

Life Prediction Approach for Stainless Steel Exhaust Manifold

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ABSTRACT

Stainless steel grades are now widely used for automotive exhaust systems, driven by the need to increase their durability and to reduce their weight. Exhaust Manifolds are subjected to more severe conditions and peak gas temperatures of 1000°C could be reached in new downsized gasoline engines. Also, longer guaranties are now required. This evolution is a direct consequence of the effort to decrease automotive pollutant emissions with new environmental regulations throughout the world. The paper will deal with the thermal-mechanical fatigue (TMF) damage prediction of fabricated automotive exhaust manifold fixed to the engine. A dedicated lifespan prediction approach was created based on elasto-viscoplastic behaviour and damage models identification from different thermal-mechanical tests. The experimental procedure will be presented, especially the high temperature cyclic plasticity tests developed on thin sheet specimens and the V-shape thermal fatigue test that simulates the TMF process observed on manifolds subjected to engine bench tests. The Chaboche model was chosen for the elasto-viscoplastic model including a kinematic hardening plastic law coupled with the Norton viscous law. Our damage model is based on the Taira non-isothermal low-cycle-fatigue LCF criteria that has recently been completed with a Larson-Miller creep damage law in order to take into account of mean stress effects due to static loading on the manifold. The paper will also present the implementation of the models in the post-processing software named XhaustLife and for Abaqus Finite element simulations.

CITATION: Santacreu, P., Faivre, L. and Acher, A., "Life Prediction Approach for Stainless Steel Exhaust Manifold," *SAE Int. J. Passeng. Cars - Mech. Syst.* 5(2):2012, doi:10.4271/2012-01-0732.

INTRODUCTION

In an effort to decrease the pollutant emission of vehicles by catalytic conversion or down-sized engine, the temperature of the exhaust gas increases with up-grading of emission control norm. Consequently the durability of the exhaust line, especially corrosion and thermomechanical fatigue (TMF) resistances, needs to be improved significantly by the use of stainless steel rather than cast iron. Moreover AISI 441 1.4509 can be insufficient for some applications where longer guaranties are requested or when peak temperature peak reaches about 1000°C. That is why a new ferritic stainless steel, designated K44X, was recently developed to fit these new demands.

The manifold is the hottest part of the exhaust system, bolted on the motor block to collect the hot burned gas and to transmit them to the catalytic converter. It is mainly subjected to a thermomechanical process. Focusing on the fatigue process, the in-vehicle loading history for the exhaust manifold is not well known and, at least for us, histograms of

maximal temperature and loads for a large population of drivers are not yet available. On the other hand, the motor bench test which is the validation test for acceptance, performed by exhaust makers, is more accessible. A typical bench cycle is recalled in [Fig. 1](#): its duration is around 1000 seconds including a full load period of 400 s leading to the highest temperature - here 900°C - and an idling period where the temperature decreases below 600°C. The maximal and minimal temperature depends on the power and stroke of the engine, but they are generally in the range from 100°C to 950°C. An exhaust manifold has to pass approximately 2000 cycles to be considered validated for production but it depends on model and car manufacturer requirements. Therefore if the manifold does not pass the test some design improvements or material evolutions are necessary.

The fractures that are observed on failed parts are characterized by orange peel/elephant skin around the cracks revealing a cumulated cyclic plastic deformation, and further by a multiple thermal fatigue crack facies ([Fig.2](#)). Some oxidation and creep damage are often observed, especially in

case of austenitic grades. The objective is to provide a fatigue design approach of stainless steel exhaust manifold based on our experiences of stainless steel behavior at high temperature and both thermal and mechanical finite element simulation [1]. The approach should help exhaust makers to optimize the material choice and the design of the manifold. The developed tool consists of post-processing software - Xhaust-Life- that includes material properties and damage laws, and which is able to predict thermal fatigue life and excessive creep deformation after a standard thermal and mechanical calculation.

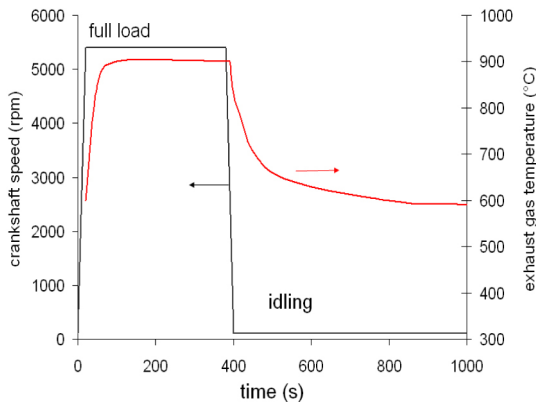


Figure 1. Example of a typical motor bench test cycle



Figure 2. Failed exhaust manifold part showing a thermal fatigue crack

MATERIAL AND EXPERIMENTAL PROCEDURES

STAINLESS STEEL

The experimental procedure is illustrated by the study performed on a new ferritic stainless steel, K44X, specially designed for very high temperature applications. Chemical analysis is given in [table 1](#) and all properties were detailed in [2]. In fact the K44X offers a significant improvement in term of thermal fatigue and creep resistance in comparison with AISI441 EN 1.4509 grade and can support peak temperature of about 1000°C.

TABLE 1. Chemical composition (wt%)

Designation	AISI - EN	C	Mn	Si	Mo	Cr	N	Other	Fe
K44X	444-1.4521	0.02	0.3	0.6	1.9	19	0.015	0.6Nb	Bal.

CYCLIC PLASTICITY TEST

For the behavior model identification, data from isothermal fatigue tests were used. In these tests, 2mm-thick flat samples were deformed on an INSTRON 8802 tensile machine according to a specific strain signal including 30 triangular waves followed by 3 square waves, $R=-1$ (Fig. 3). For each tested temperature (from 20 to 850°C), tests were performed with different strain amplitudes in the range from 0.2 to 0.6% and with 2 strain rates, 0.1 and 0.01%.s⁻¹. The experimental method earlier presented for round-specimen geometry was recently adapted for flat samples in order to do the test on sheets that are actually used to manufacture the exhaust manifolds (Fig. 4).

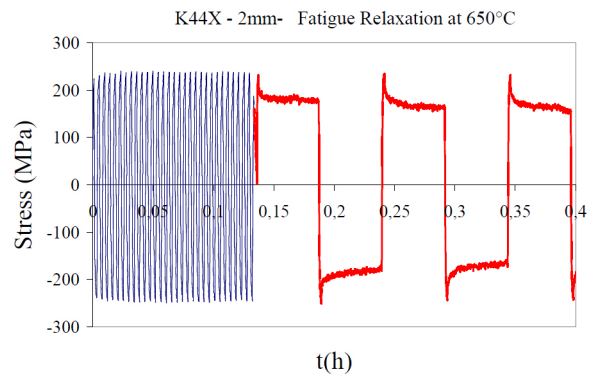


Figure 3. Example of stress signal output of a fatigue relaxation test

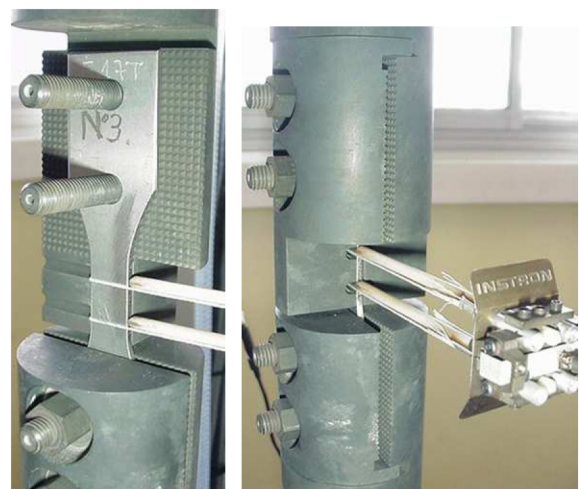


Figure 4. Equipment for material behavior identification using anti-buckling system developed for light-gauge flat samples

THERMAL FATIGUE TEST

A special test has been developed to determine the TMF resistance of steel sheet specimens. The testing rig and the experimental procedure are described in [3]. This test was designed to apply a thermal cycle to a clamped V-shaped specimen by alternating resistance heating and air cooling phases (Fig. 5). It has also been adapted to the case of welded specimens [4]. Specimens are constrained at each ends which causes strain-stress response. Specimens are taken from sheets of thickness between 1 and 2mm. Constraining force at cold state, temperature and number of cycles are recorded during the test (Fig. 6). The TMF life of a specimen is expressed as the number of cycles to failure determined conventionally as the time after which a 50% decrease of the constraining force has occurred. For a given grade, the fatigue life depends on the maximum and minimum temperature of the cycle, on dwell time at the maximum temperature and on the specimen thickness. The fatigue life is the mean value of three tests and standard deviation is below 10% (duration of one test is around 2-3 weeks). The advantage of this test is that it is both simple for classifying the TMF resistance of the stainless steel grades and representative of the TMF process occurring in exhaust manifolds, while focusing on a study of the different damage mechanisms (Figure 7). For the damage model, a wide range of data from thermal fatigue test had been used (different samples thicknesses, temperatures, sample shapes, and holding time). However, the damage model we have considered is a strain-based model and finite elements calculations had to be carried out to determine the strain amplitude for each test conditions.

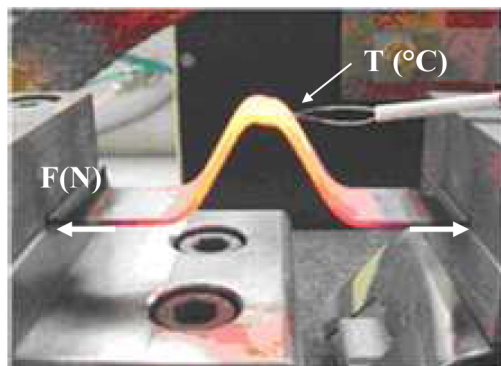


Figure 5. Thermal fatigue V-shaped test

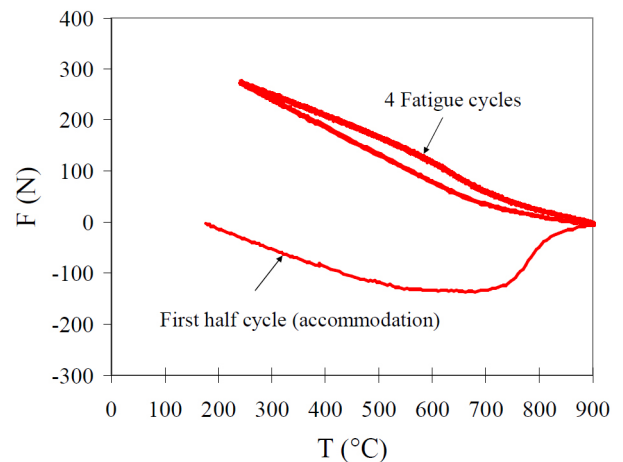


Figure 6. Typical thermal fatigue test applied to the specimen

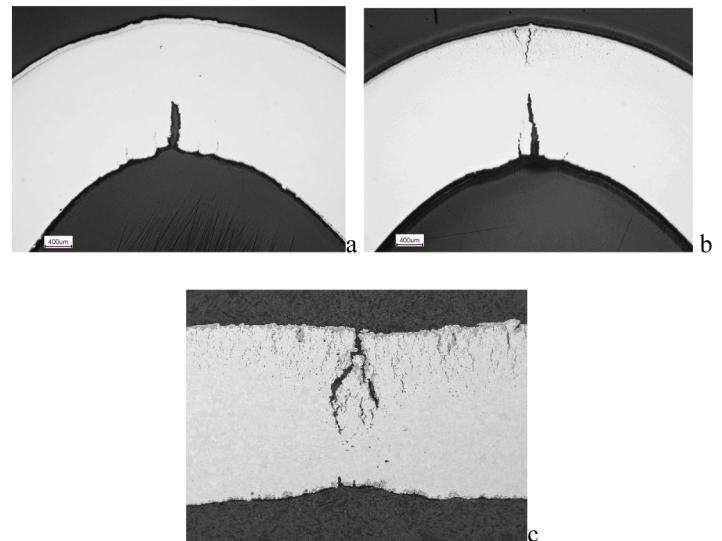


Figure 7. Damage mechanisms: a) cyclic plastic crack (out-of phase), b) cyclic plastic cracks at intrados and extrados (both out-of phase and in-phase processes) and c) strong coupling with oxidation in an in-phase thermal fatigue process.

CREEP TEST

Creep tests are performed on the same equipment that we used for cyclic plastic test. The procedure consists in the application of a constant stress and in the evaluation of the time to reach a 1% total deformation of the specimen. The creep deformation is monitored with a high temperature extensometer. Tests are performed in isothermal conditions at 750, 850 and 950°C and the time to 1%-deformation is scanned in a range of duration from 1 to about 100hours (Fig. 8). A main difficulty was to adapt the test and specimen geometry for creep tests to be carried out on flat thin-sheet (1.5-2mm).