESISTANCE TO FATIGUE FOR INFINITE LIFE - Estimative for factors k

The surface of a specimen undergoes a final polishing in the axial direction aiming at a finish without any notch effects (manufacturing marks). The factor "ka" depends on the quality of the final workpiece finish and tensile strength of the constituent material, being mathematically defined by equation 04 (Nascimento, 2011).

$$k_a = a.S_{ut}{}^b \tag{04}$$

Where, S_{ut} is the minimum tensile strength; And a and b can be determined from table 02 below.

Table 1 - Parameters for the surface modification factor (Shigley, 2005)

Surface Finishing	*Factor a* S_{ut} *(Mpa)*	*Exponent b*
Rectified	1.58	-0,085
Machined or cold rolled	4.51	-0,265
Hot rolled	57.7	-0,718
Wrought	272	-0,995

DIMENSION FACTOR (k_b)

The calculation of the dimension factor for flexions and torsions is given by equations 05 when (2.79 ≤ d ≤ 51 mm) and 06 when (51 ≤ d ≤ 254 mm)

$$k_b = \left(\frac{d}{7{,}62}\right)^{-0.1133} = 1.24d^{-0.107} \tag{05}$$

$$k_b = 0.859 - 0.000837d \tag{06}$$

For values above 254 mm, k_b ranges from 0.60 to 0.70 for bending and twisting. If the part is under axial loads, the diameter does not interfere on the fatigue resistance limit, therefore, we adopt $k_b = 1$. When the part is not rotating or the cross section is non-circular, the factor value must be calculated. In these cases the effective diameter is used, which is obtained by equating the volume of the material subjected to the load and 95% of the maximum load for the same volume of the test piece. (Shigley, 2005) and (Torres, 2011).

In the case of parts with non-circular sections, the effective diameter is calculated through equation 07.

$$d_e = 0{,}808.(bh)^{1/2} \tag{07}$$

Where, h is the height, b is the width of the rectangular section.

RELIABILITY FACTOR (k_c)

It is the probability of an element or equipment delivering faultless performance over a period of time, set by the designer, under specified conditions, it is the probability of some type of failure occurring (Shigley, 2005). The table 2 represents the values of k_c.

Table 02 - Reliability Factor (Shigley, 2005)

Reliability	*Reliability factor (%)*
50	1.000
90	0.897
95	0.868
99	0.814
99.9	0.753
99.99	0.702
99.999	0.659
99.9999	0.620

TEMPERATURE FACTOR (k_d)

When the design component will operate at a temperature other than the temperature at which the fatigue tests were performed, a correction in the fatigue strength of the material is required to suit the working temperature. With this, the temperature factor can be defined according to equation 08.

$$k_d = \begin{cases} 1 \rightarrow T \leq 350°C \\ 0.5 \rightarrow 350°C \leq T \leq 500°C \end{cases} \tag{08}$$

TENSION CONCENTRATION FACTOR (k_e)

The stress concentration is present in structures containing curvatures, notches and other form of significant perturbation in part geometry. The theoretical concentration factors, "Ke", are obtained experimentally or can be obtained in proper tables and graphs, as shown in figure 03 below. (Shigley, 2005).

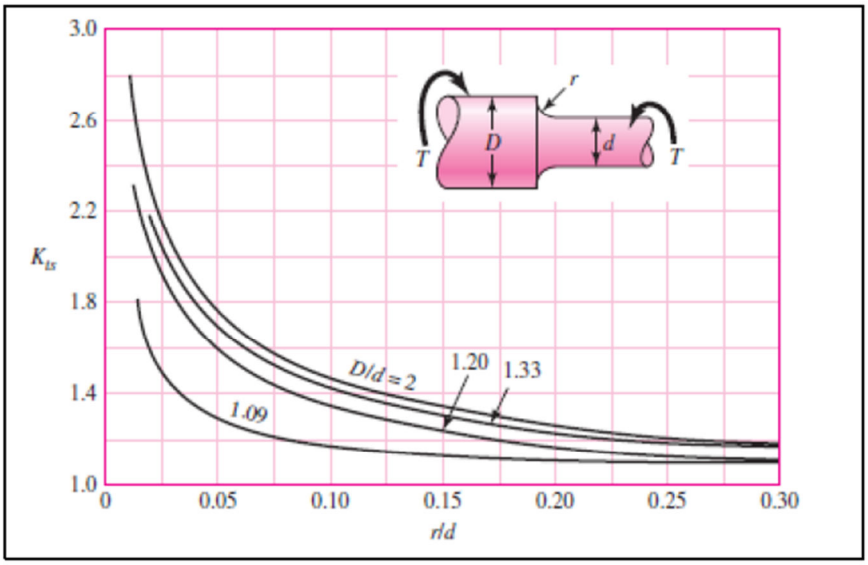


Fig. 3 - Theoretical concentration factor (Shigley, 2005)

This factor, when multiplied by the stress "σ0" (calculated by the mathematical model without the existence of notch), allows determining the maximum stress that acts on the notch according to equation 09 (Shigley, 2005).

$$\sigma_{max} = k_t . \sigma_0 \tag{09}$$

Depending on the material or its resistance, this geometric or theoretical stress concentration factor, "kt", undergoes changes, decreasing its intensity as a function of the "q" sensitivity of the notch. The relation that determines effective or practical factor was defined by Peterson by equation 10 (Shigley, 2005).

$$q = \frac{k_f - 1}{k_{t-1}} \rightarrow k_f = 1 + q(k_t - 1) \tag{10}$$

Where, k_t is the factor of static tension concentration and k_f is the stress concentration factor in fatigue.

The sensitivity to notch depends on the tensile strength limit and notch radius. The experimental values use this sensitivity varying from 0 to 1, with the most used values being between 0.6 and 0.9. (Shigley, 2005).

Calculating the factor "k_f", we can use equation 11 below to find the corrective factor k_e.

$$k_e = \frac{1}{k_f} \tag{11}$$

VARIABLE FACTOR MODIFICATION FACTOR (k_f)

The miscellaneous effects modification factor is reserved for any other type of effect that occurs on the equipment or machine element that was not mentioned. As an example we have residual stresses, corrosion, chemical environment and so on.

FATIGUE TESTING

The equipment that performs this type of test is constituted by a system of application of loads, allowing the change of intensity and direction of the effort. The tests are related to the type of effort to be applied. Among these tests, the most used are: traction-compression, torsion and rotational flexion (Shigley, 2005) and (Norton, 2004).

ROTATING FLEXION

This test consists of a test specimen subjected to bending stresses, while it is rotated about an axis, by a motor system, in a specific and constant rotation. The test starts with a certain voltage level until the rupture occurs, and the number of cycles and the voltage up to rupture are recorded. It runs with different specimens of the same material, changing only the applied voltage. The collected data are represented in diagram S - N. (Silva and Arevalos, 2011) and (Norton, 2004).

The equipment used to perform the rotary flex fatigue tests consists of a rotary counter, an electric motor, a load applicator, and supports for the test body. The motor generates the necessary rotation for the tests. The rotation counter records the number of cycles until the specimen is ruptured. For bending to occur, devices capable of applying a given load to the specimen are required, ie by the load applicators. The fixation and support of the test piece are made by mandrels and forceps (Norton, 2004).

Below, in figures 04 and 05, two models of equipment for the test of fatigue by rotating flexure are presented. The first has load application at both ends of the test body, while the second, has load application in only one end of the body.

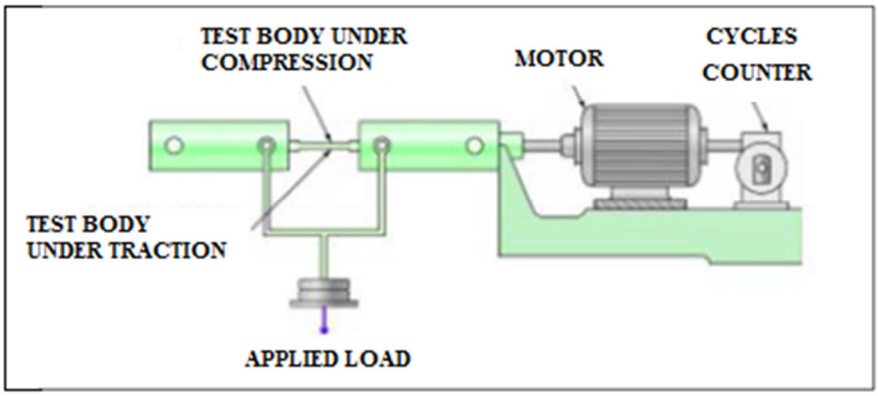


Fig. 4 - Schematic of a rotary bending fatigue test machine (Udomphol, 2012)

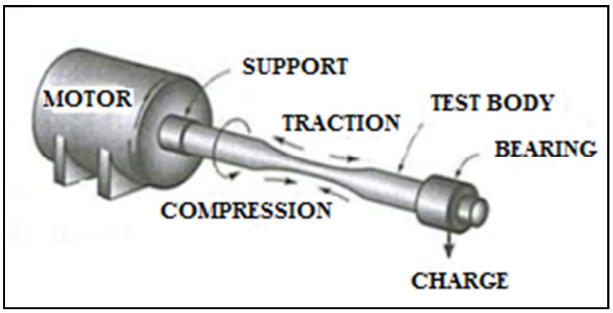


Fig. 5 - Schematic of a rotary bending fatigue test machine (Udomphol, 2012)

PROOF BODY

The test bodies used in the fatigue test vary according to the purpose of the test, the equipment, the capacity of the equipment and the way in which the material is available. In order to perform this type of test and the stress dynamics (life and deformation), standard test specimens are required in the pre-established standards. These standards specify the required dimensions and test conditions.The most used in these types of tests are generally: cylindrical with straight and cylindrical profile test section with test section defined by a radius of agreement (Norton, 2004).

The cylindrical model must follow the ASTM-606-04 standards, which specify the specimens for uniaxial loading fatigue tests with deformation control, and are applicable both for the lifting of the S-N curve and the ε-N curve of the material To be tested (Norton, 2004).

The figure 21 shows test pieces according to ASTM.

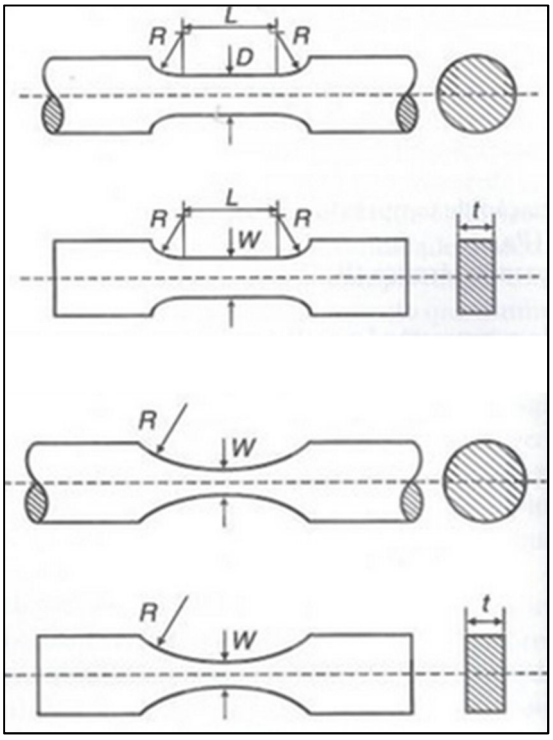


Fig. 6 - Test bodies according to ASTM E1823, E1150, E466 (Filho, 2012)

METHODOLOGY

The development of this work was divided in the following stages: initially we carried out a bibliographical revision of the theory about fatigue tests and then focusing on the type of rotational flexion. As a second step, we researched the main existing test machines for this type of test, and then chose type with load bearing at both ends of the rotary axis. Having chosen the type of machine to be analyzed, a design of the basic mechanical components of the system was carried out. The proposed kinematic scheme is shown in figure 7.

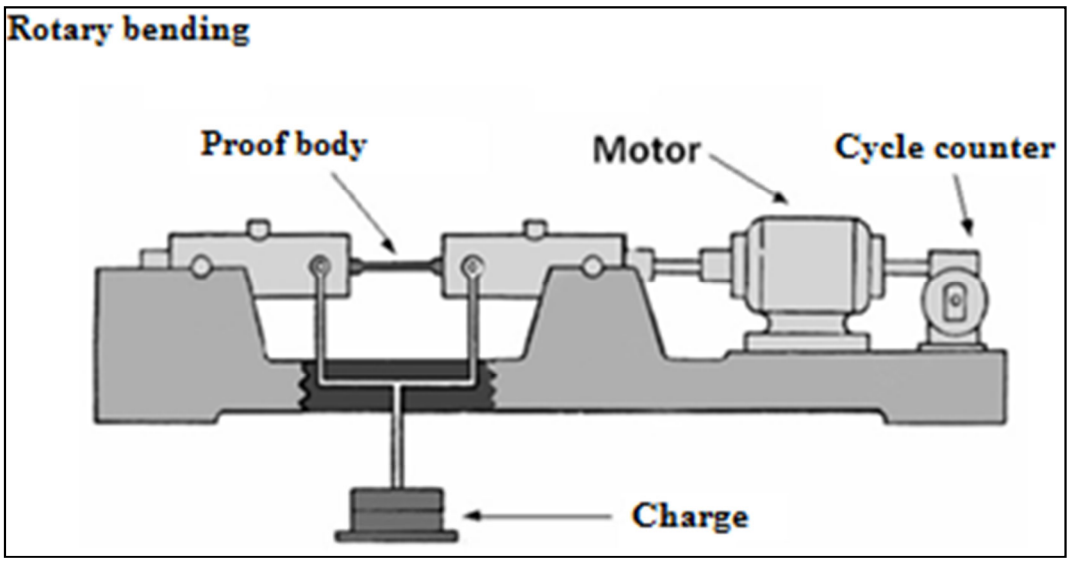


Fig. 7 - Proposed initial scheme

Through the drawing software Unigraphics NX 9.5 an outline of the project to realize the budget was realized. The project was finalized in January 2017 and the equipment is undergoing functional tests. Some improvements may be made, because as the tests involve cyclic loads, the need to include flexible couplings in order to mitigate vibrations is analyzed. From the system itself.

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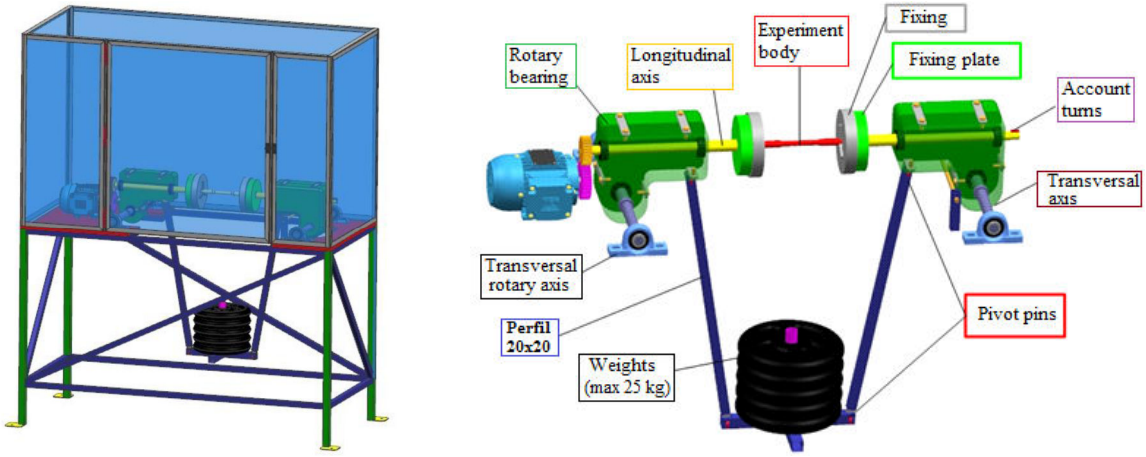
RESULTS AND CONCLUSIONS

The machine after design and construction, presents the configuration of figure 8 below where all its components can be seen



(a) Structure complete. (b) Description of components.

Fig. 8 - Machine per rotation and bending fatigue.

The stress (S) is generated by the weights that are added during the tests (washer gym), being able to be up to 25 kg, in which the cycles (N) are measured by a counter coupled to the axis of rotation, and can generate the points for a curve S-N. The table 03 showing the values for resolution the equipment.

Table 3 - Weight ratio for equivalent stress

Washer (gym)	1	2	3	4	5
Weight (kg)	5	10	15	20	25
Stress (Mpa)	50	100	150	200	250

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