DEVELOPMENT OF THERMAL FATIGUE TESTING APPARATUS

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Abstract: Thermal fatigue is a kind of fatigue that occurs in materials and equipment submitted to radical cyclical temperature changes as in thermoelectrical and thermonuclear plants, rolling mill rolls, gas turbine, diesel engines, and aircraft turbines, among others. Test techniques vary according to the problem, from specific use to general studies of the behavior of a wide class of materials, with no specific focus. The objective of this paper is to describing the development of test equipment that simulates a specific work condition, submitting specimens to temperature changes ranging from 250°C to 500°C within 30 second cycles. The specimens are also submitted to a constant tensile stress of 74 MPa, which represents specific conditions of the Removal Heat Residual System (RHR) of ANGRA 1 nuclear power plant. The piping material is affected by the thermal stratification phenomenon and there are possibilities of developing through-wall cracks as it has been observed in other plants. Specimens used can also be post-tested in a rotating bending fatigue testing machine in order to verify the influence of the thermal fatigue in the S-N mechanical fatigue curves. Specimen heating system is ohmic and the cooling is made thorough convection using compressed air. Despite the equipment be designed for reproducing very specific conditions, it is possible not only to vary the temperature limits, rate of cooling and heating, tectotherm (level) but also, to increase the tensile stress up to the limit of 980 MPa. Initial tests were carried out with stainless steel (AISI 304) specimens and results showed a decay of the S-N curves due to thermal fatigue. One can conclude that the equipment is suitable for simulating thermal fatigue in the tested material.

***Keywords**: thermal fatigue, cumulative damage, thermal stratification, S-N curves*

1. Introduction

Since 1960, in Los Alamos, when the first damage occurrence by thermal fatigue in the nuclear plant, the studies on this area have been intensified in order to avoid such damage, aiming at extending the useful life of reactors kind PWR (Power Water Reactor). The damage by thermal fatigue occurs due to the thermal stratification of the fluid inside the piping or by a fast internal fluid change with unequal temperatures, which create temperature gradients through the wall, producing local tensions in the piping. The hot and the cold fluid levels of the stratified flows conditions are separated by an interface or mixing layer, producing a phenomenon of high thermal cycling in the middle of pipe cross section. In a specific study for Angra I power plant by Maneschy (2000), it was analyzed the profile of the temperature fluctuations in the external surface of the Residual Heat Removal System (RHR) piping. This study made possible to verify the thermal fatigue conditions that were submitted to the piping materials.

As the cases all over the world have increased in such failures (see Atwood, 1999), a cooperative work between CDTN/CNEN and UFMG, development an equipment that made possible the accelerated simulation of the phenomenon in the laboratory aiming at determining the material degradation of the mechanical properties due to the thermal fatigue. Thus, the objective of this paper was projecting and constructing an equipment that could simulate a specific critical situation in the Angra I Thermonuclear Power Plant piping, submitting a typical rotating–beam test specimen to thermal fatigue and after that to rotating bending testing machine in order to allow a comparison of the curves S-N (Alternative Stress versus Life to Failure in Cycles) (see Fig 1) (see Bannantine, 1990) of the virgin material with the thermally cycled material.

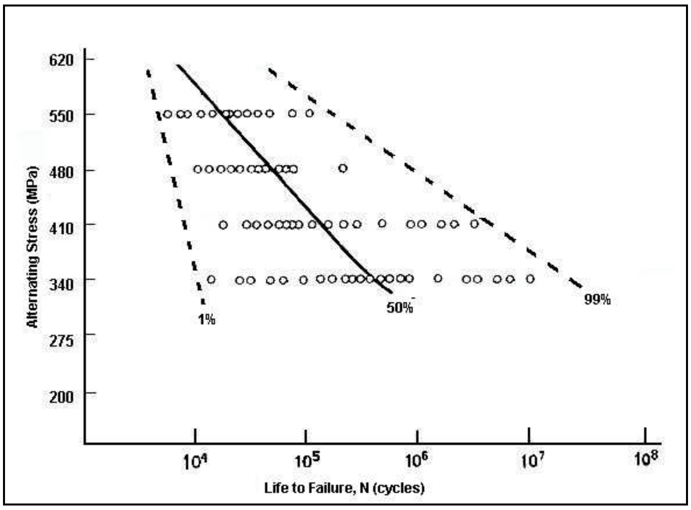

Figure 1. S-N Curves for ASTM 8620 Steel - example

2. Materials

The material used for the preliminary tests was the stainless steel type AISI 304 received in the form of 5/8" diameter rods. This material is very sensible to thermal fatigue because of the low thermal specific conductivity and high thermal expansion coefficient. The chemical composition and tensile properties are reported in Table 1 and the aspect of the structure is shown in Figure 2. The specimen is presented in Figure 3 and it follows a composition suggested by Cazaud (1957) and ASTM E 466-96 (1996). Aiming at clamping the specimen in the thermal fatigue machine, screws in their extremity were used.

Table 1. Chemical composition (wt %) and tensile properties* of AISI 304 at room temperature

C	Ni	Cr	Mn	Cu	Mo	Si	Co	S	P	Fe
0.024	**9.54**	**18.41**	**1.67**	**0.28**	**0.27**	**0.57**	**0.14**	**0.024**	**0.029**	**Res.**

YSO.2 (MPa)	UTS (MPa)	A (%)
466	**610**	**107**

*Tensile tests were performed on a tensile testing machine (INSTRON) with head speed of 0.002m/min, at room temperature (22°C) according to ASTM E-23.

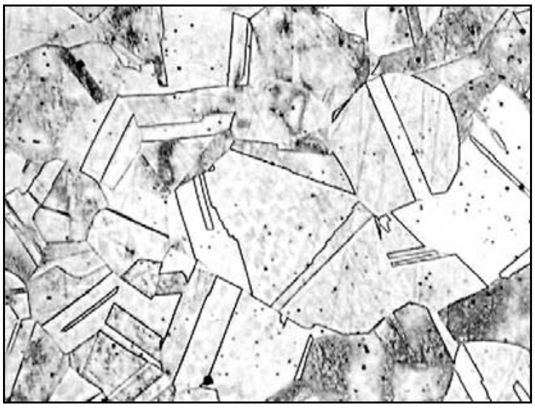

Figure 2. Stainless Steel AISI type 304 microstructure taken from specimen NR. 74

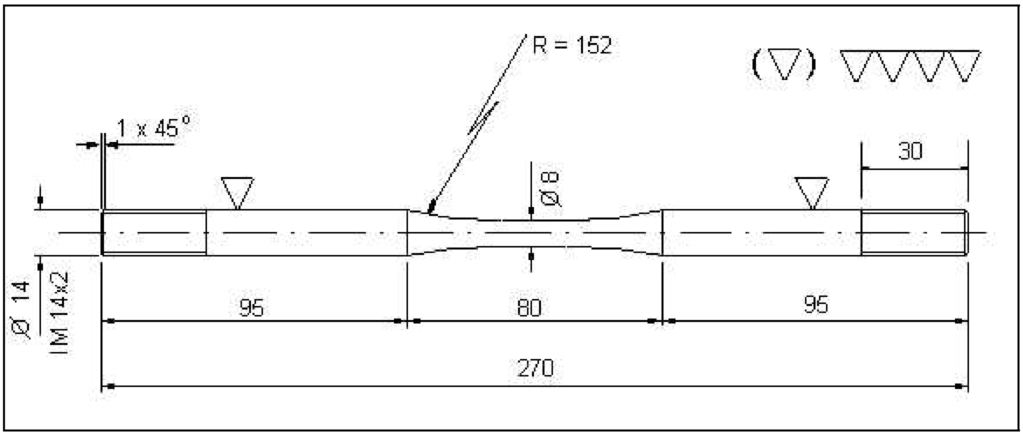

Figure 3. Shape and dimensions (mm) of thermal and mechanical fatigue specimen

3. Experimental Procedures

Based on the nuclear industry interest, which is the user of the piping material subjected to the thermal stratification, it was developed an equipment to relief the thermal fatigue resistance, considering that there is no universal equipment available in the market, because it is a technical testing, in which one tried to reproduce approximately the same conditions of the components to be tested. Having as a basis the original idea development Carden and Slade (1969), whose objective was making thermal fatigue testing of low cycle, it was projected, built and mounted an equipment in the Laboratory of Tension Analyzes at CDTN, that made possible to achieve the temperature and tension desired for development of this study. The objects of this equipment are:

- Operating several kinds of specimens;
- Automatic process;
- Low cost of the equipment;
- Operating several levels of temperature and tension;
- The chemical composition of the material is preserved;
- Hard fixed specimen;
- The cooling can be liquid or gaseous.

The assembly scheme of the thermal fatigue machine is shown in Figure 4. The temperatures are measured by using chromel-alumel thermocouples. The thermocouple is an isolated kind and fixed at surface of the central part of the specimen by a snap ring. The specimen is evolved by a tub of isolating material where the liquid or gaseous cooling flow run (see Figure 5).

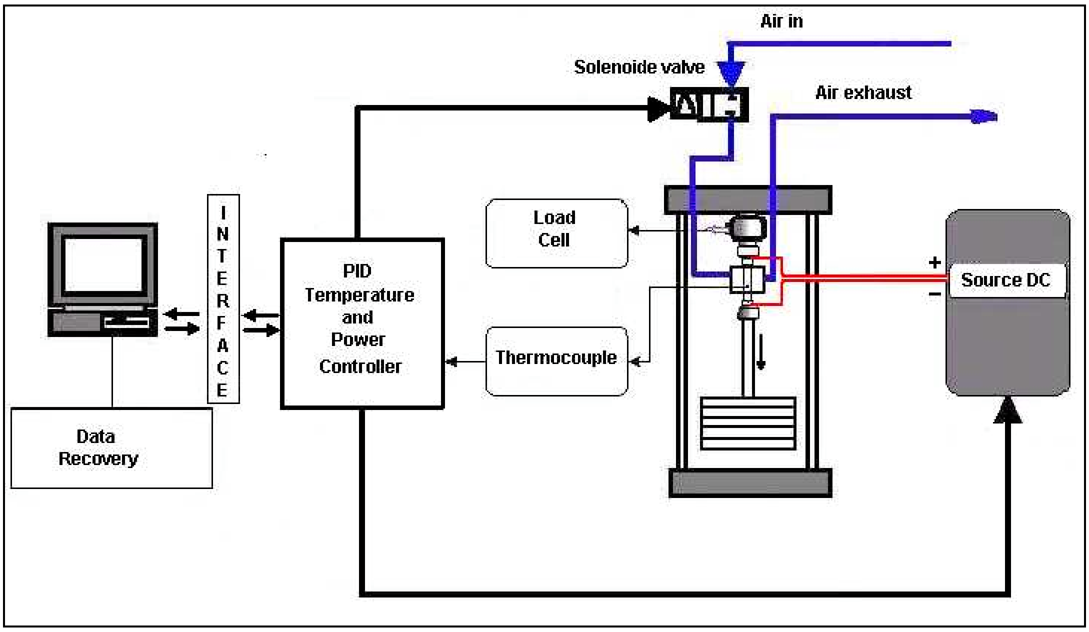

Figure 4. Scheme of the thermal fatigue test facility.

A constant current welding source (DC 1500 Amperes max.– 2,5 volts) is attached in to the extremity, which is heated by the ohmic effect. The minimal and the maximal temperatures are fixed for this experiment in 250º and 500º degrees Celsius respectively. A Temperature Controller Model 2116 PID by Eurotherm was used in, order to control the process. From room temperature, the controller keeps the source on until the specimen center achieves 500º degrees Celsius. At this stage, the source is switched off and the solenoid valve is opened, what makes the temperature falls down until 250º degrees Celsius through the air passage to room temperature by tub, when the source is again turned on in order to start the process.

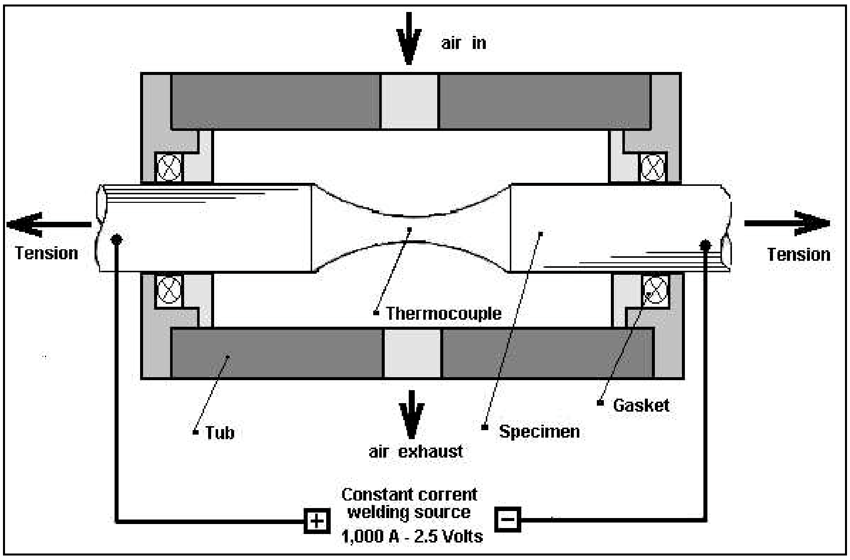

Figure 5. Scheme of the tub

3.1. Mechanical Fatigue Tests

Mechanical Fatigue Testings were carried out in the Rotating Bending Testing Machine (see Fig. 6) and the Experimental Plan chosen for making the testing was the compromising plan presented by Mansur (2002). This plan is an intermediate proposal between the traditional and the optimum. Three levels of tension were used: low, high and intermediate. There is a compromise that the allocation will always have the proportion 4:2:1, for low, intermediate and high respectively.

Figure 6. Rotating Bending Testing Machine

In this work, five levels of stress, three of them are subjects of the planning and the other two obtained by linear interpolation (see Table 2). The highest stress level was chosen as 59% of yield point, and the lowest as 46% of yield point.

Table 2. Number of specimens and respective stress

Alternating Stress (MPa)	Number of specimens
375	6
343	9
311	12
285	18
259	25

3.2. Thermal Fatigue Test

After the thermal fatigue mounting machine, preliminary tests with the following parameters were done:

- Temperature range – 250º C until 500º C
- Total time of each cycle – 24 seconds
- Tension on the specimen – 377 Kgf (7.51 Kgf/mm²)
- Kind of cooling – compressed air
- Number of cycles for each specimen – 2,000 cycles
- Constant current – 750 Ampere, 2.5 Volts

Figures 7-10 show the general mounting, the tub, the specimen mounting and the source respectively.

Figure 7. General mounting

Figure 8. Tub detail

Figure 9. Specimen mounting

Figure10. Source

The heating rate in this experiment was adjusted to achieve 500º C beginning from 250º C in 8 seconds (32 degrees per second); and the cooling rate is of 500º C until 250º C in 16 seconds (16 degrees per second) as it is presented in Fig. 11.

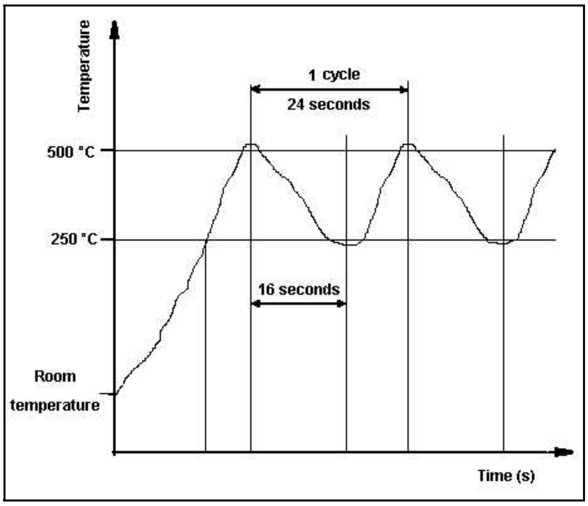

Figure 11. Aspect of thermal cycling

4. Interpretation of results

After a statistical treatment, the results obtained exclusively in the mechanical fatigue testings and the curves of 0.01%, 0.50% and 0.99% which have probabilities of failure are shown in Fig. 12.

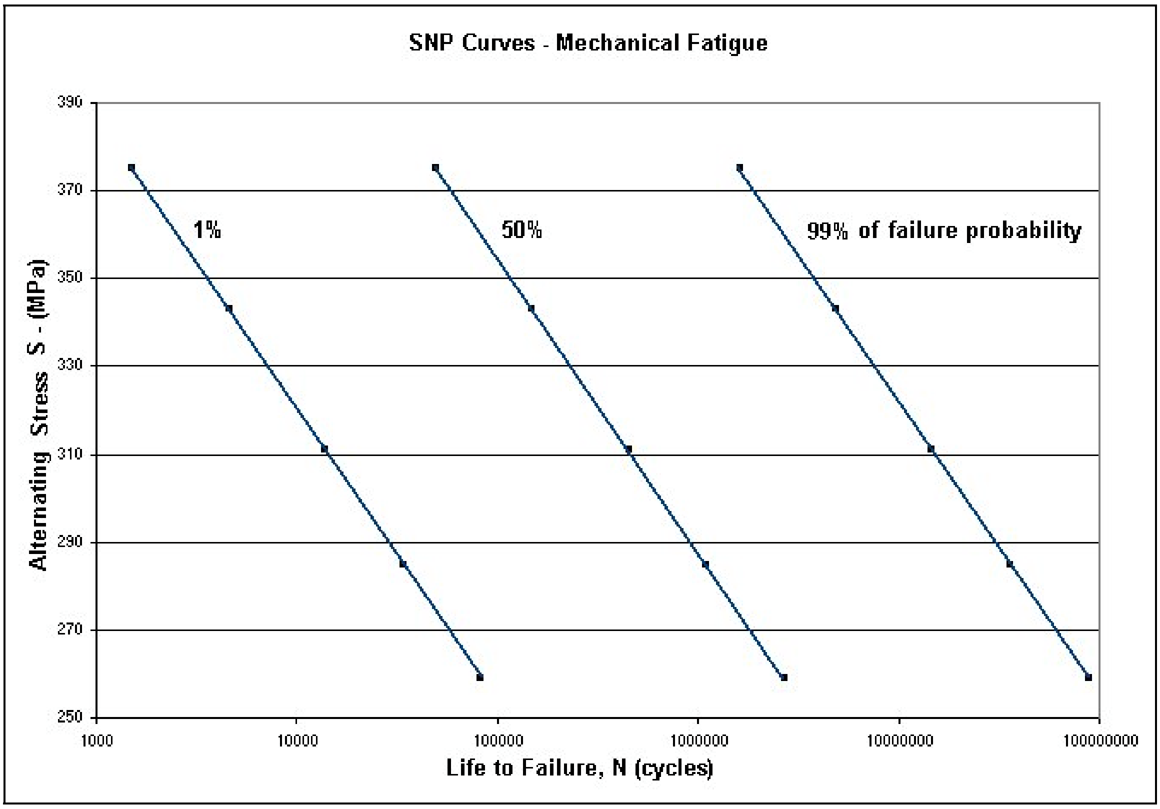

Figure 12. Results of the mechanical fatigue testing. S-N-P Diagram log-log plot

The results obtained in the mechanical fatigue testing were carried out in the specimens that were obtained first at thermal fatigue and the statistical treatment are shown in Figure 13.

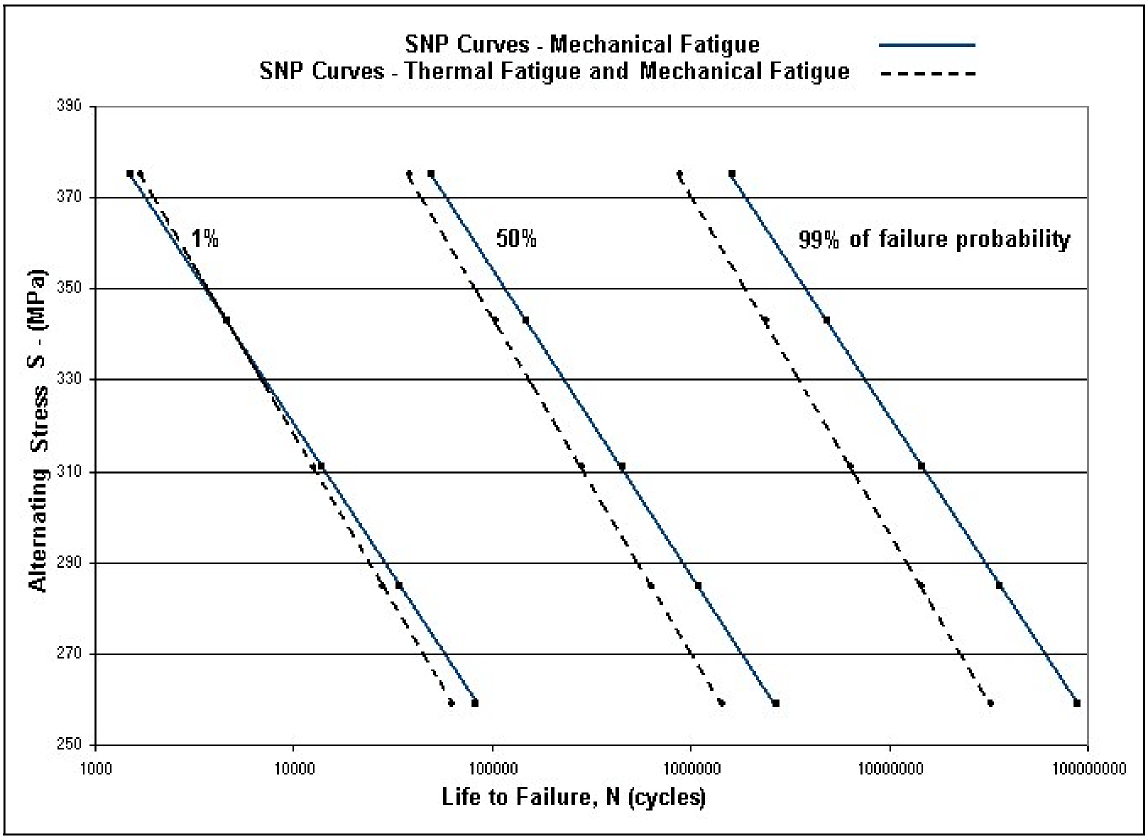

Figure 13. Overlap of the S-N-P Mechanical fatigue diagram with mechanical fatigue plus thermal fatigue

One can observe the displacement of the S-N-P curves to the right of the mechanical fatigue preceded by the thermal fatigue is shown in Figure 13. This displacement clearly quantifies the damage caused in the specimen by thermal fatigue.

5. Conclusions

- The thermal fatigue testing apparatus produced a thermal damage that could be medium through other mechanical properties of the material.
- The thermal damage produced by the machine caused a displacement of the mechanical fatigue S-N curves to the right, reducing the specimen useful life.
- In specific case, the dispersion of the data diminished a little with the introduction of the thermal damages.
- In higher alternating tensions, the influence of the thermal fatigue is minor who in low alternating tensions.
- For a probability of higher life (used in extension of life), the thermal fatigue is more harmful. Reduction of 62% of the useful life occurred.
- The thermal fatigue testing apparatus seemed to be trustful and stable according to the process parameters, such as, temperature, time and traction.
- These parameters can reach a wide range and are limited by the maximum temperature allowed by the thermocouple, the maximum tension allowed by the isolation and the constant current allowed by the welding source.
- Several types of specimens can be adapted, only by changing the grip.
- The heating is done by ohmic effect, so the specimens are restricted to electricity conductor materials. For using the non-conductor materials, it would be necessary to install a heating furnace.

6. References

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