24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-1745
MODELING OF AN EQUIPMENT FOR THERMAL FATIGUE TESTING

Sérgio Alves da Silva
sergio.alves@ifpi.edu.br
Ayrton de Sá Brandim
brandim@ifpi.edu.br
Antônio Edson Rocha Filho
Federal University of Santa Catarina, SC, Brazil
edson_engmec@hotmail.com
Flávio Alves dos Santos
Universidade Estadual do Ceará, CE, Brazil
flavio.alves@aluno.uece.br
José Oliveira Neto
Instituto Federal de Educação, Ciência e Tecnologia do Piauí, PI, Brazil
oliveirant@hotmail.com

Abstract. *This paper presents all the logical sequence for the studies carried out in the development of a thermal fatigue testing equipment, a work that allowed to put into practice technical and theoretical knowledge acquired from Science of Materials and Machine Design areas. In the design, the following parameters were taken into consideration: the final dimensions of the machine, the geometry and the type of the specimen, the total restriction and the control of the state of stress applied to the specimen in the test. The monitoring and control of those data will be achieved by using a data acquisition system, that will allow their correction "in locus" during the process.*

Keywords: *Thermal fatigue, Machine Design*

1. INTRODUCTION

At the time of a static failure, a machine part usually suffers a very large deflection, since the stress has exceeded the yield strength. Thus, many static failures signalize in advance a possible fracture and the part can be replaced before that comes to occur. However, according to Shigley (2008), the same does not happen with fatigue failure, that one is sudden and total, being therefore very dangerous. According to Callister (2008), the importance of fatigue stands in the fact that it is the main single cause of failure in metals. It is estimated that such failure comprises approximately 90% of all metal failures.

The thermal fatigue induces the part to go into states of expansion and contraction constantly. That situation causes elastic deformations in the piece and, in some cases, also plastic and permanent deformations. Regardless of how cracks can be formed by the thermal fatigue process, that type of behavior can reduce the lifespan of the parts, leading to premature failure.

The actual situation of thermal loading in service of structures and parts of machines is difficult to reproduce accurately in laboratory. However, the reproduction of the thermal cycles received must be as exact as possible. According to Brandim (2002), the specimen used in the test must be able to reproduce the working conditions of the component. That way, the results obtained would allow to evaluate the life in service of the tested material, identifying the factors that influence the durability of the alloys used.

The present work aims at the design of a small-sized thermal fatigue testing machine for using of standardized specimens, within a certain range of lengths, obeying the limits established in the standard ABNT NBR ISO 6892-1:2013. It is guaranteed the total restriction of the specimens, in order to prevent its dilation or contraction.

2. EXPERIMENTAL PROCEDURE (OR COMPUTATIONAL PROCEDURE)

Design can be defined as the set of calculations, drawings, manufacturing and assembly specifications of a structure. The design of any machine gathers the dimensioning of various components, such as motor, shafts, keys and bearings. The electric motor used is defined by the own operating parameters of the machine. The motor chosen is the WEG W22, that has the following characteristics: three-phase, four-pole, air-cooled and maximum power of 0.50 HP. After that choice, the dimensioning and the selection of the machine components was carried out.

In the machine, six axes are used. The first axis, or central axis, transmits speed and torque from the electric motor to the machine and the other five axes are intended to serve as support for the machine, by limiting the freedom of the specimens to dilate or contract during the test phases. Throughout its use, the central axis will suffer torsion and flexion, due to the torque transmitted by the fixed reduction system; while the other axes, as stationary (non-rotating) ones, become statically loaded while the loads are fixed in time. However, according to Norton (2004) such a non-rotating axis is not a transmission axis, since it is not transmitting any torque. That is, it is merely a non-rotating shaft, or a round beam, and can be designed as such.

It is known that most shaft failures occur due to loads that vary over time rather than to static stresses, and those failures generally occur at stress levels typically lower than the values of the material's yield strength. Thus, when dynamic loads are involved, theories for static loads can lead to unsafety projects, so the transmission axes must be dimensioned also considering fatigue failure.

The bearing can be defined as a support or guide on which the shaft is supported. The operation of modern machines depends mainly on the perfect functioning of their bearings. The failure of bearings, whether by sliding or by rolling, is enough reason to make machines to stop working, causing production losses. Rolling bearings are used when higher speed and lower friction are required. According to Norton (2004), rolling element bearings can be grouped into two general categories, ball bearings and roller bearings, both with many variations within these divisions.

Unlike cylindrical roller bearings, ball bearings have the capacity to work at high speeds and withstand medium loads, and therefore were used in this project. In this work, two bearings will be used, one at each end, to ensure a fit loading distribution. Each bearing will contain a keyed bushing, in order to make it a removable coupling, facilitating both the assembly/disassembly and maintenance of the system.

According to Norton (2004), ASME defines a key as "a part of disassembled machinery which, when placed in seats, represents a positive means of transmitting torque between the shaft and the hub". Keys are standardized by size and shape in various styles. They can be of several models, and the one used in this work was the parallel key, due to ease of design and manufacturing. Each component must have one of those couplings, to prevent relative movement with its axis. The keys are dimensioned from the shear caused by the transmitted torque and from the diameter of the shaft.

According to Norton (2004), since the keys are loaded in shear, it is recommended that materials used in their manufacturing were slightly more ductile than the materials used in the transmission axes. So that, in case of overstress in the system, not foreseen in the design stage, the key fails before other components can suffer any disturbance.

The main purpose of the clamping wheels is to accommodate the machine components, besides withstand all clamping efforts. The manufacturing material used depends on the service conditions of the equipment. For this work, AISI 1045 steel was chosen for the preparation of the clamping wheels. Its characteristics are presented in Table 1. As it is a component that depends directly on the loads imposed in its full operation, the most indicated way of dimensioning that element is through the Finite Elements Method (FEM), whose objective is to determine the state of stress and deformation of a solid of arbitrary geometry subject to external actions.

Table 1. Mechanical characteristics of AISI 1045 steel.

Material	*Tensile strength*	*yield strength*	*Modulus of Elasticity*
AISI 1045	*625 MPa*	*530 MPa*	*200 GPa*

In the design of the specimen, the cylindrical geometry was chosen in order to avoid live corners, that could generate stress concentration, as shown in Figure 1. The diameter of the reduced section is 6 mm, to ensure that the temperature reading was achieved both by thermocouples and by optical pyrometers, inside and on the surface, respectively.

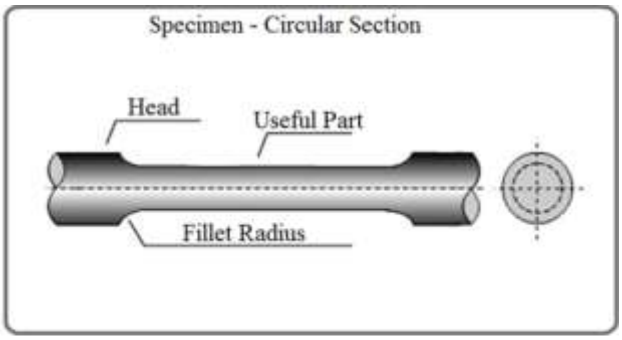

Figure 1. Geometry of the specimen.

According to Brandim (2009), during the thermal fatigue test, the specimen must be subjected to intense thermal gradients without the possibility of expanding and contracting freely, inducing the production of thermal stresses. In order to ensure the reproducibility of the test, the specimens in the condition of total restriction (hyper static systems) cannot exhibit either the phenomenon of buckling or folding.

Structures and machines are two types of assemblies often composed of elements with multiple forces and connected by pins or screws. The analysis of structures and machines are performed with the application of equations of equilibrium for forces and moments. For this project, the Finite Elements Method (FEM) was used, in order to have a more accurate approximation in the dimensioning. The main function of the machine structure is the support of the equipment and the accommodation of its components. The structure of the components will be fabricated of 40 mm x 40 mm steel square tube, with a 2.0 mm thick wall.

The electronic module will be responsible for receiving, accommodating and processing the electronic signals, received through the load cell, coupled to the specimen that will receive the stimuli, and through a radio frequency module. Those data will be sent to a computer with a software capable of processing and displaying results.

The fixed reduction or speed reducer system is a coupling of gears or pulleys, intended to increase the "force" of the engine. For this work, the spur gears system was used.

3. RESULTS AND DISCUSSION

As it generates very complex strength calculations, the Finite Element Method was used with the aid of the CAE platform (Computer Aided Engineering), in the software SOLIDWORKS®, to calculate the maximum requests that the fixing wheel will be subjected to in this application. Thus, it was designed to be reinforced by support axes, and will be built in AISI 1045 steel, which proved to be advantageous in terms of mechanical strength, besides being widely used in this type of application and easy to find in the marketplace. The wheel should have a minimum thickness of 16 mm, resulting in a comfortable safety coefficient to the application. Figure 2 shows the Finite Element analysis of the wheel.

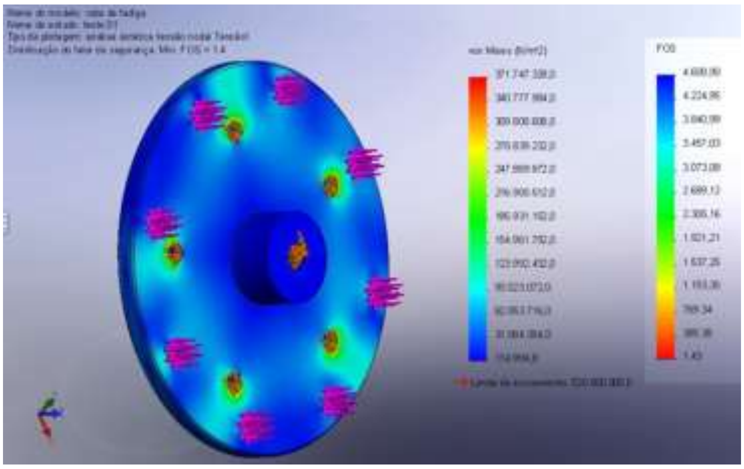

Figure 2. Analysis of finite elements of the fixing wheel.

In order to better control the rotation of the equipment, an electric control system and a fixed gear reduction system will be used. These systems rely on a frequency inverter, whose function is to reduce and control the rotation of the machine by maintaining it at the values determined by the test, and a pair of gears, which is intended to facilitate the use of the inverter, since it must operate with at least 10% of its capacity. For the fixed reduction, a reduction ratio of 4.0 was chosen, thus reducing the engine speed in half.

For standardization, and after the necessary calculations have been carried out, it was concluded that the central axis and the supporting axes (Figure 03) should have the nominal diameter of 20 mm and 16 mm, respectively. The material chosen for the manufacture of these was the steel AISI 1045 (medium carbon), as it combines good machinability and high resistance. In order to calculate the necessary reactions to the axis design, FTOOL® software was used; a structural calculation software that stands out for its simplicity and practical side.

Figure 3. Transmission axes.

Observing the objectives of this project, buckling tests were carried out on the support axes, in order to ensure that they would withstand the loads imposed, in compliance with the criteria of impossibility of dilatation or contraction of the specimens, as shown in Figure 4.

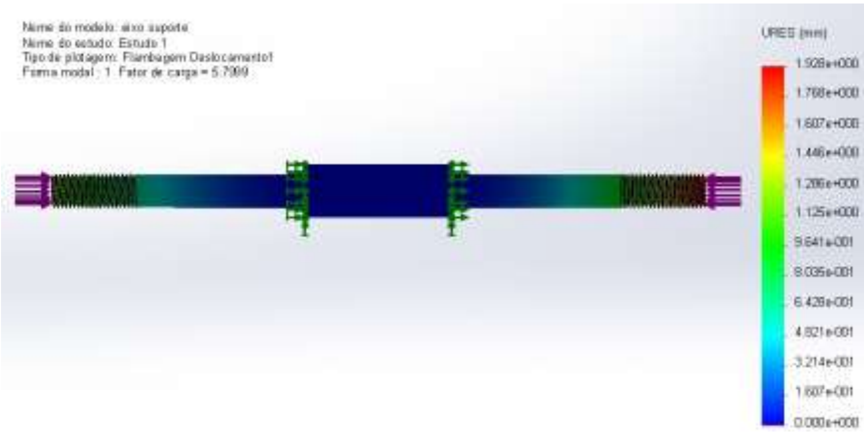

Figure 4. Analysis of finite elements of the support axis.

In addition to the fixing wheel and support axis, static simulations were also carried out around the machine structure, in order to facilitate its design, as well as to obtain a sturdy and low weight structure, as shown in Figure 5.

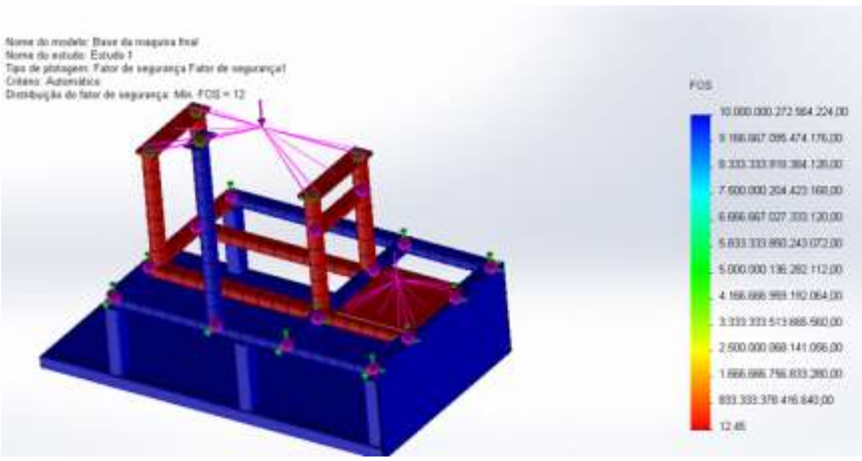

Figure 5. Analysis of finite elements of the machine structure.

Based on the nominal shaft diameter and DIN 6885/1, the keys must have a rectangular cross-section of 6 x 6 mm and a length of 400 mm, and be made of AISI 1020 steel, a mild carbon steel, for reasons already mentioned previously.

The GBR Bearing UC207 (ball rigid) was chosen to compose the system, based on the limits of rotation and dynamic loads (radial and axial) to which it will be subject, as well as price and facility of finding them in the market, thus guaranteeing a good access to spare parts.

The heating system of the specimens shall be made using a cutting torch positioned at the top of the structure, so to concentrate the flame in the center of the specimen. The cooling system will be formed by a tank, responsible for store the water used by the equipment during the entire test, and a hydraulic pump, responsible for suctioning the water and transporting it, through pipes, to the equipment.

During all phases of the test, the bodies will be monitored by the electronic unit that has a load cell, an amplifier, among other components. The load cell, in this case, will be the Líder Balanças' CS250 model, capable of supporting 5000 Kgf of load, that will be coupled to a signal accommodation module. The electrical stimulus applied to the load cell is 5 V; that signal is amplified through an INA125 amplifier, used in precision instrumentation and, following the signal flow, it will be converted into a digital signal through an A/D (analog to digital) converter, MCP3551, with a resolution of 22 bits.

This digital signal will be received by an Arduino Pro Mini model, where the data will be accommodated and sent through an XBee Series 1 module, 1mW model. Arduino boards, by default, already contain A/D converters; the need to attach another one is the fact that the standard Arduino converter has a resolution of only 10 bits. In other words, 10 bits gives a resolution of 1024 possible values, while 22 bits, 4194304 values, so, as the load cell can support 5000 Kgf, analog voltage signals generated by the load cell will be received and discretized, linearly, to the amount of A/D converter values.

Data processing in the Arduino of the electronic module is about receiving data from the A/D converter and accommodation for sending through the XBee radio. The transmission will be done through the ZigBee protocol, already implemented in the own radio, and formatted from the standard of lines CSV, where standard separators are used. In this case, ";" as separators. The data sent is: reading time (in ms) and force applied to the body (in kg).

The circuit will be powered from a 7.4 V LiPo (lithium polymer) battery, 1000 mAh, and a 5 V voltage regulator (L7805) for powering the circuit. The calibration of the circuit will be done by means of a trimpot of 200 Ω, that will make the precision adjustment in the signal amplification. A schematic of the electronic unit can be seen in Figure 6.

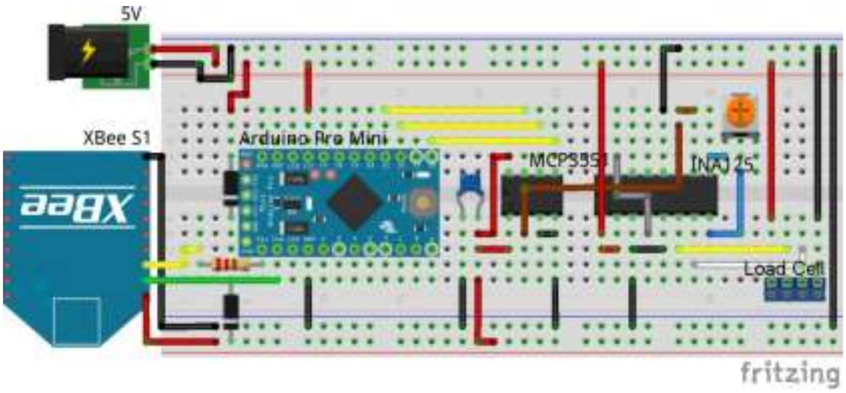

Figure 6. Schematic of the electronic unit.

In accordance with the purpose of this work, the machine will be dimensioned aiming to performing tests on specimens ranging from 70 to 150 mm, in length, obeying the minimum limit required by ISO 6892-1:2013, as can be seen in figure 7.

Figure 7. Specimens.

At the end of the project, the total weight of the thermal fatigue testing equipment was estimated at 30.0 kg. The design of the equipment can be seen in Figure 8. An exploded view, allowing to identify the components of the equipment, is in Figure 9.

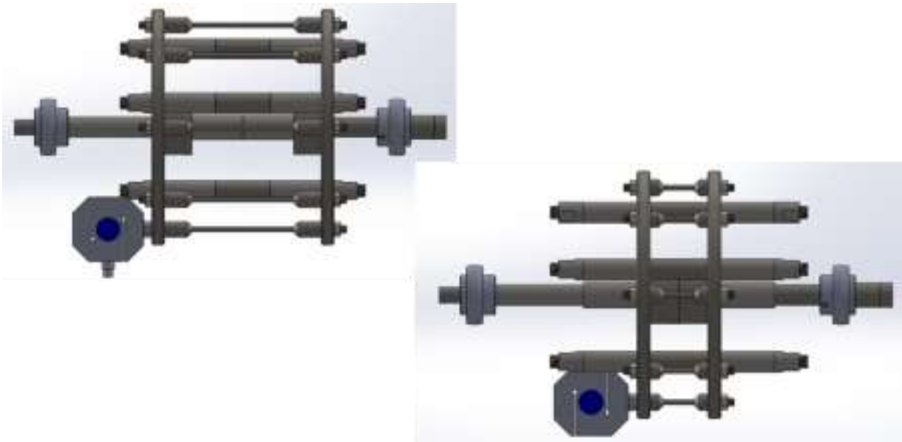

Figure 8. Arrangement of specimens.

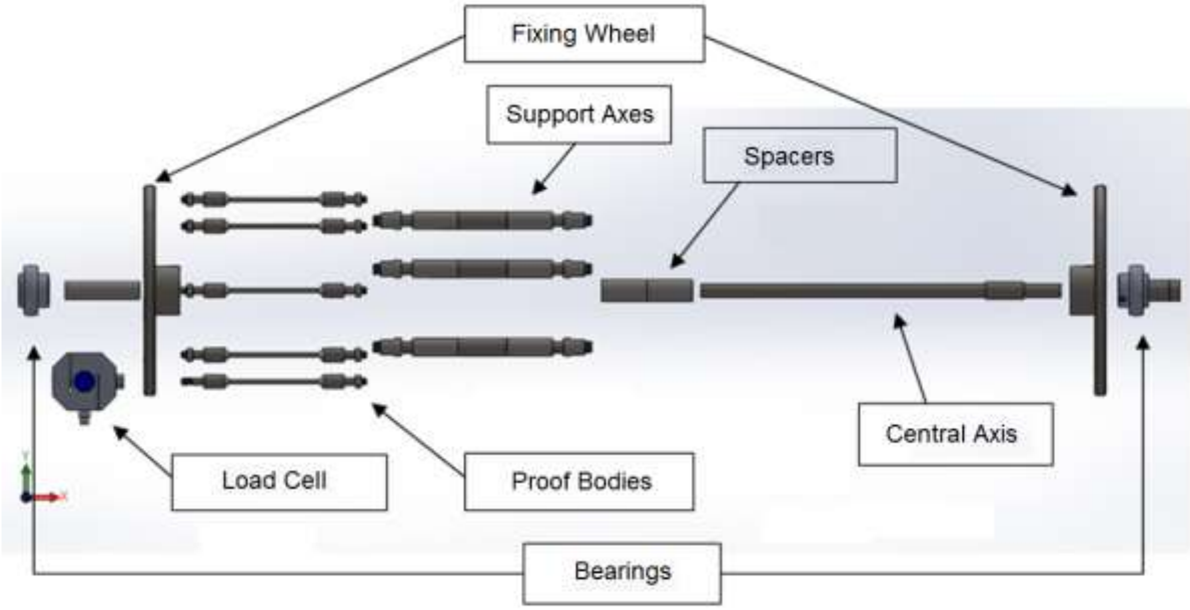

Figure 9. Exploded view.

4. CONCLUSIONS

At the end of this work, the analyses and simulations of the design of the thermal fatigue equipment proved to be reliable, and all stages of study, material selection and design were carried out, providing design safety for the next stage of the project, the construction and validation of equipment.

Fundamentals of the diverse subjects, assimilated while in Mechanical Engineering graduation, were essential for the beginning and the conclusion of this work. In this way, knowledge from areas such as Science of Materials, Machine Design and Mechanical Manufacturing were continuously applied, in the design of the mechanical components present in the project.

5. REFERENCES

ALVARENGA JÚNIOR, A. Avaliação experimental dos efeitos da fadiga térmica nas propriedades mecânicas de um aço inoxidável austenítico. 2006. 145p. Tese (Doutorado). Universidade Federal de Minas Gerais, Belo Horizonte, 2006.

ASTM E1823-96(2002); “Standard Terminology Relating to Fatigue and Fracture Testing”, 2002.

BRANDIM, A., Efeito da fadiga térmica sobre as microestruturas e propriedades mecânicas de revestimentos de aços inoxidáveis martensíticos, Tese de D.Sc., DEMA – UFSCar, pp.187, São Carlos, SP, Brasil, 2002.

BRANDIM, A. S.; SOUSA, R. R. M.; ALVES, Jr. C., "Desenvolvimento de um equipamento para ensaio de fadiga térmica", Revista Matéria, v. 14, n. 1, pp 749-758, 2009.

Callister Jr, W.D. (2008) Ciência e Engenharia de Materiais: Uma introdução. 7ª edição. Rio de Janeiro: LTC.

NORTON, Robert L. Projeto de máquinas uma abordagem integrada. 2. ed. São Paulo: Bookman editora, 2004.

SHIGLEY. J.E; MISHKE, C.R. Projeto de Engenharia Mecânica. 7. ed. São Paulo: Bookman editora, 2008.

SAE J 1397:1992; “Estimated Mechanical Properties and Machinability of Steel Bars”, 1992.

SILVA, C. R. S. Fadiga térmica de ferros fundidos brancos multicomponentes, 2003, 131f, Dissertação (Mestrado em engenharia metalúrgica), USP, São Paulo, 2003.

SARRIA, O.J.H., Desenvolvimento de um equipamento para ensaio de fadiga térmica, Tese de D.Sc., PPG-CEM, Engenharia de Materiais, UFSCar, pp. 179, Abril 2001.

SURESH, S. Fatigue of Materials, 2 ed, Cambridge, Cambridge University Press, 1998.

WEG – WEG w22 motor trifásico tecnico – catalogo – português – br <http://www.weg.net/br/Media-Center/Central-de-Downloads/Resultado-da-Busca/%28byURL%29/br|Produtos-e-Servicos|Motores-Eletricos|Industriais|W22-Premium> acessado 11/02/2014

6. RESPONSIBILITY NOTICE

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