

Damage Mechanisms of Stainless Steels under Thermal Fatigue

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ABSTRACT

Thermal fatigue of austenitic and ferritic stainless steel grades has been experimentally and numerically investigated. A special test has been developed to determine the thermal fatigue resistance of clamped V-shaped specimens. This test permits to impose thermal cycle by alternating resistance heating and air cooling. The thermal fatigue life of a specimen is expressed as the number of cycles to failure. For a given grade, the fatigue life depends on the maximal and minimal temperature of the cycle, holding time at the maximal temperature and specimen thickness. The advantage of this V-shape test is that it is a simple procedure quite representative of the thermal fatigue process occurring in an exhaust manifold. This test is well suited to perform a study of damage mechanisms and to compare stainless steel grades. Examination of the failed specimens indicated that cracks could be mainly attributed to out-of-phase (OP) thermal fatigue process especially in case of ferritic grades. For austenitic steels (AISI304 EN1.4301, AISI321 EN1.4541 or AISI308 EN1.4828) at a critical temperature or above, an in-phase (IP) thermal fatigue mechanism is coupled with oxidation and creep, which are further significantly reducing the lifetime. Therefore, the service temperature range of austenitic grades is more limited than ferritic grades. Despite their lower yield stress at high temperature, ferritic grades exhibit a very good thermal fatigue resistance at elevated peak temperatures because of their very good cyclic oxidation behavior, creep resistance and their low coefficient of thermal expansion. Consequently a dedicated titanium or niobium stabilized ferritic offer was developed for the hot part of the exhaust system (from manifold to catalytic converter) that includes 14%Cr (K11X 429/425 1.4595), 17%Cr (K41X 441 1.4509) and 19%Cr (K44X modified 444 1.4521) grades in order to cover the peak temperature range from 900°C to 1050°C.

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INTRODUCTION

Background

Our study deals with the development of numerical lifetime assessment tools dedicated to the design of stainless steel parts operating at high temperature in cycling conditions, typically for maximal temperature up to 1050°C. Target applications are automotive exhaust components like manifolds, catalytic converters or exhaust gas recirculation systems but also for solid oxide fuel cell bipolar plates or burner components. In such part, cyclic thermal stresses and plastic strains are generated in areas where thermal expansion is constrained and may lead to the failure of the part. Watanabe paper [1] was the first to present an accurate thermal fatigue description of a stainless manifold, in particular the paper brought the evidence of an OP fatigue process as the main cause of cracks. Therefore material selection and part design appear to be main driving forces for the improvement of the thermal fatigue resistance of exhaust components.

Objectives

In aim to support the use of stainless steel in fabricated exhaust manifold application, studies were conducted to develop stainless steel grades that provide suitable high-temperature mechanical properties and also to propose methods for thermal fatigue design of such components [1,2,3]. Our approach consists in the simulation of the thermal fatigue process at laboratory scale using "V-shaped" specimens and in the calibration of a damage model for finite element analyses. The Taira's thermal fatigue damage is chosen and relates the fatigue life, plastic strain amplitude and maximal temperature by a Manson-Coffin type law [4]. In parallel, the elasto-viscoplastic behavior of the materials was determined in the range of typical service temperatures, like Chaboche model but some others have been proposed [5,6]. The complete approach was detailed in different references [7,8,9], and the objective of the present paper is to review the fatigue damage mechanisms under cycling temperature that differ as a function of the material grades and of in-service temperatures.

MATERIALS

The studied materials are stainless steel grades that could be used in the form of bent and hydroformed tubes or deep-drawn sheets for manifold applications [6]. In comparison to cast-iron manifolds, fabricated stainless manifolds offer higher durability and lightweight design. In fact, the considered thicknesses are in range from 1 to 3 mm. Three families of grades can be distinguished (Tab.1):

- Titanium and niobium stabilized ferritic stainless steel grades containing from 11 to 20% Cr, like AISI 441 (EN1.4509), are characterized by low ultimate tensile strengths at temperature above 850°C (around 40 MPa), a low thermal expansion coefficient around $12 \cdot 10^{-6}/^{\circ}\text{C}$ and a good cyclic oxidation resistance. Creep resistance of ferritic grades can be significantly improved by an intergranular precipitation of stable niobium intermetallic compounds.
- Austenitic stainless steel grades containing around 18% Cr and 10% Ni, like AISI 304, 321 (EN1.4301, EN1.4541) are characterized by higher ultimate tensile strengths than ferritic ones (around twice those of ferritic grades), but also a high coefficient of thermal expansion around $18\text{--}20 \cdot 10^{-6}/^{\circ}\text{C}$, and poor cyclic oxidation resistance at temperatures above 800°C;
- Austenitic refractory grades, containing at least 20% Cr and 12% Ni, like AISI 308Si/302B (EN1.4828) whose properties are close to austenitic grades (HT strength, CTE) but with better oxidation behavior especially when rare earth elements (Ce, La, Y) are added. However in cyclic conditions, their oxidation resistance above 900–950°C is limited. Addition of rare earth elements in AISI 308Si can improve the oxidation resistance a little bit for some steels, such as AISI/UNS 30815 EN1.4835. In this category, a refractory nickel alloy with 23%Cr (601-alloy) was also tested.

Table 1. Comparison of high temperature properties for the different families of alloys.

Grades		CTE ($10^{-6}/^{\circ}\text{C}$) 20–800°C	Ultimate Tensile Strength (MPa)	
			600°C	850°C
FSS grades	441 1.4509	11.5	270	35
ASS grades	304 1.4301	18.8	340	100
Refractory grades	308S 1.4828	19.2	400	140
Special alloys	601-alloy 2.4851	17.1	580	150

THE V-SHAPED TEST

Experimental Procedure

A special test has been developed to determine the thermomechanical fatigue (TMF) resistance of steel sheet specimens (Fig.1). This test permits to impose a thermal cycle on a clamped V-shaped specimen by alternating resistance heating and air cooling (Fig. 2) Specimens are taken from

sheets of thickness between 1 and 2mm. The procedure has also been adapted to the case of welded specimens [10]. Specimens are constrained at both ends which causes strain-stress response at the top of the “V” when the temperature fluctuates. Clamping force (thermal stresses) at minimal temperature, temperature and number of cycles are monitored during the test. Typical fatigue response of the specimen is shown on Fig.3 and includes a first half cycle of plastic accommodation followed by stabilized fatigue loops. For fixed conditions, cracks initiate and propagate at the top of the V after a given number of cycles. That leads to a loss of stiffness and to drop of the clamping force. The thermal fatigue life of a specimen is expressed as the number of cycles to failure determined conventionally as the number of cycles after which the clamping force has decreased by 50% (Fig.4). For a given grade, the fatigue life depends on maximal and minimal temperature of the cycle but also on holding time at maximal temperature and on specimen thickness. Key parameters of the test affecting the fatigue life are listed on table 2. The advantage of this test is that it is a simple procedure to compare stainless steel grades performance but is also representative of the thermal fatigue process occurring in an exhaust manifold, which makes it useful to carry out a study of the damage mechanisms. Because of their higher coefficient of thermal expansion, austenitic grades are submitted to higher thermal stresses. However this rig simulates what really occurs in a clamped structure subjected to thermal cycling like some components of hot part of the exhaust line, especially manifold clamped to the engine block.

Table 2. First order parameters of the V-shape test rig

Material	
Coefficient of thermal expansion	Higher the CTE, higher the thermal stresses, lower the cyclic oxidation resistance
Mechanical behavior	HT strength resistance
Sample geometry	
Thickness	Higher the thickness, higher the stresses
V-dimension	Shorter the V-height, higher the stresses
Test Rig parameters	
Thermal Cycle	T max, $\Delta T = T_{\text{max}} - T_{\text{min}}$, holding time τ
Free Length	Longer the length, higher the stresses

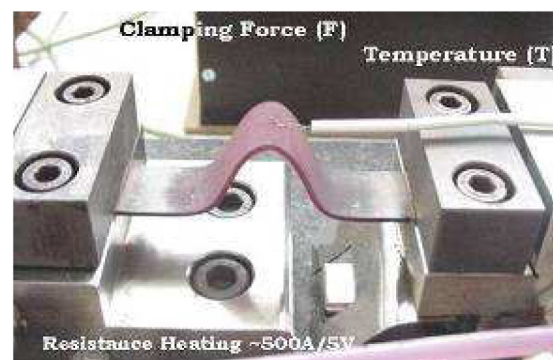


Figure 1. Principle of the V-shaped thermal fatigue test

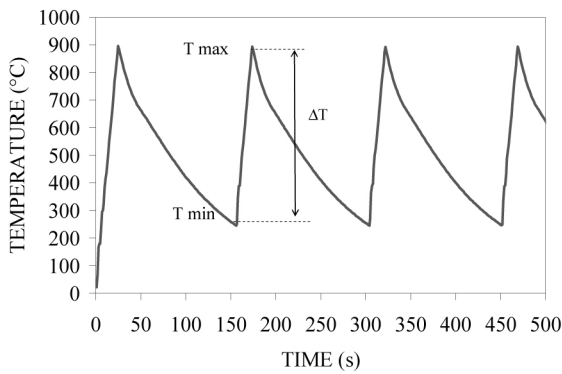


Figure 2. Typical thermal cycle 250-900°C (a holding time at T max can be added)

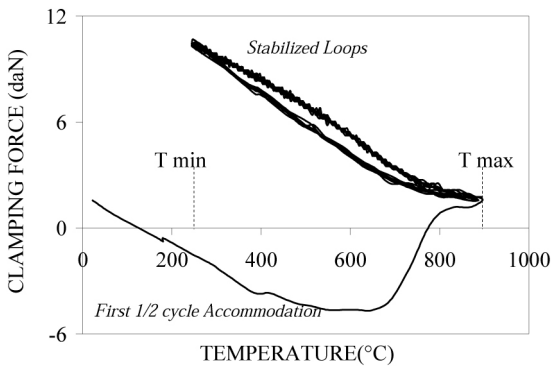


Figure 3. Measured force-temperature loops showing first an accommodation followed by stabilized fatigue loops

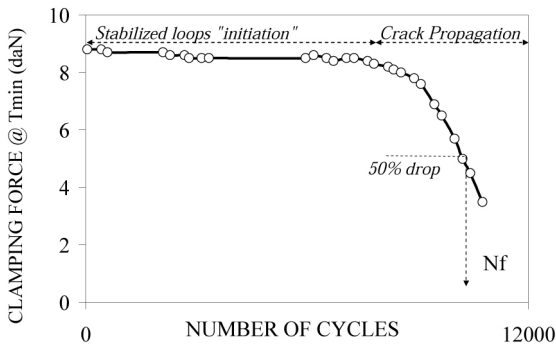


Figure 4. Determination of thermal fatigue life (Nf) based on maximal force measurement

Mechanical Analysis

The finite element modeling of the V-shaped test was achieved with Abaqus to evaluate the mechanical strain and stress in order to calibrate a thermal fatigue damage model. Plastic strain is indeed difficult to measure and was therefore assessed numerically. The theory and procedure are detailed in [4,9] and the Taira model expressed by the following equation was calibrated for several grades.

$$N_{TF} = \lambda(T_{max}, T_{min}, \tau) (\Delta \epsilon_{epcum})^{\beta}$$

N_{TF} is the thermal fatigue life expressed as a function of the viscoplastic strain amplitude $\Delta \epsilon_{epcum}$, a material exponent β and a function λ that depends on temperatures T_{min} , T_{max} , and holding time τ .

In fact, the mechanical state at the top of the V is characterized by an alternating dissymmetrical bending process where intrados (inner curve of the V) and extrados (upper curve of the V) behave differently. Due to the initial curvature, intrados area is more stressed than the extrados area (neutral fiber is shifted toward extrados). On the other hand, the maxima of stress (in absolute value) are observed at the minimal temperature for which the mechanical properties are the highest. As shown on Fig.5 the phasing between stress (or mechanical strain) and temperature signals is opposite for intrados and extrados sides. An out-of-phase mode is indeed observed at intrados (tension at the minimal temperature) and an in-phase mode (tension at the maximal temperature) is observed at extrados (Fig.6).

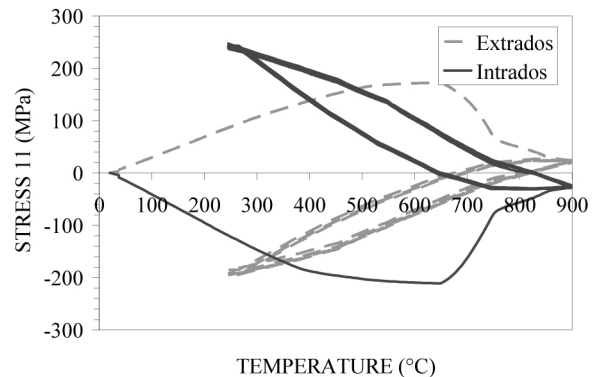


Figure 5. Stress loops for both sides of the V-shape area, showing in-phase TMF loading on extrados and out-of-phase on intrados.

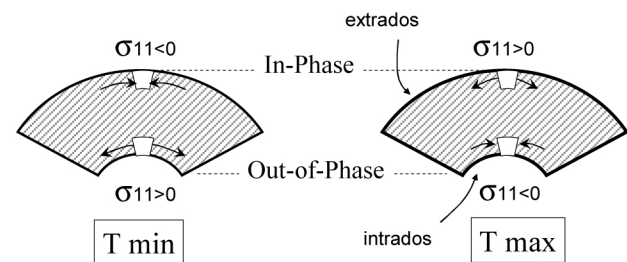


Figure 6. Schema of in-phase TMF at extrados and out-of-phase TMF at intrados.

Consequently the accumulation of plastic strain is done differently at intrados and extrados: the IP and OP modes will play significantly on the coupling between plastic strain, creep and oxidation (Fig.7). The IP mode (tension at the highest temperature) favors the creep and oxidation damage.

For the thermal fatigue damage calculation using our modified Taira model, a method was previously proposed to take into account the phasing between temperature and stress (IP or OP mode) and was implemented in Xhaust. Life post-treatment for Abaqus [9]: the phasing between thermal cycle and the mechanical cycle has to be computed first.
 Documents
 AVA
 Stochastic Hub