MATEC Web of Conferences **165**, 16003 (2018) https://doi.org/10.1051/matecconf/201816516003
FATIGUE 2018

Thermomechanical fatigue behaviour of ferritic stainless steel grades for high temperatures applications

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Abstract. Nowadays high temperatures resistant materials are needed to resist to high temperature applications (up to 1000°C), such as automotive exhaust gas manifolds. Some developed stainless steel grades, including ferritic grades or austenitic refractory grades, can be used in this temperature range and both in continuous or cyclic thermal conditions. In order to predict the thermomechanical fatigue damage of stainless steel parts submitted to cyclic thermal loading and constrained bonding conditions, the elasto-viscoplastic model by Chaboche is determined for a wide range of temperatures, of strain amplitudes and strain rate levels thanks to isothermal traction-compression tests. The validation procedure is performed afterward by comparison with stabilized behavior under non isothermal conditions on a dedicated thermal fatigue test performed on V-shape specimens. Results of simulation show very good fitting with the experimental curves which would lead to a more accurate fatigue life prediction. A damage model was derived from Taira's thermal low-cycle fatigue model to include dwell-time period at high temperature and creep-oxidation effect. In this paper the example of K44X, a dedicated grade for high temperatures applications, is presented.

1 INTRODUCTION

Although electric vehicles start to be highly developed nowadays, thermal engine cars but also hybrid vehicles still need appropriate materials for the exhaust line. As a consequence of the decrease of the pollutants emissions of vehicles (high reduction of NOx, HC, PM from Euro 3 to Euro 6), the temperature of the exhaust gas tends to increase. Therefore, corrosion and thermomechanical fatigue resistance of exhaust line need to be improved by the use of stainless steel rather than cast iron [1].

Today some austenitic and ferritic grades are proposed as high temperatures resistant stainless steels. Austenitics stainless steels grades present higher mechanical properties at high temperatures but the advantage of ferritic grades is a lower coefficient of thermal expansion. K44X (AIISI 444, EN 1.4521), a high temperature ferritic grade, offers an important improvement in terms of thermal fatigue and creep resistance in comparison with AIISI441 (EN 1.4509) grade, can overtake temperature peak of about 1 000°C. It has to be pointed out that this grade was especially developed for high temperature applications and that it could not be substituted by a regular 1.4521/444 grade. The other advantage of ferritic stainless steel grades is their free Nickel content which involved higher price stability.

An example of high temperature application is exhaust manifolds which are now commonly made of stainless steels. However, increasing their durability is still a challenge. Indeed, these components are the hottest parts of the exhaust system, bolted on the motor block to collect the hot burned gas and to feed them into the catalytic converter, those parts are subjected to creep, oxidation and thermomechanical fatigue. As motor bench tests are expensive, modelling the manifold under the thermal loading by finite element analysis is a cost effective and a time saving solution.

In order to predict lifetime of such components, a V-shape fatigue test was developed to reproduce in laboratory typical thermomechanical loading of the hot end of the exhaust line. High temperature and thermomechanical properties of our grades are investigated through this test and through isothermal tests since few years. In addition, damage models are identified at high temperatures and used to predict lifetime of components. To get those damage predictive models, a behavior model need first to be identified thank to isothermal cyclic tests [2-4].This paper presents the identification of the behavior and damage models for K44X at high temperatures.

2 MATERIAL AND EXPERIMENTAL PROCEDURE

2.1. Materials

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The K44X is a monostabilized niobium 1.4521 ferritic material dedicated to high temperature applications; its typical chemical composition is given Table 1. The 2% Molybdenum content increases the high temperature tensile strength compared to an AIISI441 (EN 1.4509). The Niobium prevents against chromium carbides precipitation during heat treatment and welding and therefore provides a good corrosion resistance [5]. In parallel, the excess of Niobium leads to the precipitation of niobium at grain boundaries which improve the creep resistance of the material ("pinning effect" of the grain boundaries avoiding grain boundaries sliding)[6]. The material keeps its complete ferritic structure up to 1025°C and presents a very good oxidation behavior because its low coefficient of thermal expansion is also close to the one of its oxide layer: unlike austenitic grades, spallation of the oxide at high temperatures is unlikely. Even if the mechanical properties of ferritic stainless steels are intrinsically lower than austenitic grades, the advantages of cyclic oxidation, creep and thermomechanical fatigue behavior make the K44X a suitable material for high temperature components.

EN grade designation	C	Cr	Si	Mn	Mo	N	Nb	Fe
1.4521	0.02	19	0.6	0.3	1.9	0.015	0.6	Bal.

Table 1. Chemical composition of K44X – EN1.4521

The considered thickness for exhaust application is often below 2mm and the surface finished of the tested specimens for this study is 2D (non skinpassed).

2.2. High temperature tensile test

High temperature tensile tests are carried out according to EN ISO 6892-2 standard on a 100KN INSTRON tensile machine with a 1000°C-resistance furnace. Flat specimens are cut along the rolling direction. In general two or three samples are tested per condition. After a 2h heating procedure, tensile tests are performed at a constant displacement rate of 0.54mm/min.

2.3. Isothermal cyclic test

In order to identify the elastoviscoplastic behavior model, isothermal test are performed on LCF flat specimens cut along the rolling direction. The cyclic tests are carried out from 20°C to 1000°C with an INSTRON 8802 tensile machine with a resistance furnace, according to a specific strain signal. The tests are performed with different strain levels (maximal strain value: 0.2, 0.4 and 0.6%) and with two different strain rates (0.1 and 0.02%/s) at a fixed temperature. The first part of the signal is composed of 20 triangular waves (for material accommodation) with a maximal strain value of 0.2% and a strain rate of 0.1%/s. The next parts of the signal are composed of three triangle waves piloted by deformation and three square waves (relaxation phenomena, piloted by displacement) with a strain ratio of R=-1 for each strain level/strain rate condition (i.e: 6 conditions). An example of signal for one strain level/strain rate condition is given Figure 1.

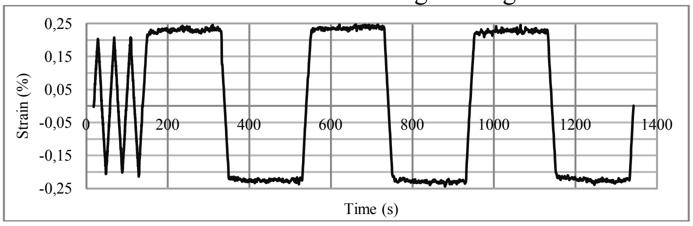

Figure 1. Extract of a strain signal during the test, triangle parts are piloted by deformation and the relaxation parts by displacement.

For this test, at high temperatures, only one sample is used for time saving due to 3 hours of heating procedure. This experimental procedure is validated through additional intermediate signal parts which have to be reproducible, the microstructure and grain size are also checked. To prevent buckling of the flat sample, an anti-buckling system is used (see next figure).

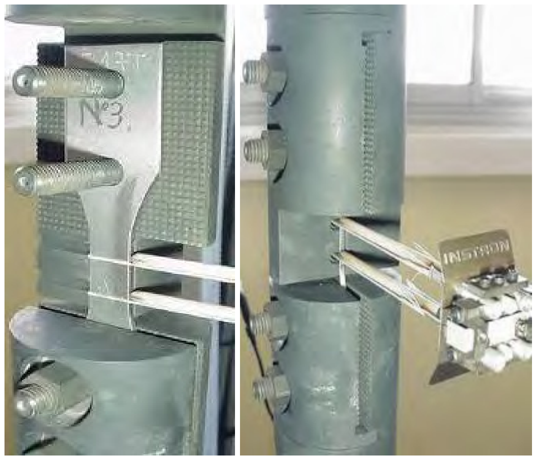

Figure 2. Anti buckling equipments developed for light-gauge flat samples

2.4. V-shape thermal fatigue test

This V-shape test was initially developed to reproduce typical thermomechanical fatigue (TMF) conditions that hot end line undergoes. Today, this test also enables to classify the different stainless steel grades in term of thermomechanical fatigue lifetime but also in terms of damage mechanisms. From the results, a damage behavior model is identified to predict, through finite element simulation analysis, the fatigue lifetime of hot application components and their risky zones.

The specimens are taken from stainless steel sheets of thickness between 1 and 2 mm along the rolling direction and then bended to obtained a V-shape. During the TMF test, the V-shape sample is held by its ends in fixed jaws and is heated up by Joule effect which causes a stress strain response. The thermal stresses in the jaws and the temperature are monitored during the test by means of a force cell and a thermocouple welded on the sample surface respectively. The thermal cycle is composed of a heating, a natural convection air cooling phase and can also include a dwell time (up to 180s).

Interactions between creep and cyclic oxidation phenomena are less or more pronounced depending on the maximal temperature and the holding time. The intrados of the sample is solicited out of phase (compression during heating) and the extrados is solicited in phase.

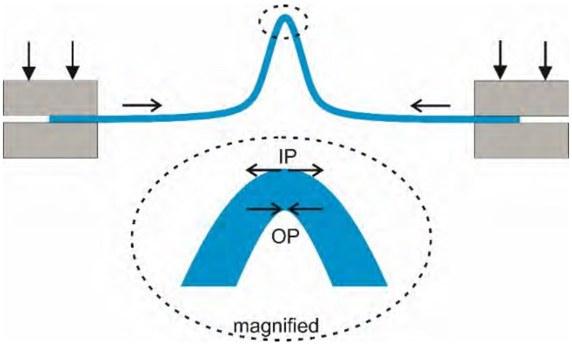

Figure 3. Stress loading of V-shape sample during heating

The lifetime is determined at 50% decrease of the maximal stress compared to the stabilized value in order to avoid an increase of current density. Depending on the maximal and minimal temperature, the dwell time but also the specimen thickness, the test duration is around 3 weeks or more.

3 CONSTITUTIVE MODELS

3.1. Behaviour model

No strain measurement can be carried out during V-shape tests. The cumulated plastic strain for each test condition is calculated thanks to a behavior model and to finite element analysis with a post processor of Abaqus. The elastoplastic model by Chaboche is an accurate model to describe stainless steel behavior at high temperature, especially when a material is subjected to cyclic loading, because it takes in account the viscous effects present at high temperatures unlike an elastoplastic model (especially when T>500°C)[7].
In this model, a non linear kinematic hardening is combined with an isotropic hardening and the Norton viscoplastic law. Strain partition is assumed [8].

$$\underline{\underline{\varepsilon}}_{tot} = \underline{\underline{\varepsilon}}_{th} + \underline{\underline{\varepsilon}}_{el} + \underline{\underline{\varepsilon}}_{vp} \quad (1)$$

The elastic part and the thermal part of the strain are described as:

$$\underline{\underline{\varepsilon}}_{el} = \frac{(1+\nu)}{E}.\underline{\underline{\sigma}} - \frac{\nu}{E}.Tr(\underline{\underline{\sigma}})\underline{\underline{I}} \quad (2)$$

$$\underline{\underline{\varepsilon}}_{th} = \alpha.\Delta T.\underline{\underline{I}} \quad (3)$$

The yield criterion includes isotropic and kinematic hardening and is defined by:

$$J_2(\underline{\underline{\sigma}} - \underline{\underline{X}}) - R \geq 0 \quad (4)$$

From the yield criterion, the viscoplastic strain tensor is deduced:

$$\dot{\underline{\underline{\varepsilon}}}_{vp} = \frac{3}{2}\cdot\dot{p}\,\frac{\underline{\underline{\sigma}}' - \underline{\underline{X}}'}{J_2(\underline{\underline{\sigma}} - \underline{\underline{X}})} \quad \text{where} \quad \dot{p} = \left\langle \frac{J_2(\underline{\underline{\sigma}} - \underline{\underline{X}}) - R}{K} \right\rangle^n \quad (5)$$

The subscript (') indicated the deviatoric part of the tensor and the dot (·) stands for the time derivative. The non linear back stress X (kinematic hardening) and the isotropic hardening R are defined by:

$$\dot{\underline{\underline{X}}} = \frac{2}{3}C\cdot\dot{\underline{\underline{\varepsilon}}}_{vp} - D\cdot\underline{\underline{X}}.\dot{p} \quad (6)$$

$$\dot{R} = b(Q-R).\dot{p} \quad (7)$$

As the behavior material is determined on stabilized material, the isotropic hardening is constant since no change of the viscoplastic radius is assumed.

$$R = R_0 \quad (8)$$

3.2. Taira model

The thermomechanical fatigue damage model is based on Taira's model which is an adaptation of the Manson-Coffin formula to non isothermal low cycle fatigue [9]. The number of cycle up to failure is described as a function of the cumulated plastic strain and of the temperature. The predicted thermal fatigue lifetime is expressed in number of cycle as followed:

$$N_f = \lambda(T_{eq}) \,.\, \Delta\varepsilon_{pcum}{}^{n} \quad (9)$$

$$\text{where } \Delta\varepsilon_{pcum} = \int_{cycle} \sqrt{\frac{2}{3}(\varepsilon_{ij}^{p} : \varepsilon_{ij}^{p})}\,dt \quad (10)$$

$\Delta\varepsilon_{pcum}$ stands for the cumulated plastic strain during one stabilized cycle. The exponent n may depend on an effective temperature for a given grade. λ is a function of the equivalent temperature and of the dwell time defined first by [4] in order to take into account time-dependent effect like oxidation. The parameters a and b are parameters evaluated from experimental data.

$$T_{eq} = \frac{T_{\max}}{1 - aT_{\max}\ln(1 + b\tau)} \quad (11)$$

4 RESULTS

4.1. Isothermal tests and Chaboche model identification

The Chaboche model, already determined up to 850°C, is described in [10]; until now for higher temperatures, the materials parameters were carefully extrapolated. Materials data have been updated and determined at 920 and 1000°C. The results are mainly focused on higher temperatures such as 1000°C. The isothermal results for 0.1%/s strain rate at the different strain levels are given Figure 4.

https://doi.org/10.1051/matecconf/201816516003

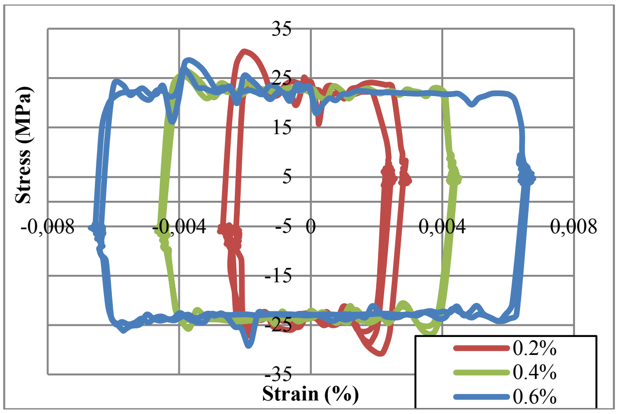

Figure 4. Isothermal cyclic tests results at different strain levels for 0.1%/s strain rate at 1000°C

The results above show that stress strain signal amplitude of the signal does not exceed 25MPa which highlights a very low mechanical behavior at 1000°C. At this temperature, the material is highly viscous and a difference of 6MPa can be observed between the maximal stress reached with the low and the high strain rate tests. Given the flat plastic part, kinematik hardening part is almost negligible (C/D ratio →0) such as the elastic part.

A microstructure study enables to check eventual grain growth during the test. For the "as received sample", very few thin intragranular Nb-precipitates are observed. For the LCF tested specimen, the head of the specimen, where the grains are the less deformed, was studied. The grain size measurement shows no grain growth during the cyclic test. Few niobium precipitates are observed in the grains but a lot can be observed at the grain boundaries and where they have coarsened. This precipitation of Niobium reduces the grain boundary sliding by pinning effect providing a high creep resistance for K44X, the precipitation does not modify the behavior model along the cyclic test and the amplitude of the intermediate additional stress-strain signal is reproducible from a test part to another.

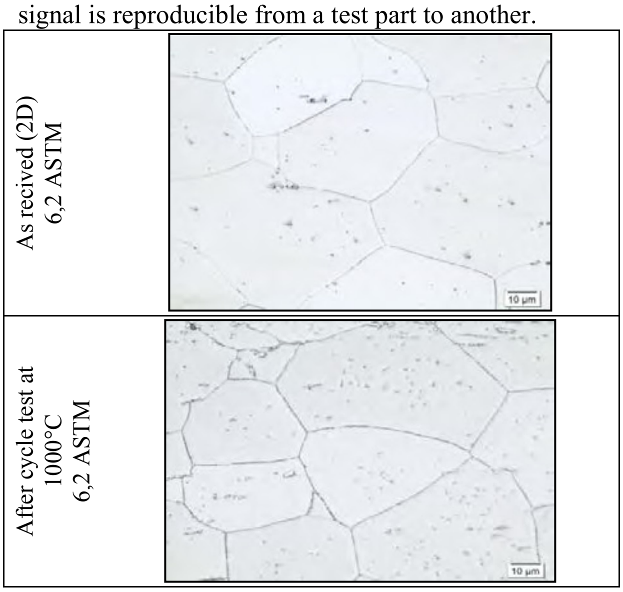

Figure 5. Microstructure study of the sample before and after isothermal cycle test at 1000°C

The 6 tested conditions enable to determine the Chaboche model at 1000°C, the parameters are validated in isothermal conditions but also an isothermal conditions.

Isothermal validation

To validate the obtained model in isothermal conditions, an additional test with different strain rate (0.08%/s) and strain amplitude (1.0%) was carried out. This test, not taking into account during the identification, was simulated with the determined Chaboche parameters. At 1000°C, a very good correlation is obtained between the two signals.

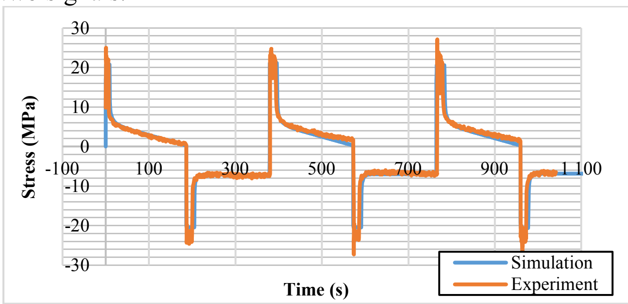

Figure 6. Validation of the behavior model in isothermal conditions at 1000°C

Anisothermal validation

Although the Chaboche model is calibrated with isothermal tests, the model is used in non isothermal conditions. In order to validate the Chaboche model in anisothermal loading, comparison of the experimental data of V-tests (recorded loading and temperature) and a simulated V-shape specimen with the obtained behavior model and finite element simulation with Abaqus is carried out.

The simulation of a 2mm thick V-shape sample between 950 and 250°C without dwell time was performed with Abaqus. The results are compared with the first and the 1000th cycles of the experimental test. A good correlation is obtained in terms of load amplitude but also in terms of area under the curve.

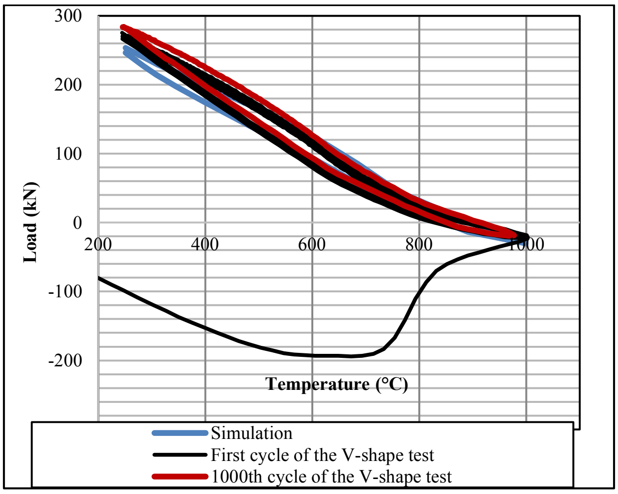

Figure 7. Anisothermal validation of the Chaboche model between 250 and 1000°C

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Comparison with tensile test results

The elastoviscoplastic behavior of the material can be related with general mechanical properties, especially the ultimate tensile stress (UTS). An elastoplastic stress value (EVP stress), close to the maximal stress of a strain-stress curve with strain rate of 0.1%/s, was calculated for each temperature (see Figure 8). A linear relation between the UTS and the EVP stress is obtained highlighting the close relation between the identified parameters and typical mechanical properties. Indeed, with the increase in temperature, there is a general drop in mechanical properties with an increase in viscosity: the proportion of the viscosity part of the material behavior increases. With the increases in temperature there are also drops in elastic modulus but also in the kinematic and isotropic hardening. The proportions of those parts with respect to the EVP stress at each temperature are given Figure 9.

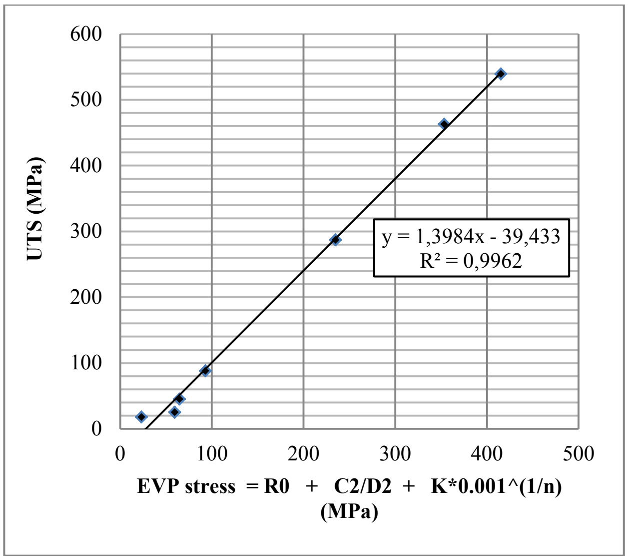

Figure 8. Ultimate tensile stress and behavior model correlation for K44X

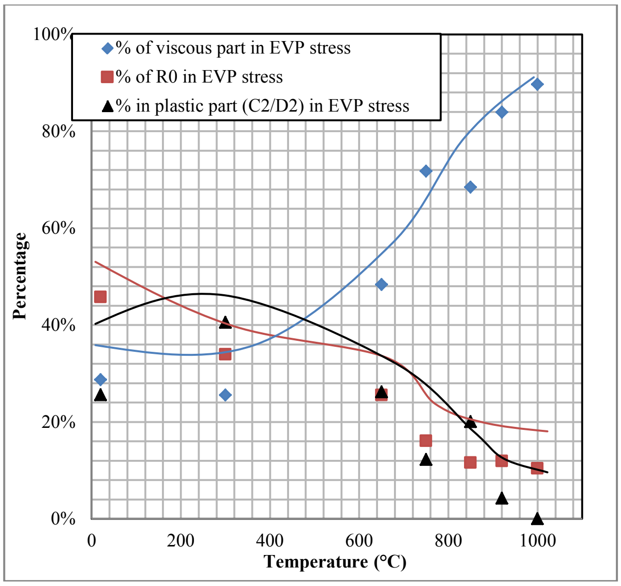

Figure 9. Material behavior evolution with the temperature

4.2. Thermomechanical fatigue tests and Taira model identification

The elastoviscoplastic model but also a large database of thermomechanical fatigue tests are needed to identify the damage model. TMF tests are carried out up to 1050°C and post mortem samples analysis enables to better understand damage mechanisms. For ferritic grades, failure is driven by out of phase mechanisms in the intrados of the V-shape specimen due to the low cyclic oxidation sensitivity and the low thermal expansion. Indeed, for austenitic grades, at high temperature, the cracks tip tends to open in extrados (tensile loading) increasing the oxidation risk. The K44X high creep resistance leads to a conservation of the V-shape of the specimen and to a high lifetime in thermomechanical loading up to 1025°C. Above 1050°C, the damage is more pronounced and grain growth can occur.

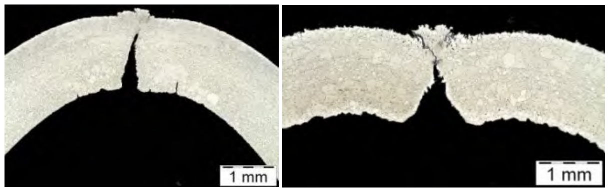

Figure 10. Post mortem analysis of V-shape samples (left maximal temperature of 950°C/ right maximal temperature of 1050°C)

Depending on the thickness of the V-shape specimen, the length between the jaws, the height of the specimen, the maximal temperature reached during the test, the lifetime can be less or more important. The increase of thickness leads to higher thermal constraints and so to a decrease of lifetime. Figure 11 shows, for tests with a minimal temperature of 250°C, the effect of the thickness on the lifetime of the V-shape sample.

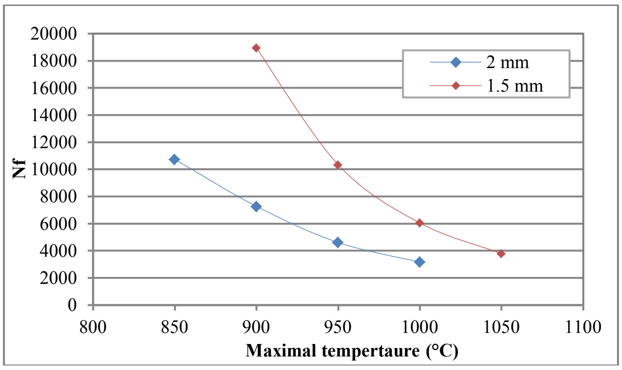

Figure 11. Effect of the thickness of the V-shape specimen on fatigue lifetime (Minimal temperature of 250°C, no dwell time)

From the thermomechanical V-test results and the simulations of this test through Abaqus (elastoviscoplastic model), determination of $\Delta\varepsilon pcum$ values on the top of the V are carried out enabling the identification of the Taira model. The thermomechanical fatigue lifetime of component can be predicted thank to a post processor of Abaqus, Xhaust_Life®, critical areas are highlighted and different design of component can be tested, compared and enhanced.

5 DISCUSSION

The identification of the behavior model (Chaboche) shows good agreement with the experimental data. In the case of thermal fatigue damage model, no measurement can be carried out during the tests. That is why a finite element analysis is required to get the cumulated plastic strain for each test conditions before identifying the damage model. The lifetime prediction demonstrates good correlation with experimental data. Comparison between lifetime calculations on manifold and motor bench test confirms those assessments.

However, some critical areas observed after the simulation and by OEM are often close to welded area. Studied were performed on welded V-shape specimens nonetheless, testing a welded sample is challenging because the configuration of the specimen has to be well chosen. From the different tested welded specimen geometries, the "edge join" geometry seems the most relevant (Figure 11). The lap join specimens were highly deformed during the tests leading to a high scattering in the results and the butt join are less representative of real manifold conditions. A large amount of tests with different grades, thickness, temperatures need to be first performed to determine the damage criteria.

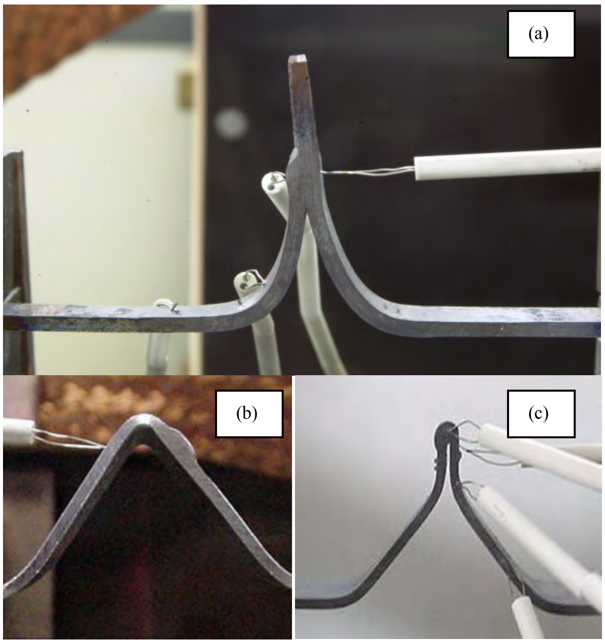

Figure 12. V-shape test with weld specimen configuration ((a) lap join; (b) butt join; (c) edge join)

6 CONCLUSION

K44X is a cost effective solution for high temperature applications because of its really good thermal fatigue behavior due to its lower thermal expansion coefficient and its oxidation resistance at high temperatures. Its chemical composition with high niobium content enables a high creep resistance; the molybdenum increases the tensile strength making this grade suitable for exhaust manifold.

The elastoviscoplastic mechanical behaviour of K44X was determined for a wide range of conditions and up to 1000°C thank to isothermal cyclic traction-compression tests. In parallel, thermomechanical fatigue tests were also performed to classify TMF resistance of the stainless steel grades and studying the damage mechanisms involved. The TMF tests also enable to determine Taira fatigue damage model proposed to predict lifespan of components. With the identified damage model the simulation of thermal fatigue loading in exhaust parts is carried out and critical area in terms of fatigue lifetime can be detected. The comparisons with OEM observation show really good agreement with the simulation. However, critical areas subjected to thermomechanical fatigue are sometimes observed in welded zones. Thus, the resistance of thermal fatigue of weld joins need also to be investigated through new welded V-shape samples.

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8 NOMENCLATURE

σ	Stress tensor
X	Tensor variable of Kinematic hardening
R	Isotropic hardening variable
R0,	Isotropic hardening constant
Q, b	Material parameters for isotropic hardening
C	Initial hardening variable of Frederick-Armstrong formula
D	Recovery parameter of Frederick-Armstrong formula
ν	Poisson's ratio
K, n	Norton law parameters
T	Temperature
εtot	Strain tensor
εvp	Viscoplastic strain tensor
εth	Thermal strain
εel	Elastic strain tensor
p	Accumulated plastic strain
E	Young Modulus
Δεpcum	Equivalent viscoplastic strain amplitude during a stabilized cycle