Car manifold's fatigue life under thermo mechanical loadings

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Abstract Car manifolds undergo severe thermo mechanical loadings. Due to their complicated geometry, they are made of several components welded together. In the welded zone, one can observe geometrical discontinuities (surface finish and welding defects) and a behaviour mismatch between the weld metal and the base metal. This discontinuity induces a lifetime reduction. The aim of this study is to elaborate a fatigue criteria to predict lifetime of a stainless ferritic car manifold. In a first step, an original experimental method has been developed to identify a simplified but realistic behaviour model for each material in the weldment. In a second step, a comprehensive campaign of isothermal fatigue life tests has been done on welded and non welded specimens.The influence of behaviour mismatch on the lifetime reduction factor is experimentally analysed as a function of temperature. We propose to model the base metal's fatigue life by an energetic approach and by an approach developed by Lemaître [LEM 96], based on continuum mechanics. The application to the welded structure is presently under study.

1 INTRODUCTION

Many industrial components undergo severe thermo mechanical loadings. Due to their complicated geometry or their important size, they are often made of several components welded together. These weldments are microstructurally and mechanically heterogeneous across the weld joint. Due to this discontinuities, weldments can be potential sites of the fatigue failure, inducing a significative lifetime reduction.

Several authors have investigated weldment's influence on low cycle fatigue lifetime, in isothermal conditions. It has been shown that the fatigue life is influenced on the one hand, by the geometry of the weld : back strip geometry, welding defects. On the other hand, it is also influenced by the interaction of the different cyclic plastic behaviour of the materials which compose the weldment. In particular, strain distribution in the weldment plays a key role in low cycle fatigue. If the present materials have close fatigue strength limit, the structure will allways break in the zone where strain concentrates [OKA 88].

In the automotive industry, several components, like manifolds or cylinder blocks, are subjected to thermo mechanical loadings. In order to respect the specifications in terms of fatigue life, it is required to pass several times by the following steps: design, testing and correction. In order to reduce the number of iterations, engineers need accurate and less time consuming computational tools. Some work has been done to provide accurate models for manifold's lifetime estimation. Most of them have not taken into account the effect of weldments on fatigue life. The present work is an attempt to characterize the fatigue life of a ferritic tubular car manifold, considering the reduction factor lifetime due to weldments.

In order to get an accurate prediction of the manifold lifetime, it is important to numerically evaluate the mechanical response in the critical zones. In a first part, we investigate the behaviour of the base metal and welds that compose a stainless ferritic car manifold subjected to high temperature loadings. The base metal (BM) is a X2CrTiNb18 stainless steel. The filler metal is a X3CrNb17 stainless steel. From an industrial point of view, it is important to characterize the weld's behaviour in the simplest way. Then, we developed an innovative experimental procedure that allows evaluating an average but realistic behaviour of the weld.

In a second part, the fatigue life of the welded zone is investigated. A comprehensive campaign of isothermal fatigue life tests has been conducted on welded and non welded specimens. The influence of behaviour mismatch on the lifetime reduction factor are experimentally analysed as a function of temperature. We propose to model the BM's fatigue life by an energetic approach and by an approach developed by Lemaître [LEM 96], based on continuum mechanics. The application to the welded structure is presently under study.

2 STUDY OF MATERIAL’ S BEHAVIOR

2.1 Materials

The base material investigated in this study is a stainless ferritic steel. It is a low carbon steel with high chromium content. Its cubic metallurgical structure is stable until melting. Under temperatures lower than 1000°C, this steel is subjected to few precipitations. Precipitation of Laves Phase Nb is more likely to happen and is known to have a beneficial effect on creep resistance [BUC 04] . The filler material is a X3CrNb17. It is very similar to base metal's composition. Changes have been done to improve weldability.

2.2 Specimens

Weldments often present a complex metallographic structure, where three main domains can be distinguished: filler metal, heat affected zone (HAZ), parent metal. The heat affected zone is where the base metal has been heated to a high temperature and allowed to cool fairly rapidly. Depending on the welding process and the micro structural stability of the base metal, its metallurgical properties are more or less affected in the HAZ. For instance, Gaffard [GAF 04] showed that the HAZ of a 9Cr1MoNbV weldment was composed of three sub zones: coarse grained austenite, fine grained austenite, martensite partially transformed in austenite. To characterize a welded zone, it is therefore necessary to have a good understanding of its metallurgy.

Moreover, it has been shown that weldments' fatigue life can be strongly influenced by global mismatch ratio, defined as the ratio of the yield strength of weld metal to that of the base metal, and by the local mismatch ratio, defined as the ratio of the yield stress of weld metal to that of the HAZ [RAV 04]. Specimens should then have a yield stress similar to industrial tube.

According to these considerations, choosing specimens to characterize behaviour of weldments is not a simple matter.

In some cases, weldments are big enough to draw specimens or micro specimens directly from the industrial structure [MAD 04]. Sometimes, HAZ is so small that no drawing could be done. To characterize their behaviour, some researchers try to reproduce its structure by appropriate heat treatments [PAN 05]. This method is interesting but time consuming.

In our case, we have decided to make samples as close as possible to the industrial welded tube:

- Base metal specimens (type I) have been taken from tubes similar to the one used for industrial manufacturing. These specimens present the following advantages: similar grain size and surface finish compared to industrial tubes, presence of strain hardening due to tube forming like industrial tubes.

- Specimens for weld behaviour identification (type II) have been made according to the following procedure. In a base metal tube, a groove has been machined and filled with filler metal by GMAW (gas metal arc welding) process, with the industrial welding parameters, see Fig. 1.

Therefore, with this type of specimen, we will identify an equivalent behaviour for filler metal and HAZ. Two reasons justify this choice: this geometry is similar to the one found in the industrial configuration (see Fig. 1); microstructures of filler metal and HAZ are close.

FIG 1 – micrography of a) type II specimen, b) industrial weld

2.3 Isothermal test procedure and identification of a model

Low cycle fatigue tests under total strain control have been performed on the two types of specimens. Strain has been recorded with a 10 mm gauge length extensometer with alumina rods. The temperature test range is 20°C to 850°C. The procedure of low cycle is based on the ones developed by [ZHA 02] and [VEL 06]. For each temperature, one specimen is submitted to different sequences of strain cycles, exhibiting the following characteristics of the material: cyclic hardening/softening, kinematic hardening, viscous effect. For type II specimens, the two rods are placed in the groove. The response of an equivalent weld, including HAZ and filler metal, is then monitored.

Base metal presents cyclic softening during first hundred cycles. Thereafter, its cyclic behaviour is stable. Cyclic softening amplitude is important at 20°C and continuously decreases with temperature. Indeed, recovery of strain hardening due to tube forming is thermal activated. Equivalent weld metal presents cyclic hardening during first cycles. Its cyclic behaviour is saturated in a very short time. At any test temperature, the highest stress level for same strain loading is lower in the weld than in the base metal.

According to the previous experimental behaviour, it is proposed to describe the cyclic behaviour of the weld and base metal with an elastoviscoplastic model developed by [CHA 89]. A set of parameters has been identified for each test temperature.

2.4 Prediction capability assessment

Since we expect to simulate the mechanical response of a car component under high temperature loadings, we should verify that the models, identified in isothermal conditions, are able to correctly predict mechanical response of the materials under thermomechanical loadings.

Thermomechanical tests have been carried out on base metal specimens. These tests were performed under mechanical strain and temperature control. Four types of TMF (thermo mechanical fatigue) tests were performed: In-Phase (IP) test (maximum strain occurs at maximum temperature), Out-Of-Phase (OP) test (maximum strain occurs at minimum temperature), Out-Of-Phase-Compression (OPC) test, and Out-Of-Phase-Traction (OPT) test. The comparison between experiments and simulations were satisfactory, see for more details [ROB 06].

We have considered that, as a first approximation, weld behaviour can be assimilated to the behaviour of an equivalent material, including filler metal and HAZ. This strong assumption has been validated by the following procedure:

- one strain control LCF test has been performed on a bi material test, see Figure 2 at 20 °C. A volumetric finite element simulation of this test has been performed using ABAQUS software where the two elastoviscoplastic models have been implemented through the developer tool Z-Mat (Zset package, 1996). In order to validate the equivalent material, calculated and measured axial force-strain responses have been successfully compared, see Figure 2.

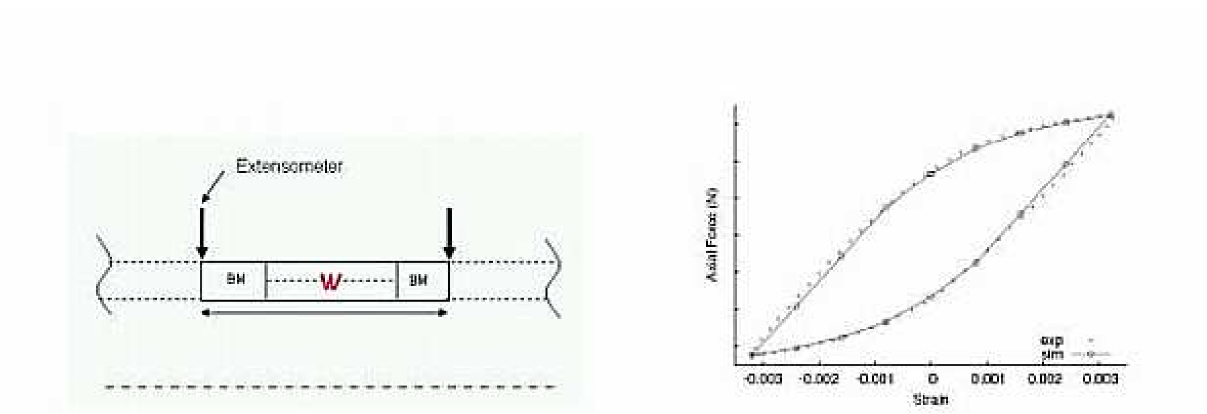

FIG 2- Bi material specimen a) sketch, b) axial Force Strain curve

- one test realised in the same conditions but with a local strain measurements by means of image stereo correlations.

The comparison in between simulations and experiments allows to conclude that the bi material hypothesis is acceptable.

3 EXPERIMENTAL FATIGUE LIFE STUDY

3.1 Procedure

Isothermal fatigue tests have been conducted at five different temperatures: 300, 500, 600, 700 and 800°C. The experimental set is identical to the one used for the previous tests. In the case of the welded specimens, the weld is only 2 mm large and is placed at the centre of the working zone. The distribution of strain in between base metal and weld metal is therefore highly dependent on the ratio of the size of the weld to the gauge length (10 mm).

3.2 Fatigue test results

The Manson-Coffin and Whoeler curves at 300°C, 600°C and 700°C, for the base metal and the welded specimens are given on figures 3 to 7. Concerning Whoeler curves, the slopes for BM and welded specimens are significantly different. This suggests the stress distribution in the welded specimens is dependent on the level of strain load. The slope of the Manson Coffin curves are on the contrary quite close, which allows defining a fatigue reduction life for the structure based on the level of measured plastic strain. The Manson-Coffin law has the following expression :

$$\Delta\boldsymbol{\varepsilon}_p / 2 = \boldsymbol{a} \times \boldsymbol{N}_R^c \qquad (1)$$

The reduction fatigue life is given by:

$$\boldsymbol{R}_{\Delta\boldsymbol{\varepsilon}_p} = \left(\boldsymbol{a}_W / \boldsymbol{a}_{BM}\right)^c \qquad (2)$$

This reduction factor goes from (1/3.67) at 300°C to (1/2.16) at 700°C.

In the same way the plastic mismatch ratio in between welded metal and BM reduces with temperature going from 0.76 at 300°C to 0.95 at 700°C. It seems then that as welded material and BM tends to get similar behavior, the influence of weld on fatigue life is reduced. Some specimens were examined by means of Scanning Electron Microscope after being etched. The post mortem observations reveals that for all the temperatures, only transgranular cracks are observed. The position of the cracks depends on the level of temperature. At 500°C, cracks are concentrated in and near the welded zone. Whereas, at 700°C, cracks are situated in all the working zone. Post mortem observations then correlate the previous remark.

4 FATIGUE LIFE FOR BASE METAL

The Manson-Coffin law is usually well adapted to low cycle fatigue lifetime. Nevertheless, it is meaningless when considering anisothermal loading since there is no representative plastic strain amplitude.

Since the forming of cracks requires a dissipation of energy, it seems quite natural to introduce an energetic parameter to describe the fatigue of metals. Based on the work of Skelton [SKE 91] , Charkaluk [CHAR 00] has successfully applied an energetic approach to predict fatigue life of a car manifold. This approach considers that the dissipated energy per cycle at stabilization is a good indicator of the material's fatigue loading, and can therefore be related to the number of cycles to failure. However, Charkaluk has shown that it is not a simple matter to correctly evaluate the amount of energy dissipated per cycle in the case of multiaxial loadings.

Based on continuum mechanics, some authors have proposed to introduce a damage variable D which models the loss of resisting area due to micro-cracks and micro-cavities ($0<D<1$). Failure of the representative volume element then occurs when D reaches its critical value. Damage, in his isotropic formulation, is coupled to elasticity and visco-plasticity by means of the effective stress tensor. Strain and stress redistributions in a structure, can therefore be taken into account while damage increases.

The damage evolution law proposed by Lemaitre [LEM 96] is the following:

$$\dot{D} = \left(\frac{Y}{S}\right)^{s} \dot{p} \text{, if } p \geq p_{D} \text{, } Y = \frac{\sigma_{eq}^{2} R_{v}}{2E} \tag{3}$$

The time integration of this equation allows for the quantification of damage for any complex loading like thermo mechanical loadings. The damage strength *S*, the damage exponent *s*, the critical damage D_c are material parameters and p_d is the loading dependent damage threshold. The energy density release rate *Y* is function of the effective equivalent stress and of a triaxility function R_v.

In the present study, an energetic approach and the Lemaitre's damage model are applied to the base metal.

The energetic criterion proposed by Charkaluk is :

$$w_{s} = a \times N_{R}^{c} \tag{4}$$

,with a and b material constants.

To the contrary of the material studied by Charkaluk, the energy dissipated per cycle by BM depends significantly on the level of temperature, in the range of temperature considered. In order to get a unique criterion for all temperature, w_s is divided by the ultimate stress [BUC 04]. Ultimate stress is not a material constant and is relatively scattered. Although this aspect has not been considered, this criteria gives a fast and reasonable fatigue lifetime prediction for base metal in isothermal conditions, see figure 8.

The damage evolution, and therefore the fatigue life, as defined by Lemaître is characterized by 4 material parameters. The damage threshold p_d and the critical damage D_c have been deduced from the damage versus cumulated plasticity curve obtained from cyclic tests, damage being evaluated by its influence on the elasticity modulus. The damage strength *S* and the damage exponent *s* have been numerically adjusted by comparing experimental and simulated maximum stresses. The identification procedure follows what Sermage proposed [SER 00]. The parameter D_c is around 0.2 for all temperatures. The parameter *s* is closely related to the slope of the Manson-Coffin's curve. Since this slope is almost constant with temperature, *s* has been optimized only at 600°C and keep identical for the other temperatures. For all the temperatures except 700°C for which experimental results are significantly scattered, the Lemaître's law predicts the specimen's lifetime with an error of less than 20%

5 CONCLUSION

The aim of this study is to provide car manifold designers with helpful tools for fatigue lifetime prediction.

In a first step, thanks to an innovative experimental procedure we have been able to analyze the behaviour of the welded zones of a car manifold. We have then realized a comprehensive isothermal fatigue test campaign on welded and non welded tubular specimens. Two criteria have been identified for BM's fatigue lifetime prediction. Anisothermal tests validation will be handled soon. Comparison in between fatigue life of welded and non welded specimens has shown that as temperature increases, the reduction factor due to the weld reduces. This observation could be explained by the fact that welds and BM tends to get closer behaviour inducing less strain concentrations. A numerical study of welded specimens' mechanical response will be performed to confirm this hypothesis. Moreover, some fatigue tests will be interrupted in order to compare crack localization, time to initiation and propagation in function of specimens' type and temperature. Based on these information, a suitable fatigue lifetime criterion for welded structure will be developed..

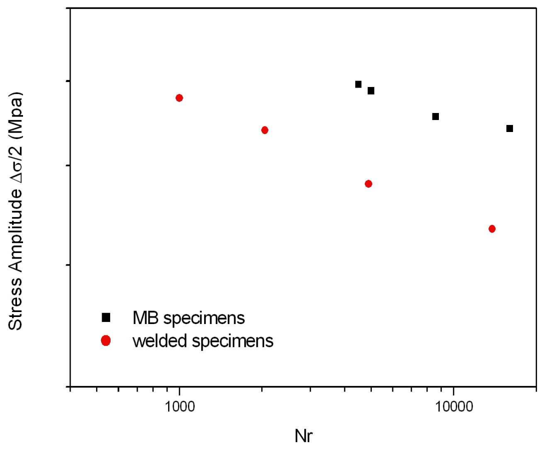

FIG 3 -Whoeler curve at 300°C

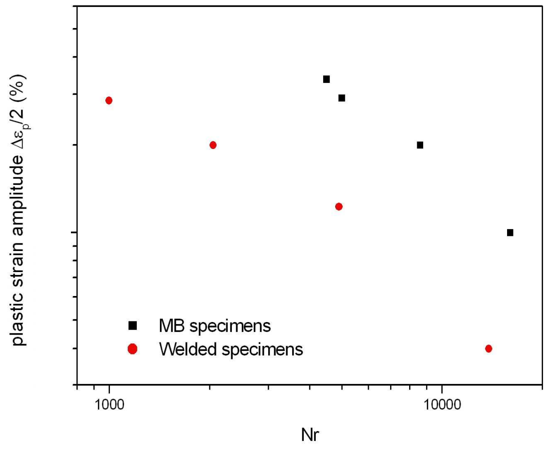

FIG 4 - Manson-Coffin curve at 300°C

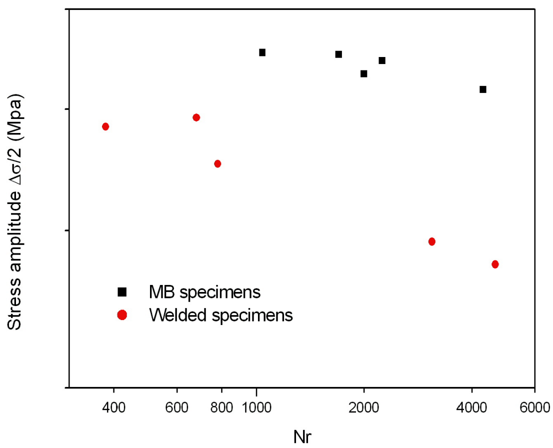

FIG 5 -Whoeler curve at 600°C

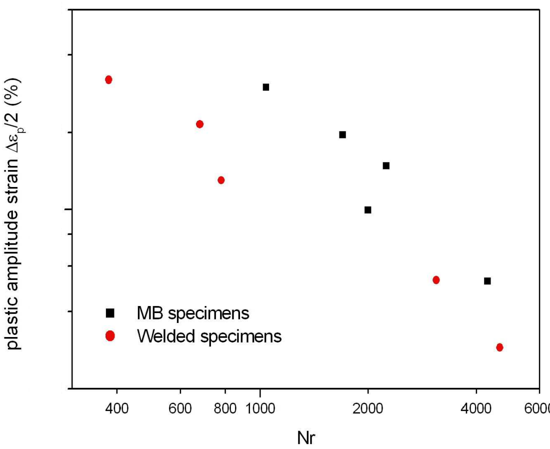

FIG 6 - Manson-Coffin curve at 600°C

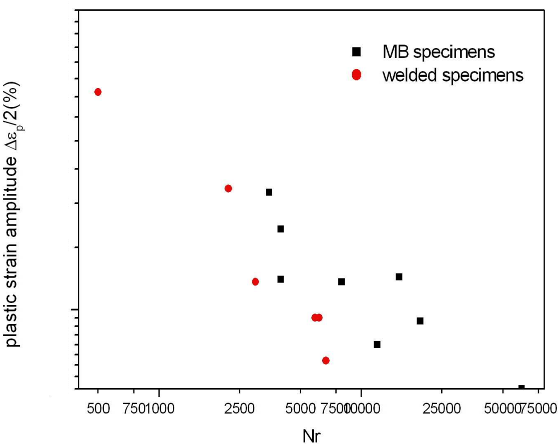

FIG 7 - Manson-Coffin curve at 700°C

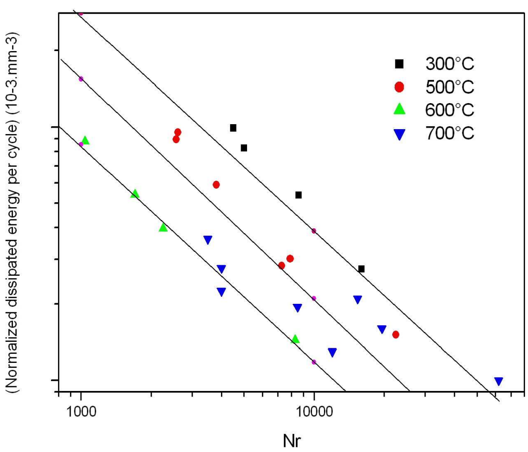

FIG 8 – Energetic criteria for life prediction

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