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LCF and TMF on ferritic stainless steel for exhaust application

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Abstract

Due to the more stringent and upcoming laws in terms of environment protection field, the required temperatures in combustion chamber need to be higher in order to reduce particles emissions. This target is reached by engine downsizing (see FIAT and Ford) together with the application of turbochargers, but the new altered conditions lead to a design of exhaust gas manifold that has to take into account an improvement in terms of temperature up to 1050°C. Above all, materials characterization has to be carried out in order to represent, as close as possible, real operative conditions. Usually, materials for exhaust gas manifold are characterized from HCF, LCF and TMF point of view by testing on cylindrical specimens, but this way it’s not possible to detect the effect given by rolling process. In these last years CRF has designed and developed a particular kind of antibuckling in order to allow LCF and TMF characterization on flat specimen at high temperatures with fully reversed strain cycle.

This paper will show the results of LCF characterization carried out on flat specimen (th=1.5 [mm]) in strain ratio condition $R_{\varepsilon}=-1$ at temperatures of 600[°C] and 800[°C]. Furthermore, results of several TMF tests will be showed.

Keywords: LCF; TMF; exhaust manifold; flat specimen; antibuckling

Nomenclature

| Symbol | Description               |
|--------|---------------------------|
| $N_f$  | Number of cycles to failure |
| $2N_f$ | Number of reversals to failure |
| $\Delta \varepsilon_{\text{TOT}/2}$ | Total strain amplitude |

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1. Introduction

The more stringent laws in terms of environment protection made the car makers working on different sides. One of these is the increase of exhaust gas temperature in order to reduce the CO₂ emission, but the result is that thermal conditions are extremely critical for materials usually involved. The particular kind of stress-strain status of exhaust components required a development of new methodology to characterize stainless steels in order to reach a correct sizing of them. In fact usually this kind of materials are characterized using standards test with cylindrical specimen geometry, but manifold are normally produced starting from steel sheets; it’s clear that in this way is not possible to understand the real fatigue behavior and how it could be influenced by rolling process. CRF fatigue laboratory has designed and tested an anti-buckling for high temperature characterization of ferritic stainless steel sheets for exhaust application allowing to perform LCF and TMF test at high temperatures.

2. LCF Characterization

LCF test was accomplished with a specimen with thickness 1.45 [mm] and width 16 [mm]. Before testing the oven temperature was set up in order to reach a maximum difference of temperature of 0.5% within the gage length, therefore at test temperature of 600 and 800[°C] the maximum difference was 3 and 4[°C] respectively. Obviously a cooling device was used to avoid an increase of temperature of load cell and several actions were taken to render the clamping devices coaxial to avoid specimens bending. An event like this one makes the test not valid, because of a contribution to failure due to flexural stress.

The tests were carried out with fully reversed total strain controlled method with an MTS fatigue testing machine. The strain amplitude used for definition of Coffin Manson curve (Eq.1) ranges between 0.2[%] and 0.9[%] with a strain ratio Rₑ=−1 and frequency of 0.25 [Hz] (1 cycle per 4 seconds). The lifetime (Nf) is defined as the number of cycles which corresponds a stress decreasing of 20[%] compared to the stress reached at mid-life.

\[
\frac{Δε_{tot}}{2} = \frac{σ' f}{E} \left(2N_f\right)^b + ε' f \left(2N_f\right)^c
\]  

(1)
2.1. LCF 600[°C]

The experimental data list about characterization at 600[°C] on flat stainless steel specimen is reported below, including the following parameters:

- The number of reversals
- Total, plastic and elastic strains amplitude
- Stress amplitude and cyclic elastic modulus (the average will be used for Coffin Manson formula and cyclic curve definition)

| Reversals [2Nf] | Total strain amplitude | Plastic strain amplitude | Elastic strain amplitude | Stress amplitude | Cyclic Elastic modulus [GPa] |
|-----------------|------------------------|--------------------------|-------------------------|-----------------|-----------------------------|
| Test 1          | 870                    | 0.601                    | 0.355                   | 0.246           | 351                         | 142                        |
| Test 2          | 430                    | 0.898                    | 0.639                   | 0.259           | 373                         | 144                        |
| Test 3          | 2860                   | 0.299                    | 0.080                   | 0.219           | 309                         | 141                        |
| Test 4          | 2380                   | 0.298                    | 0.081                   | 0.217           | 323                         | 149                        |
| Test 5          | 954                    | 0.499                    | 0.251                   | 0.248           | 331                         | 134                        |
| Test 6          | 1444                   | 0.398                    | 0.165                   | 0.233           | 333                         | 143                        |
| Test 7          | 592                    | 0.699                    | 0.437                   | 0.262           | 361                         | 138                        |
| Test 8          | 6024                   | 0.248                    | 0.038                   | 0.210           | 288                         | 137                        |
| Test 9          | 16186                  | 0.197                    | 0.015                   | 0.182           | 244                         | 134                        |

Reversals-strain amplitude graphical analysis is showed below (Fig.1). The main peculiarity of this chart concerns the transition life (life at which there’s intersection between elastic and plastic curve) which is placed at about 1000 reversals and the elastic component which ranges between 0.18[%] and 0.26[%] with scarce slope.

Fig. 1. Coffin-Manson diagram for LCF characterization at 600[°C].
2.2. LCF 800[°C]

The same range of strain amplitudes for 600[°C] characterization was also used for 800[°C]. As in previous case on table 2 the required data for calculus of Coffin-Manson parameters are reported.

Table 2. Experimental data list for LCF characterization at 800[°C]

| Reversals [2Nf] | Total strain amplitude | Plastic strain amplitude | Elastic strain amplitude | Stress amplitude [MPa] | Cyclic Elastic modulus [GPa] |
|-----------------|------------------------|--------------------------|--------------------------|-------------------------|-----------------------------|
| Test 1 918      | 0.699                  | 0.631                    | 0.068                    | 85                      | 125                         |
| Test 2 1962     | 0.499                  | 0.439                    | 0.060                    | 74                      | 124                         |
| Test 3 2562     | 0.398                  | 0.341                    | 0.057                    | 72                      | 126                         |
| Test 4 4736     | 0.297                  | 0.264                    | 0.051                    | 63                      | 123                         |
| Test 5 6362     | 0.248                  | 0.192                    | 0.056                    | 61                      | 109                         |
| Test 6 512      | 0.899                  | 0.834                    | 0.065                    | 87                      | 133                         |
| Test 7 1326     | 0.596                  | 0.532                    | 0.064                    | 77                      | 120                         |
| Test 8 5458     | 0.247                  | 0.196                    | 0.051                    | 63                      | 123                         |
| Test 9 11622    | 0.199                  | 0.138                    | 0.061                    | 46                      | 76                          |

Fatigue phenomenon at 800[°C] is mainly governed by plastic strain, while elastic strain has scarce relevance. This latter is always in a range between 0.05[%] and almost 0.07[%] hence, in this case, the elastic component will be represented by a curve with an extremely low slope on Coffin-Manson diagram. Furthermore, the transition life is located where characterization was not carried out (about 10^5 reversals), so out of LCF physical field. This way the transition life is only a result of math analysis as showed on fig.2.

Fig. 2. Coffin-Manson diagram for LCF characterization at 800[°C].
2.3. LCF comparison 600[°C] and 800[°C] characterizations

Coffin Manson parameters are represented on table below (tab.3). It is evident that between 600[°C] to 800[°C] testing temperatures there are great differences like a huge decrease of fatigue strength coefficient and fatigue ductility coefficient too.

| Testing temperature [°C] | Fatigue strength coefficient $\sigma_f$ [MPa] | Fatigue strength exponent $b$ | Fatigue ductility coefficient $\varepsilon'_f$ [mm/mm] | Fatigue ductility exponent $c$ | Cyclic Elastic modulus $E$ [GPa] | Cyclic strength coefficient $k'$ [MPa] | Cyclic strain hardening exponent $n'$ |
|--------------------------|---------------------------------------------|-------------------------------|-----------------------------------------------|-------------------------------|-------------------------------------|---------------------------------------|---------------------------------------|
| 600                      | 691                                         | -0.102                        | 3.886                                         | -1.062                        | 140                                 | 658                                   | 0.108                                 |
| 800                      | 226                                         | -0.151                        | 0.400                                         | -0.607                        | 117                                 | 417                                   | 0.317                                 |

Looking to the graphical comparison on fig.3, 800[°C] curve presents:

- For high values of strain amplitude a shorter life (in terms of reversals) in comparison to 600[°C] curve
- Plastic component has a slope lower than 600[°C] curve
- Between 0.15[%] and 1[%] values of strain amplitude, there is a difference of maximum 1500 reversals with a reached life at 800[°C] (in terms of reversals) longer than 600[°C] case.
- Out of this field the roles are inverted and, particularly under 0.15[%] value of strain, 800[°C] curve shows an important decrease in terms of life cycles.

![Fig. 3. Coffin-Manson diagram for LCF characterization comparison 600[°C] and 800[°C].](image)

3. TMF Characterization

A correct exhaust system sizing can be reached not only considering HCF and LCF characterization, but also through thermo-mechanical fatigue evaluation; in fact the real component is subject to several cycles of strength due to thermal expansion of the engine head, but, at the same time, manifold has its own thermal expansion too.

Carrying out a TMF characterization required a complete redesign of the anti-buckling device, because of higher stressing conditions, and a new heating system based on electromagnetic induction.
This way it was possible to perform a thermal cycle between 100[°C] and 600[°C] with a proportional total strain governed by constraint factor “G”. This one establishes the amount of not allowed elongation that specimen would reach due to thermal strain. For example a constraint factor correspondent to 80[%] means that total strain will be equivalent, for each level of temperature, to 20[%] of thermal strain. At the moment only three test have been done within different levels of constraint factor: 100[%], 80[%] and 60[%]. Before starting each test two procedures have been carried out:

- Evaluating a law to determinate the thermal strain at temperature changes from 100[°C] to 600[°C]
- Making an assessment of elastic modulus for each temperature from 100[°C] to 600[°C]

Then it was possible to control test progression with a total strain equivalent to:

- 0 for G=100[%] case
- 20[%] of thermal strain, for G=80[%] case
- 40[%] of thermal strain, for G=60[%] case

With a constraint factor correspondent to 100[%] (as showed on fig. 4) the mechanical strain is always opposite to thermal strain, having the same absolute values for each temperature. The result is that total strain is always equivalent to “zero”. Furthermore, figure 4 shows only the first cycle and the first heating ramp of the second cycle, so, starting from a condition of zero strain and zero stress, the increase of temperature gives a compression status until -400[MPa] at the end of the elastic law. Afterwards, in order to maintain the same value of total strain during the increasing of temperature, the material is subject to a stress reduction because of transition in plastic region. This behaviour proceeds until the maximum temperature where mechanical strain reaches its maximum (absolute) value. Subsequently, there is a holding phase of temperature and strain, then a cooling phase leading the material to 100[°C] and maximum stress status near 500[MPa]. During this last phase, from 400[°C] to 370[°C], material shows (at about -0.4[%] of strain) another plastic region transition until the end of cycle. The first cycle completed, it is possible to see a new heating phase (second cycle) with an elastic behaviour, parallel to the first one, until an overlapping of plastic behaviour of the first cycle.

![Fig. 4. Stress vs. total, thermal and mechanical strain diagram: constraint factor G=100[%].](image)

The comparisons among the hysteresis due to the three different constraint factors used for TMF test is showed below (fig. 5). Considering that higher values of constraint factors lead to higher stress status, it’s easy to detect main differences between the tests. The chart shows the first cycle for each typology of test, so the starting condition is the same (“zero stress” and “zero strain”) for all specimens at 100[°C] temperature. For G=60[%] case only the
first ramp to maximum temperature was missing, but the first heating ramp has a much more relevant slope as the constraint factor is higher. Furthermore, mechanical strain and stress gap reach much more high values as constraint factor grows.

Consequently the energy losses (hysteresis area) for G=100[\%] case are greater than 80[\%] and 60[\%] cases, while the life time to failure is inversely proportional as showed in table 4 and fig.6

Table 4. TMF test: mechanical strain vs. number of cycles to failure (three values of G factor used)

| Constraint factor G [%] | Mechanical strain [%] | Number of Cycles to failure [Nf] |
|------------------------|-----------------------|----------------------------------|
| 100                    | 0.614                 | 719                              |
| 80                     | 0.534                 | 1100                             |
| 60                     | 0.404                 | 2665                             |

Fig. 6. Mechanical strain vs. number of cycles diagram.
Following this procedure it is possible to assess the material behavior in TMF condition starting from an analysis of strain status of the most critical zones on exhaust system.

Some remarks on testing conditions:

- Although an induction heating unit was used, the time required for a cycle (comprehensive of heating, holding and cooling time) is about 260 [sec], so the test with G=60[%] took about 200 hours of effective testing time. Obviously the cycle could be optimized changing for example the heating rate or the holding time at maximum temperature.
- Furthermore, the maximum achieved temperature was limited by “Curie point” where the material loses its magnetic properties and by the max power of the induction heating system.

4. Conclusions

A proper sizing of an exhaust manifold needs a complete fatigue characterization of stainless steel covering HCF, LCF and TMF fields. Tests must be carried out by using specimens taken from steel sheets used for real component manufacturing in order to consider the effect given by rolling process.

HCF characterization at R.T., 400[°C] and 700[°C] in “zero to max stress” Rσ=0 conditions (not reported on this paper) was the first step of this experimental activity but the real challenge was to face LCF and TMF characterization.

To perform LCF tests, a particular kind of anti-buckling was designed and manufactured by Fiat Research Centre to prevent bending effect of specimens. Two characterizations in LCF condition with Rε=-1 (fully reversed strain cycle) were carried out at 600[°C] and 800[°C]. The main remarks on the achieved results are: at the temperature increasing the elastic law became less relevant. Between values of strain amplitude of 0.2[%] and 0.9[%], the life time achieved by material at 800[°C] is higher than at 600[°C] case, while out of this range the life time at 600[°C] is higher as resulting from math analysis.

The same anti-buckling, after several modifications, was used for thermo-mechanical fatigue characterization. TMF tests were performed based on a thermal cycle between 100[°C] and 600[°C] with variable constraint factor. This allows to perform a baseline about the material behavior as function of real constraint/temperature conditions (i.e. engine head/exhaust manifold), hence the specimen was allowed to reach only a part of thermal expansion that naturally it would be reached if free.

At the moment, due to the long time required for each cycle, only three tests were carried out using different values of constraint factor, in fact the lower of these (60[%]) made the test running for about 200 hours.

The versatility of the anti-buckling designed by CRF fatigue laboratory could open many expectations for characterization of materials for exhaust applications, provided as sheet form, not only from LCF but also from TMF point of view.

References

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