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Experimental investigation of the behavior and the low cycle fatigue life of a welded structure

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ABSTRACT

Strain controlled low cycle fatigue tests are performed at 300 °C under tension compression on an 18%Cr ferritic stainless steel using base metal and welded specimens. Changes in the microstructure and geometry of the weld bead have a negative impact on the specimens' lifetime. Digital image correlation is used to get information on strain gradient in specimens. Potential drop measurements as metallographic observations are used to monitor micro-cracking. The significance of the results is discussed using finite element computations of welded specimens and observations of fracture surfaces. A tentative rationale is proposed using an energy based micro-crack growth model.

1. Introduction

Stainless steels are widely used for the exhaust line of cars, in particular for catalytic convertors due to their high oxidation resistance. They offer alternate solution of exhaust manifolds that are traditionally made of cast iron. Austenitic and ferritic stainless steels have a better resistance to high temperature corrosion and oxidation than cast iron. Ferritic stainless steels are less expensive due to the absence of nickel and they have better thermal conductivity and lower expansion coefficients than austenitic alloys [1,2].

The international control to decrease vehicle polluting emission by catalytic conversion tends to increase exhaust gas temperatures up to 800–950 °C. Manifolds are then enduring more and more severe thermal cyclic stresses during start up, shut down operation near the most clamped areas, which may lead to the failure of components. Such components operate under thermal–mechanical low cycle fatigue (LCF) and manifolds made of stainless steels have to be welded at many places. Therefore a methodology has to be established to design welded manifolds, which combines several difficulties: modeling of the material behavior, of the weld bead and LCF lifetime assessment.

LCF is very difficult to model under high temperature conditions because non-linear computations are required. The major task is to identify an elasto-plastic constitutive model or an elasto-visco-plastic model. Such an effort has been made in our group to investigate Chaboche type models for ferritic stainless steels [1–3] or improved models for cast iron [4] and more recently for ferritic 18%Cr steels [5].

Design engineers need efficient structure analysis and simple models. A simplified method has been introduced for high cycle fatigue [6] at room temperature, that uses rigid elements to model the weld bead. This method could be adapted to low cycle fatigue provided that the weld does not change significantly the constitutive behavior of the base material. This assumption needs to be validated but may be reasonable in the case of ferritic steels.

Once stress analysis is performed from thermal loading and boundary conditions [7], fatigue lifetime can be estimated by post-processing stress and strain fields. A lifetime criterion based on low cycle fatigue test data is most often used [7]. Robustness arguments support the renewed interest for dissipated plastic energy criteria instead of usual strain ranges as introduced by Manson and Coffin. In low cycle fatigue, numerous authors have proposed to use inelastic energy [8,9] and more recently [10–12] to correlate crack initiation results and dissipated plastic energy. Constantinescu and co-workers [13] have produced convincing evidence that this dissipated plastic energy concept in a post-processing analysis can predict crack locations and give pretty good estimate of lifetime to crack initiation in actual components.

However the effect of the weld on the low cycle fatigue life must be assessed. Most studies concentrate on establishing *S–N*

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curves for smooth specimens that are tested along a direction perpendicular to the weld bead [14–16]. Radaj [17], Sonsino and coworkers [18] proposed to use notch stress concepts which basically aim at modeling the stress state at the weld toe. They distinguish between thick and thin walls to define an equivalent notch radius. Recently, Zaletelj [15] in a careful study investigated the LCF life at room temperature of base metal 1.4512 (AISI 409) and welded specimens. They concluded that the weld joint is the main reason of fatigue life reduction under strain controlled conditions.

The present study is part of an investigation that aims at obtaining a methodology to design welded hot structures such as exhaust manifolds that operate under repeated thermal shock. The purpose was to investigate the effect of the weld on the LCF life of ferritic steel under strain-controlled conditions. Many experimental studies on base alloys subjected to uniform loading have distinguished between the crack initiation period defined to some microstructure unit, like a grain size in polycrystals, and the crack propagation period [19,20]. At high temperature the growth law of small cracks is expected to control to a large extent the LCF life to crack initiation (see Skelton for several reviews [21,22]). Numerous rationales have already been proposed like empirical laws, cyclic J integral arguments, or other equations [23–25]. Therefore it was intended to clarify this issue in the case of welded specimens to give a more physical basis to the criterion to be used in the design of components subjected to LCF.

This article reports low cycle fatigue results under tension compression strain control at 300 °C on an 18%Cr steel 1.4509 (AISI 441) using base metal and welded specimens. Digital image correlation is used to get information on strain gradient in specimens. Potential drop measurements as metallographic observations are used to monitor micro-cracking. A model for the LCF lifetime of welded specimens is then proposed. The weld bead is modeled using volume elements that respect the actual weld bead geometry and that present a material behavior identical to the behavior of the base material. A crack propagation based LCF lifetime model using energy parameters is calibrated with experimental lifetime results from base material and welded specimens. The significance of the model and its parameters is discussed using potential drop, striation spacing and optical measurements performed on a plate specimen and on a welded specimen.

2. Material

2.1. Material description

The material chosen for this study is an industrial ferritic stainless steel for automotive application, F18TNb (corresponding to AISI 441 or EN 1.4509 grades). Its chemical composition is detailed in Table 1. Plate specimens are machined from 2-mm-thick plates.

A butt-welded joint is created between two 2-mm-thick plates by a classical arc-welding process, the welding direction being parallel to the rolling direction (RD) of the sheet. As received, plates were welded using a metal inert gas (MIG) process using 1.4511 steel as filler, using the same conditions as for exhaust manifolds. Welded plates were supplied by Aperam. Welded specimens are extracted from this welded plate, the weld bead being located at the center of the specimen.

Table 1
Chemical compounds of the studied ferritic stainless steel (at. weight) [1].

C	N	Cr	Ti	Nb	Si	Mn	Fe
0.017	0.02	17.67	0.15	0.50	0.59	0.42	Bal.

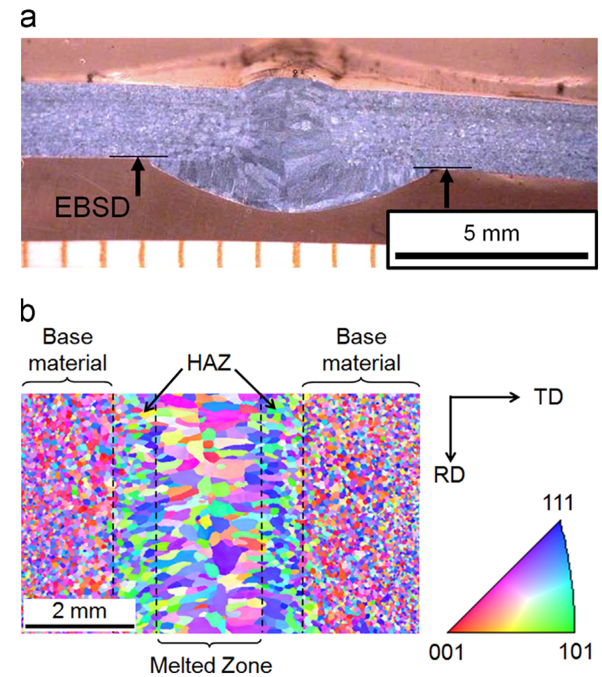

Fig. 1. Weld microstructure. (a) Microstructure revealed by aqua regia and (b) orientation image map of the weld performed on the side of the larger overlap after removal of the weld bead.

Fig. 1a shows the microstructure of the asymmetrical weld bead, revealed by a solution of aqua regia (85% H_2O, 10% HNO_3, 5% HCl). Three distinct zones appear in the microstructure:

- Small equiaxial grains in the plate.
- Larger grains at the center of the weld bead, stretched along the thermal gradient created during the welding process, perpendicularly to the welding direction.
- Middle-sized equiaxed grains in the heat affected zone (HAZ), making the link between the base material and the melted zone. The temperature of the material was high enough during the welding process to induce local grain coarsening.

An EBSD map shown in Fig. 1b is performed on the perpendicular plane represented in Fig. 1a, after removal of the weld bead, in order to get quantitative information on grains' size and shape. Using the software OIM Analysis 6.1, the mean grain size is estimated along the rolling direction (RD) and along the transverse direction (TD) using the intercept method. The analysis is conducted on two zones:

- The plate or base material which is composed of the left and right sides in Fig. 1b.
- The welded zone which is composed of the melted zone and the HAZ. Indeed, the estimation of the grain size cannot be conducted on the HAZ alone because this zone is narrow and does not count enough grains. The melted zone and the HAZ are grouped together to create one unique zone, large enough to obtain a valuable assessment of the grain size.

In the plate, the average grain size is significantly lower than in the welded zone and quite similar along both directions: 43 μm along RD and 49 μm along TD. In the welded zone, the average grain size is 184 μm along TD and 96 μm along RD, confirming the stretch of the grains along TD. Mechanical properties of the