THERMO-MECHANICAL FATIGUE CHARACTERISATION OF A NEW FERRITIC STAINLESS STEEL FOR VERY HIGH TEMPERATURE EXHAUST PARTS

L. Faivre[a], P.-O. Santacreu[a], A. Acher[a]

[a] Aperam Stainless France, Isbergues

Abstract The increase of service temperature of the engine is a challenge that car manufacturers have to face when it comes to comply with more and more severe depollution standards. The requirements in terms of exhaust gas temperature could soon reach and overtake the limits of stainless steel grades commonly used for hot end of exhaust line. Although stainless steel solutions allow higher service temperatures than cast iron ones, most of the common grades used for manifold and turbocharger applications (1.4509, 1.4541, 1.4828, etc.) can not be used above 950°C.

This paper aims at presenting the characterization procedures and results of a new ferritic stainless steel grade – named K44X – which has been developed to withstand service temperature up to 1000°C. With 19% of chromium content, 2% of molybdenum and niobium additions, this grade complies respectively with EN 1.4521 and AISI 444 classifications. Thanks to this chemical composition, K44X shows higher strength, better fatigue resistance and better creep resistance than common ferritic grades while presenting also lower thermal expansion and higher cyclic oxidation resistance than austenitic grades.

A wide range of high temperature properties have been investigated in the range 750-1000°C including tensile, creep, cyclic oxidation, HCF and thermal fatigue tests. K44X results were then compared to other stainless steel grades dedicated to high temperature applications.

In the development of an industrial exhaust part, motor bench tests are essential but long and expensive. To assess the thermal fatigue behaviour of a material, independently of the part design, a simplified test has therefore been used. The aim is to reproduce exhaust manifold service conditions in terms of thermal and mechanical constraints on a simple V-shaped sample.

As lifetime prediction tools turn out to be crucial in the design of an exhaust part to reduce the need for motor bench tests, various models are also proposed for K44X in this paper : a Chaboche elasto-viscoplastic behaviour model, a strain-based thermal fatigue damage model and a creep criterion. Moreover, both damage criteria are integrated into an Abaqus post-processor called Xhaust-life which allows lifetime calculations for various stainless steel grades thanks to its material library included.

1 INTRODUCTION

In the framework of a continuous toughening of emission legislation (e.g. Diesel NOx levels divided by 3 in 10 years from Euro 3 to Euro 5 standards), car manufacturers have been considering downsizing and catalytic conversion as a way to reduce pollutant emission, both solutions implying an increase of the exhaust gas temperature. Stainless steel fabricated manifolds, in addition to offering possible weight saving, allow higher service temperature in comparison to cast iron solutions. However, the trend toward higher service temperature of the manifold suggests that in a near future, a service temperature of 1000-1050°C would be possible. Nevertheless, most of today's stainless steel grades (1.4509, 1.4828) commonly used in this application can not offer suitable TMF properties or even metallurgical stability at these temperatures. A ferritic stainless steel grade complying with EN 1.4521 & AISI 444, with 19% chromium content, addition of molybdenum and niobium has therefore been developed to take up this challenge. Indeed, K44X offers a solution up to 1000°C thanks to a low thermal expansion (typical of ferritic stainless steels) but higher tensile properties, fatigue and creep resistance than common ferritic grades used today. In this paper, a wide range of high temperature properties (HCF, thermal fatigue, creep, cyclic oxidation) relevant for manifold and other high temperature applications will be detailed, compared to existing stainless steel grades, and used to propose behaviour and damage models.

2 MATERIALS

Different types of stainless steels were compared in this study from both ferritic and austenitic families, the latter having significant Nickel content which implies a higher price volatility.

Within the ferritic family, a new grade - named K44X - containing 19%Cr, 2%Mo and with a Nb stabilization was proposed to offer improved high temperature mechanical properties. Its detailed composition is given in the Table 1, together with other ferritic (1.4512, 1.4510, 1.4509) and austenitic (1.4828) stainless steel grades dedicated to high temperature applications.
All the tests presented hereafter have been carried out on flat samples in a standard 2B or 2D metallurgical state (cold rolled and annealed), in the thickness range commonly used on hot end exhaust applications (between 1,5 and 2mm).

EN Grade designation	C	Cr	Si	Mn	Mo	Ni	N	Other	Fe
1.4512	0.01	11.5	0.5	0.3	-	-	0.01	Ti=0.2	Bal.
1.4510	0.02	16.5	0.35	0.3	-	-	0.015	Ti=0.4	Bal.
1.4509	0.02	17.8	0.6	0.3	-	-	0.015	Ti+Nb=0.6	Bal.
K44X – 1.4521	0.02	19	0.6	0.3	1.9	-	0.015	Nb=0.6	Bal.
1.4828	0.05	19.3	1.6	1.3	-	11.4	0.03	-	Bal.

Table 1: Typical chemical composition of mentioned stainless steels (mass percent)

3 PROCEDURE AND EXPERIMENTAL RESULTS

Various TMF characterizations were performed including HCF, and thermal fatigue testing. However in exhaust applications, these damage mechanisms are closely correlated to other damage mechanisms such as cyclic oxidation or creep which affects the fatigue cracking . Therefore, additional experimental data (tensile properties, cyclic oxidation, creep) are also presented to assess the relative performance of the selected grades regarding these different properties.

3.1 High temperature properties

3.1.1 Tensile test

Tensile properties - especially the yield strength - are obviously linked to the fatigue limit performance of a material. High temperature tensile tests were carried out according to EN 10002 standard on an INSTRON 5582 machine equipped with a 1000°C-resistance furnace. After a 2h heating step, tensile tests were performed at a displacement rate of 0.54 mm/min.
Figure 1 presents the yield strength between 750 and 1000°C and confirmed that austenitic stainless steel grades have intrinsically higher strength at high temperature than ferritic due to a different crystallographic orientation (FCC instead of CC for ferritic). Within the ferritic family, K44X shows about 30% higher yield strength (and UTS) than 1.4509 thanks to its addition of molybdenum and niobium. The solid solution effect of these alloying elements in 19%Cr-stainless steels was proven to be significant [1].

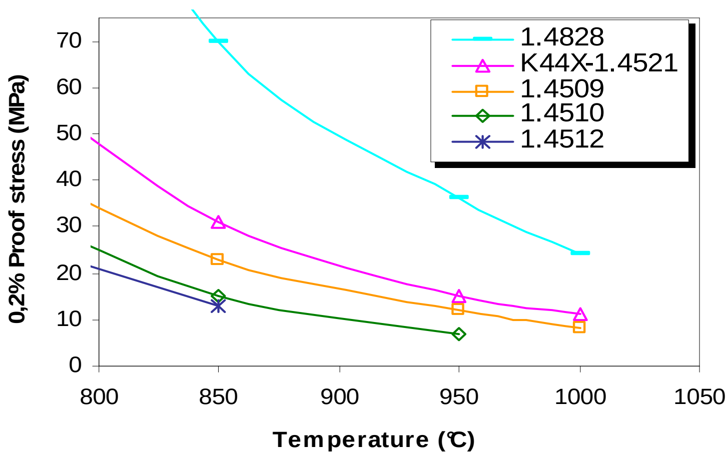


Figure 1 : Yield strength as a function of temperature

3.1.2 *Cyclic oxidation*

The anisothermal conditions underwent by high temperature exhaust parts involves cyclic oxidation process. This process has a direct impact on fatigue crack initiation and propagation since oxides formed on the surface or along the fatigue cracks have very poor mechanical properties, as can be observed on Figure 7-c. A cyclic oxidation test was therefore performed on 20x30mm samples periodically introduced in an oxidation furnace (air) and cooled down by forced convection. The thermal cycle is composed of 5min heating, 20min holding and 5min cooling. Oxidation kinetics is expressed by the ratio of the mass gain to the total sample area as a function of time, each results being a mean value of at least 4 measurements.
The cyclic oxidation behaviour of a grade is highly dependent on its thermal expansion properties and on the difference to its oxide properties (CTE of chromium oxide <10.10^{-6}/°C between 20-800°C). Since austenitic stainless steels have a stronger thermal expansion than ferritic stainless steels (see *Table 2*), these grades are more sensitive to oxide spalling-off at high temperatures (>900°C) in cyclic conditions and their oxidation kinetics is significantly higher than those of ferritics (Figure 2). Within the ferritic family, K44X shows however a better oxidation resistance than 1.4509 especially after 400h : a strong acceleration of oxidation kinetics (breakaway process) can be noticed on 1.4509 while K44X keeps parabolic kinetics.

	1.4828	1.4509	1.4521
CTE 20-800°C [10^{-6}/°C]	19	12,5	12

Table 2 : Coefficient of thermal expansion of various stainless steels between 20-800°C

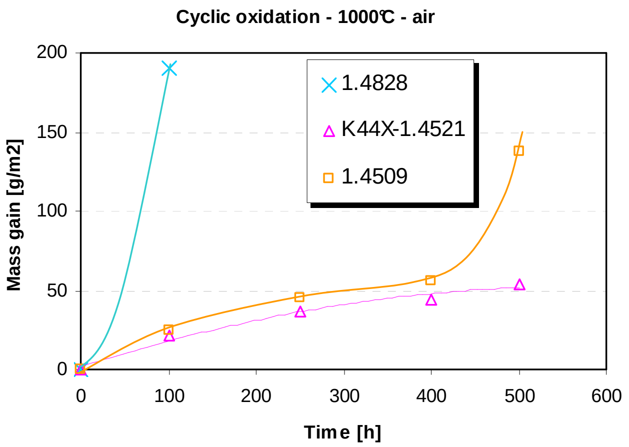
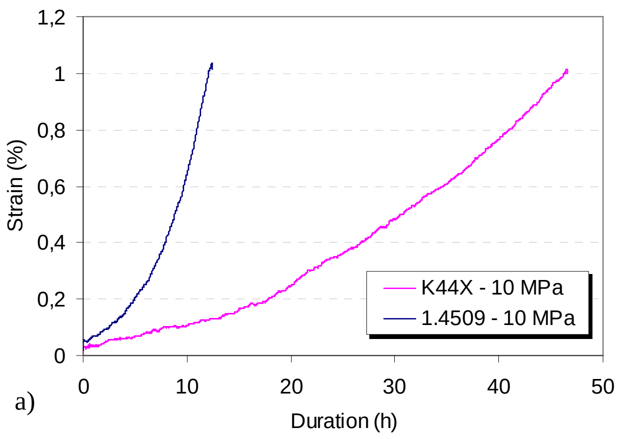


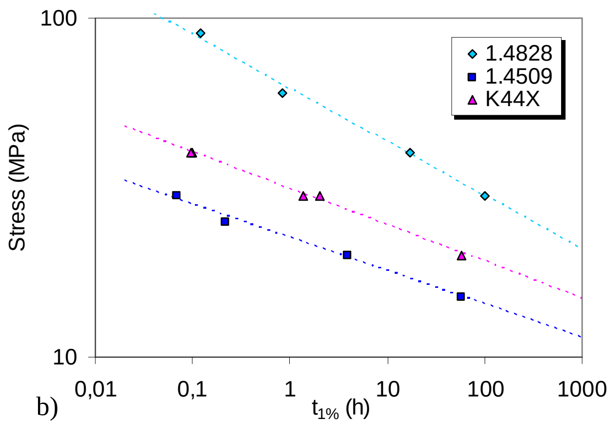
Figure 2 : Cyclic oxidation kinetics in air for a 20-1000°C cycle

3.1.3 *Uniaxial creep test*

Creep deformation can alter not only the dimensional integrity of an exhaust part but also the TMF processes during the hot phases. Indeed, it may affect the stress field in the part and modify the crack propagation when it induces a significant number of creep cavities at the grain boundaries.
Uniaxial creep tests were hence performed on the same equipment that tensile tests. Specimen were submitted to constant load while their deformation was monitored thanks to an extensometer up to 1% of creep strain (Figure 3-a). Tests were performed in isothermal conditions between 750 and 950°C and for duration up to 100h.
The ranking of stainless steel grades for creep resistance did not depend on the temperature and was in agreement with high temperature tensile properties (see 3.1.1). The austenitic grade presented the highest resistance to creep whereas 1.4509 still appeared less resistant than K44X, as shown in Figure 3-b for 850°C results. The stress leading to a $t_{1\%}$ of 100h was indeed estimated to be in the range of 40-60% of the yield strength, whatever the grade or the temperature.



a)



b)

Figure 3 : (a) Example of creep curves at 950°C and (b) stress VS time to 1% creep strain at 850°C

3.2 Fatigue properties

3.2.1 High cycle fatigue tests

High temperature fatigue limit at 2 million cycles were determined on an hydraulic tensile machine equipped with a furnace through tensile-compression test with a stress ratio of -1. Frequencies from 10 to 20 Hz were used for the stress-signal.
Since endurance limit is obviously correlated to the yield strength at high temperature, K44X presents logically higher fatigue limit than 1.4509 (about 50% more at 850°C, see Figure 4) thanks to the higher mechanical strength mentioned previously.

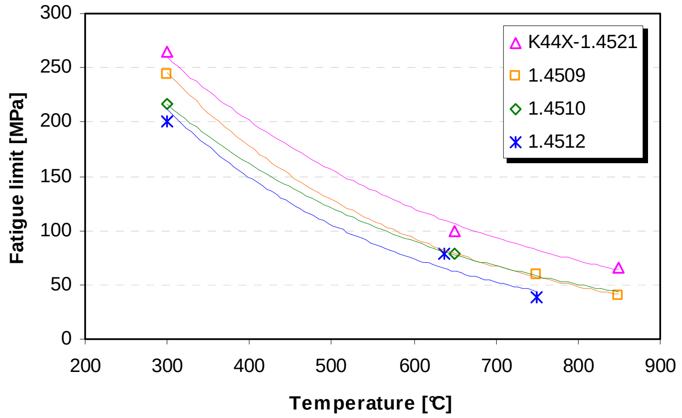


Figure 4 : Fatigue limit at 2 millions cycles as a function of the temperature (R=-1)

3.2.2 Thermal fatigue tests

This test was developed to reproduce with a simple procedure the complex in-service TMF conditions that a manifold undergoes. In this procedure a V-shaped sample is held by its ends in fixed jaws and is heated up by Joule effect (Figure 5). Both thermal stresses in the jaws and the temperature are monitored during the test by means of a force cell and a thermocouple welded to the sample surface respectively. The thermal cycle is composed of a heating ramp-up at 20°C/s, a cooling phase through forced convection and may include a holding time at high temperature (up to 180s). A typical value for the thermal cycle duration is 2 min for a 250-950°C cycle without holding time. The maximal thermal stress (at low temperature) reaches a stabilized value after a plastic accommodation process which takes place in the very first cycles (Figure 5-b). The lifetime was determined at 50% decrease of the maximal thermal stress compared to the stabilized value in order to reduce the effect of overheating at the final stage of the test (section reduction induced by cracking leads to an increase of current density).

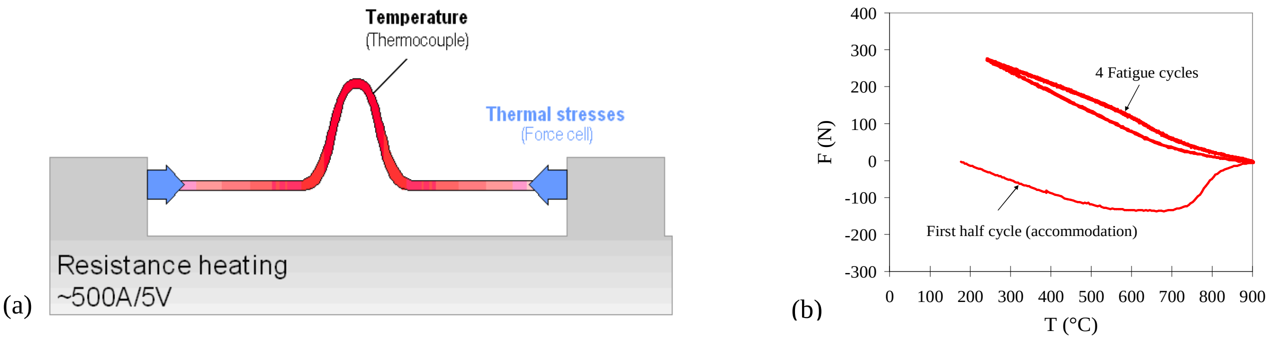


Figure 5 : Thermal fatigue test on V-shaped specimen : (a) principle and (b) thermal stresses evolution.

In this test, interactions between creep and cyclic oxidation phenomena is more pronounced with higher upper temperature (T_{max}) and with longer dwell time at high temperature (τ).
It can be noticed on Figure 6 that the austenitic grade 1.4828, despite a higher strength, exhibits lower thermal fatigue resistance in the present conditions. The thermal fatigue mechanisms are actually different from ferritic ones, as can be seen on post-mortem cross sections (Figure 7-b&c). In ferritic grades, failure is driven by out-of-phase mechanisms in the inside curvature of the samples whereas in the austenitic grade, both out-of phase and in phase mechanisms compete with each others. This can be explained by the higher thermal expansion and the higher cyclic oxidation sensitivity of austenitic grades, and this coupling between fatigue and oxidation has a higher impact on the outside curvature of the samples - where cracks are opening at high temperature – than in the inside curvature. For ferritic grades, K44X exhibits longer lifetime than 1.4509 (from 10 to 30% increase) at every tested temperature. In the other hand, 1.4512 grade presents very poor performance in thermal fatigue at high temperatures, which confirmed that this grade is not suitable for service temperature above 800°C.

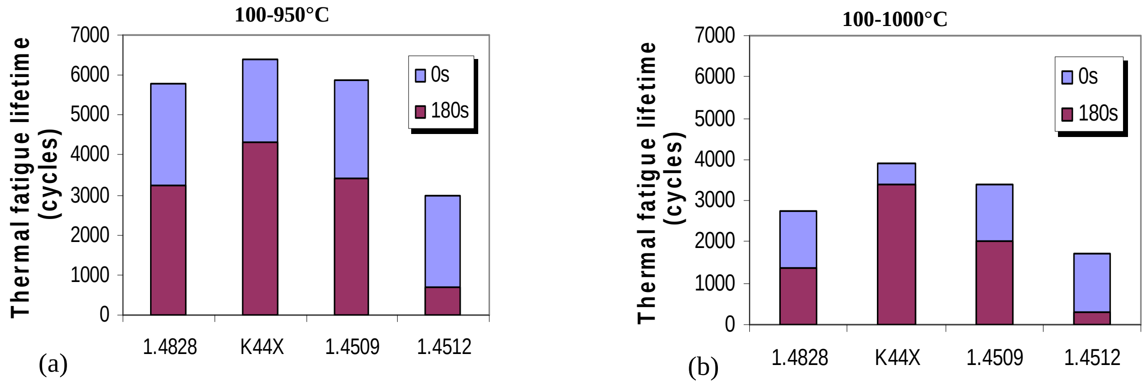


Figure 6 : Thermal fatigue life on 1.5mm-thick specimens : for (a) 100-950°C and (b) 100-1000°C thermal cycle with or without dwell time at high temperature

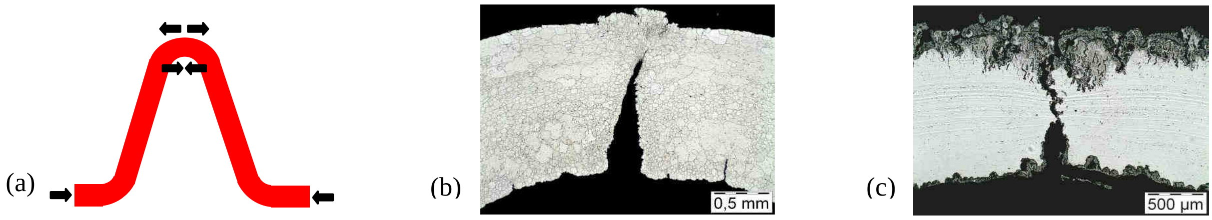


Figure 7 : (a) Stress loading of V-shaped sample during heating and different damage mechanisms : (b) out-of-phase cracking for ferritic grades and (c) both out-of-phase and in-phase cracking for austenitic grades (T_{max}=950°C, τ=0)

3.3 Material behaviour model calibration

In order to provide relevant experimental data for the calibration of the constitutive model, 2mm-thick flat samples were deformed on an INSTRON 8802 tensile machine according to a specific strain signal : 30 triangular waves followed by 3 square waves with a strain ratio equals to -1 (Figure 8-b). This signal was chosen to induce strain accommodation processes in the first part of the test (triangular waves) and a stress relaxation in the second part (square waves). For each tested temperature (from 20 to 850°C), the tests were performed with strain amplitudes in the range 0,2 to 0,6% and with 2 different strain rates (0.1 and 0.01%.s^{-1}). Similar procedure had been described previously [3] for cylindrical specimen but an adaptation of the equipment was required to prevent buckling of flat samples (Figure 8-a).

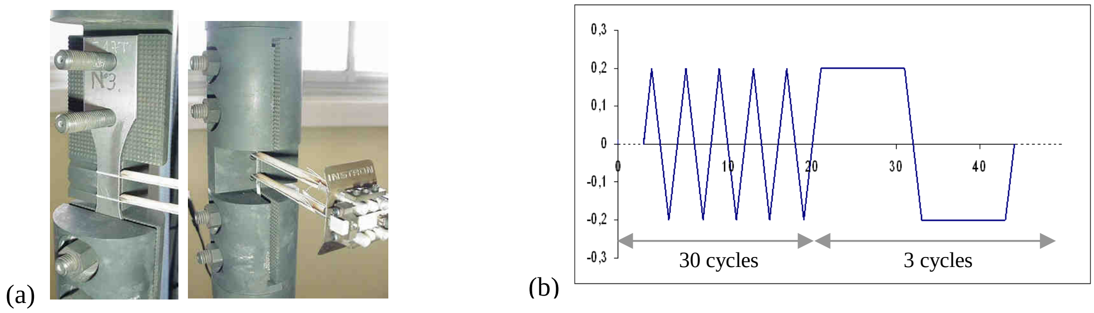


Figure 8 : Procedure for material model calibration (a) anti-buckling equipments developed for light-gauge flat samples and (b) strain signal used for the test

4 MODELS FOR LIFETIME PREDICTION

Motor bench tests are complex and expensive but necessary for the exhaust part validation. Hopefully, finite elements calculations can reduce the number of motor bench tests needed in the development and the optimization of an exhaust part. Such calculations need a material behaviour model and a damage model as input data.

4.1 Constitutive model

In our approach, an elasto-viscoplastic model proposed by Chaboche [2] was chosen to describe the material behaviour at high temperature under cyclic loading. This model combines a non linear kinematic and isotropic hardening with a Norton creep approach. It had been described previously [3] and proved a relatively good correlation with experimental data on non-isothermal TMF conditions although it had been calibrated on isothermal TMF data. Figure 9-a & b presents an example of experimental data used for calibration and shows the comparison between experimental data and simulation.

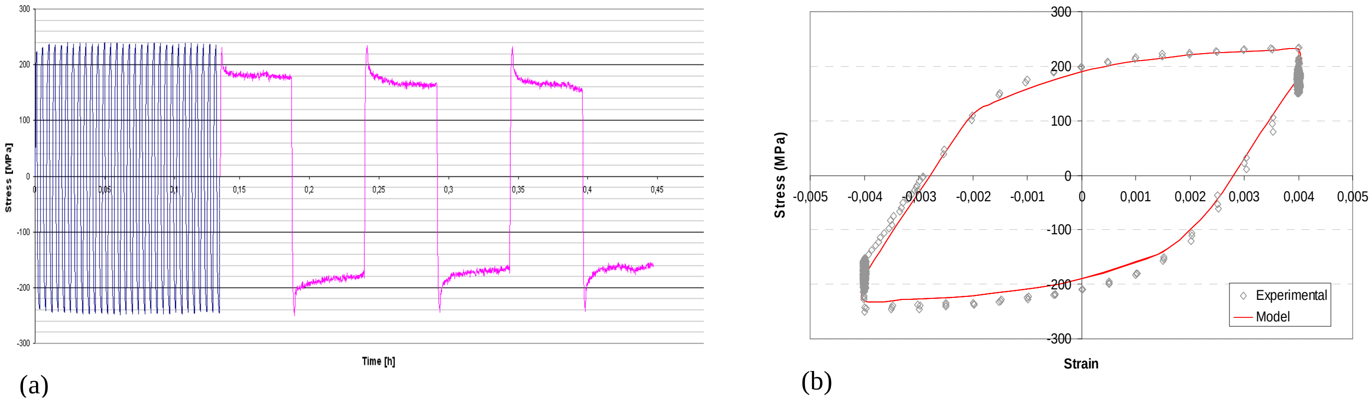


Figure 9 : Calibration of K44X model : (a) stress VS time and (b) stress VS strain ($\dot{\varepsilon}$ =0,1%.s^{-1}, T=650°C)

4.2 Thermal fatigue damage

A strain-based approach was chosen for the life prediction. It is based on Taira's work [4] who proposed an adaptation of Manson-Coffin formula to describe thermal fatigue damages.
In this approach, the thermal fatigue life N_{TF} is expressed as a function of the viscoplastic strain amplitude, a material exponent t and a coefficient λ that depends on an equivalent temperature T_{eq}:

$$N_{TF} = \lambda(T_{eq}).\left(\Delta\varepsilon_{eq}\right)^{t} \quad (8)$$

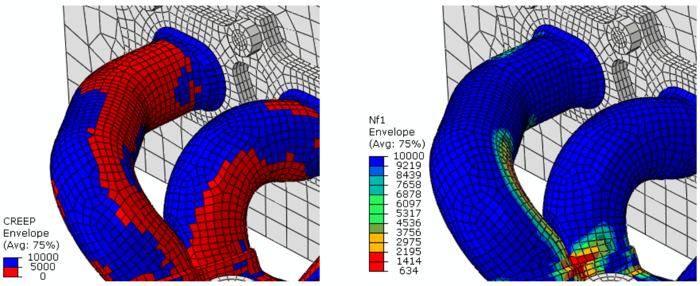
$$\text{With } \Delta\varepsilon_{eq} = \int_{cycle}\left[\cdot\frac{2}{3}\dot{\underline{\underline{\varepsilon}}}^{vp} : \dot{\underline{\underline{\varepsilon}}}^{vp}\right]^{1/2} dt$$

In the Taira's model T_{eq} depends on the damage processes involved (slip or diffusion) and is equal to the maximum temperature of the thermal cycle T_{max}, when diffusion process is the controlling damage mechanism. However, an adaptation had been proposed to take into account the effect of a dwell time at high temperature τ:

$$T_{eq} = \frac{T_{max}}{1 - aT_{max}\ln(1 + b\tau)} \quad (9)$$

With a and b material parameters evaluated from the TF tests.

This predictive model has been calibrated on a wide range of experimental data with maximal temperatures between 650°C and 1000°C and with dwell times up to 180 seconds. FEM computation using the above mentioned constitutive model (§4.1) were carried out to assess viscoplastic strains $\Delta\varepsilon_{eq}$. Corresponding thermal fatigue models for K44X and other common stainless steel grades (1.4509, 1.4828, etc.) have been integrated into an Abaqus post-processor software (Xhaust-life) which can be used in the design process of an exhaust part [5]. Thermal fatigue life have been calculated on various manifold designs (illustrated in Figure 10-b) and compared to motor bench test results. A relatively good correlation was generally observed with regards to the crack localization, the relative performance of K44X and 1.4509 and the lifetime estimation.



(a) (b)

Figure 10 : Lifetime calculations on a post-processor software (Xhaust-life): (a) creep and (b) thermal fatigue criterion

4.3 Creep damage

In addition to the thermal fatigue life approach, a predictive method has been proposed to take also into account creep damages in the design of an exhaust part. Although creep and fatigue can interfere in a complex way, the proposed model is limited to pure creep mechanisms and aims at highlighting a risk of permanent deformation on the exhaust part.
It is based on a simple Larson-Miller approach [6] :

$$\begin{cases} P = T\cdot(\log t + C) \\ \log\sigma = B + m\cdot P \end{cases} \quad (1)$$

with B, C, m material parameters

This leads to the following relationship between the time to 1% creep strain and the equivalent stress :

$$t_{1\%} = 10^{-C}.(10^{-B}.\sigma_{eq})^{\frac{1}{m.T}} \quad (2)$$

The equivalent stress proposed by [7] was used to take into account the effect of stress triaxiality :

$$\sigma_{eq} = \left\langle (1-\varsigma).\sigma_{VM} + \varsigma.Tr(\underline{\underline{\sigma}}) \right\rangle \quad (3)$$

with σ_{VM} the Von-Mises equivalent stress
$Tr(\sigma)$ the trace of the stress tensor (related to hydrostatic pressure)
ζ a coefficient fixed at 0.15

It is actually a special case of the Hayhurst criterion [8] which is a combination of the three stress invariants. Finally a critical number of cycles can be deduced from this time to 1% creep strain and the dwell time τ:

$$N_C = \frac{t_{1\%}}{\tau} \quad (4)$$

Figure 10-a shows how this simple creep model can highlight potential critical areas on a manifold.

5 CONCLUSIONS

In the design of hot end exhaust applications, ferritic stainless steels are cost effective solutions in comparison to austenitic refractory grades. Their low thermal expansion properties induces a lower sensitivity to cyclic oxidation and therefore constitutes an advantage, especially for temperatures above 900°C. For this reason, 1.4509 is now widely used on manifold application up to 950°C. However, car manufacturers tend to increase the service temperature of their engine to comply with more severe depollution standards. In this context, K44X can be an effective material solution for exhaust application up to 1000°C. It also offers longer lifetime than 1.4509 at lower temperatures thanks to a higher strength, and to an improved oxidation, creep and thermal fatigue resistance.

In an effort to reduce the need for motor bench tests in the design process of a manifold, damage models - a modified Taira model and a Larson-Miller creep model - were proposed to predict TMF damage of K44X and other stainless steel grades. These models were integrated into a post-processor software to make easier their use on FEM calculations.

6 REFERENCES

[1] N. Fujita et al, Effect of Nb on high-temperature properties for ferritic stainless steel, Scripta Materialia, Vol. 35, No. 6, pp. 705-710, 1996

[2] J. Lemaitre, J.-L Chaboche, Mécanique des Matériaux Solides, Dunod Eds., 1985

[3] L. Bucher, P.O Santacreu, A. Köster, L. Remy, Elasto-Viscoplastic Behavior of the Ferritic Stainless Steel AISI 441-EN 1.4509 from Room Temperature to 850°C, Journal of ASTM International, Vol. 3, No. 7, Paper ID JAI13197, 2006.

[4] Taira, S., (1973), Relationship between thermal fatigue and low-cycle fatigue at elevated temperature, Fatigue at elevated Temperatures, ASTM STP 520, ASTM, p. 80-101.

[5] G.Chinnouilh, P.O.Santacreu, J.M.Herbelin, Thermal Fatigue Design of Stainless Steel Exhaust Manifolds, SAE Tech. Paper, 2007 – 01 – 0564, Detroit 2007

[6] F.R. Larson and J. Miller, A Time-Temperature Relationship for Rupture and Creep Stresses, Trans. ASME, Vol 74, p 765–771, 1952

[7] E.Contesti, G.Cailletaud and C.Levaillant, Creep damage in 17-12-SPH stainless steel notched specimen : metallographical study and numerical modeling, 5th Int. seminar on inelastic analysis and life prediction on high temperature environment, Paris, July 1985.

[8] D.R. Hayhurst, Creep rupture under multiaxial states of stress, J. Mech. Phys. Solids 20, 381-390